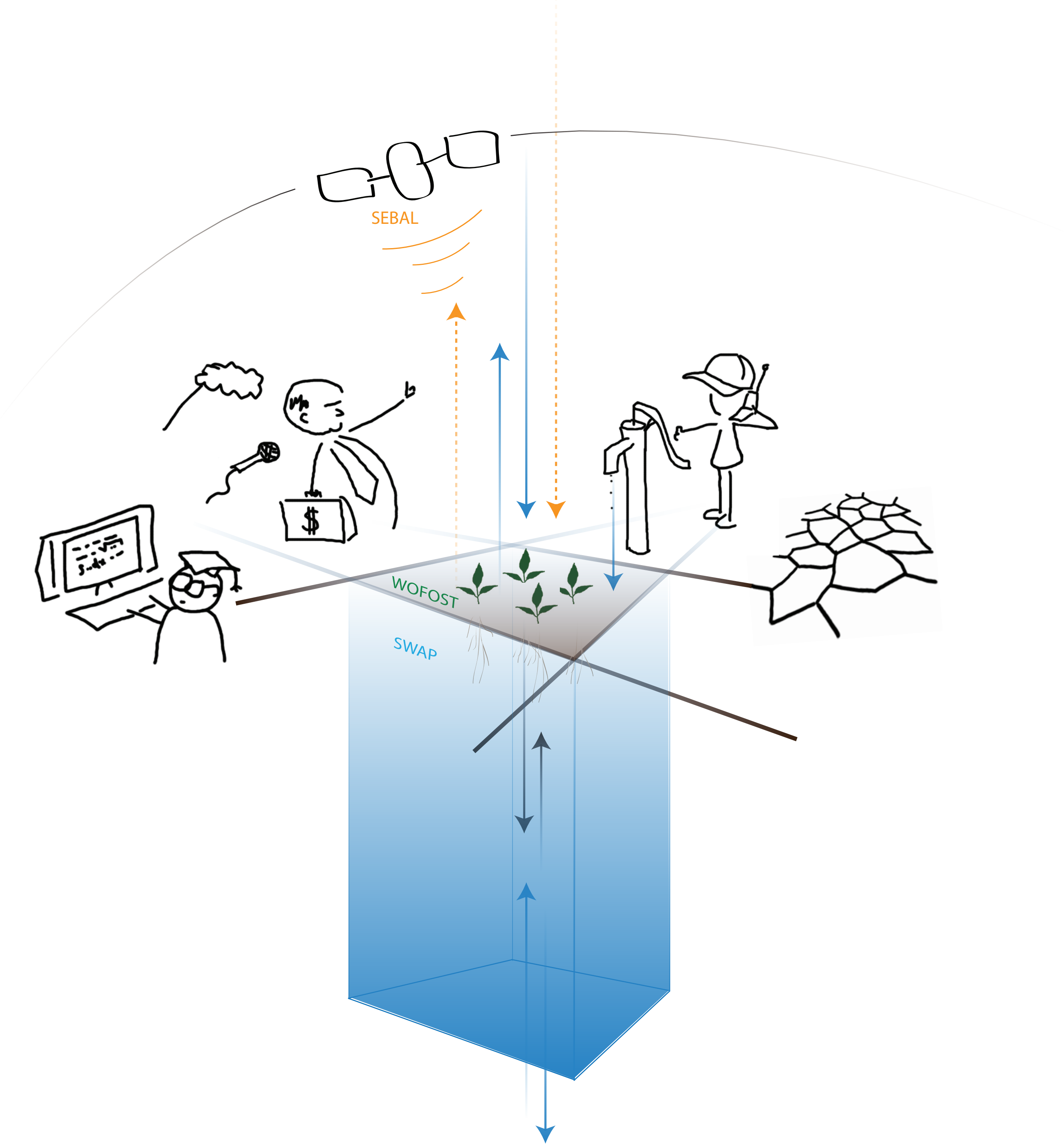
Efficient water use in agriculture

Leading perceptions of key actors in research, policy and practice evaluated at field scale in Tadla basin Morocco and lower Limpopo basin Mozambique



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On the cover

Illustration by the author. The figures illustrate key actors in improvement of efficient water use at the agricultural field, involved in practice, through research or at policy level. Key actors observe an agricultural field. Also the used models are indicated. The Soil-Water-Atmosphere-Plant model (SWAP) is a hydrological model that simulates transport of water, solutes and heat in the vadose zone, interacting with vegetation development. The WOrld FOod STudies simulation model (WOFOST) is used for the quantitative analysis of the growth and production of annual field crops. The Surface Energy Balance Algorithm for Land model (SEBAL) utilizes the surface energy balance to estimate aspects of the hydrological cycle.

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by

C.T. van der Leer - Groen

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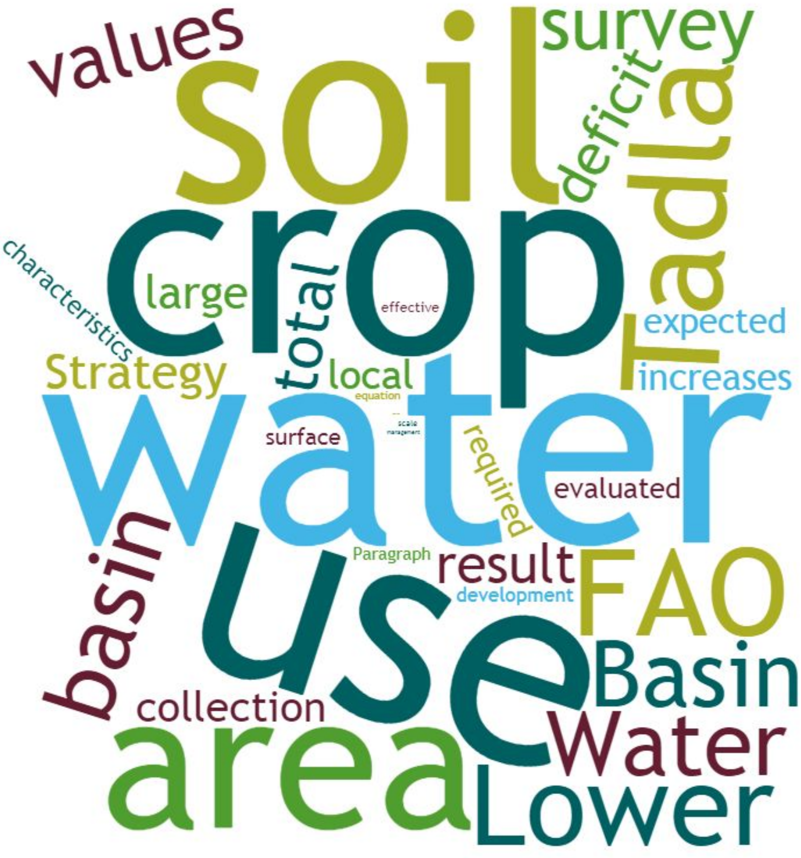

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Contents

Preface

One's task is not to turn the world upside down,
but to do what is necessary at the given place
and with a due consideration of reality

- Dietrich Bonhoeffer

Attempts for improvement of efficient water use are made at global policy level, as demonstrated in this thesis. I do believe that joining forces and development of general policies is crucial. However, globalization has increased complexity and cooperation requires communication and shared knowledge. If you are interested in the challenges that can be observed for the improvement of efficient water use in agriculture, you have to read on.

During my research I had the pleasure to interview multiple people involved in this complex issue. Farmers, consultants, policy makers and researchers. Although the subject of my research is a global question, the focus is at the scale of the agricultural field. An important observation from my research (spoiler) is that the potential for improvement of efficient water use at a field and the best choice on the strategy to obtain this improvement, is highly site-specific. Although I do think that my research is a relevant contribution to the attempt to tackle the problem of efficient water use at a global level, I strongly believe in the relevance of confined interventions and improvements based on local information. The above quote by Dietrich Bonhoeffer can be interpreted to this end. I dedicate this quote to the people I met during my research.

I would like to use the rest of this page for some words of thanks. First, I am thankful for the peace of God that was with me every day of this research and which I learned to seek and know better. This is life giving, highly recommended. Also Niek, my husband, I owe you huge dept of gratitude, for your love, care and encouragement during this research. Times were exhausting sometimes but always full of joy, I see how this was possible because you helped me focus on what is most important in life. I am thankful for my family and friends. Although I discovered a deep love for programming I also found I cannot live without your companionship and 'gezelligheid'. Tijmen van Oldenrijk, Daniël van Dijk, Karin Bremer and Joreen Merks, thank you also for our conversations on the topic of this research, your listening ear, thoughts and suggestions have inspired me during several stages of my research. For practical support I would like to thank the WA+ team at IHE Delft, especially Tim Hessels: thank you for your time and readiness to help. During my reseach I had the opportunity to travel to Mozambique for field measurements and interviews. This was supported by FutureWater, thanks to Martijn de Klerk and Nadja den Besten. Thank you Nadja and also Ante Zoric, for your help but moreover for your friendship in Mozambique. Because of you, local research went really smoothly and it was a great time. This trip was financially supported by two funds. Stichting Het Lamminga Fonds and Stichting Universiteitsfonds Delft, thank you for your support. Last but not least, I would like to thank my graduation committee. Wim Bastiaanssen, Jos van Dam, Susan Steele-Dunne and Silvia Alfieri. Thank you Wim for introducing me to this fascinating subject. I am thankful for the space you have given me to develop this research and to learn and discover. Thank you also for the meetings we had and your helpful suggestions, I am impressed by your knowledge and experience in this field. Thanks Susan for your challenging questions and supporting suggestions the few times we met. Silvia, thank you for your support over email. Jos, a special word of thanks to you. Your enthusiasm and interest in my research, words of encouragement and advise have been important. Also I am very excited about the knowledge and experience I developed from the use of your model. This expertise from Wageningen is a valuable contribution to what I learned at the TU Delft.

To the reader, I hope you will enjoy reading this thesis.

C.T. van der Leer - Groen
Delft, 10th November, 2017

Abstract

Expected increase of world wide food demand requires improvement of efficient water use in agriculture in arid and semi-arid regions. The Food and Agriculture Organization (FAO) of the United Nations, the Directorate-General for International Cooperation (DGIS) of the Netherlands and many more key actors at the level of policy, research and practice are involved to obtain this improvement. However, this thesis demonstrates that there is little agreement between key actors regarding most relevant indicators for efficient water use and most effective strategies to obtain an improvement of efficient water use at the agricultural field.

At field scale, present indicators and strategies are analyzed. Two typical actual fields are simulated for a single growing season using the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST), calibrated against output from the Surface Energy Balance Algorithm for Land model (SEBAL). Remote sensing and model data is used to significantly reduce field work generally required in hydrological research. The obtained baseline scenarios are a plausible representation of the actual fields. Furthermore, SWAP/WOFOST allows for the simulation of various strategy scenarios. Ten different strategies for improvement of efficient water use are observed. The model output of baseline and strategy scenarios is used for computation of 13 different indicators for efficient water use. Hence, quantification of improvement of efficient water use by strategies according to possible indicators is obtained. Strategies and indicators correspond to present perceptions of key actors. The used methodology for field scale analysis is proven effective in this research. It is expected to be applicable for other regions and crop varieties. Recommendations are made concerning the methodology and future research on improvement of efficient water use in agriculture. The fields observed in this research are a general surface irrigated winter wheat field in Tadla basin Morocco and a sub surface irrigated smallholder maize field in the Lower Limpopo basin Mozambique. This thesis demonstrates that the effect of strategies is field specific. In general, a significantly larger potential for improvement is observed for the smallholder maize field. Also, trusted strategies are shown to be counter-effective. Furthermore, change in efficient water use is greatly uneven and sometimes opposing by different indicators.At the winter wheat field, the target of 25% increase of the water productivity indicator used by DGIS is not met by any of the observed strategies. At the maize field this target is met by, among other strategies, elimination of irrigation. However, this also results in a 87% decrease of seasonal yield. Key actors use multiple different water productivity indicators, that are expressed in $kg\ m^{-3}$ and correspond to 'crop per drop' or more vague and conceptual definitions for water productivity used at the FAO. The change to optimal seed quality at the smallholder maize field results in a water productivity increase ranging between -26 and +148% by different water productivity indicators. The -26% is obtained according to the indicator used by DGIS. This thesis demonstrates that the results from this indicator are misleading, caused by the use of biomass production in the nominator of the water productivity definition. Yield production is more representative for the desired field performance. The 'drop' in the water productivity denominator can refer to applied irrigation water as observed in the UN Sustainable Development Goal (SDG) indicator 6.4.1, or to other water balance fluxes including evapotranspiration or transpiration. Evaluating the applied irrigation water is relevant when data is available regarding efficient use of water for other purposes than field application. This is outside the scope of this research. Evapotranspiration and transpiration provide information on the consumption of water by the observed system and by the crop. These quantities can be accurately monitored with remote sensing technologies.

Therefore this thesis suggests that in arid and semi-arid regions, the water productivity indicator defined by yield divided by crop transpiration is the most relevant indicator for efficient water use to the purpose of food security. Although there is currently little agreement among key actors, the largest consensus on a relevant indicator was found for this definition. It is also demonstrated that indicators are often unclear to key actors involved in practice or at policy level and that key actors involved in research are most critical. This implies possible challenges in implementation of a single indicator for global use. In world wide monitoring of this indicator, the greatest challenge is expected in the computation of yield from biomass production for which land use classification is required. This thesis therefore also emphasizes the need for the development of methodologies that allow world wide mapping of agricultural land use.

Nomenclature

List of Acronyms

ADB	Asian Development Bank
API	Application programming interface
ARA	Administração Regional de Águas (Regional Water Authority)
ARA-Sul	Administração Regional de Água do Sul (Water Authority in Southern Region)
Bact	Actual Biomass production rate
CA	Casas Agrarias (Farmer Associations)
CBS	Centraal Bureau voor Statistiek (Statistics Netherlands)
CHIRPS	Climate Hazards Group InfraRed Precipitation with Stations
CoP	Community of Practice
CVS	Comma Separated Values
CWFS	Center for World Food Studies
DEM	Digital Elevation Map
DGIS	Directorate-General for International Cooperation
DNA	Direcção Nacional de Águas (National Water Directorate)
DNGRH	Direcção Nacional de Gestão de Recursos Hídricos (National Directorate of Water and Resource Management)
DVS	Development Stage
EC	electrical conductivity
EE	Google Earth Engine code editor
ENSO	El Niño Southern Oscillation
ET	evapotranspiration
ETpot	potential evapotranspiration
ETref	Reference Evapotranspiration
EWU	Efficient Water Use
FAO	Food and Agriculture Organization
GBWP	Gross Biomass Water Productivity
GDAL	Geospatial Data Abstraction Library
GDP	Gross Domestic Product
GEMI	Global Expanded Monitoring Initiative
GLAAS	Global Analysis and Assessment of Sanitation and Drinking-Water
GLDAS	Global Land Data Assimilation System
GUI	Graphical User Interface
GVA	Gross Value Added
HI	Harvest Index
HWSD	Harmonized World Soil Database
HydroSHEDS	Hydrological SHuttle Elevation Derivatives at multiple Scales
ICID	International Committee on Irrigation and Drainage
IDE	Integrated Development Environment
IE	Irrigation Efficiency
IGG	department Inclusive Green Growth
IMWI	International Water Management Institute
INIR	Instituto Nacional de Irrigação (National Irrigation Institute)
INO	Oceanic Niño Index
ISIC	International Standard for Industrial Classification
ITCZ	Intertropical Convergence Zone
IWR	Irrigation Water Requirement
JMP	Joint Monitoring Program
L7	Landsat 7 imagery
L8	Landsat 8 imagery
LAI	Leaf Area Index
MDSAR	Massingir Dam and Smallholder Agricultural Rehabilitation project
NASA	National Aeronautics and Space Administration
NBWP	Net Biomass Water Productivity
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration
NRMSD	Normalized Root Mean Square Deviation or Error
ORMVA	Regional Office for Agricultural Development

PMV	Plan Maroc Vert
PoC	Proof of Concept
pySEBAL	Surface Engergy Balance Algorithm for Land model in Python language
RAW	Readily Available Water
RBL	Regadio do Baixo Limpopo (Water Board in the Lower Limpopo Basin)
RMSE	Root Mean Square Error or Deviation
S2	Sentinel 2 imagery
SDG	Sustainable Development Goal
SDGs	Sustainable Development Goals
SEBAL	Surface Energy Balance Algorithm for Land model
STRM	Shuttle Radar Topography Mission
SWAP	Soil-Water-Atmosphere-Plant model
Tact	Actual Tranpiration
TAW	Totally Available Water
TDS	Total Dissolved Solids
Tpot	Potential Transpiration
UN	United Nations
USGS	United States Geological Survey
WA+	Water Accounting plus
WaPOR	Water Productivity through Open access of Remotely sensed derived data
WOFOST	WOrld FOod STudies simulation model
WP	Water Productivity
WUE	Water Use Efficiency
WWF	World Wildlife Fund

Glossary

Baseline scenario	Scenario of field performance without implemented strategy
Darcy's equation	General equation for one-dimensional unsaturated flow
Efficient water use at the agricultural field	Preferential use and performance of water at the agricultural field, in the light of limited water resources and rising food demand, allowing multiple perceptions.
Improvement of efficient water use in agriculture	By a strategy, according to an indicator, quantified by difference of indicator for baseline scenario and indicator for strategy scenario
Indicator for improvement of efficient water use at the agricultural field	An indictor which can be quantified from the performance and water balance components of the agricultural field
Key actor perception regarding efficient water use in agriculture	Includes view of key actor on efficient water use in agriculture including its significance, potential relevant indicators and potential effective strategies for improvement
Key actors in efficient water use in agriculture	People involved in agricultural water use and/or the discussion on efficient water use. Can be involved on various levels such as practice, research and policy
Key actors involved at policy level	Group of key actors involved in (the discussion on) efficient water in agriculture at policy level
Key actors involved through research	Group of key actors involved in (the discussion on) efficient water in agriculture at research level
Key actors involved in practice	Group of key actors involved in (the discussion on) efficient water in agriculture at practical level
Mualem equation	General equation for hydraulic conductivity, soil hydraulic function describing the ease of movement of a fluidthrough a porous
Penman-Monteith general combination equation	Standardized method by the FAO for computation of evapotranspiration rates
Richards' equation	General equation for water flow in variably saturated soils, combination of Darcy's and the continuity equation for soil water considering infinitely small soil volumes
Soil water retention curve	van Genuchten analytical θ(h) function, used to predict soil water storage, saturation, field capacity and wilting point
Strategy for improvement of efficient water use at the agricultural field	A strategy which can be implemented at the agricultural field, resulting in an improvement of efficient water use
Strategy scenario	Scenario of field performance with implemented strategy
SWAP/WOFOST	Simulation of SWAP using the detailed crop growth module from WOFOST
Van Genuchten analytical θ(h) function	See 'Soil water retention curve'
Level of involvement	Refering to key actors involved in practice, through research or at policy level

List of Symbols and operators

$^{\circ}C$	$[K-273.15]$	Celcius
α	$[-]$	soil hydraulic shape parameter
B_{act}	$[t\,d^{-1}\,ha^{-1}]$	actual biomass production rate, dry mass
$B_{SO,act}$	$[t\,d^{-1}\,ha^{-1}]$	actual biomass production rate, dry mass of storage organs
Bm^3	$[m^3]$	billion cubic meter
CH_2O	$[-]$	carbohydrates
cm	$[10^{-2}m]$	centimeter
CO_2	$[-]$	carbon dioxide
d	$[8.64\,10^4\,s]$	day
ΔS_i	$[m^3]$	irrigation water volume stored over an observed time span
ΔT	$[^{\circ}C]$	temperature or air, difference
dS	$[10^{-1}\,S]$	decisiemens
$e_{act,mean,day}$	$[kPa]$	vapor pressure, actual, daily mean
$e_{sat,mean,day}$	$[kPa]$	vapor pressure, saturated, daily mean
EC_{sat}	$[dS\,m^{-1}]$	electrical conductivity level at which crop salt stress starts
$ET_{crop,pot}$	$[m^3]$	crop evapotranspiration, potential volume
ET_{crop}	$[m^3]$	evapotranspiration of crop, volume
$ET_{non-crop}$	$[m^3]$	evapotranspiration of other vegetation or soil, volume
ET_{pot}	$[mm\,d^{-1}]$	potential evapotranspiration rate
ET_{ref}	$[mm\,d^{-1}]$	reference evapotranspiration rate
g		gram, unit of mass in the International System of Units
GJ	$[10^9\,J]$	giga joule
H	$[W\,m^{-2}]$	surface sensible heat flux
$H_{mean,day}$	$[kg\,kg^{-1}]$	humidity, daily mean
ha	$[10^4\,m^2]$	hectare
HI	$[-]$	harvest index
IWR	$[m^3]$	accumulated volume of irrigation water requirement
J	$[W\,s]$	Joule
K		Kelvin, unit of temperature in the International System of Units
K_{sat}	$[cm\,d^{-1}]$	hydraulic conductivity, saturated
kg	$[10^3\,g]$	kilogram
kJ	$[10^3\,J]$	kilo Joule
km^2	$[10^6\,m^2]$	square kilometer
kPa	$[10^3\,Pa]$	kilo pascal
L	$[10^3\,cm^3]$	liter
LAI	$[-]$	leaf area index
λ	$[-]$	soil hydraulic parameter, exponent in Mualem equation
λE	$[W\,m^{-2}]$	latent heat flux
m		meter, unit of distance in the International System of Units
m^2		square meter, unit of area in the International System of Units
mg	$[10^{-3}\,g]$	miligram
mm	$[10^{-3}\,m]$	millimeter
Mm^3	$[m^3]$	million cubic meter
n	$[-]$	soil hydraulic shape parameter
O_{act}	[%]	soil organic content, actual
O_{pot}	[%]	soil organic content, potential
P_{day}	$[mm]$	precipitation, daily accumulation
$P_{mean,day}$	$[Pa]$	surface pressure, daily mean
P_e	$[m^3]$	precipitation, effective volume
Pa	$[kg\,m^{-1}\,s^{-2}]$	pascal
$pF2$	$[cm]$	field capacity, pressure head
$pF4.2$	$[cm]$	wilting point, pressure head
Q	$[m^3]$	water volume
Qh	$[m^3]$	horizontal water flux volume
Qv	$[m^3]$	horizontal water flux volume
$R_{s,day}$	$[KJ\,m^{-2}]$	incoming shortwave radiation, daily accumulation
$RH_{mean,day}$	[%]	relative humidity, daily mean

s		second, unit of time in the International System of Units
S		Siemens, unit of electric conductance in the International System of Units
SM	$[cm^3\ cm^{-3}]$	soil moisture content
SM_{act}	$[cm^3\ cm^{-3}]$	soil moisture content, actual
SM_{opt}	$[cm^3\ cm^{-3}]$	soil moisture content, optimal
SM_{rz}	$[cm^3\ cm^{-3}]$	soil moisture content in root zone
SM_{ts}	$[cm^3\ cm^{-3}]$	soil moisture content in top soil
$\sum(I-\Delta S_i)$	$[mm]$	seasonal irrigation water depth, not stored
$\sum A_i$	$[m^3]$	accumulated irrigation water volume applied for irrigation
$\sum B$	$[kg\ ha^{-1}]$	accumulated biomass production, total dry mass
$\sum B$	$[kg]$	accumulated biomass production, total dry mass
$\sum B_{act,y}$	$[kg\ ha^{-1}\ y^{-1}]$	accumulated actual biomass production, annual total dry mass
$\sum B_{act}$	$[t\ ha^{-1}]$	accumulated (seasonal) actual biomass production, total dry mass
$\sum B_{SO,act}$	$[t\ ha^{-1}]$	accumulated actual biomass production, dry mass of storage organs
$\sum C$	$[mm]$	seasonal interception water depth
$\sum E_{act}$	$[mm]$	seasonal evaporation water depth, actual
$\sum E_i$	$[mm]$	seasonal evaporation water depth, actual from irrigation
$\sum E_{pot}$	$[mm]$	seasonal evaporation water depth, potential
$\sum ET$	$[m^3]$	accumulated evapotranspiration volume
$\sum ET_{act,y}$	$[m^3\ ha^{-1}\ y^{-1}]$	accumulated actual evapotranspiration, annual volume
$\sum ET_{act}$	$[m^3]$	accumulated actual evapotranspiration volume
$\sum GVA_i$	$[USD]$	accumulated gross value added by irrigated agriculture
$\sum I$	$[mm]$	accumulated (seasonal) depth of irrigation water applied
$\sum Q$	$[mm]$	seasonal groundwater percolation water depth
$\sum Q_{in}$	$[m^3]$	accumulated total flux into the system, water volume
$\sum Q_{out}$	$[m^3]$	accumulated total flux out from the system, water volume
$\sum T_{act,y}$	$[m^3\ ha^{-1}\ y^{-1}]$	accumulated actual transpiration, annual volume
$\sum T_{act}$	$[m^3]$	accumulated transpiration water, actual volume
$\sum T_{act}$	$[mm]$	seasonal transpiration water depth, actual
$\sum T_{pot}$	$[mm]$	seasonal transpiration water depth, potential
$\sum T_i$	$[m^3]$	accumulated transpiration water volume from irrigation water
$\sum T_i$	$[mm]$	seasonal transpiration water depth, actual from irrigation
$\sum U_{B,i}$	$[m^3]$	accumulated volume of irrigation water used beneficially
$\sum U_B$	$[m^3]$	accumulated volume of water used beneficially
$\sum U_{BC}$	$[m^3]$	accumulated volume of water beneficially consumed
$\sum U_{C,crop}$	$[m^3]$	accumulated volume of water consumed by the crop
$\sum U_{C,i}$	$[m^3]$	accumulated volume of irrigation water consumed
$\sum U_C$	$[m^3]$	accumulated volume of water consumed
$\sum W_i$	$[m^3]$	accumulated water withdrawal volume for irrigation application
$\sum Y$	$[kg\ ha^{-1}]$	accumulated yield production, dry mass
$\sum Y$	$[kg]$	accumulated yield production, dry mass
$\sum Y$	$[t\ ha^{-1}]$	seasonal yield production, actual
$\sum Y_y$	$[kg\ ha^{-1}]$	accumulated yield production, dry mass, yearly
t	$[10^3\ kg]$	tonne weight
T_{act}	$[mm\ d^{-1}]$	transpiration rate, daily actual
T_{crop}	$[m^3]$	crop transpiration volume
$T_{max,day}$	$[°C]$	temperature, daily maximum
$T_{mean,day}$	$[°C]$	temperature, daily mean
$T_{min,day}$	$[°C]$	temperature, daily minimum
T_{pot}	$[mm\ d^{-1}]$	transpiration rate, daily potential
T_{red}	$[mm\ d^{-1}]$	transpiration reduction rate, daily
T_{rel}	$[-]$	transpiration rate, daily relative
θ_{crop}	$[m^3]$	water content of crop, volume
$\theta_{non-crop}$	$[m^3]$	water content of other vegetation, volume
θ_{res}	$[cm^3\ cm^{-3}]$	soil moisture content, saturated
θ_{sat}	$[cm^3\ cm^{-3}]$	soil moisture content, residual
θ_{seed}	$[-]$	seed moisture content, fraction
USD		United States Dollars, currency
W	$[J\ s^{-1}]$	Watt
$wind_{mean,day}$	$[m\ s^{-1}]$	wind speed, daily mean
y		year

1
Introduction

Currently, 7.3 billion people live on this planet. This population is expected to reach 8.5 billion by 2030 and 9.7 billion in 2050 (UN Department of Economic and Social Affairs, 2015), other studies state that by then the world's food demand is 60 percent greater than it is today (Breene, 2016). The population of the African continent is expected to be doubled to 2.4 billion in 2050, requiring a 100 percent increase in food demand (United Nations World Water Assessment Programme (WWAP), 2015; Bish, 2016). Water is crucial in the agricultural food production but unlike the population the amount of water on this planet does not increase and only a small fraction is fresh and available. Water is withdrawn from rivers and aquifers for human activities, 70 percent of these withdrawals are used in agriculture (Food and Agriculture Organization of the United Nations - FAO, 2003). Natural ecosystems might withdraw a similar amount of water from shallow and deep water tables (Bastiaanssen et al., 2014), constraining increase of human uptake. Increasing food demand and limited water resources require efficient water use in irrigated agriculture for the coming decades.

1.1. Perceptions regarding efficient water use in agriculture

In 2015 the United Nations (UN) adopted 17 Sustainable Development Goals (SDGs) to be reached in 2030, including the Sustainable Development Goal (SDG) indicator 6.4.1 to "substantially increase water use efficiency over time" (Reidhead et al., 2016). UN-Water coordinates the UN's work on water and sanitation including SDG indicator 6.4.1 concerning efficient water use. UN-Water aims at universal and transformative goals and targets (UN-Water, 2017*c*) and monitors progress using a coherent global monitoring mechanism developed by the Global Expanded Monitoring Initiative (GEMI) (UN-Water, 2016*a*). The GEMI cooperates with Proof of Concept (PoC) countries that test the applicability of the GEMI monitoring framework as a whole and for indicators specifically (FAO, 2016*c*). A recent Work in Progress Workshop attended by indicator coordinators, representatives of GEMI-Target Teams from UN organizations, experts and representatives of all PoC countries (ter Horst & de Vries, 2016) revealed confusion in terminology and definitions regarding efficient water use. Targets and indicators are ambiguous or too general, generating only little feedback to policymaking, leading to a lack of clarity in responsibility distribution and challenges in data collection. The PoC countries consider efficient water use to be highly relevant but the defined targets and step-by-step methodology for monitoring water use efficiency provided by the GEMI (UN-Water, 2017*a*) still allow individuals to have different perceptions regarding the practical meaning of improvement of efficient water use in agriculture. The Food and Agriculture Organization (FAO) of the UN is the custodian agency of SDG indicator 6.4.1. The FAO also struggles to obtain universal and applicable definitions of efficient water use which is apparent in the multiple different terms used in the FAO's global water information system AQUASTAT developed by the Land and Water Division (FAO, 2016*a*).

While the UN adopted the target to increase 'water use efficiency', the Dutch ministry of Foreign affairs aims at increasing 'water productivity' by 25 percent in the water programs it supports. Local deviations from this target can be achieved after approval of the Dutch Ministry of Foreign Affairs (Ministry of Foreign Affairs of the Netherlands, 2013). The Government of the Netherlands maintains special relationships for with 'partner countries' for development cooperation. The vast majority of these countries are part of the African continent. The Dutch Ministry of infrastructure and Environment and the Ministry of Foreign affairs are two key actors in support of SDG indicator 6.4.1. Also Dutch companies and research institutes are involved in projects to increase water productivity in water-scarce areas and in the development of monitoring systems using remote sensing data (Graveland et al. 2016, Netherlands Water Partnership 2017).

In literature concern among researchers about confusion in definitions is expressed (Bos & Nugteren 1990, Bastiaanssen & Bos 1999, Perry 2007). This confusion is apparent in the attempt of the Netherlands, UN Member State and PoC country, to implement SDG indicator 6.4.1. Furthermore, in obtaining actual improvement in efficient water use in agriculture, many more key actors are involved, adding to the amount of leading perceptions. Observed confusion proves not only the presence of multiple possible perceptions but also the lack of overview in this range of discrepancies.

In this study, the broad and vague term ‘efficient water use’ is chosen deliberately to seek an objective perspective, incorporating all possible perceptions on the purpose, gains and losses in agricultural water use. Improvement of efficient water use is desired for a baseline scenario. Implementation of a strategy results in a strategy scenario. An indicator of efficient water use is quantified for both the baseline performance and strategy performance. The difference between these values defines the improvement of efficient water use. Different efficiencies and productivities can be used as indicators of efficient water use. Key actors’ perceptions of efficient water use include different indicators and strategies for improvement in agriculture.

1.2. Problem definition and aim of this research

The worldwide issue of water availability and food security is complex. This research aims at the quantitative evaluation of different possible perceptions on the improvement of efficient water use in irrigated agriculture. Choices on spatial scale lead to the actual problem statement. The observed temporal scale and the selection of the study area allow for the formulation of the research question. Methods are selected to answer this question.

1.2.1. Problem statement

It is at the level of the agricultural field where water management scenarios are implemented and actual improvement of efficient use can be obtained. The agricultural field is part of an irrigation system and river basin. Analysis of the detailed scale of the agricultural field provides insight in the actual physical processes between soil, water, atmosphere and plant, including water and solute movement in the variably saturated soil near the earth surface. This insight is essential for understanding human impact on the system (van Dam et al., 1997). (Burt et al., 1997) states that knowing exactly what happens to the applied water is crucial for evaluation of irrigation performance. However, prior research also states (Perry, 2007) that using a frame of reference smaller than the global and long-term scale requires careful attention to the flows across the borders of the selected spatial and temporal reference frame. The smaller the frame of reference, the more complex and significant these cross border flows become. The importance of the consideration of performance of irrigation at different spatial scales is stressed in prior research (Droogers & Kite, 2001; Bastiaanssen & Bos, 1999). The conclusions of this study in which field scale is considered should therefore be combined with large scale analysis to enable sound water management decisions. The aforementioned lack of insight in different perceptions on improvement of efficient water use in agriculture and the selected spatial scale of the agricultural field leads to the following problem definition:

Perceptions regarding efficient water use at field scale in irrigated agriculture, containing different strategies for improvement and indicators to measure improvement, can lead to different and possibly conflicting water management strategies at the field. The way perceptions relate at the level of field practices is unknown. At best, appearance of conflicts or similarities can be intuitive but data on quantified results is lacking.

1.2.2. Research question

This research concerns the improvement of efficient water use in the African continent where the Kingdom of the Netherlands is involved in obtaining this improvement, motivated by the UN's SDGs for 2030. Two different study areas are selected. In these areas irrigated agriculture is observed, where water is diverted for crop use. Rain fed agriculture is not part of this study. The temporal scale is a single growing season. Long time analysis requires large amounts of data and processing which is not feasible in the scope of this research. Consequently, long term dynamics such as changes in ground water reservoirs and climatic changes are not incorporated. Considered strategies for improvement generate direct effect on the field. Considered indicators allow the quantification of efficient water use from the performance of a single growing season. Year to year rainfall variability is observed, selected seasons are representative for a common dry season. In the discussion on efficient water use and short-term strategies, attention should be given to long term expectations. The conclusions of this study should be combined with long term analysis to enable sound water management decisions. For each of the observed study areas, the most common crop is selected. In each area, evaluation of perceptions is executed on an actual field where agricultural performance is representative for the area. The fields in the two areas have different characteristics, e.g. irrigation method, soil type, weather conditions and crop species. The analyzed fields represent field irrigated winter wheat in Tadla Basin in Morocco and smallholder maize cultivation in the lower Limpopo Basin in Mozambique where subsurface irrigation is supplied by management of the shallow water table. The analyzed perceptions are those of Dutch and local key actors representing a wide range of water and food professionals. These choices lead to the following research question:

> *Representative irrigated agricultural field in both the Tadla Basin in Morocco and the Lower Limpopo Basin in Mozambique are considered. Strategies and indicators regarding improvement of efficient water use at field scale in irrigated agriculture can be identified among local and Dutch key actors. To what degree do these perceptions result in differences or even conflict when implemented at the field?*

1.2.3. Methods

This study analyses perceptions of key actors regarding improvement of efficient water use in irrigated agriculture in two study areas. Strategies to obtain improvement of efficient water use at the field and indicators to quantify this improvement are defined. Following, these strategies are applied at the field and the different indicators are quantified for each strategy. Leading perceptions are thus evaluated and compared.

To analyze various indicators of efficient water use, ideally all components of the local water balance need to be known and thoroughly understood, including their likely variabilities in space and time (Droogers & Bastiaanssen, 2002). In analysis of the actual field, this requires measurements of large amounts of ground data. Evaluating scenarios of different improvement strategies is preferably done on the exact same field under the exact same meteorological circumstances, which is impossible in practice. The application and evaluation of strategies and indicators of efficient water use at the field is therefore executed using the combination of remotely sensed techniques and hydrological models. Hydrological models can fill the gap between measured and required data and allow for scenarios to be evaluated (Droogers & Kite, 2001). The need for field data to verify whether the hydrological model gives a plausible representation of reality can be diminished by the use of remotely sensed techniques deriving terms of the water balance. This has been validated by ground data to have an accuracy of 95 percent at the spatial and temporal level of the agricultural field during a growing season (Bastiaanssen et al., 2005). Application of hydrological models and remote sensing data allows for the simulation of actual fields as observed in the recent past.

1.2.4. Aim of research

This research is relevant as awareness of differences and quantification of the consequences of the various possible perceptions can lead to improvement in collaboration between different key actors. Collaboration between actors is assumed to be crucial in obtaining actual improvement regarding efficient water use, to ultimately secure food security.

1.3. Thesis outline and guides for reading

In Chapter 2 the applied methodology is described. The methods include the procedure for perception selection, the Surface Energy Balance Algorithm for Land model (SEBAL), the hydrological Soil-Water-Atmosphere-Plant model (SWAP) and the WOrld FOod STudies simulation model (WOFOST). Also procedures for quantification, frequency analysis of key actor perception and data collection procedures are presented. The reader is provided with a brief background and a discussion on each method regarding its use and relevance in agricultural water management, the input data it requires and the motivation to use this method for this particular research.

Chapter 3 introduces the area of study of this research. This chapter concerns both the perceptions and selected physical fields, including results of preliminary analysis. First the observed group of key actors is presented, including their position in the discussion on improvement of efficient water use in agriculture, practical relationship and influence on the agricultural field and perceptions regarding efficient water use. Secondly an introduction to the agricultural fields is given, including relevant characteristics and the regional context. The chapter also presents selected strategies to obtain improvement and indicators used for improvement of efficient water use, which are used in the simulation analysis.

In Chapter 4 the results of this study are presented. This includes first relevant observations on the calibration procedure. Secondly, the result of the calibration of SWAP and WOFOST against results from SEBAL and field measurements is presented. The calibration for both of the fields provides a baseline scenario which is a plausible representation of the actual situation as observed in a growing season in the recent past. Upon this baseline situation, different strategies are implemented for improvement of efficient water use, resulting in strategy scenarios. Efficient water use is quantified according to different possible indicators, computed for both the baseline and strategy scenarios. In this chapter the improvements obtained by the strategies according to the different indicators are presented. The chapter also presents the result of the perception frequency analysis, revealing which strategies and indicators are seen as most effective and most relevant by key actors.

Chapter 5 provides a discussion on the results and an evaluation of the applied methods.

Chapter 6 presents a brief answer to the research question and reevaluates the problem statement.

2
Methodology

This research analyzes perceptions regarding efficient water use in agriculture, observed at field scale. Hydrological simulation combined with remote sensing analysis is proven useful to this end and does not require time intensive and costly ground data accumulation. The methods are found to be accurate in previous research and allow for evaluation of multiple scenarios (Droogers & Kite, 2001; Bastiaanssen et al., 2005). The methodology applied in this research contains the selection of perceptions to be evaluated, the hydrological Soil-Water-Atmosphere-Plant model (SWAP), the WOrld FOod STudies simulation model (WOFOST) and Surface Energy Balance Algorithm for Land model (SEBAL). Additionally, calculation procedures, frequency analysis and data collection processes are applied.

First, a general description of the methodology is presented indicating different project elements. In the paragraphs to follow, these elements are individually introduced. On the used models this chapter provides a brief background, explanation of the application in this research, discussion on its use and relevance in the current and general hydrological research and an overview of the data required for the method. The other procedures are also introduced and a discussion is provided on the use and relevance of these tools in the current and general hydrological research.

2.1. General description of methodology

Visualizations are used to support the description of the research methodology. In Fig. 2.1 an overview of the general methodology is given. In this illustration, sections of colored background indicate the four different phases in this research: Preliminary analysis, Model calibration and simulation, Calculation of results and Subsequent analysis. These phases are briefly introduced in this paragraph. Also illustrated by Fig. 2.1 with dotted frames are the three procedures that are applied repeatedly in this research:

- For each field > For each strategy > For each indicator

The illustration visualizes the relation between the different phases and elements in this research with arrow connections. The upper part of the illustration reveals the **Area of research**, being key actors in improvement of efficient water use at the agricultural field and these actual field monitored by satellites.

The **Preliminary research** involves the selection of perceptions from key actors. The resulting strategies and indicators are used for model simulation and calculations. The applied procedure for the selection of perceptions results in a collection of strategies and a collection of indicators. This is further described in paragraph 2.2. Also considered preliminary research is the Surface Energy Balance Algorithm for Land model (SEBAL) analysis generating parameters that are used in the model calibration. This SEBAL analysis is conducted for each actual field, further introduced in Paragraph 2.3. The results of this preliminary analysis are presented in Chapter 3.

In the phase of **Model calibration and simulation**, first the SEBAL generated parameters are used for the calibration of Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST). This results in the field baseline scenario being a plausible representation of the actual field. This calibration is conducted for each field separately, resulting in a baseline scenario for each actual field. SWAP and WOFOST are further introduced in the paragraphs 2.4 and 2.5. Following, a strategy is simulated by adjustment of the input for the baseline simulation, resulting in a field strategy scenario which is different from the baseline scenario of this field. Strategy simulation is done for each actual field, for each strategy from the collection of strategies. The result is a collection of strategy scenarios for each actual field. Strategy simulation is conducted using SWAP/WOFOST. The result of the model calibration and simulation of strategies is presented in Chapter 4.

In the third research phase concerns **Calculation of results**. In this phase the efficient water use performance of both the baseline and strategy scenarios are computed, according to the collection of indicators. The SWAP/WOFOST model output parameters are used in the calculations. This results in a quantification of the improvement of efficient water use at the actual field obtained by a strategy, computed according to an indicator. This is obtained for each actual field, for each strategy, for each indicator. The results for each field is an evaluation of the collection of strategies according to the collection of indicators. This dataset is the result of this research. The exact procedure for this quantification can be found in paragraph 2.6. The result of these quantifications is presented in Chapter 4.

The additional **Subsequent analysis** concerns a study on the frequency distribution of the occurrence of the evaluated perceptions among key actors. This is further described in paragraph 2.7. The results of this frequency analysis is presented in Chapter 4.

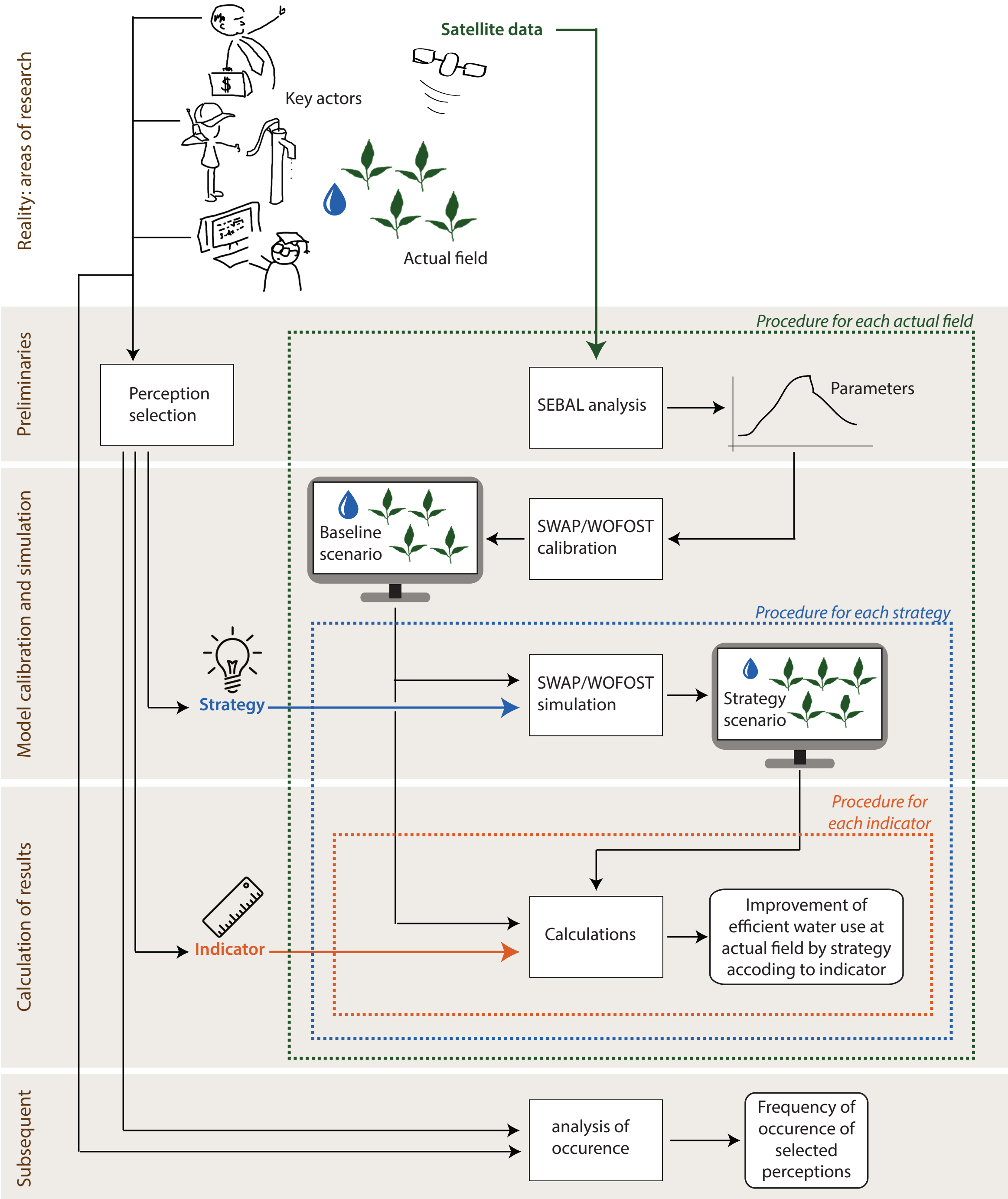


Fig. 2.1: Visualisation of area of research and general research methodology including research phases (colored background) and repeatedly applied procedures (dotted frames). Relation of different elements is indicated with arrows.

2.2. Perception selection procedure

Among key actors in the improvement of efficient water use at the agricultural field, different perceptions regarding this improvement are observed.

A collection of leading perceptions is evaluated in this research. The selection of perceptions is part of the preliminary analysis of this research. The position of this step within the methodology of the total research (see Fig. 2.1) is indicated in Fig. 2.2. An overview of the observed key actors is presented in Paragraph 3.1. This includes an introduction to the involvement in the improvement of efficient water use and present perceptions regarding this improvement. In Paragraph 3.3 the deduced collection of strategies analyzed in this research is presented. In Paragraph 3.4 the deduced collection of indicators analyzed in this research is presented.

In the current paragraph, first the used approach towards the broad concept of perceptions is presented. Following, the applied procedure for the deduction and selection of perceptions from the group of key actors is given.

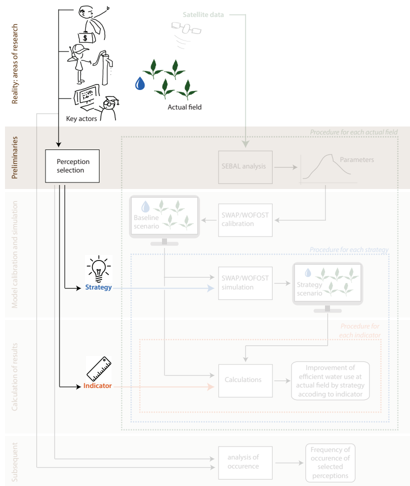


Fig. 2.2: Selection of perceptions highlighted in general methodology (see larger overview in Fig. 2.1)

2.2.1. Definition and use of perceptions regarding efficient water use in agriculture

A complete study on perceptions is multi-disciplinary involving various sociological aspects outside the scope of this research. This research employs a mere technical approach. The following definitions are used (Oxford University Press, 2017). Perception: *'the way in which something is regarded, understood, or interpreted'*. Efficient: *'achieving with minimum expense and accomplishing in a competent way'*. This allows multiple interpretations and views on what is to be achieved or accomplished, what can be seen as expenses and how this is done in a competent way. A perception regarding the improvement of efficient water use is assumed to include (1) a conviction regarding how to achieve this improvement and (2) a belief regarding how to verify the achievement of this improvement. Technically this is (1) a strategy and (2) an indicator. Literature suggests that indicators of performance in irrigated agriculture should preferably depend on internal factors within the control of the designer or operator of the agricultural system (Perry, 2007). This research considers perceptions which satisfy one or both of the following criteria:

1. Including strategies for the improvement of efficient water use in irrigated agriculture, of which the implementation can be realized at field scale for a particular growing season.
2. Including indicators by which improvement of efficient water use in agriculture can be quantified by measurements at field scale in a single growing season for both the baseline scenario and strategy scenario.

2.2.2. Applied methods in the selection of strategies and indicators

In Fig. 2.3 the applied procedure of perception selection is visualized. This preliminary analysis is directly connected to the group of key actors. The selected group of key actors are people involved in the improvement of efficient water use at the agricultural field, either directly or in the current global discussion on this issue. This research focuses on areas where improvement of efficient water use is desired and where the Government of the Netherlands and Dutch companies and research institutes are involved. The observed fields, simulated for a growing season in the recent past, are found in Tadla Basin, Morocco and the Lower Limpopo Basin, Mozambique. Key actors are involved through various levels: policy and funding, practical and local involvement, research and planning. A field visit to the research area in Mozambique in May 2017 has allowed for group meetings and personal interviews with farmers, local government officials, consultants and other local experts. These key actors are involved merely at the level of practice and policy. In the Netherlands an additional series of personal interviews was conducted with key actors involved on the level of policy and research. A complete list of interviewees is included in Appendix A.

Perceptions are studied through governmental publications and scientific literature, key actor group meetings and by personal interviews. These methods are further introduced in the following sections. From the acquired, strategies and indicators conform the criteria used in this research are deduced. A selection is made of the most frequently used strategies and indicators to be the subject of analysis in this research. The result is a collection of different strategies to be applied at the agricultural field for improvement of efficient water use and a collection of different indicators to quantify the improvement of efficient water use for both the baseline and strategy scenario.

Academic and governmental publications Literature is consulted. Perceptions present at the Dutch Government and involved United Nations organizations are stated or reflected available publications. The perceptions of Dutch key actors at the level of research are assumed to be influenced by prominent international research, this has been confirmed in personal interviews. Thus a thorough literature study is conducted.

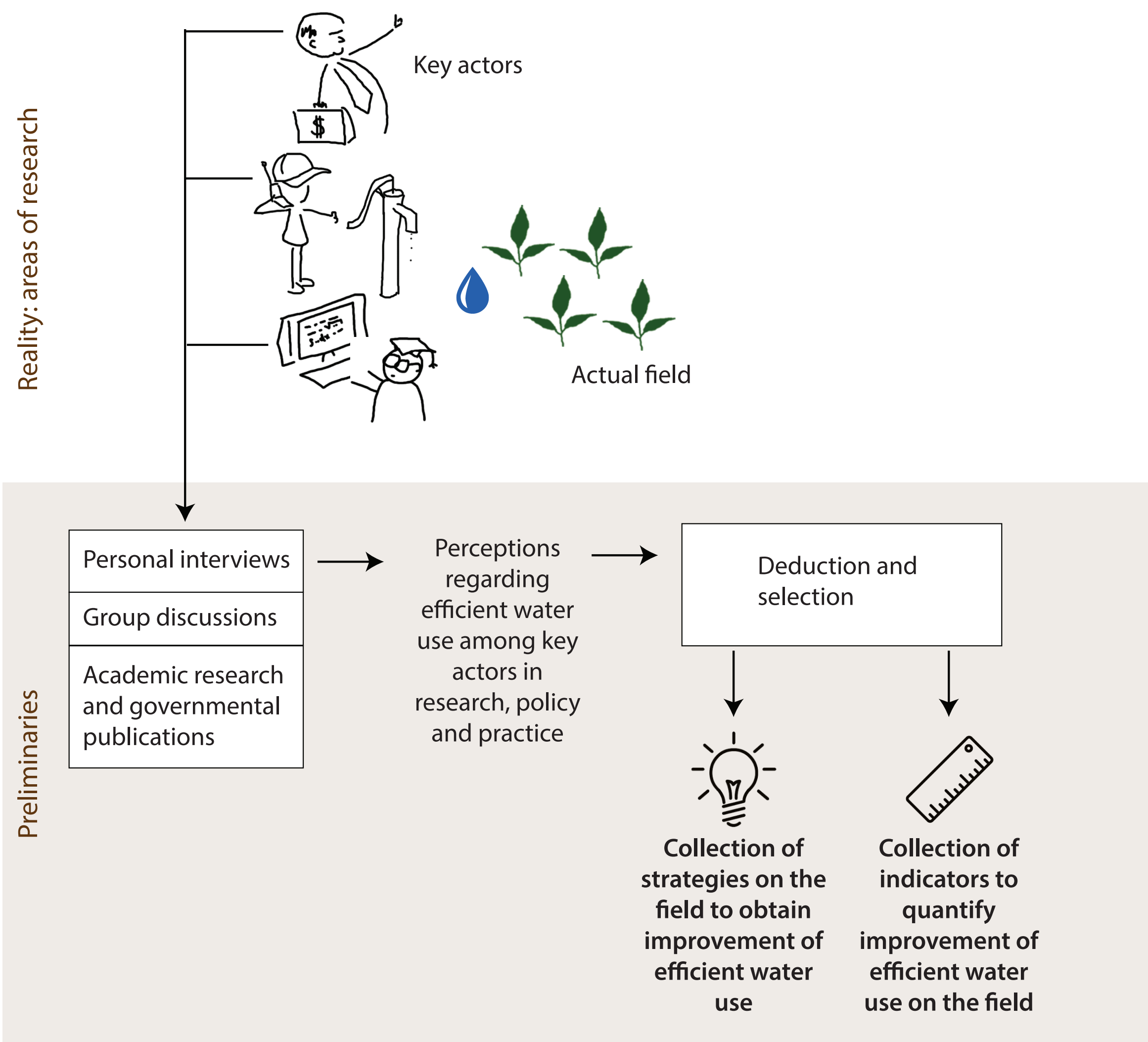


Fig. 2.3: Visualization of detailed procedure for selection of perceptions from key actors, including personal interviews, group discussions and literature.

Personal interviews with key actors in the Netherlands Conducted personal interviews in the Netherlands are non-structured. The interviewee is asked about his concern towards efficient water use in agriculture and world wide food security. When an individual expresses efficient use of water to be relevant, he is asked about specific strategies to obtain improvement and indicators to verify this at field scale. When broad terms are used the interviewee is asked to explain his perception if possible. For example, *Water Productivity* is a broadly applicable indicator that can be used in various ways. A possible explanation of this term could be *Amount of crop yield kilograms per hectare produced on the field in a season, divided by the amount of water in cubic meter per hectare applied by the farmer on the same field and in the same season.* The term water productivity is frequently applied by the Directorate-General for International Cooperation (DGIS) of the Government of the Netherlands. If the interviewee does not mentioned this term, he is asked directly if he is familiar with this term, what he thinks it actually means at field scale and whether he regards water productivity to be a relevant indicator of efficient water use.

Personal interviews with local key actors Conducted personal local interviews in Mozambique are semi-structured. Interviews are conducted with support of local translators. Standard open and pre-defined open questions are used. Additionally, the interviewee is asked to respond to a collection of statements by which a simplified version of the Q-sorts method is applied to filter perceptions. Beside insight in local perceptions regarding efficient water use at the agricultural field, local interviews are also used to obtain insight in the operation of the local agricultural system, farmer practices and field performance. This information is used in decisions made for the simulation of the observed field.

Group discussions Both in Mozambique and the Netherlands, key actors group meetings are attended. DGIS commissioned a Community of Practice (CoP) for companies and research institutes in the Netherlands, revolving around the topic of water productivity. In 2017, a series of master classes were organized to this end. These sessions were attended in Wageningen, the Netherlands, at March 2^{nd} and May 10^{th} 2017. Information from presentations, group discussions and personal conversations is obtained and contacts were made to be followed up by personal interviews. In Mozambique, a group meeting is arranged with local farmers from the observed agricultural area. This took place near Xai-Xai, Mozambique, at May 17^{th} 2017. The meeting was attended by 12 farmers. The statements used in the local personal interviews were discussed in the group, after discussion of each statement a vote indicated the diversion of opinions within the group. Another meeting was attended at the Mozambican Direcção Nacional de Gestão de Recursos Hídricos (National Directorate of Water and Resource Management) (DNGRH) for water resources management. In this meeting at the National Directorate, DNGRH managers were informed with a presentation and group discussion on a trust fund project approved by the Asian Development Bank (ADB) on monitoring of crop water productivity. This meeting took place in Maputo, Mozambique, at May 24^{th} 2017.

2.3. The Surface Energy Balance Algorithm for Land model: SEBAL

The Surface Energy Balance Algorithm for Land model (SEBAL) utilizes the surface energy balance to estimate aspects of the hydrological cycle.

Multiple hydrological models exist, predicting energy balances and regional evapotranspiration. The difficulty in the validation of these models is the limited availability of field data. SEBAL is a physically based 'multi-step' algorithm using the surface energy balance (Bastiaanssen, 1995). This method utilizes remote sensing data, diminishing the need for on-site hydrological data (Bastiaanssen et al., 2005). Result of the SEBAL analysis is used for the calibration of the Soil-Water-Atmosphere-Plant model (SWAP). Generating results from SEBAL is part of the preliminary analysis in the current research. The position within the general methodology of this study (see Fig. 2.1) is indicated in Fig. 2.4.

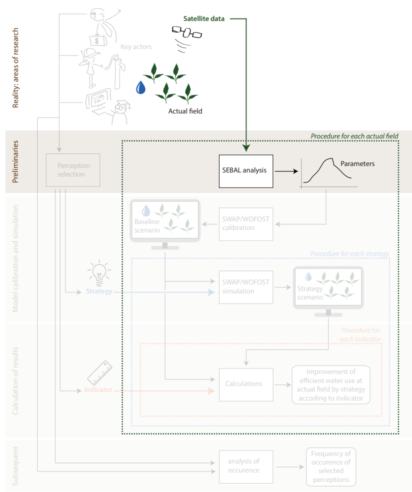


Fig. 2.4: SEBAL analysis highlighted in general methodology (see larger overview in Fig. 2.1)

This paragraph first provides an introduction to SEBAL. Secondly, the application of SEBAL in this research is explained. Following, a discussion is given on the value of this method in the current research and in hydrological research in general. Finally, this paragraph provides an overview of the required data for the application of SEBAL for its application in the current research.

2.3.1. Introduction to SEBAL

The Surface Energy Balance Algorithm for Land (SEBAL) origins from an estimation of evaporation from shallow groundwater tables in the Western Desert of Egypt (Bastiaanssen & Menenti, 1990) and is in continuous development since. The initial application of the model was the assessment of evaporative depletion in river basins. During the nineties the focus shifted to water consumption of irrigated crops. In this research the latest pySEBAL 3.3.6 beta version for Landsat imagery is used (Hessels et al., 2017)

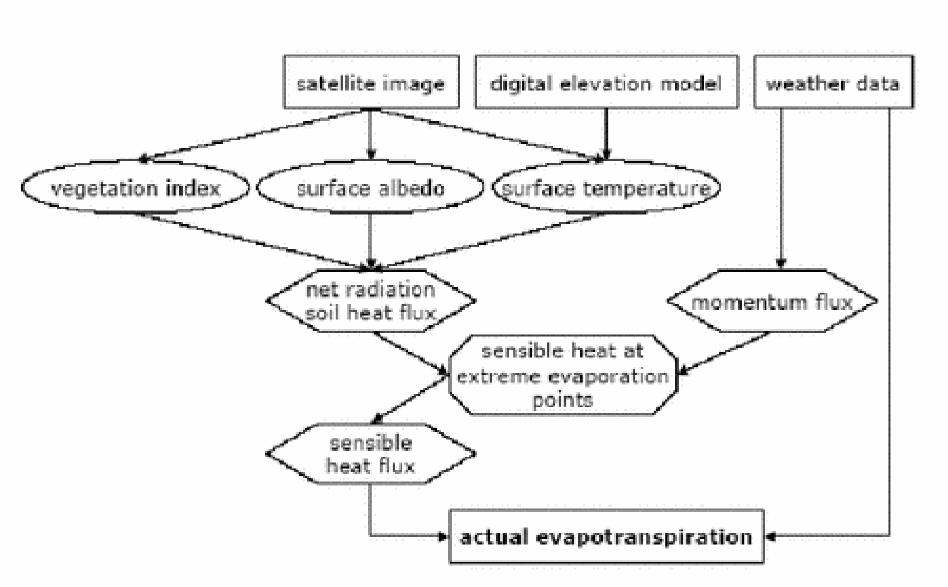


Fig. 2.5: Schematic view of energy balance and ET computations with SEBAL (WaterWatch, 2016)

An overview of the energy balance and evapotranspiration (ET) computations with SEBAL is given in Fig. 2.5 (WaterWatch, 2016). SEBAL is an image processing model comprised of 25 computational steps by which the model calculates actual and potential evapotranspiration rates ET_{act} $[mm\ d^{-1}]$ and ET_{pot} $[mm\ d^{-1}$, as well as other energy exchanges between land and atmosphere. Calculations are based on radiances in the visible, near-infrared and thermal infrared part of the electromagnetic spectrum which are obtained from Remote Sensing products including Landsat imagery. For every individual pixel SEBAL computes an energy balance with resistances for momentum, heat and water vapor transport. These day specific resistances are functions of the soil water potential, wind speed and air temperature change. Instantaneous fluxes are computed for time of satellite overpass which is scaled up to a 24 hour period. This algorithm uses temperature, hemispherical surface reflectance and Normalized Difference Vegetation Index (NDVI) combined with their interrelationships to infer surface fluxes for a wide spectrum of land types. SEBAL provides an assessment of the water balance components needed for the validation of hydrological models, using remote sensing data. To obtain this, the relationship between visible and thermal infrared spectral radiances of areas with a sufficiently large hydrological contrast is used (Bastiaanssen et al., 1998).

SEBAL is different from other Remote Sensing flux algorithms in some of its characteristics. The surface sensible heat flux H $[J\ m^{-2}\ s^{-1}]$ is fixed at the so called hot and cold pixel. These two points anchor the range of H and the evaporative fraction. Therefore these two pixels should be divided between very dry terrain where the latent heat flux λE $[J\ m^{-2}\ s^{-1}]$ approaches zero, and very moist terrain where H approaches zero. The vertical difference in air temperature ΔT is computed from inversion of the sensible heat flux at the anchor points. This implies that neither radiometric surface temperature, nor air temperature measurements are involved in the computation of ΔT. This ΔT is linearly related to radiometric surface temperature, this relationship depends on the satellite image chosen and the area, climate and time of overpass and is often referred to as the "self-calibration" approach. Because of this self-calibration, additional calibration to the specific site of research is not required. The biomass production processes in SEBAL are described by absorption of solar radiation by chlorophyll where the conversion of this energy into a dry matter production is established by means of a light use efficiency. This formulation in SEBAL for crop growth is largely similar to most numerical crop growth simulations and global scale ecological production models. However, crop development is not computed from soil type prevailing water management conditions and farmer practices but prescribed through satellite measured NDVI and temperature time profiles (WaterWatch, 2016).

2.3.2. Method of application of SEBAL in current research

The Surface Energy Balance Algorithm for Land model (SEBAL) is used to obtain actual field parameters for a general performing field. This is used to calibrate the Soil-Water-Atmosphere-Plant model (SWAP) with the generic crop growth WOrld FOod STudies simulation model (WOFOST). In Fig. 2.6 the application of SEBAL in this research is visualized. The SEBAL simulation is part of the preliminary analysis in the current research. In SEBAL daily output is obtained for dates of Landsat 8 overpass within the growing season of the observed crop in the observed area. This is conducted for each of the analyzed actual fields. Additionally to the Landsat data, data is required for elevation, soil characteristics, meteo and land use. The required datasets and procedures for collection and processing are described in paragraph 2.3.4.

The latest version of pySEBAL is supplied with an Excel input file. Use of pySEBAL requires installation of specific Python modules and computer settings. The model is still under development by the Water Accounting plus (WA+) team (van der Zaag et al., 2016) and new updates on the pySEBAL code and necessary computer settings are generated continuously. The SEBAL computation generates raster data which is spatially distributed. The analysis is conducted for a significantly large area which is generally larger than the area of interest, ensuring the availability of a hot and cold pixel in each image. The resulting collection of data maps is visually inspected and compared with information from local experts. Some dates for which Landsat imagery is available are usable because of cloud coverage, severe dryness within a dry period or severe wetness when the Landsat image is generated right after an intense precipitation event.

Table 2.1: Actual field parameters retrieved from SEBAL for calibration of SWAP and WOFOST

ET_{ref}	Reference Evapotranspiration rate assuming grass	$[mm\ d^{-1}]$
LAI	Leaf Area Index	[-]
Albedo	Crop reflection coefficient	[-]
T_{pot}	Transpiration rate, potential	$[mm\ d^{-1}]$
T_{act}	Transpiration rate, actual	$[mm\ d^{-1}]$
SM_{ts}	Soil moisture content in top soil	$[cm^3\ cm^{-3}]$
SM_{rz}	Soil moisture content in root zone	$[cm^3\ cm^{-3}]$
B_{act}	Biomass production rate, actual	$[kg\ ha^{-1}\ d^{-1}]$

A general performing field is selected from the collection of fields for the crop of interest when the SEBAL output is assumed to be representative for the area. This collection of fields is defined through land use classification described in Paragraph 2.8.1. The geographical location of the field of interest and the spatially distributed data allows for aggregation and selection of single actual field parameters to be used in the calibration of SWAP and WOFOST. A separate python script is developed to deduce field specific parameters from the SEBAL spatially distributed output, included in Appendix B. The parameters obtained from SEBAL for dates of Landsat imagery within the growing season of the crop of interest are listed in Table 2.1.

Estimations of dates of local crop emergence and harvest are used to estimate the timing of the growing season for which the SEBAL analysis is conducted. Actual dates of sowing and harvest can vary within a region and crop type. From a time series of Leaf Area Index (LAI) the crop phenology for the specific field is

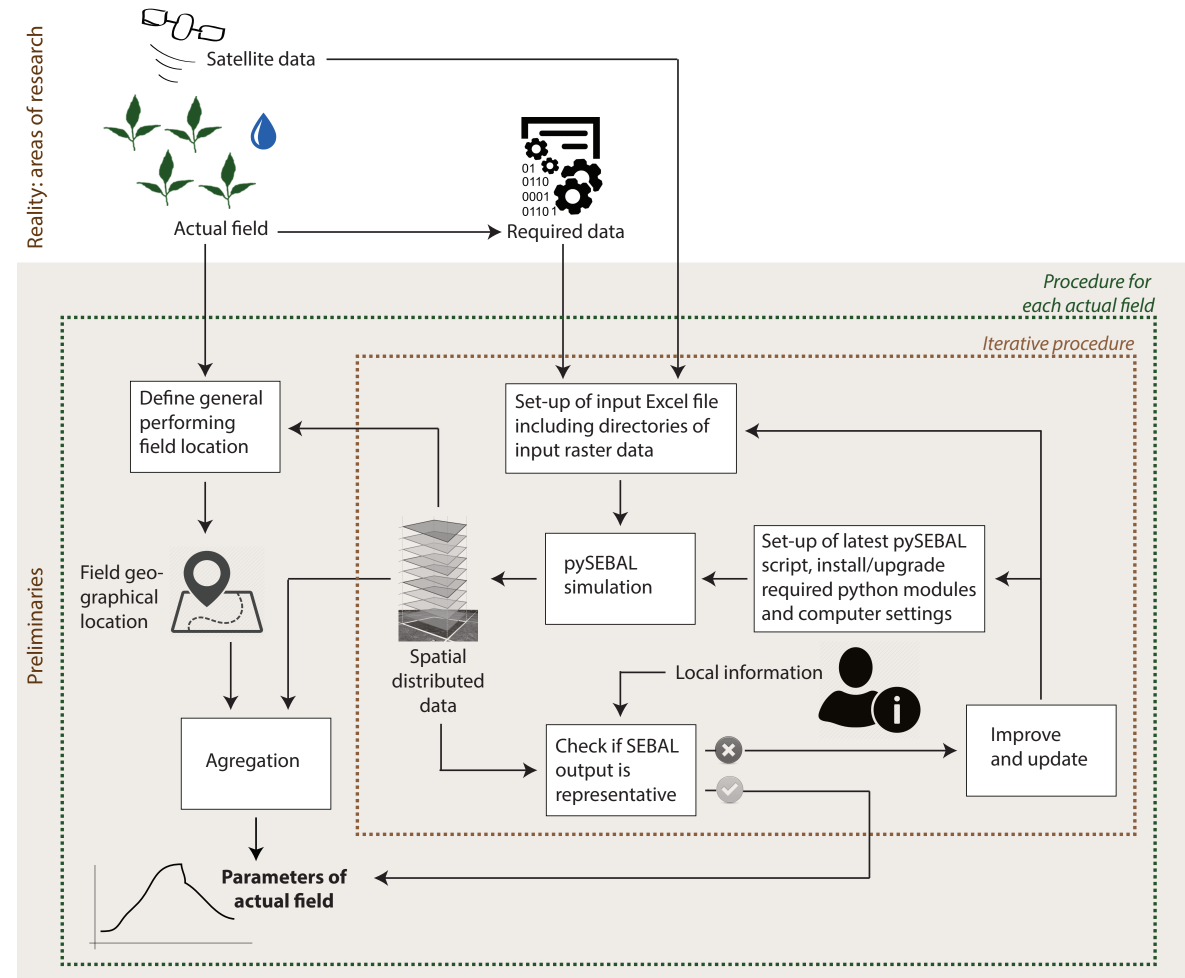


Fig. 2.6: Application of SEBAL to obtain parameters of actual field

deducted more precisely: dates of crop emergence, anthesis/blooming and maturity/harvest which is significant information in the calibration of SWAP and WOFOST. The albedo is an input parameter in WOFOST. The parameters ET_{ref}, LAI, T_{pot}, T_{act}, SM_{ts}, SM_{rz} and B_{act} indicated in Table 2.1 are the output parameters of SWAP and WOFOST against which these models are calibrated for the regions and growing season of interest.

2.3.3. Discussion on SEBAL in current and general hydrological research

In prior research, accuracy assessment of evapotranspiration (ET) fluxes computed by SEBAL has been conducted for various climatic conditions at both field and catchment scales. The typical accuracy at field scale is 85% for 1 day increasing to 95% on a seasonal basis. The model has been applied in more than 30 countries worldwide (Bastiaanssen et al., 2005), cited 391 times in academic publications (Madisch et al., 2017). According to Madisch et al. (2017), 398 different publications include the term "Surface Energy Balance Algorithm for Land". The use of SEBAL in hydrological research is widely accepted.
The assumption is made in this research that SEBAL generates an accurate estimation of actual field parameters without needing further calibration. SWAP and WOFOST are calibrated against the SEBAL output to simulate individual fields that are a plausible representation of actual fields. Accurate SEBAL analysis is crucial for successful calibration of SWAP and WOFOST. The applied SEBAL analysis using satellite data can be seen as a functional replacement of field work. It is therefore highly relevant in the current research, in the scope of this research the same data could not have been collected by field work.

2.3.4. Overview of required data for the use of SEBAL

For two areas of research, SEBAL analysis is conducted for the growing period of the crop of interest. For this application of SEBAL using the latest pySEBAL 3.3.6 beta version for Landsat imagery, the following data is required:

- Estimation of local growing season (dates of emergence and harvest) for crop of interest, obtained from prior research and the FAO crop calendar (Food and Agriculture Organization of the United Nations, 2010).
- Polygons of fields with crop of interest in observed area, obtained from a land use classification described in paragraph 2.8.1.
- Landsat images including six shortwave bands (blue, green, red, near-infrared, and two mid-infrared bands), one or two thermal bands and metadata file. Accessed through GloVis (U.S. Department of the Interior & Survey, 2017), a next-generation global visualization viewer providing access to select data sets within the remote sensing archive of the United States Geological Survey (USGS).
- Meteorological data: Daily meteorological data for moments of Landsat 8 overpass within crop growing season: accumulated incoming shortwave radiation $R_{s,day}$ [$KJ\ m^{-2}$], mean air temperature $T_{mean,day}$ [$°C$], mean relative humidity $RH_{mean,day}$ [%], mean wind speed $wind_{mean,day}$ [$m\ s^{-1}$]. Additionally, instantaneous values are required for the same parameters. This is retrieved from Global Land Data Assimilation System (GLDAS) by NASA/GSFC/HSL (Rodell et al., 2015), described in paragraph **??**. For instantaneous values a representative three hour period is used.
- Elevation data: Digital Elevation Map (DEM) for the area of analysis, based on Hydrological SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (U.S. Department of the Interior & U.S. Geological Survey, 2010). See Appendix G for background information.
- Soil moisture data: saturated moisture content for soil top layer and sub layer [$cm^3\ cm^{-3}$], residual moisture content for soil top layer and sub layer [$cm^3\ cm^{-3}$], moisture content at pF2 (field capacity) [$cm^3\ cm^{-3}$], moisture content at pF4.2 (wilting point) [$cm^3\ cm^{-3}$]. HiHydroSoil model data is used (de Boer, 2016). See Appendix G for background information.

2.4. The Soil-Water-Atmosphere-Plant model: SWAP

The Soil-Water-Atmosphere-Plant model (SWAP) is a hydrological model that simulates transport of water, solutes and heat in the vadose zone, interacting with vegetation development.

SWAP in this research is combined with the detailed WOrld FOod STudies simulation model (WOFOST) for crop growth. These models are applied to accurately quantify the effect of various water management scenarios on the on crop growth in agricultural fields. SWAP and WOFOST are used in the model calibration and simulation phase of this research. SWAP is first calibrated using a simple crop module instead of the more detailed WOFOST model, this initial calibration is described in the current paragraph. In paragraph 2.5 the use and calibration procedure of WOFOST is described. The position of SWAP in the general methodology of this study (see Fig. 2.1) is indicated in Fig. 2.7. Parameters from the Surface Energy Balance Algorithm for Land model (SEBAL) analysis are assumed to be an accurate representation of the actual field and are used for the calibration of SWAP. The calibration procedure is executed for each observed actual field. The method by which the SEBAL parameters are obtained is described in paragraph 2.3.

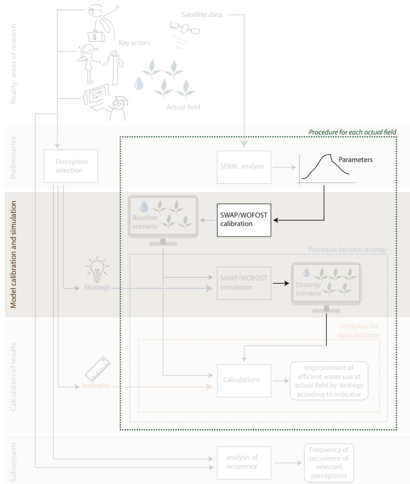


Fig. 2.7: SWAP analysis highlighted in general methodology (see larger overview in Fig. 2.1)

This paragraph first provides an introduction to the model SWAP. This involves its characteristic, structure, prominent equations and applications of SWAP. An extended explanation on the most important processes and equations in the SWAP simulation is included in Appendix C. For a complete understanding of the model, documentation is available by Kroes et al. (2009). Secondly in this paragraph, the use of SWAP in this research is explained. Thirdly, a discussion is provided on the value of this method in the current research and in general hydrological research. Finally, the paragraph provides an overview of the required data for the used application of SWAP.

2.4.1. Introduction to SWAP

SWAP is a vertically directed, one-dimensional model of field scale. The vertical domain reaches from a plane just above the canopy to a plane in the shallow groundwater (Kroes et al., 2009). SWAP is the successor of the agrohydrological model SWATRE (Feddes et al., 1978). SWAP 2.0 was published by van Dam et al. (1997) and Kroes et al. (2001). For this research the latest version available at the approval of this research is used. This is SWAP 3.2.36 (van Dam, 2000), launced in November 2011. In July 2017, SWAP 4.0.1 was launched (Kroes et al., 2017). This newer version of SWAP is currently available but has not been used in this research.

Prior research reports this model to be a powerful tool in simulating the field water cycle and evaluate irrigation practices (Ma et al., 2011). SWAP enables the simulation of all the terms of the water balance at a high temporal resolution on a daily basis (Droogers & Bastiaanssen, 2000). Vertical water movement is caused by pressure head difference. In SWAP it is Darcy's equation for one-dimensional unsaturated flow which is used combined with the continuity equation for soil water considering infinitely small soil volumes, resulting in the general equation for water flow in variably saturated soils, known as Richards' equation. Soil water flow is calculated by solving Richards' equation numerically with an implicit, backward, finite difference scheme. The soil hydraulic functions are described with the Mualem-Van Genuchten relations with a modification near saturation. Penman-Monteith is applied calculating the potential evapotranspiration ET_{pot} of uniform surfaces. Actual transpiration depends on root zone conditions of moisture and salinity and crop-specific critical pressure heads. Actual evaporation is determined by the capacity of the soil to transport water to the soil surface. The soil hydraulic functions and semi-empirical equations are used to determine the soil capacity to transport water. SWAP includes a simple crop module. This module prescribes crop development, not determined by external stress factors. The simple module can be used when crop development is only used as an upper boundary condition for soil water movement. In SWAP the generic crop growth WOrld FOod

STudies (WOFOST) simulation model can be used, allowing the simulation of actual biomass production B_{act}. WOFOST is a sensitive model which requires calibration for specific crop type and geographic location, further introduced in the next paragraph. The SWAP model domain and transport processes are visualized in Fig. 2.8.

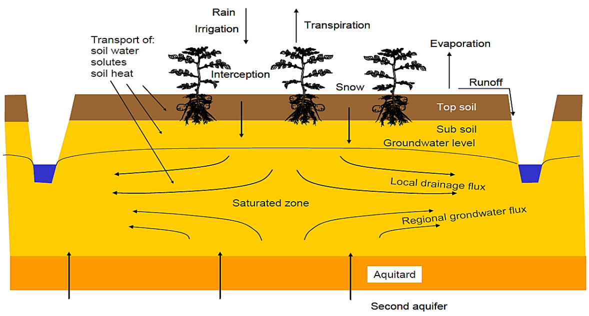


Fig. 2.8: The SWAP model domain and transport processes described by Kroes et al. (2009)

SWAP employs the TTUTIL library to read the ASCII input files in easy format. Output is generated in ASCII and binary files. SWAP input files consist of required data and various parameters that can be adjusted by the user. SWAP requires the following input files:

- .swp – general input file
- .crp – crop input file
- .yyy – meteo input file per calendar year

Additional files for detailed rainfall data, initial soil moisture condition, run-on, detailed soil hydraulic parameters, lateral drainage, bottom boundary conditions or soil surface temperatures are optional, and can be called from the main .swp file. The SWAP setup package contains the calibrated input for a field in the Hupsel catchment in The Netherlands, covering the years 1980-1982. Additionally, meteo files for Wageningen 1954-1999 and various crop files are provided. SWAP is a very flexible model with numerous options. Input parameters can be adjusted for a specific simulation, choices are made regarding methods for calculation and switches are used to determine which aspects to include in the simulation. in the .swp file the soil profile is characterized and decisions are made on those phenomena that the soil layer is subjected to.

The simulated system can be seen as a soil column having top- and bottom boundary conditions and a soil profile. Different characteristics of the top, bottom and profile determine the fluxes in and out of the system and the changes in the soil column. The column is visualized in Fig. 2.9.

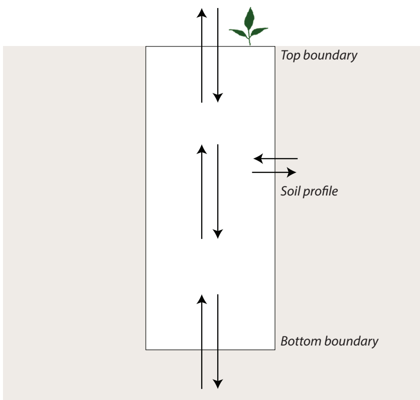


Fig. 2.9: Soil column simulated in SWAP, boundaries described for top, bottom and soil profile.

2.4.2. Method of application of SWAP in current research

In Fig. 2.10 the application of SWAP in this research is visualized. The calibration of SWAP for an actual field and season is executed in a series of steps. Each step is an iterative process which is repeated upon a satisfying level of similarity with the SEBAL output corresponding to this step. The procedure is repeated until all steps are completed, resulting in a calibrated set of input parameters for SWAP simulation using the simple crop module. The daily meteorological data is not adjusted. For this calibration, scripts were developed using Python Programming Language (Python Software Foundation, 2017) to run SWAP and to extract and visualize the SWAP and SEBAL output as desired. Calibration of SWAP and WOFOST against SEBAL generates a baseline scenario for the observed field. The result for the winter wheat field in Tadla Basin, Morocco is presented in Paragraph 4.2. The result for the smallholder maize field in Lower Limpopo Basin, Mozamibque is presented in Paragraph 4.3.

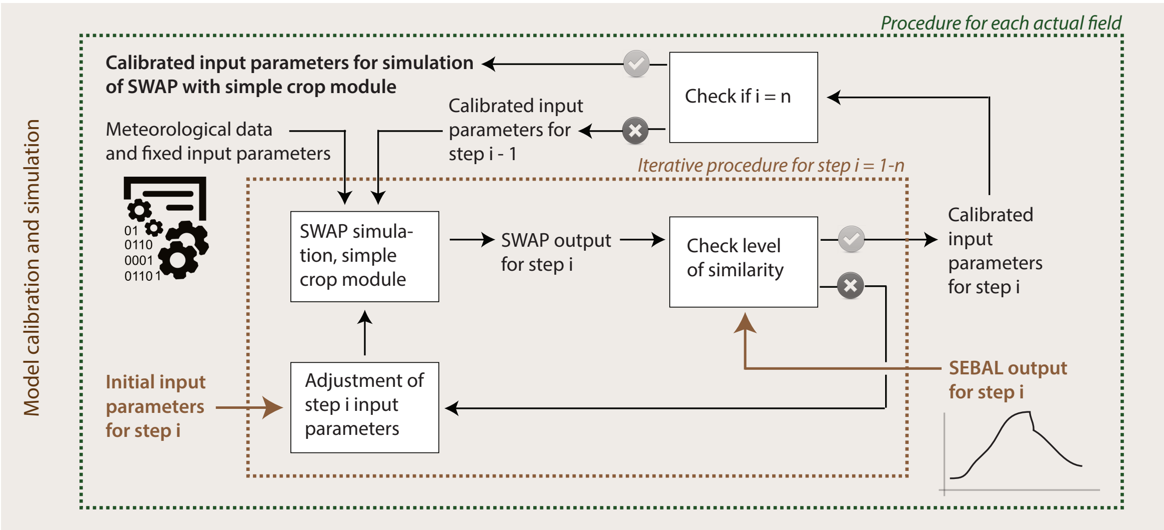


Fig. 2.10: Application of SWAP with simple crop module to obtain calibrated input parameters

Different sources are used for the required parameters: input files from a different but comparable calibration of SWAP, literature on specific characteristics and expert knowledge obtained from local experts, SEBAL analysis or field measurements. Some parameters are used directly from these sources and used as fixed parameters indicated in Fig. 2.10. Other parameters that are more variable for different geographical areas or specific field crop or crop variety are calibrated where the parameter is adjusted within a plausible range.

Fixed parameters in SWAP In the application of SWAP in this research prior to calibration, fixed parameters are determined. These parameters concern the exclusion of several phenomena, soil layering, assumptions concerning the soil hydraulic functions, sensitivity to salinity, settings for the top soil and bottom boundary definition. These settings correspond to the explanation on the SWAP processes included in Appendix C.

In this research, several phenomena are not included in the simulation. This applies to hysteresis, similar media scaling, preferential flow due to macro pores and the computation of heat transport. No snow accumulation and melt or soil water flow reduced by frost is considered.

Layering of the soil profile and thickness of the individual compartments is essential for the soil water flow computation in Richards' equation. The first sublayer consists of 5 compartments of 1 cm thickness. The second sub layer has 5 compartments of 5 cm. These two sub layers are the first soil layer. The third sublayer consists of 7 compartments of 10 cm. The last sub layer consists of 4 compartments that are each 50 cm in thickness. Thus the total column used in this simulation has a height of 300 cm. This choice corresponds to suggestions in prior research (Dam & Feddes, 2000). The layering is visualized in Fig. 2.11.

Assumptions are made concerning the soil hydraulic functions. Hysteresis is not considered, the α [−] parameter of the main wetting curve for hysteresis is equal to the α [−] parameter for the main drying curve. The air entry pressure head is known to be equal to -$1/\alpha$. The measured saturated vertical hydraulic conductivity is assumed to be equal to the fitted saturated vertical hydraulic conductivity following Bartholomeus et al. (2015). The other soil hydraulic parameters for each soil layer are required input data for application of SWAP.

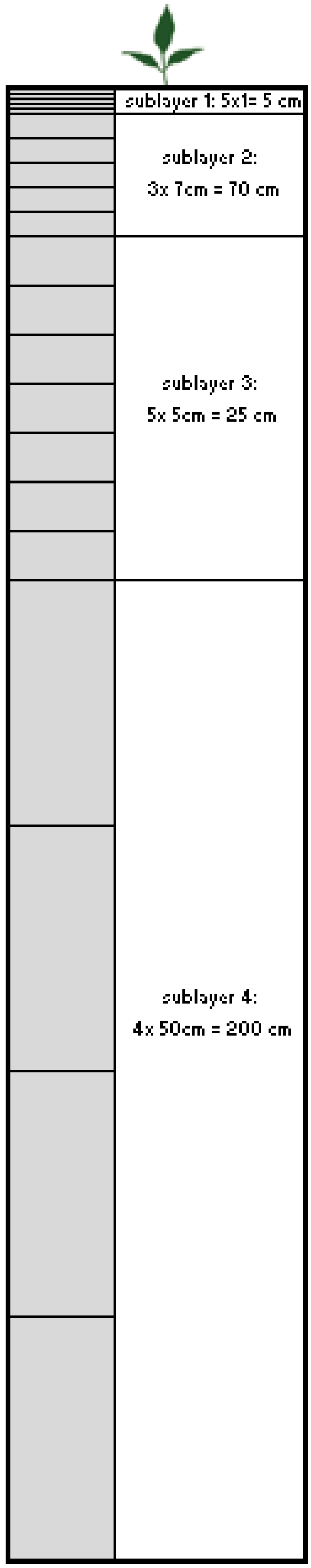


Fig. 2.11: Applied soil layering in SWAP

The conducted simulations include solute transport, as the soil moisture content SM [$cm^3\ cm^{-3}$] and actual transpiration rate T_{act} [$mm\ d^{-1}$] can be influenced by solute concentrations [$mg\ cm^{-3}$]. Solute concentration in precipitation and irrigation water is neglected. The initial soil solute concentration in the soil profile is defined for each field. Solute adsorption is considered as well as solute decomposition and mixed reservoir of saturated zone. For each field, the relation between EC_{sat} [$dS\ m^{-1}$] and crop reduction is determined by EC_{sat}. At this level, salt stress starts and root water uptake declines. For the relation between concentration and EC_{sat}, conversion factors are required, obtained from prior research.

Regarding ponding, runoff and runon the default settings in SWAP are applied. This includes a thickness of 2 cm for runoff in case of ponding, a drainage resistance for surface runoff of 0.5 days and an exponent in the drainage equation of surface runoff of 1.0. The soil evapotranspiration rate E_{pot} [$mm\ d^{-1}$] is not computed from a soil factor but from reference evapotranspiration ET_{ref} [$mm\ d^{-1}$] using crop characteristics or crop factor. For the reduction of E_{pot}, SWAP is set to compute a reduction to maximum Darcy flux and to maximum Boesten/Stroosnijder (Boesten & Stroosnijder, 1986) using the corresponding soil evaporation coefficient of Boesten/Stroosnijder. Top soil temperature is said to be computed from air temperature of meteo input file.

SWAP allows several options for the definition of the bottom boundary. It can be prescribed by time series of ground water level, bottom flux, soil water pressure head at the soil profile bottom compartment or hydraulic head in deep aquifers. There is also an option for free drainage or outflow or a bottom flux equal to zero. The different options require different parameters. The selection for the applied method is determined by the local situation and available data. The selection of free drainage does not require additional parameters. The selection of a prescribed time series of bottom flux records may require calibration when no data is available. The initial soil moisture condition is defined by an initial ground water level assuming equilibrium. Lateral drainage, infiltration or interflow in the soil profile can be simulated but does not apply when a deep ground water table and free drainage at the soil column bottom is observed. When lateral drainage is observed from open channels or drain tubes then resistance of drainage and infiltration, drain spacing and case of open channels water levels in time are defined for each number of the the present drainage levels. Drain spacing and channel characteristics are determined from visual inspection of satellite images and from local expert knowledge.

Table 2.2: Steps in calibration of SWAP with simple crop module against SEBAL

Step	Obtained output	Calibrated parameters
1	Dates of anthesis and maturity (DVS)	Temperature sums: TSUMEA, TSUMAM
2	Leaf Area Index (LAI)	Leaf Area Index: LAI
3	Potential transpiration (T_{pot})	Crop characteristics: CH, KDIF, KDIR, ALBEDO, RSC
4	Actual transpiration (T_{act}); Relative transpiration (T_{rel}); Soil moisture content top soil (SM_{ts}); Soil moisture content root zone (SM_{rz})	Irrigation settings: IRDATE, IRDEPTH; Soil characteristics: KSAT, ALFA, NPAR; Critical pressure heads: HLIM3H, HLIM3L, HLIM4

Calibration of SWAP The required n amount of steps indicated in Fig. 2.10 are four steps, indicated in Table 2.2. The specific output for each step is obtained by adjustment of a selection of parameters. The parameters mentioned in the table are described in the previous section with the introduction of SWAP. Calibrated parameters following from step i are used as fixed input parameters for step i+1.

As the crop development stage directly affects the main crop characteristics, it is important to calibrate crop development stage first. Thus, the first calibration step the temperature sums are varied until the crop Development Stage (DVS) was found at the correct dates of anthesis (DVS = 1.00) and maturity (DVS = 2.00). In the second step the Leaf Area Index was obtained directly by indicating the Leaf Area Index (LAI) from SEBAL for a series of crop development stages. In the third step the crop characteristics were adjusted within realistic ranges until satisfactory potential transpiration T_{pot} was obtained. The fourth and last step is most complex where after the potential situation also the actual situation is calibrated. Here both the actual transpiration T_{act} and the soil moisture content for top soil SM_{ts} and root zone SM_{rz} is obtained. When in the previous step accurate values for the T_{pot} are found, also relative transpiration can be calibrated. The fourth step is accomplished by adjustment of irrigation settings, soil characteristics and critical pressure heads for the crop root water uptake.

2.4.3. Discussion on SWAP in current and general hydrological research

The SWAP model is freely available online. During the period 2004-2017 the model is downloaded from more than 150 countries (Research, 2017). In Fig. 2.12 the spatial distribution of unique SWAP downloads worldwide is visualized. Searching on ResearchGate for "Soil Water Atmosphere Plant Model" results in 1020 different publications. SWAP has been used in prior research to evaluate efficient water use at the agricultural field. Ma et al. (2011) applied SWAP to evaluate the field water cycle for a winter wheat-summer corn double cropping system in Beijing, China under deficit irrigation. With this simulation, amounts of water saving and ground water recharge under optimal irrigation schedules were estimated. A study by Jiang et al. (2011) observes deficit irrigation with saline water in arid regions of China, concluding SWAP to be a useful tool to study water and salt transport and to evaluate irrigation practices. In a recent study (Hunink et al., 2011), evaluation and comparison of different models that provide relevant soil water information for deficit irrigation has been conducted including APSIM, AquaCrop, CROPSYST, DSSAT, STICS, SWAP, SWAT and WOFOST. These crop simulation models were evaluated with the main objective to deliver updated information on the soil water content and possible effects on crop stress from daily meteorological data. The model structure is therefore required to be water oriented rather than crop-growth-oriented and straightforward to use. Ranking the different models according to these objectives resulted in a highest score for SWAP. In a different publication SWAP was used to evaluate the water balance for irrigated maize in Australia (Yinhong Kang et al., 2011). This study successfully analyzed opportunities to save water through improved irrigation scheduling and recycling of drainage water, improving irrigation water productivity at the crop and irrigation system levels.

Bastiaanssen & Bos (1999) encourage the use of hydrological models to investigate the consequences of management interventions on irrigation performance.

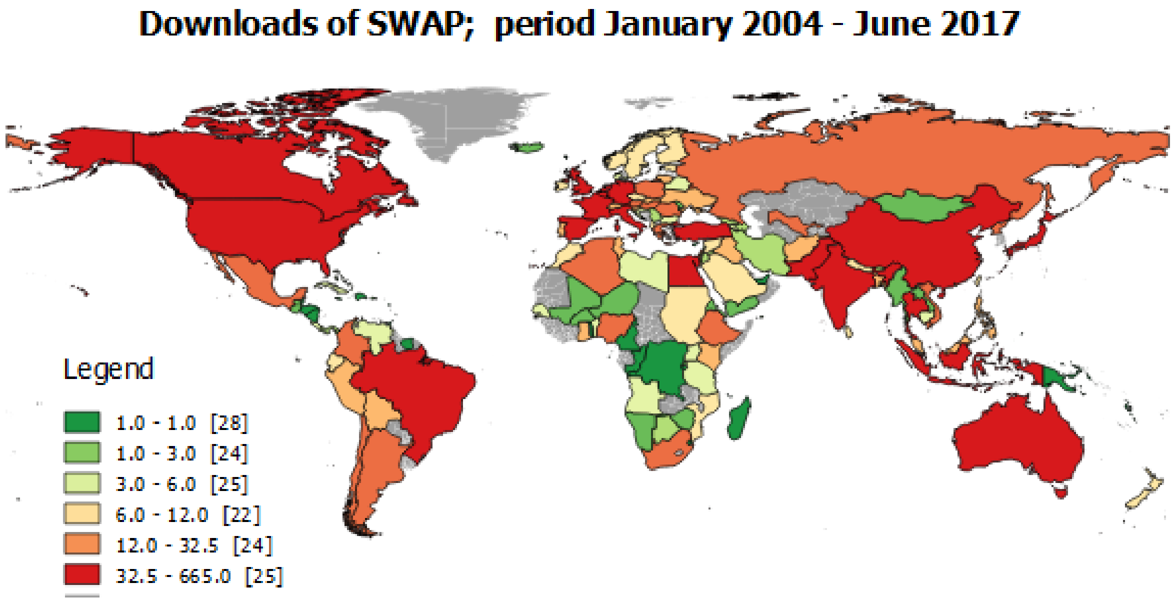


Fig. 2.12: Spatial distribution of unique SWAP downloads worldwide 2004-2017. (Research, 2017)

2.4.4. Overview of required data for the use of SWAP

For two areas of research, SWAP is used to simulate actual fields in the recent past that are representative for the region, where the main crop type is cultivated with general performance. The exact geographical location of a field is required in order to use spatial distributed remotely sensed input data and the SEBAL analysis that is used for the calibration. Most accurate calibration of SWAP against SEBAL is obtained using a maximum of local information and accurate estimations of characteristics, some of this information is season specific.

- Main crop type and dates of emergence, maturity and harvest, determined from SEBAL results for specific field.

- Geographical location: field altitude and latitude. Digital Elevation Map (DEM) is obtained from Hydrological SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS) (U.S. Department of the Interior & U.S. Geological Survey, 2010). See Appendix G for background information. Conducted land use classifications are described in Paragraph 2.8.1.

- Daily meteorological data for model spin up phase and growing season: total incoming shortwave radiation $R_{s,day}$ $[KJ\ m^{-2}]$, minimum and maximum air temperature $T_{min,day}$ $[^{\circ}C]$ and $T_{max,day}$ $[^{\circ}C]$, mean actual vapor pressure $e_{act,mean,day}$ $[kPa]$, mean wind speed $wind_{mean,day}$ $m\ s^{-1}]$ and accumulated precipitation P_{day} $[mm]$. Precipitation data is obtained from a local ground station (Direccao de operacao - Regadio do Baixo Limpopo, 2017) and the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) data archive by United States Geological Survey (USGS) (Funk et al., 2014). Other meteorological data is used from Global Land Data Assimilation System (GLDAS) by NASA/GSFC/HSL (Rodell et al., 2015). Data collection procedure described in Paragraph 2.8.2.

- Knowledge on local situation: Main crop type and estimations of crop characteristics, soil characteristics, ground water interaction with soil column, seasonal crop yield, irrigation applications and salinity. Soil hydraulic parameters are obtained from HiHydroSoil model data (de Boer, 2016), more information provided in Appendix G. Field experiments are described in Paragraph 2.8. Other local information is obtained from literature.

2.5. The WOrld FOod STudies model: WOFOST

The WOrld FOod STudies simulation model (WOFOST) is used for the quantitative analysis of the growth and production of annual field crops.

The WOFOST for crop growth is applied in this study as crop growth module in the Soil-Water-Atmosphere-Plant model (SWAP). Simulation using SWAP/WOFOST is part of the calibration and simulation phase of this research. The position within the general methodology of this study (see Fig. 2.1) is indicated in Fig. 2.13. The application of WOFOST is a continuation of the use of SWAP described in paragraph 2.4 where SWAP is calibrated using the simple crop module. Calibration of SWAP with WOFOST is obtained using the calibrated input parameters of SWAP with the simple crop module as initial input parameters. In the calibration of SWAP/WOFOST, output parameters from SEBAL are used. The result is a simulation of the baseline scenario of the actual field. This procedure is carried out for each actual field. The baseline scenario is used to simulate a strategy upon. This is done for each evaluated strategy. The result is a collection of strategy scenarios for each actual field.

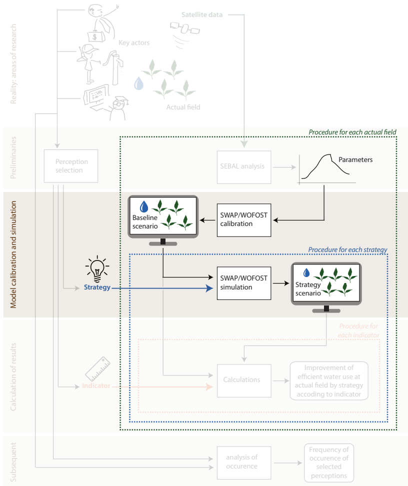


Fig. 2.13: WOFOST analysis highlighted in general methodology (see larger overview in Fig. 2.1)

This paragraph first provides an introduction to the model WOFOST. An extended explanation on the most important processes in WOFOST is included in Appendix D. For a complete understanding of the model, documentation is available by Boogaard, Van Diepen, Rötter, Cabrera & Van Laar (2014). Secondly in this paragraph, the use of WOFOST in this research is explained. Thirdly, a discussion is provided on the value of this method in the current research and in hydrological research in general. Finally, this paragraph provides an overview of the required data for the application of WOFOST in this research.

2.5.1. Introduction to WOFOST

The WOrld FOod STudies (WOFOST) is a generic crop growth model. WOFOST originated in the framework of interdisciplinary studies on world food security and on the potential world food production by the Center for World Food Studies (CWFS) in cooperation with the Wageningen Agricultural University and the DLO-Center for Agrobiological Research and Soil Fertility. By the end of the 1960's, C.T. de Wit, professor of Theoretical Production Ecology at Wageningen Agricultural University recognized the potential of computers to facilitate the description of natural phenomena. WOFOST is a member of the family of models developed in Wageningen by the school of C.T. De Wit. These models follow the hierarchical distinction between potential and limited production, and share similar crop growth sub models, with light interception and CO_2 assimilation as growth driving processes, and crop phenological development as growth controlling process. The development of WOFOST has been connected to the need for its application in various studies carried out by DLO Winand Staring Centre (SC-DLO). WOFOST 7.1 (van Keulen & Wolf, 1986; Spitters et al., 1989; Supit et al., 1994; Hijmans et al., 1994; Boogaard et al., 1998) used in this research is developed to simulate potential production and limited production due to water and/or salinity stress.

WOFOST computes absorbed radiation by solar radiation and crop leaf area. WOFOST also takes photosynthetic leaf characteristics and possible water and/or salinity stress into account, when computing the produced carbohydrates CH_2O. CH_2O provides energy for living biomass (maintenance respiration) and is converted into structural material during which weight is lost (growth respiration). Produced material is partitioned among roots, leaves, stems and storage organs, determined by partitioning factors depending on the development stage. The fraction partitioned to the leaves determines leaf area development and hence the dynamics of light interception. This is visualized schematically in Fig. 2.14. In the simple crop module of SWAP which can be used instead of WOFOST, the Leaf Area Index (LAI) is forced directly by the user as a function of crop development stage, not influenced by physical processes as incorporated in WOFOST. In

WOFOST, dry weight of the plant organs is obtained by integrating growth rates over time. During the development of the crop, part of living biomass dies due to senescence. Unlike the simple crop module, WOFOST enables the simulation of actual crop biomass production B_{act}.

SWAP employs the TTUTIL library to read the ASCII input files in easy format. Output is generated in ASCII and binary files. SWAP input files like the .crp input file consist of required data and various parameters that can be adjusted by the user. Using WOFOST requires a more detailed .crp input file than where the simple crop module is applied. A description on the general structure of SWAP and use of the simple crop module is given in paragraph 2.4. This section describes the detailed WOFOST .crp input file used in SWAP. Light interception and CO_2 assimilation are the main crop growth driving processes. Some simulated crop growth processes like the maximum rate of photosynthesis and the maintenance respiration are influenced by temperature. Other processes are a function of the phenological crop Development Stage (DVS), including the partitioning of assimilates or decay of crop tissue. The parameters are dependent on crop type and the selected sites of research and require calibration.

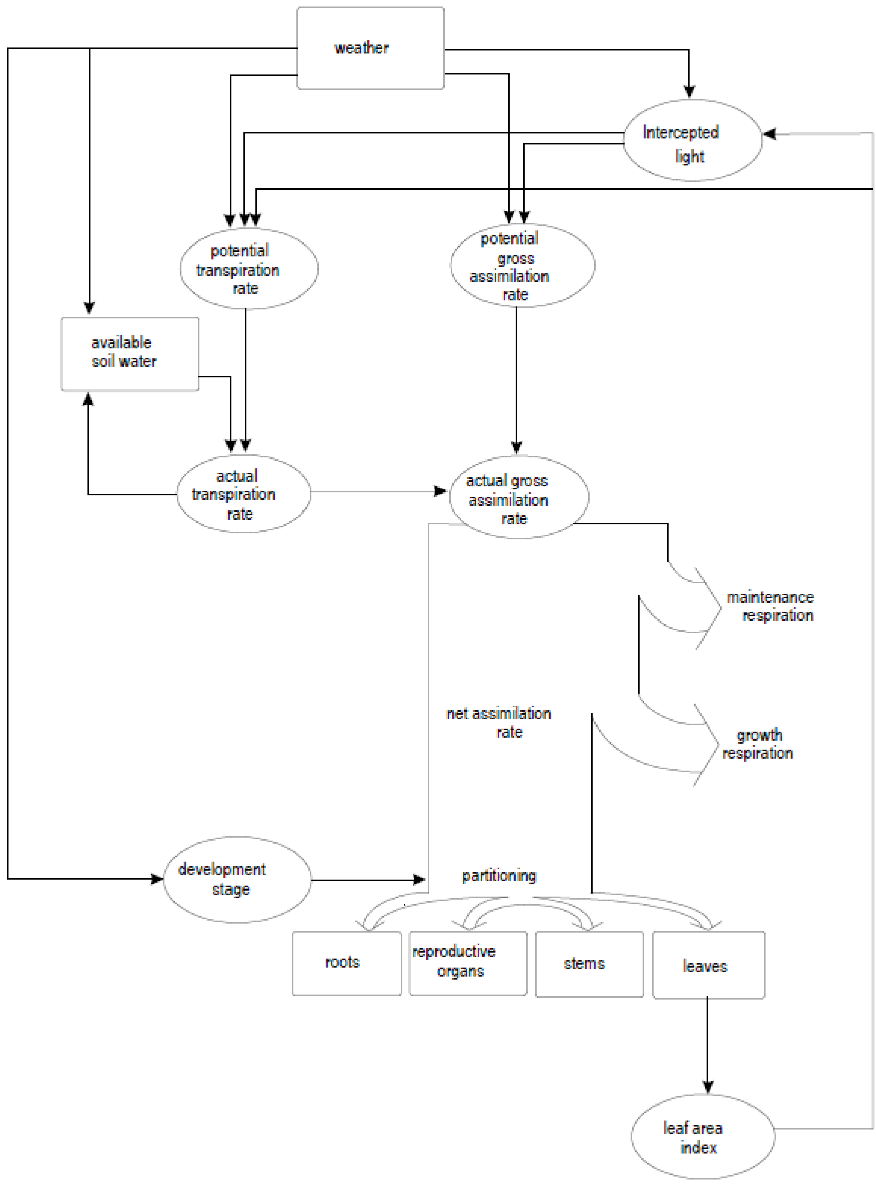


Fig. 2.14: Major eco-physiological processes used in the simulation of crop growth in WOFOST (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014)

2.5.2. Method of application of WOFOST in current research

In Fig. 2.15 the application of WOFOST in this research is visualized. WOFOST was developed as a generic model but it achieves better results for crop growth simulation if the model variables are calibrated for site-specific conditions (Wit & Wolf, 2010). The procedure for the calibration of SWAP/WOFOST is similar to that of the calibration of SWAP with the simple crop module. The resulting input parameters of SWAP with the simple crop module are used as initial parameters in the calibration of SWAP/WOFOST. The output of SWAP/WOFOST is compared with SEBAL data. Parameters for SWAP/WOFOST are adjusted until a satisfying level of similarity. This is applied for a series of steps, ultimately resulting in a calibrated baseline scenario representing the actual performance of the field. This is carried for each of the actual fields. In order to simulate a series of strategy scenarios for each baseline scenario, the calibrated input of the baseline scenario is adjusted for a specific strategy. This procedure is repeated for each baseline scenario or actual field, for each of the studied strategies. In this section first the calibration of SWAP/WOFOST is described. Following, the method for simulation of strategy scenarios in SWAP/WOFOST is described.

For the calibration of SWAP/WOFOST, scripts were developed using Python Programming Language (Python Software Foundation, 2017) to run SWAP and to extract and visualize the SWAP and SEBAL output as desired. In addition to the initial parameters from the calibration of SWAP using the simple crop module, different sources are used for the required parameters: input files from a different but comparable calibration of SWAP, literature on specific characteristics and expert knowledge obtained from local experts, SEBAL analysis and field measurements. Some parameters are used directly from these sources and used as fixed parameters. Other parameters that are more variable for different geographical areas or specific field crop or crop variety are calibrated where the parameter is adjusted within a plausible range. The obtained SWAP/WOFOST input files for the calibrated baseline scenarios and simulated strategy scenarios of observed fields are included in Appendix J. Files for the calibrated baseline scenario of the winter wheat field in Tadla Basin are printed in this Appendix. These and all other files are available online, URLs are presented in the Appendix.

Fixed parameters in SWAP/WOFOST The calibration of SWAP/WOFOST is a continuation of the calibration of SWAP described in 2.4. The same fixed parameters apply. Assumed to be calibrated sufficiently using the simple crop module are the critical pressure heads for crop root water uptake (parameters HLIM1, HLIM2U, HLIM2L, HLIM3H, HLIM3L, HLIM4) and crop characteristics for root growth (parameters RDI, RRI, RDC).

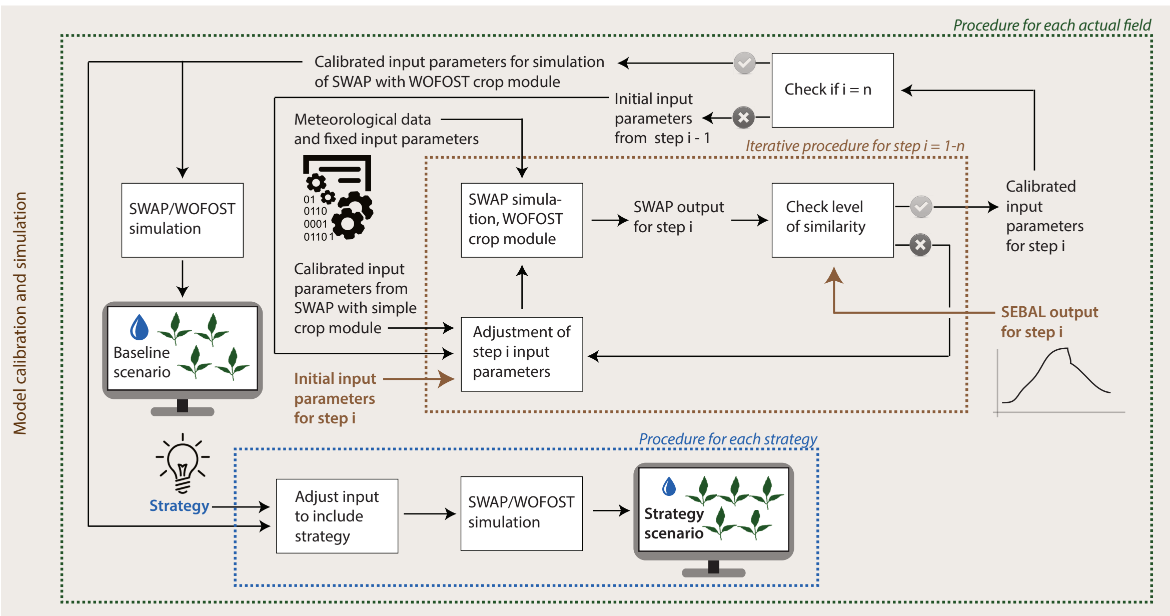


Fig. 2.15: Application of SWAP with WOFOST to obtain baseline scenario and strategy scenario

Calibration of SWAP/WOFOST The required n amount of steps indicated in Fig. 2.15 are six steps, listed in Table 2.3. The specific output for each step is obtained by adjustment of a selection of parameters. The parameters mentioned in the table are described in the previous section with the introduction of WOFOST. In the system dynamics of WOFOST different elements are connected. In the calibration of SWAP visualized in Fig. 2.10, calibrated parameters following from step i are used as fixed input parameters for step i+1. However in the calibration of WOFOST the calibrated input parameters for step i-1 are used as initial input parameters for step i and can be adjusted in this step. Calibration is more likely to succeed using initial values that require only small adjustments. This is why parameters that were defined in the first five steps are calibrated again in the sixth step. For the first step the calibrated parameters from SWAP using the simple crop module are used as initial parameters. For parameters that were not included in the simple crop module, initial values are used from calibrations of WOFOST for the same crop type, calibrated for the same area or an area with similar characteristics. For the first two steps, WOFOST is calibrated for the optimal or potential production scenario which implies no water- or salinity stress. This optimal scenario is created with irrigation scheduling for maximum relative transpiration and no simulation of solutes. In the third to last step the actual scenario is observed. This means that the irrigation scheduling for maximum relative transpiration is not used and solute transport is simulated. Calibrated irrigation and salinity settings for the simple crop module are applied. In the calibration of WOFOST, no adjustments are done in the soil characteristics and settings for irrigation, drainage and salinity. These are assumed to be accurately calibrated using the simple crop module where crop growth merely functions as a top boundary condition for the soil column.

In the **first** step the crop phenology is defined, using a life span of leaves under optimum conditions that exceeds the length of the growing cycle. In this step the correct dates for anthesis (DVS = 1.00) and maturity (DVS = 2.00) are obtained.

The **second** step involves the calibration for the potential transpiration for the optimal production scenario. Parameters for crop characteristics, initial values, the green surface area and assimilation are calibrated against the SEBAL ouput for leaf area index (LAI) and potential transpiration.

In the **third** step the actual scenario is applied. The actual transpiration and soil moisture content is calibrated by adjusting parameters for death rates, conversion factors and reduction factors for senescence, crop water use and root growth.

Since adjustments concerning the actual transpiration affect also the leaf area index (LAI) and hence the potential transpiration, an additional **fourth** step is necessary where small adjustments are applied until satisfactory results for both LAI, Tact, Tpot and SM are obtained. In this step where crop characteristics are calibrated also the life span of leaves under optimum condition is set at a reasonable value.

The **fifth** step involves the calibration of the actual dry mass biomass production and total yield, for which the harvest index and crop moisture content can be used (FAO and DWFI, 2015). Seasonal yield is either used directly from local information or else with available harvest index it is computed from the totally produced dry mass. In the .crp input file the partitioning of the total above ground dry matter into plant organs, conversion factors and maintenance respiration settings are adjusted until the correct biomass production and yield value is obtained.

An additional **sixth** step is required since adjustments for biomass production also effect the earlier calibrated aspects of the crop. Parameters are adjusted slightly until satisfactory results for LAI, Tact, Tpot, SM, total biomass production and yield.

Table 2.3: Steps in calibration of SWAP with WOFOST against SEBAL

Step	Obtained output	Calibrated parameters
1	Dates of anthesis and maturity (DVS)	Temperature sums: TSUMEA, TSUMAM. DTSMTB, DVSEND
2	Potential transpiration (T_{pot}); Leaf Area Index (LAI)	Crop characteristics: CH, KDIF, KDIR, ALBEDO, RSC, TDWI, LAIEM, RGRLAI, SLATB, SPA, SSA, TBASE
3	Actual transpiration (T_{act}); Soil moisture content top soil (SM_{ts}); Soil moisture content root zone (SM_{rz})	Death rates: PERDL, RDRRTB, RDSTB; Conversion factors: CVL, CVO, CVR, CVS;
4	Leaf Area Index (LAI); Potential transpiration (T_{pot}); Actual transpiration (T_{act}); Soil moisture content top soil (SM_{ts}); Soil moisture content root zone (SM_{rz})	Crop characteristics: CH, KDIF, KDIR, ALBEDO, RSC, TDWI, LAIEM, RGRLAI, SLATB, SPA, SSA, TBASE; Death rates: PERDL, RDRRTB, RDSTB; Conversion factors: CVL, CVO, CVR, CVS, RFSETB; Crop water use: HLIM1, HLIM2U, HLIM2L, HLIM3H, HLIM3L, HLIM4; Root growth: RDI, RRI, RDC
5	Actual biomass production (BP_{act}); Seasonal yield (Y)	Conversion factors: CVL, CVO, CVR, CVS; Maintenance respiration: Q10, RML, RMO, RMR, RMS, RFSETB; Partitioning: FRTB, FLTB, FSTB, FOTB
6	Leaf Area Index (LAI); Potential transpiration (T_{pot}); Actual transpiration (T_{act}); Soil moisture content top soil (SM_{ts}); Soil moisture content root zone (SM_{rz}); Actual biomass production (BP_{act}); Seasonal yield (Y)	Crop characteristics: CH, KDIF, KDIR, ALBEDO, RSC, TDWI, LAIEM, RGRLAI, SLATB, SPA, SSA, TBASE; Death rates: PERDL, RDRRTB, RDSTB; Conversion factors: CVL, CVO, CVR, CVS, RFSETB; Crop water use: HLIM1, HLIM2U, HLIM2L, HLIM3H, HLIM3L, HLIM4; Root growth: RDI, RRI, RDC; Maintenance respiration: Q10, RML, RMO, RMR, RMS, RFSETB

Simulation of strategy scenarios in SWAP/WOFOST With the calibration of SWAP/WOFOST, calibrated input parameters are obtained. Simulation through SWAP/WOFOST using these parameters generates the field baseline scenario which is a plausible representation of the actual field performance. Simulating strategy scenarios implies adjustment of the calibrated input parameters. Simulation through SWAP/WOFOST using the adjusted input parameters results in a strategy scenario for the actual field, representing 'what if'. Illustrated by an example: the strategy 'eliminate irrigation' implies changing the input of SWAP/WOFOST such that in this scenario no irrigation is applied. Simulation through SWAP/WOFOST then results in the corresponding strategy scenario which in this example reveals what would have happened if irrigation was not applied at the actual field. The procedure for selection of strategies is described in Paragraph 2.2. The strategies selected for simulation are presented in Paragraph 3.3. The selected strategies are general to be applicable at different agricultural fields. Simulated strategies are not optimized in SWAP/WOFOST.

2.5.3. Discussion on WOFOST in current and general hydrological research

A prior study reports that WOFOST has the possibility to simulate the growth of any annual crop growing at any location (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014). In research the interest has risen over the years to estimate yield of crops before harvest. From this perspective, WOFOST is found to be successful in simulating maize crop growth and yield (Rauff & Bello, 2015; Murthy, 2004). In a study by Amiri et al. (2011), WOFOST is evaluated under irrigation management against a data set of rice cultivation field experiments. On average, Root Mean Square Error or Deviation (RMSE) of the model were 389-553 $kg\ ha^{-1}$ for total biomass, 139-246 $kg\ ha^{-1}$ for biomass of storage organs and 0.46 - 0.58 $cm^2\ cm^{-2}$ for LAI. For these crop variables, normalized RMSE values were 10-14 for total biomass, 7-16 for biomass of storage organs and 54-83 for LAI. The study concludes that LAI from WOFOST simulation generally exceeded measured values.

The application of WOFOST in SWAP allows the computation of actual biomass production driven by physical processes, connected to the dynamics of soil moisture in the soil column. Adjustments of input parameters allows for the simulation of different strategy scenarios for improvement of efficient water use on the field. In the current research, fertile soil and healthy crops are assumed. It is therefore not possible to evaluate strategies that enhance crop health and fertility. To observe advanced pesticide, nitrogen and phosphorus transport including volatilization and kinetic adsorption, SWAP could be used in combination with the detailed chemical transport models PEARL for pesticides and ANIMO for nutrients. In the current research, simulated strategies are not optimized. To exactly define the potential improvement of efficient water use for an observed field, optimization of strategies is required. Instead in the current research for each strategy a general version is simulated. For the intended purpose of the current research, use of the model WOFOST is therefore highly relevant.

2.5.4. Overview of required data for the use of WOFOST

The use of SWAP with WOFOST requires the same data as the use of SWAP with the simple crop module as described in Paragraph 2.4.4. Additionally it is desirable to have WOFOST input parameters calibrated for the same crop type in the same or a similar region. WOFOST is a very sensitive model and within crop species varieties exist. Calibration will always be required. Parameters for a similar simulation will be close to the parameters to be obtained from calibration. Use of these 'nearly calibrated' parameters is desired since this will limit the amount of required iteration loops in the calibration process. Initial WOFOST input parameters from similar simulations are used when available from prior research.

2.6. Quantification: efficient water use at the agricultural field

The results are calculated in the third research phase. They represent the improvement of efficient water use according to leading perceptions.

For each observed and simulated field, efficient water use of both the baseline and the collection of strategy scenarios is computed, according to the collection of different indicators. The SWAP/WOFOST model output parameters are used in the calculations. The position of these calculations in the general methodology of this study (see Fig. 2.1) is indicated in Fig. 2.16. For this element of the current research, the results of all previously described methods are required. Using SWAP/WOFOST, for each observed field a baseline scenario and a collection of strategy scenarios is generated. Subsequently, for each baseline scenario and for each of the strategy scenarios in the two collections, a collection of indicators is to be computed. The values for efficient water use from baseline scenarios and strategy scenario can be compared and evaluated to indicate and quantify improvement. Since the thus generated data set is large, a structured approach is required.

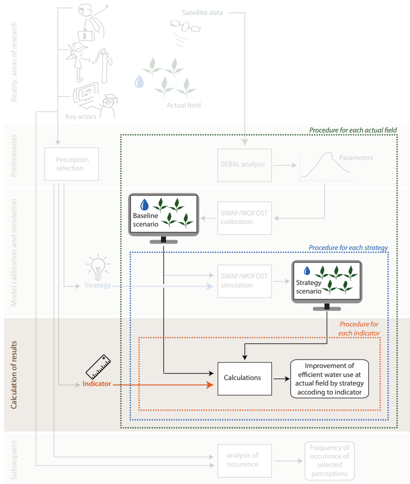


Fig. 2.16: Calculations highlighted in general methodology (see larger overview in Fig. 2.1)

The method for this structured analysis is presented in this paragraph. First, the method used for the calculations is introduced. Secondly, a discussion is provided on the place of this method in the current research and general hydrological research.

2.6.1. Methods used for the quantification of efficient water use

Multiple fields, multiple strategies and multiple indicators require a structured approach for computation of the resulting values for efficient water use and improvement. As presented in the previous phase om model simulation, model output for each scenario is obtained. In the current phase, scripts are developed using Python Programming Language (Python Software Foundation, 2017) where the output is used for computation of indicators for each baseline and strategy scenario. The developed scripts allow for the computation of efficient water use according to each indicator and improvement from baseline by each strategy. Increases of efficient water use by various strategies and according to various indicators for a specific field can thus be evaluated. Additionally, the difference between the two observed fields can be observed.

In Fig. 2.17 the observed system for the agricultural field is indicated with a dotted frame. This system represents the agricultural field simulated using the Soil-Water-Atmosphere-Plant model (SWAP) and the WOrld FOod STudies simulation model (WOFOST) over the period of the observed growing season. The flows visualized with arrows are the total water volumes that have entered or left the field within the growing season. The visualized quantities are elements of a simulated baseline or strategy scenario. These elements are used in the calculation of the observed indicators for efficient water use. Water depths are expressed in mm. Variation in the field is not observed, the values represent field averages.

Indicators for efficient water use at the agricultural field can concern an effect or contribution of irrigation water only, in this case the effect or contribution of natural present water volumes should not be included. At the field effects originate from both irrigation water and naturally present water. In the SWAP/WOFOST simulation the distinction between the effect of these two water sources is not made. To quantify the contribution of irrigation water only, for each field also the rain fed scenario is simulated. This means that no irrigation is applied, the output of the rain fed scenario represents the effect of the naturally present water. To obtain the effect of the irrigation water only for a baseline or strategy scenario, elements from the rain fed scenario can be subtracted from the elements of the irrigated strategy or baseline scenario. This can be illustrated with the following equation:

$$Output_{by\ irrigation} = Output_{simulation,\ baseline} - Output_{simulation,\ rainfed}$$

Use of the SWAP/WOFOST for simulation of baseline and strategy scenarios results in limitations in possible computations. The spatial scale is limited to the agricultural field, distribution losses between water withdrawal and water application at the field cannot be computed. In stead of volume of *water withdrawn*, the volume of *water applied* at the field is used. For the volume of *water consumed*, actual evapotranspiration ET_{act} is used. This means that other consumptive uses including ET other than from the crop and also crop moisture content, is neglected. In the observed fields, no crop stress from salinity is observed. Hence, leaching is not necessary and percolation for leaching of salts is not a beneficial use in the observed systems. Volumes or water depths of *crop consumption*, *beneficial use* and *beneficial consumption* are assumed to be equal to actual transpiration T_{act}.

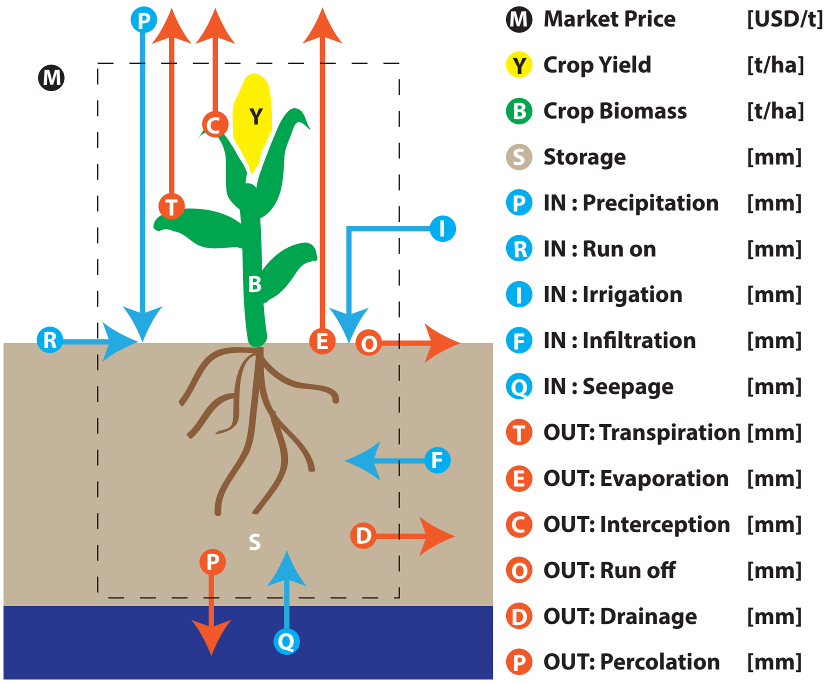


Fig. 2.17: Visualization of the observed system (within dotted lines) simulated in SWAP/WOFOST, representing a single field for a single growing season. Arrows indicate the incoming and outgoing seasonal fluxes. These and other field characteristics and aspects of agricultural performance are generated output from the simulation.

2.6.2. Discussion on quantification in current and general hydrological research

The computation of values of efficient water use from the output of model simulations is the essence of the current research. As has been stated in the previous section, this research is limited to the possibilities in the simulation using SWAP/WOFOST. However, the simulation output gives the opportunity to compute multiple different indicators. Output of simulation of the rain fed scenario can be subtracted from the irrigated baseline scenario in order to quantify the effect of the irrigation water only.

Until now, the combination SWAP/WOFOST has not been used for this purpose. Continuation of the use of this approach would be relevant to other agri-hydrological studies.

2.7. Frequency analysis of strategies and indicators with key actors

From open and semi-closed interviews, literature study and input from group discussions, strategies and indicators are selected as presented in previous paragraphs. Insight in frequency distribution of the support from key actors for individual strategies and indicators is obtained with a survey.

Simulation of strategy scenarios according to the collection of strategies and quantification of efficient water use at baseline and strategy scenarios according to the collection of indicators, has allowed evaluation of the observed perceptions. This has generated relevant insight in differences between the observed fields, the observed strategies and the observed indicators. However, no information is available on the frequency of occurrence of the different perceptions among the total group of indicators. After analysis and conclusions regarding different perceptions, it is relevant to observe how many key actors support the evaluated strategies and indicators.

In this paragraph first the applied method for the conducted frequency analysis is presented. Secondly, a discussion is provided on the place of this method in the current research and general hydrological research. The developed survey is included in Appendix K. In Appendix L a list of survey participants is included.

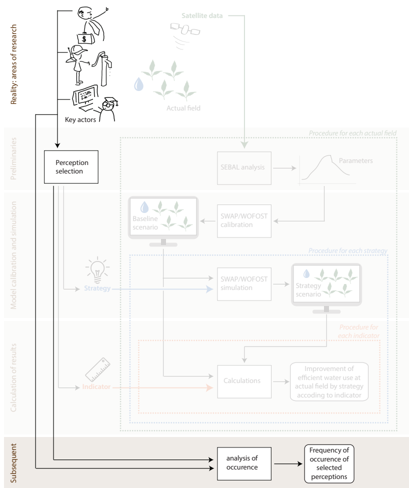


Fig. 2.18: Subsequent analysis highlighted in general methodology (see larger overview in Fig. 2.1)

2.7.1. Methods used for the frequency analysis for occurrence of perceptions

To quantify the frequency of key actors in support of the evaluated strategies and indicators, a web survey is used. The collections of strategies and indicators is presented to a large group of key actors. Key actors are involved at the level of policy, research and practice. Because of these different levels and back grounds, there can be little common ground in communication and understanding between key actors. In the survey, for each simulated field the key actor is asked to evaluate the potential relevance of the possible indicators and the potential effectiveness of the possible strategies.

The survey is developed for the key actor who has a minimum of agro-hydrological and knowledge and for the key actor who is limited in available time to complete the survey. Therefore, the two presented fields are simplified and generalized. A minimum of necessary information is provided. A more in-depth survey would require a large amount of information and explanation for the key actors from all the involved levels, and would thus require more time from the interviewee to complete the survey. The developed survey is expected to require 20 minutes time for completion.

More than 80 key actors from the Netherlands, Mozambique, Morocco and other nationalities involved in the discussion are personally invited for participation in the survey from a network which is developed for this purpose. Four important key actors are contacted personally and asked to distribute the survey in their personal network which is expected to generate at least 80 more invites. Additionally the survey is distributed via the LinkedIn account of W.M.G. Bastiaanssen, who is an expert in the subject of this research and has over 1,300 followers on the LinkedIn of which 25% is expected to active on this medium. The survey is estimated to reach in total 485 key actors. The survey is made available for multiple weeks. A final response rate of 20% is expected. This is expected to generate 97 survey responses.

For a case with surface irrigation and for a case with sub-surface irrigation, indicators and strategies are presented and the participant is asked to select one of the following options:

- For each indicator:
  - Most relevant
  - Relevant
  - Not relevant
  - Misleading
  - Unclear
- For each indicator:
  - Most effective
  - Effective
  - Not effective
  - Counter-effective
  - Unclear

Additionally, from the collection of indicators and from the collection of strategies the participant is asked to select the single most relevant respectively effective option for a general case of an irrigated agricultural field. Participants are also asked to select their level of involvement in agricultural water use and/or the discussion on efficient water use in agriculture, where the following options are provided:

- Practice
- Research
- Policy
- Not involved

Questions in the survey cannot be skipped. The survey allows for the observation of evaluation of strategies and indicators by key actors, for each level of involvement separately. Insight is given in which indicators and strategies are trusted by the participants. Additionally, the response 'unclear' provides insight in indicators and strategies that key actors are not familiar with. The responses that of participants that are 'not involved' can be removed from the dataset.

2.7.2. Discussion on frequency analysis in current and general hydrological research

Online surveys are often used to reach large groups of respondents. Surveys are often short and clear and very specific. For longer and in-depth surveys for large research or development projects, respondents can be paid.

The content of the survey used in the current research is specific but concerns complex issues, the presented cases are simplified and generalized. The participants have various backgrounds, the given information and explanation might not have been sufficient for each participant to completely understand the presented questions and options for response. Therefore, the option 'unclear' might also be used to indicate that the provided information is not sufficient for the participant to give another response. The use of an online survey for the current research allows participation of multiple key actors. However, key actors in practice like farmers in the observed fields might not have access to internet to participate in the survey. The survey is distributed using the network of the researchers involved. It is therefore expected that the majority of the participants will be involved at the level of research.

2.8. Data collection procedures

The methods presented in previous paragraphs require sets of input data that are not directly available in its suitable format. Specific procedures for data collection are required for land use classification of the observed areas and for retrieval of daily meteorological data for the areas and period of observation. This is conducted in the **ee!** (**ee!**). Google Earth Engine code editor (EE) is a web-based Integrated Development Environment (IDE) for the Earth Engine JavaScript API. Code Editor features are designed to make developing complex geospatial workflows fast and easy. Computations using remote sensing data can be done without downloading these large datasets. In the following sections, the methods for land use classification and meteorological data retrieval are explained. For each method a discussion on its relevance in the current and general hydrological research is given.

2.8.1. Methods of land use classification with NDVI

The use of the Surface Energy Balance Algorithm for Land model (SEBAL) and Soil-Water-Atmosphere-Plant model (SWAP) requires a land use classification in the observed areas for the observed season. Specifically, fields of a single crop is of interest need to be localized. This is obtained from land use classification using the Normalized Difference Vegetation Index (NDVI) from satellite data. Optical satellite images from Landsat 7 imagery (L7) and Landsat 8 imagery (L8) (U.S. Geological Survey, 2017) and Sentinel 2 imagery (S2) (European Space Agency, 2017) are utilized, see background information in Appendix G.

Two variations of the method are applied, briefly described in the following sections. The first method is a classification where a ground truth dataset on land use is available. This is applied for Tadla Basin. A complete report is included in Appendix E, the obtained result for Tadla Basin is presented in Paragraph 3.2.1. The second method is a classification where no ground truth is available, in this method information on crop phenology for the crop of interest is used. This second method is applied for localization of plots where maize is cultivated in the observed area in the Lower Limpopo Basin. A complete report is included in Appendix F, the obtained result for the Lower Limpopo Basin is presented in Paragraph 3.2.2.

Classification using ground truth data With available ground truth data on land use, the area is classified comparing the development in of NDVI in time for each pixel in the area with the vegetation development in the pixels of which the crop type is known. Thus a land use classification for the area of study is obtained, from which pixels with the crop of interest can be found. When the ground truth land use dataset is significantly large, it can be divided for each crop type into a set that is used for calibration and a set that is used for validation. This allows for a verification of the accuracy of the classification result. The available ground truth dataset consists of polygons for different crop types. From the collection of polygons for each crop type, a random selection of points is made for a set training set and when possible for a validation set. In these points theNDVI development over time is observed. The Landsat and Sentinel imagery is limited by cloud coverage. Parts of images containing clouds are not usable and pixels with cloud coverage have been removed from each image, resulting in gaps in the dataset. Averages of a certain period of time including a combination of Sentinel and Landsat data can solve for this problem. Sentinel data is preferred because of its fine precision. However this might not be enough to solve for cloud gaps in the data set. A study conducted for this purpose, described in more detail in Appendix E, revealed that the best result is obtained using both L7, L8 and S2 in monthly averages. Every pixel in the observed area is classified according to the monthly development of NDVI. The result can be validated using the validation data set that was not used in the classification, revealing the accuracy of the classification.
This method is applied in Tadla Basin in Morocco, where a land use data set is available for the observed season (CRTS, 2016). This dataset represents 1,038 ha including 17 crop types, two tree varieties and fallow land. Based on visual analysis, 22 ha of bare or urban area and 20 ha of water bodies was added manually to the dataset. An area of 613 ha is used for validation including six major crop types. This was used for classification of 3,440 km^2. For the six major crop types including the crop of interest the accuracy of the classification was estimated. In this area wheat is among the most common crop types and is also the crop of interest in this research. From the classification result, polygons with wheat cultivation are extracted to be used in this research. The method is presented in more detail in Appendix E. The result used from this classification method for Tadla Basin is presented in Paragraph 3.2.1.

Classification using crop phenology When no ground truth data on land use is available, the crop of interest is studied for typical dates of sowing, emergence and harvest and growing rates during the crop cycle. This information is obtained from literature and local expert knowledge. This is used to determine requirements for NDVI development in time. These requirements can be enhanced when more information is available about the area and season including other crop types, the intensity by which the area is used for agriculture, drought, flooding and natural vegetation. To solve for dataset gaps from cloud coverage, NDVI imagery from Landsat and Sentinel are combined over periods of time. The specific crop of focus, season and additional information results in custom made NDVI requirements. Thus pixels are found with a large likelihood for the crop of interest.
This method is applied in the agricultural so called 'family sector' area near Xai-Xai, Mozambique, consisting of small plots where maize is the most common crop and the crop of interest in the classification. Maize is cultivated in two seasons in the observed time span, dates of sowing and harvest are known from literature and local information. The area is prone to flooding and not cultivated areas are covered with reed. For two maize growing seasons the total area of 1211 ha is classified. The area is frequently limited by clouds. Pixels are selected that have high likelihood of maize cultivation for both seasons and of which the L8 to be used in the SEBAL analysis is least limited by cloud coverage. This results in a set of polygons where cultivation of maize in both seasons is likely and SEBAL analysis with L8 is possible. The method is presented in more detail in Appendix F. The result from this classification method used for Lower Limpopo Basin is presented in Paragraph 3.2.2.

Discussion on land use classifications with NDVI in current and general hydrological research Land use and land cover are two separate terminologies which are often used interchangeably (Dimyati et al., 1996). Land cover refers to the physical characteristics of earth surface, captured in the distribution of vegetation, water, soil and other physical features of the land, including those created solely by human activities, for example urban areas. Land-use refers to the way in which land has been used by humans and their habitat, usually with accent on the functional role of land for economic activities such as agriculture. (Rawat & Kumar, 2015) suggests that understanding landscape patterns, changes and interactions between human activities and natural phenomenon are essential for proper land management and decision improvement. In current research, earth resource satellites data are considered very applicable and useful for land use/cover change detection studies (Yuan et al., 2005; Brondizio et al., 1994). (Rawat & Kumar, 2015) gives a description of extensive research efforts that have been made by international scholars for land use/land cover change detection using remotely sensed images. Human determined land use/cover and its interaction with natural systems often has a large role in hydrological research. In-field classification is expensive and time consuming and can only be executed during the time period of study. Methods using remote sensing data are cheaper and can be computed for moments in the past. The combination of remote sensing analysis and a ground truth data set that can be used for validation allows quantification of the accuracy of the applied method and applying this method on large regions, without the laborious in-field classification of this whole region. This can be executed in regions without spatial variations in for example soil type. For the method without a ground truth data set, it is beneficial that no in-field analysis is required. However this method is less preferred since local information will still be required and the result cannot be validated so that the accuracy of the applied method is unknown.

2.8.2. Method of retrieval of meteorological satellite data for SWAP weather input

Daily meteorological data is used from available local stations, or from remote sensing analysis from the Global Land Data Assimilation System (GLDAS) by NASA/GSFC/HSL (Rodell et al., 2015) and for precipitation the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) data archive by United States Geological Survey (USGS) (Funk et al., 2014). This data is accessed trough Google Earth Engine. A script is developed to obtain daily average, total, minimum and maximum values for an area of interest and export this in a **CSV!** (**CSV!**) format which can easily be transferred to the SWAP meteorological input files. Thus daily local meteorological data required in SWAP can be obtained without retrieving spatial datasets. This method requires the geographical location of the field or fields of interest. For use of SEBAL, also meteorological input data is required, both daily and instantaneous values for day and time of satellite overpass. The GLDAS products are available for each 3-hour period. For daily values, the same values are used that are retrieved for SWAP which does not require additional retrieval since the days of SEBAL analysis are within the simulation period of SWAP. For the instantaneous values, values are retrieved corresponding to the 3-hour period that is

most representative for the Landsat satellite time of overpass.
Daily relative humidity RH [%] used in SEBAL is computed from daily mean specific humidity $H_{mean,day}$ $[kg/kg]$, surface pressure $P_{mean,day}$ $[Pa]$ and mean air temperature $T_{mean,day}$ $[°C]$, using standardized methods (Allen et al., 1997). The instantaneous value is obtained likewise. For computation of the actual vapor pressure $e_{act,mean,day}$ $[kPa]$ used in SWAP, the same standardized methods are used but instead of the mean air temperature $T_{mean,day}$ $[°C]$, the minimum and maximum air temperatures $T_{min,day}$ $[°C]$ and $T_{max,day}$ $[°C]$ are used.

Discussion on GLDAS and CHIRPS in current and general hydrological research Meteorological data is highly significant in the application of both SEBAL and SWAP in the application of Penman-Monteith in both models. The GLDAS air temperature data products compared with global meteorological observations archived from the Global Historical Climatology Network (GHCN) indicates a fairly high accuracy of the GLDAS data for daily temperature although the quality is not always consistent in different regions of the world (Ji et al., 2015). GLDAS is found to perform better than its North American counterparts NLDAS and GRIDMET (Blankenau, 2017). Prior research (Wang et al., 2011) reports that the daily downward shortwave radiation $R_{s,day}$ $[KJ\ m^{-2}]$ product from GLDAS is overestimated significantly when compared to observations from ground stations, especially during warm seasons. Simulation of crop growth is sensitive to input of solar radiation, the crop energy source. Hence, overestimated data on solar radiation used in SWAP/WOFOST can be expected to result in overestimated biomass production for the observed area.
Among other satellite based rainfall estimates, the CHIRPS data was found most suitable for drought assessment for the period 1998-2015 in the Upper Blue Nile Basin, Ethiopia (Bayissa et al., 2017). In another study, seven satellite-based rainfall data sets in Burkina Faso, West Africa were evaluated, comparing the products to ground data for the years 2001–2014 on a point to-pixel basis at daily to annual time steps. Daily products of all data sets were found to perform poorly, showing underestimation of rainfall amounts and correlating weakly with rain-gauge data. As the evaluation time step increased, the performance of the satellite-based rainfall products improved. For drought monitoring other products are prefered, CHIRPS is recommended for flood monitoring (Dembélé & Zwart, 2017). In-field meteorological data collection is not part of the current research. Data from ground stations is used when available, especially for precipitation data. GLDAS and CHIRPS are considered the best available satellite-based rainfall and meteo estimations currently available.
Computation of actual vapor pressure $e_{act,mean,day}$ $[kPa]$ and relative humidity $H_{mean,day}$ $[kg/kg]$ using standardized methods with mean temperature $T_{mean,day}$ $[°C]$ or the minimum and maximum air temperatures $T_{min,day}$ $[°C]$ and $T_{max,day}$ $[°C]$ (Allen et al., 1997) is expected to generate different meteorological data used in SWAP and SEBAL. In both models, the saturated vapor pressure $e_{sat,mean,day}$ $[kPa]$ is computed from the input data. Vapor pressure has a significant role in the Penman-Monteith combination equation which is used in both models. The use of different temperature data is expected to result indifferent values of potential evapotranspiration (ET) computed in SWAP and SEBAL.

2.8.3. Method of field work for retrieval of local data for SWAP input

A few field measurements are obtained in the Fidel Castro drainage system in the Lower Limpopo Basin near Xai-Xai Mozambique where the observed field is located. This includes inspection of soil layering, soil infiltration capacity measurements and salinity measurements.

Soil layering During field measurements soil samples are taken over the width of the system on various distances from the sand dunes towards the lowlands, over a depth up to 150 cm. This measurement is done using a hand-operated ergonomic soil auger. These instruments are commonly used to carry out manual drilling and sampling in a great variety of different soils in an ergonomically sound way. It is particularly suitable for general soil investigation (description of the layering, geology, archeology) as well as taking samples for such activities as environmental research (Eijkelkamp, 2012).

Infiltration Using a double ring infiltrometer test in saturated soil indicated a low infiltration rate. The double ring infiltrometer is a simple instrument used for determining water infiltration of the soil. The rings are partially inserted into the soil and filled with water, after which the speed of infiltration is measured. The double ring limits the lateral spread of water after infiltration (Eijkelkamp, 2015).

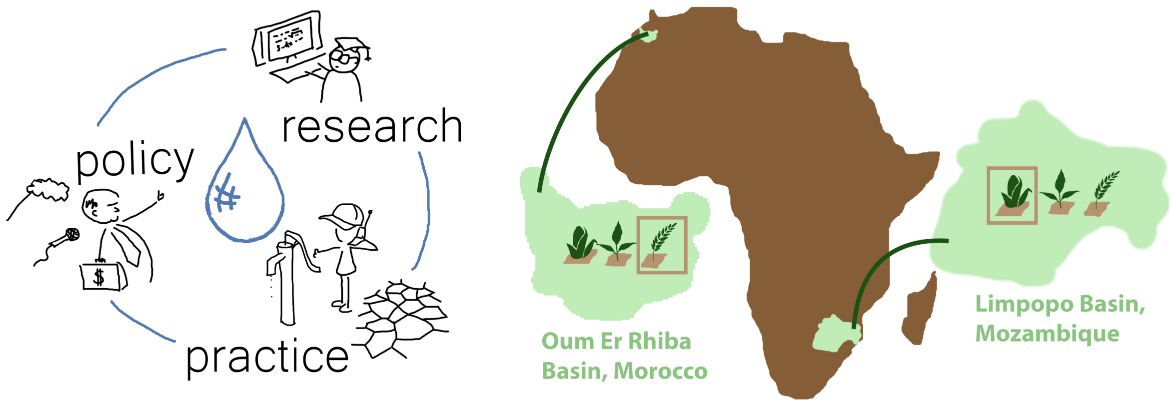
Salinity Salinity data is obtained using a CTD-diver. The CTD-Diver (Nova Metrix LLC, 2017) is a submersible data logger for long-term uninterrupted, real-time water level monitoring using a pressure sensor when submerged at a fixed level under the water surface. The pressure sensor measures the equivalent hydrostatic pressure of the water above the sensor diaphragm to calculate the total water depth. In addition to a pressure sensor, the CTD-Diver is also equipped with a 4-electrode conductivity sensor for measuring the true or specific electrical conductivity of the water. The Diver autonomously measures conductivity, pressure and temperature and records them in its internal memory. The Diver is ideal for ground and surface water level applications.

precipitation data A record of precipitation data for 2016-2017 is obtained from the Regadio do Baixo Limpopo (Water Board in the Lower Limpopo Basin) (RBL) near Xai-Xai Mozambique (Direccao de operacao - Regadio do Baixo Limpopo, 2017). Precipitation depth P_{day} $[mm]$ is daily measured at the pumping station Bombagem de Umbapi downstream of the observed area. Distance to the observed field is 6.7 km. For the observed field near Xai-Xai Mozambique this set of ground truth data is used instead of the CHIRPS data which is used where no ground truth is available.

3
Research sites

Actual sites of research are observed for field scale analysis. This concerns both physical locations of agricultural field and perceptions held by key actors. Food security and related water use is a world wide issue. This research' focus is the involvement of the Netherlands in improvement of efficient water use in areas within the African continent. The selected countries are Mozambique and Morocco. In this chapter the fields and key actors selected for analysis are presented. This overview is the result of the preliminary analysis. The perception selection is described in paragraph 2.2 and the procedures for data collection are described in paragraph 2.8.

In the current chapter, the first paragraph presents the observed key actors. This includes for each group of key actors an introduction and overview of the observed perceptions. The second paragraph introduces the agricultural fields used in the analysis, including their context and characteristic relevant for the simulation. In Paragraph 4 and 5 the collections of strategies and indicators are presented, deducted from the key actors' perceptions and applicable at the observed fields.



(a) (b)

Fig. 3.1: Visualization of research sites: a) Dutch and local key actors in improvement of efficient water use at the agricultural field on the level of policy, research and practice; b) Two distinct areas in the African continent in Oum Er Rhiba Basin, Morocco and Limpopo Basin, Mozambique.

3.1. Observed key actors

Key actors in the improvement of efficient water use at the agricultural field contribute on different levels e.g. policy, research and practice, illustrated in Fig. 3.1(a). The increase of water use efficiency according to the United Nations (UN) Sustainable Development Goals (SDGs) is the responsibility of the Food and Agriculture Organization (FAO) of the United Nations, on behalf of UN-Water. In the Dutch government, the Directorate-General for International Cooperation (DGIS) of the Ministry of Foreign Affairs is responsible for an increase of water productivity in development cooperation policy in foreign countries. This includes the coordination, implementation and funding. Also involved from the Netherlands are research institutes, non-profit organizations and for-profit corporations, involved in the increase of efficient water use in African countries. Local key actors in both Morocco and Mozambique have an important role in the process of improving efficient water use at the agricultural field.

In the following sections information is provided on each of these key actors. Literature, publications and results from interviews, attended presentations and input from group discussions is consulted. For confidentiality the interviewees are not mentioned by name. A complete list of the conducted personal interviews is given in Appendix A. This research evaluates strategies and indicators that can be simulated and quantified in SWAP/WOFOST, where the focus is a single field and a single growing season. Each group of key actors is first introduced. This introduction focuses on responsibilities toward the agricultural field and the issue of food security, and on the connection of the key actors to the observed agricultural fields. Secondly, perceptions of the key actors are presented, focusing on indicators for efficient water use, strategies to improve efficient water use and relevant terminology used. Finally for each group of key actors a concluding section is included.

Equations of indicators and definitions for strategies are highlighted in the following sections. Abbreviations used for indicators correspond to the units of the indicator rather than to the terminology used by the key actor. The following abbreviations are used for indicators:

- **WP** for water productivity [$various\ m^{-3}$]
- **WUE** for water use efficiency [-]
- **EWU** for efficient water use [$various$]

Strategies are abbreviated to **Strat**. Relevant terms are *printed in italics*.

3.1.1. UN-Water and the Food and Agriculture Organization of the United Nations (FAO)

UN-Water coordinates the efforts of international organizations and United Nations entities regarding issues in water and sanitation. This also includes from the UN SDGs for 2030 target 6.4, to address water scarcity and substantially reduce the number of people suffering from water scarcity. This is made concrete in an indicator for efficient water use in agriculture, Sustainable Development Goal (SDG) indicator 6.4.1: "Change in *water-use efficiency* over time". Additionally, other indicators and terminology is used by the FAO.

Introduction The Food and Agriculture Organization of the United Nations (FAO) on behalf of UN-Water is the responsible entity regarding global monitoring of SDG indicator 6.4.1. The FAO aims at the realization of global data, accessible through their Global Water Information System AQUASTAT, to provide countries with data to use on regional level. Although the FAO is responsible for a global monitoring framework, individual UN member states carry the responsibility for monitoring and reporting of SDGs and are seen as the main beneficiaries of improved access to higher quality data. Although global data is desired, UN-Water acknowledges that the monitoring initiatives of the individual member states must be sensitive to national needs (UN Water, 2016*b*). The tasks of the FAO regarding monitoring of water use efficiency are summarized as: 'compiling country data at the global level and supporting countries in their monitoring efforts' (UN-Water, 2017*b*). The monitoring of indicator 6.4.1 is integrated into the inter-agency Global Expanded Monitoring Initiative (GEMI), part of the UN-Water Integrated Monitoring System of targets related to water and sanitation within SDG 6. GEMI is established in 2014 and meant to complement the Joint Monitoring Program for Water Supply and Sanitation (JMP, by the World Health Organization (WHO) and United Nations Children's Fund

(UNICEF)) and the Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS, from UN-Water). The first phase of GEMI implementation is planned for 2015-2018, the framework is in continuous development and a global baseline reportage is expected in 2018. Following, development of monitoring efforts will likely continue and cover the whole SDG period up to 2030. At the end of this period, JMP, GEMI and GLAAS together are expected to monitor global progress towards the entirety of the sixth Sustainable Development Goal (Reidhead et al., 2016). The focus of GEMI is to integrate and expand existing monitoring efforts. Member states are provided with 'Step-by-step methodologies for monitoring SDG 6 global indicators', working documents are in continuous development (UN-Water, 2017*a*).
UN-Water and the FAO are not involved in agricultural water use at the fields observed in this analysis. Like in all agricultural areas, the FAO aims at monitoring water use in these fields.

Indicators At UN-Water and FAO, multiple indicators for efficient water use are found. This includes the aforementioned SDG indicator 6.4.1 but also the WaPOR water productivities and various other indicators used by FAO, documented in the FAO terminology portal.

SDG indicator 6.4.1 is computed as the sum of water use efficiencies of irrigated agriculture, industry and services, weighted according to the proportion of water withdrawn by each sector over the total withdrawals. A water withdrawal is seen as a volume of water abstracted from a river, lake, reservoir or aquifer. Water use efficiency is expressed in added value per volume of water withdrawn in $[USD\ m^{-3}]$, according to UN-Water (2017*a*). In this report this term is labeled as $WP_{SDG\ 6.4.1}$, representing the SDG 6.4.1 indicator for irrigated agriculture.

$$WP_{SDG\ 6.4.1} = \frac{\sum GVA_i}{\sum W_i} \tag{3.1}$$

$\sum GVA_i$ $[USD]$ is the Gross Value Added by irrigated agriculture and $\sum W_i$ $[m^3]$ is the irrigation water withdrawal. This is not dimensionless and therefore technically not an efficiency but a productivity. This confusion is also found in other UN-Water documentation (United Nations World Water Assessment Programme (WWAP), 2015). According to the Monitoring Methodology, indicator 6.4.1 is meant to inform on the economic component of the 6.4 target, highlighting sectors where water-use efficiency is lagging behind the efficiency other sectors. It is specifically stated by UN-Water (2017*a*) that the indicator does not aim at giving an exhaustive picture of the water utilization in a country and that the information is to be complemented by other targets and indicators. In the current Monitoring Guide concerning for SDG 6 (UN-Water, 2016*a*) UN-Water stresses the necessity to look at the water cycle in its entirety to ensure sustainable management of water and sanitation for all (UN Water, 2016*b*). UN-Water also states that water management is most appropriate at basin scale since water resources are naturally confined to water basins. UN-Water stresses that coherence in the policies and decision-making of different sectors and parts of governments is important.

The FAO is currently in partnership and funded by the Government of the Netherlands, to develop a program for monitoring and improvement of the use of water in agricultural production. The target is to develop a publicly accessible near real time database using satellite data which will allow monitoring the performance of water use in agriculture, more specifically: agricultural water productivity. The first output of the program is the development of an operational methodology to develop an open-access database to monitor land and water productivity: the FAO portal to monitor Water Productivity through Open access of Remotely sensed derived data (WaPOR) (FAO, 2017*d*). WaPOR monitors and reports on agriculture water productivity over Africa and the Near East. The portal monitors and reports on agricultural water productivity in Africa and the Near East. Water productivity assessments and other computation–intensive calculations are powered by Google Earth Engine. The first beta release of WaPOR is launched in April 2017, publishing Level 1 data (continental scale, 250 m resolution) from April 2009 to December 2016. Level 2 data (country and basin scale, 100 m resolution) allows for a subdivision into the main crops: maize, wheat and rice, with an additional category for 'other crops'. Additional crops covering more than 10% of the area are classified in level 3 data (scheme scale, 30 m resolution). Level 2 near real time is released in September 2016. In October 2016 a first pilot

area for level 3 is launched. WaPOR is expected to be increasingly improved during the course of 2017 and is expected to last until October 2019 (FAO, 2017*c*).
Two *water productivities* are used in WaPOR level 1 data (FAO, 2017*d*): Gross Biomass Water Productivity (GBWP) and Net Biomass Water Productivity (NBWP). The range of these productivities in the WaPOR area is found from 0 to 6. GBWP expresses the quantity of output (above ground biomass production) in relation to the consumed entity (actual evapotranspiration). In this report the term is labeled as WP_{WaPOR_1}, water productivity according to the WaPOR definition with the gross amount of water used for biomass production. NBWP expresses the quantity of output (above ground biomass production) in relation to the beneficially consumed entity (actual canopy transpiration). In this report the term is labeled as WP_{WaPOR_2}, water productivity according to the second WaPOR definition representing the net amount of water used for biomass production.

$$WP_{WaPOR_1} = \frac{\sum B_{act,y}}{\sum ET_{act,y}} \tag{3.2}$$

$$WP_{WaPOR_2} = \frac{\sum B_{act,y}}{\sum T_{act,y}} \tag{3.3}$$

WaPOR portal observes annual accumulations per hectare. $\sum B_{act,y}$ $[kg\ ha^{-1}\ y^{-1}]$ is the accumulated above ground dry matter biomass production. $\sum ET_{act,y}$ $[m^3\ ha^{-1}\ y^{-1}]$ is the accumulated actual evapotranspiration water volume. $\sum T_{act,y}$ $[m^3\ ha^{-1}\ y^{-1}]$ is the accumulated actual transpiration water volume. GBWP provides insights on the impact of vegetation development on consumptive water use and thus on water balance in a given domain. Contrary to gross water productivity, net water productivity is particularly useful in monitoring how effectively crops and other vegetation use water to develop biomass and subsequent yield.
Both the research areas in Morocco and Mozambique are included in the WaPOR level 2 database. The documentation and WaPOR portal is accessible via de FAO main website. The main partners for implementation are UNESCO-IHE Institute for Water Education and the International Water Management Institute (IMWI). While the WaPOR portal is launched in April this year and the level 1 data has already been used by the Netherlands in monitoring over 2016 (Ministry of Foreign Affairs of the Netherlands, 2017*b*), searching the UN-Water website for "WaPOR" or "Remote Sensing" gives no results. A search for "Database" results in the message that FAOs' AquaCrop Version 6.0 is now available, published in June 2017 (UN-Water, 2017*d*).

The FAO maintains a Term Portal to be accessed trough their website (FAO, 2017*b*). The portal has been created to store, manage and update concepts, terms and definitions related to the various fields of FAO's activities. Each entry in the portal is validated, categorized and documented with an entry number. The portal is used to verify the definitions used by the FAO. When referring to a definition the entry number is given in this report.

Regarding *water use efficiency*, the FAO makes a distinction between *water use efficiency* and *water-use efficiency*. Water use efficiency (entry 100689) is known at FAO as WUE and represents the ratio between effective water use and actual water withdrawal. Categorized under irrigation, WUE represents the ratio between estimated plant water requirements (through evapotranspiration) and actual water withdrawal. In this report the term is labeled as WUE_{FAO_1}, water use efficiency according to the first definition by FAO for irrigated agriculture. Water-use efficiency is also known as 'irrigation water-use efficiency' (entry 99365) and is defined as the amount of biomass or seed yield produced per unit irrigation water applied. This is a productivity and is labeled in this research as WP_{FAO_1} for biomass production and WP_{FAO_2} when yield production is used. These terms referred to as water use efficiencies at FAO, are expressed in the following equations:

$$WUE_{FAO_1} = \frac{\sum ET}{\sum W_i} \tag{3.4}$$

$$WP_{FAO_1} = \frac{\sum B}{\sum A_i} \tag{3.5}$$

$$WP_{FAO_2} = \frac{\sum Y}{\sum A_i} \tag{3.6}$$

Where $\sum ET$ $[m^3]$ is the accumulated evapotranspiration volume, $\sum W_i$ $[m^3]$ is the accumulated agricultural withdrawal water volume for irrigation. $\sum B$ $[kg]$ is the accumulated above ground dry matter biomass production, $\sum Y$ $[kg]$ is the produced yield and $\sum A_i$ $[m^3]$ is the applied irrigation water volume. The terms solely focus on irrigated agriculture and irrigation water, the input of natural water is not evaluated.

For *irrigation efficiency* three definitions can be found with the FAO. Although the aforementioned FAO definitions for *water use efficiency* in eq. (3.4), (3.5) and (3.6) are defined for irrigated agriculture, the FAO terminology for irrigation water-use efficiency is different from irrigation efficiency. First, irrigation efficiency (entry 34338 and 101083) is defined as a measure of the amount of irrigation water beneficially used, divided by the amount of water applied. In this report the term is labeled as WUE_{FAO_2}, representing irrigation efficiency according to the first definition by the FAO. Second, in a remark on agricultural water withdrawal (entry 100437) irrigation efficiency is used as a synonym for the water requirement ratio or WR Ratio. In this report the term is labeled as WUE_{FAO_3}, irrigation efficiency according to the second definition by the FAO. The water requirement ratio is the ratio between the net irrigation water requirement or crop water requirements and the amount of water withdrawn for irrigation including the losses. Irrigation or crop water requirements are defined as the volume of water needed to compensate for the between potential evapotranspiration and effective precipitation over the growing period of the crop. The FAO states that scheme level this irrigation efficiency or water requirement ratio can vary from less than 20% to over 95%. The FAO report on irrigation water requirement and water withdrawal by country (Frenken & Gillet, 2012) uses the water requirement ratio as a synonym for irrigation efficiency, referring to the ratio between irrigation water requirement and the amount of water withdrawn for irrigation. The document reports that this ratio is often referred to as 'water use efficiency', referring to FAO Water Report 38 (Steduto, Faures, Hoogeveen, Winpenny & Burke, 2012). The use of the expression is subject to debate at the FAO (Perry & Kite, 2003). (Frenken & Gillet, 2012) clarifies that this debate concerns the word efficiency which implies that water is being wasted when the efficiency is low which is not necessarily true. The recoverable fraction of the non-consumed water can be used further downstream in the irrigation scheme, it can flow back to the river or contribute to the recharge of aquifers. In FAO's Technical Handbook on Pressurized Irrigation Techniques (Phocaides, 2007) the crop water requirement is not used to define irrigation efficiency but used as a determining factor in predetermining define irrigation scheduling, to improve crop yields and increase water savings (Phocaides, 2007). Thirdly, irrigation efficiency (entry 100557) is defined by FAO as the dimensionless ratio or percentage of the irrigation water consumed by crops of an irrigated farm, field or project to the water diverted from the source of supply. In this report the term is labeled as WUE_{FAO_4}, representing irrigation efficiency according to the third definition by FAO. This definition is also used in FAO's Technical Handbook on Pressurized Irrigation Techniques (Phocaides, 2007). According to this definition, when measured at the field or plot irrigation efficiency is known as "field irrigation efficiency", when measured at the farm head gate "farm irrigation efficiency" or "farm delivery efficiency" and when measured at the source of supply "overall efficiency". Regarding this overall irrigation efficiency, a separate term is available (entry 100558), stating this term is known as the overall efficiency or project efficiency or Ep, where Ep = Ec x Eb x Ea. Project efficiency is further defined (entry 100559) as the ratio between water made directly available to the crop and that released from the headwork. This definition for overall irrigation efficiency is also used in the FAO irrigation manual (Savva & Frenken, 2002) and the FAO Irrigation and Drainage Paper No. 24 on crop water requirements (Doorenbos & Pruitt, 1977). Conveyance efficiency or Ec (entry 100551) is the ratio of the water received at the inlet of a block of fields to the water released at the headwork. Field canal efficiency or Eb (entry 100556) is the ratio between water received at the field inlet and that received at the inlet of the block of fields. Field application efficiency or Ea (entry 100555) is the ratio between water directly available to the crop and that received at the field inlet. Conveyance and field canal efficiencies are sometimes combined and called distribution system efficiency (entry 100552) or Ed, where Ed = Ec x Eb. Thus, Ep = Ed x Ea. This third definition is used from the traditional definition of irrigation efficiency by Bos & Nugteren (1990), where the field application efficiency Ea is defined as the quantity of water needed, and made available, for crop evapotranspiration, to avoid undesirable water stress in the plants throughout the growing cycle. Using the term 'consumed' in the nominator suggests that both beneficial (crop ET) and non-beneficial (non-crop ET) are included, while the definition by (Bos & Nugteren, 1990) is clearly focused on crop need only. Also, the definition of (Bos & Nugteren, 1990) mentions ET needed by the crop which is a potential consumption and not the quantity that is actually consumed. It is not clear how FAO defines *consumed water* in this indicator.

$$WUE_{FAO_2} = \frac{\sum U_{B,i}}{\sum A_i} \tag{3.7}$$

$$WUE_{FAO_3} = \frac{IWR}{\sum A_i} \tag{3.8}$$

$$WUE_{FAO_4} = \frac{\sum U_{C,i}}{\sum W_i} \tag{3.9}$$

Where $\sum U_{B,i}$ $[m^3]$ is the accumulated volume of irrigation water used beneficially, $\sum A_i$ $[m^3]$ is the applied irrigation water volume, IWR $[m^3]$ is the irrigation water requirement volume, $\sum U_{C,i}$ $[m^3]$ is the consumed volume of irrigation water and $\sum W_i$ $[m^3]$ is the accumulated agricultural withdrawal water volume for irrigation. The concepts of *beneficial use* and *consumption* are not further clarified by FAO.

Concerning *water productivity*, three conceptual definitions are offered by FAO. The terms "Net Biomass Water Productivity" and "Gross Biomass Water Productivity" are not available in the FAO Term Portal. On the subject of irrigation (entry 100667), water productivity is defined as a ratio of product output over water input. In this report the term is labeled as WP_{FAO_3}, water productivity according to the first definition for water productivity by FAO. The term can be at different scales and different outputs. The output can be goods, services, an environment service or function. The output can be expressed in term of yields, nutritional value or economic return. On the subject of agriculture (entry 100972) water productivity is defined as growing more food or gaining more benefits with less water. Increasing water productivity is specified as increasing the value produced per unit of water. In this report the term is labeled as WP_{FAO_4}, water productivity according to the second definition by FAO. A third definition defining "crop water productivity" (entry 100533) is simply defined as crop production per unit of water, with the note that this is often expressed in kg/m3. In this report the term is labeled as WP_{FAO_5}, water productivity according to the third definition by FAO. This third definition was officiated at the FAO expert meeting on crop water productivity (Kassam & Smith, 2001).

$$WP_{FAO_3} = \frac{Gain_{product}}{Water_{irrigation}} \tag{3.10}$$

$$WP_{FAO_4} = \frac{Gain_{value}}{Water} \tag{3.11}$$

$$WP_{FAO_5} = \frac{Gain_{crop}}{Water} \tag{3.12}$$

Only WP_{FAO_5} is known to be expressed in $kg\ m^{-3}$, although it is unclear whether the produced crop is measured against dry biomass or yield, at what point the water volume is measured and whether this includes only irrigation water or also natural water sources. The first two definitions are deliberately vague on the 'Product' and 'Value' since can represents various desirable things. All three definitions focus merely at the output or product, the source or scale of the 'Water' input is not at all defined. WP_{FAO_3} clearly focuses at irrigation water. In WP_{FAO_4} and WP_{FAO_5} this is not clarified which suggests that also natural water input could be included.

Strategies The term *water saving* is not clearly defined by FAO but often used as the decrease of the volume of water used, which often contributes to efficient water use according to various indicators used by FAO. About water saving in irrigation (entry 100979) FAO remarks that the main technologies to enhance water saving likely to be used in developing countries are underground and drip irrigation. This strategy by FAO is labeled in this report as $Strat_{FAO_1}$.

- $Strat_{FAO_1}$ = Change irrigation method to drip irrigation

Mentioned in the same entry as additional advantages of these water saving technologies and in particular of drip irrigation is increasing yield and reducing salination rate. On 'water savings' (entry 61445) FAO emphasizes that beside the field other water users should not be deprived at that thus the water systems introduced at the field must be supported with water management techniques.

FAO defines *deficit irrigation* (entry 73718 and 101156) as an irrigation practice whereby water supply is reduced below full crop-water requirements whereby mild crop stress is allowed with minimal effects on yield. The term 'regulated deficit irrigation' (entry 100891) is defined as an irrigation strategy imposing water stress either at a particular growth period or throughout the whole growth season. This strategy by FAO is labeled in this report as $Strat_{FAO_2}$.

- $Strat_{FAO_2}$ = Regulate deficit irrigation

Terminology The SDG Monitoring Guide (UN-Water, 2016*a*) and Step-by-step Monitoring Methodology (UN-Water, 2017*a*) provide insight in the definitions and terminology used by UN-Water concerning water scarcity and efficient water use. The goal of target 6.4 is to address water scarcity and substantially reduce the number of people suffering from water scarcity. The *physically water scarcity* is defined to prevail when more than 75% of available water resources is withdrawn. Additionally, *economic scarcity* is stated to prevail when malnutrition exists although less than 25% of available water resources is withdrawn. According to the documentation, the term *water use* in indicator 6.4.1 is seen as a general and non-specific, describing any action through which water provides a service. According to the provided normative interpretation and rationale this concerns economic activities. Seen by the organization as highly relevant are those with high water use: agriculture, industry and services, defined according to the International Standard for Industrial Classification (ISIC) of All Economic Activities.

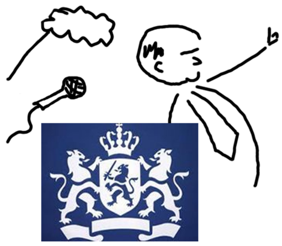
At the FAO, *water use* (entry 101031) is defined as the withdrawal of water for multiple purposes. The agricultural purpose is irrigation where water is partly consumed by crops, and partly required to flush salts out of the soil. This definition suggests that all water is either consumed by crops or used for leaching. This suggests that all water withdrawn is used beneficiary, other uses like evaporation, runoff or losses between withdrawal and field application are not mentioned. The term or concept *Beneficial (water) use* is not included in the FAO term portal, although it is included without further clarification in a definition for irrigation efficiency, see eq. (3.7). The general term for *water withdrawal* is also used related to SDG indicator 6.4.1, see eq. (3.1). Water withdrawal is defined by FAO (entry 101123 and 41734) as the gross amount of water extracted from the resources for a given use, which includes conveyance losses, consumptive use and return flow. Additionally, *agricultural water withdrawal* (entry 100437) is defined as the annual quantity of water withdrawn for irrigation and livestock purposes. This is further defined with the remark that this includes renewable freshwater resources as well as potential over-abstraction of renewable groundwater or withdrawal of fossil groundwater, use of agricultural drainage water, desalinated water and treated wastewater. Livestock watering is sometimes included, in some countries this is categorized as municipal water withdrawal. FAO states that concerning water withdrawal for irrigation, the value far exceeds the consumptive use of irrigation because of water lost in its distribution from its source to the crops. This is contradicting the aforementioned definition of water use. The FAO uses a separate definition for *consumed withdrawn water* (entry 100679) being water withdrawn from water courses for use in agriculture, industry or domestic purposes and thereby removed from freshwater resources. Examples of removed water are given: water that has evaporated, transpired, been incorporated into products and crops, consumed by human beings or livestock or ejected directly to the sea or into evaporation areas (blind watershed). Not included in consumed withdrawn water are water losses during the transport of water. It is stated that consumptive water use is not the same as water use. Furthermore, *not consumed withdrawn water* (entry 100680) is defined as water that has been withdrawn for use and is not consumed. It is stated that most water withdrawn returns to surface waters or aquifers after it has been used, although it is not indicated whether this is consumptive or non-consumptive use.

Concluding UN-Water is persistent in the use of the term *efficiency* for SDG indicator 6.4.1 see eq (3.1) which this is not a dimensionless ratio. Contradiction and vagueness is obvious in the terminology used by the FAO. The WaPOR terminology see eq (3.2),(3.3) is clear but not incorporated in the general FAO Term Portal or the UN-Water publications. The *productivity* indicators promoted by the FAO see eq (3.10),(3.11),(3.12) are conceptual and not clearly defined.
A selection of the suggested indicators and strategies is used for further analysis using model simulation. In the simulations used in the current research, distribution losses between water withdrawal and water application at the field are not simulated and can therefore not be computed. Instead of drip irrigation, only sprinkler irrigation can be simulated. To compute the Gross Added Value, market prices can be used. Multiple indicators are not specific. For quantification in the following analysis clear indicators are required which can be seen as interpretations of the non-specific indicators.

3.1.2. The Directorate-General for International Cooperation of the Netherlands (DGIS)

In the Dutch government, the Directorate-General for International Cooperation (DGIS) of the Ministry of Foreign Affairs is striving for an increase of water productivity in development cooperation policy in foreign countries. This water productivity is often referred to as *crop per drop*.

Introduction In the organizational structure of the Ministry of Foreign Affairs of The Netherlands, the Secretary-General, Deputy Secretary-General and Directors-General are the most senior civil servants. The Directors-General head the Directorates-General, which serve the political leaders within specific spheres of foreign policy. The Directorate-General for International Cooperation (DGIS) of the Ministry of Foreign Affairs is responsible for development cooperation policy in foreign countries including its coordination, implementation and funding (Government of the Netherlands, 2017*a*). In 2016 DGIS spent a total of 194 million € was spent world wide on the theme 'Water' (Ministry of Foreign Affairs of the Netherlands, 2017*a*).



UN Member States including the Netherlands are expected to develop their own road maps for SDG implementation and are invited to complement the global monitoring framework with additional indicators at national, regional or program level. The current Monitoring Guide (UN Water, 2016*b*) is work in progress to be revised based on country feedback. GEMI cooperates with Proof of Concept (PoC) or pilot countries who support in the development of a global framework for monitoring by testing the provided methodologies and collecting data for the SDG indicators (ter Horst, 2016). These countries are Senegal and Uganda in Africa, Jordan in the Middle East, Bangladesh in Southern and Eastern Asia, Peru in Latin America and the Netherlands in Europe (FAO, 2016*c*). PoC countries including the Netherlands test the applicability of the GEMI monitoring framework, as a whole and for indicators specifically, and provide feedback (the Netherlands IHP-HWRP Committee, 2016).

In an interview with DGIS it was emphasized that monitoring of the effect of development cooperation projects has become more important over the last years. The variety of of possible perceptions and definitions regarding efficient water use in agriculture is experienced as a significant problem. A point of debate is whether capacity building at the ministries is relevant or that investment in local employees should be preferred. In the complex issue of food security and efficient water use knowledge is regarded very important. The interviewee believes a strong private sector is key in independent monitoring, instead of realizing this from within a government that can be corrupt and instable. DGIS is the funding party in FAO's WaPOR portal realizing world wide open-access data on water productivity. While the portal is in full development key actors in the improvement of efficient water use in agriculture need to become familiar with this data. In 2017 DGIS commissioned the Community of Practice (CoP) Water Productivity project in the Netherlands, with the objective to create a community of practice among main stakeholder organizations in the water sector, concerning the use of water productivity and the WaPOR database. A series of four master classes was held to create familiarity, stimulate the uptake and inspire creative applications for the datasets and proposed methodologies regarding water productivity. This program focused at small and medium-sized enterprises and non-profit organizations in the Netherlands who are interested in the theme of food security and water saving in regions with water scarcity. Another measure by DGIS to promote water productivity is a series of trainings in partner countries of the Netherlands around the world where Dutch embassies and local key actor are introduced to concept of water productivities and the WaPOR database.

Morocco is not a Dutch partner country for development cooperation but the Netherlands does support activities in Morocco concerning agriculture and the environment (Government of the Netherlands, 2017*b*).
For several decades Mozambique has been a partner country for Dutch development cooperation. In the period up to 2017, the theme of food security is among the main priorities (Government of the Netherlands, 2017*b*). Projects funded by DGIS are monitored. For 2016, no statistical data is available according to the latest yearly report of the department Inclusive Green Growth (Ministry of Foreign Affairs of the Netherlands, 2017*a*). The report mentions an increase in water productivity between 2009 and 2015 in six target countries including Mozambique. This progress towards the 25% increase by 2017 for several partner countries in Africa including Mozambique was also reported by an earlier government publication (Ministry of Foreign Affairs of the Netherlands, 2015). This suggests a high priority of the Netherlands towards an increase of water productivity in Mozambique. In the Multi-Annual Strategic Plan (MASP) for Mozambique for the years 2014-2017, a budget of 35.7 million € is mentioned for improved food security in 2014-2017. However in this report the term 'water productivity' has a marginal place and 'water use' is not mentioned (embassy in Mozambique, 2013). In a report from the Dutch embassy in Maputo (The Netherlands embassy in Mozabique, 2017), the only current project aiming at an increase in water productivity is carried out in the Zambezi river basin. This document uses data from the FAO WaPOR database for results in 2006, and indicates relative to the baseline year a decrease in Biomass Water Productivity expressed in $[kg\ m^{-3}]$. The 2016 country report for Mozabique by DGIS (2017) reports a total expenditure of 29.31 million € for this year. Food security and Water are mentioned as important themes. This is specified in highlights of safe access to agricultural areas and access to safe and affordable drinking water. Growth in agricultural production is due to extension of cultivated area, production rates in the country remain low. Water use or water productivity is not mentioned in this document.

Indicators In partner countries of the Netherlands, the Dutch government aims at an increase of 25% in water productivity between 2009 and 2017. This is one of the three main targets in development cooperation (NLgovernment, 2017). Water productivity is defined as crop yield per unit of water.

The most recent government publication on development cooperation (Ministry of Foreign Affairs of the Netherlands, 2017*a*) uses the indicator *efficient water use* in agriculture, expressed in kg maize per m^{-3} water volume. In a publication on the results of development cooperation in 2016 (DGIS, 2017) DGIS states that investment in sustainable and inclusive development is profitable and that the UN Sustainable Development Goals (SDGs) will remain the framework until 2030. The SDGs include indicator 6.4.1 presented in eq. (3.1). Yearly reports (Ministry of Foreign Affairs of the Netherlands, 2016, 2017*b*) are published by the Department Inclusive Green Growth (IGG) of the Ministry of Foreign Affairs on the progress of Dutch development cooperation regarding this theme. Projects are classified according to their result area, of which the first is *efficient water use* in agriculture. This efficient water use is expressed in $[kg\ m^{-3}]$. Each project in this area is evaluated by DGIS using the following questions:

1. To what extent has the ratio between crop yield and water use been improved in a sustainable manner in the target area of your program ('more crop per drop')?
2. To what extent has your program contributed to this result?

In 2016 the department IGG (Ministry of Foreign Affairs of the Netherlands, 2016) mentions the expected remote sensing based data on water productivity, referring to the WaPOR portal introduced in Paragraph 3.1.1. WaPOR data includes water productivities presented in eq. (3.2) and (3.3). The department expects this data to support improved water management and improve reporting quality, allowing for monitoring of agricultural water use at an unprecedented scale and level of detail. In 2017 the department reports (Ministry of Foreign Affairs of the Netherlands, 2017*b*) that with the launch of the WaPor database indeed agricultural yield data as well as evapotranspiration data can be measured in near real time. This has generated the ability to monitor agricultural water use at large spatial and temporal scale. The department states that this data can support both policy making for improved water management and local farmers. The IGG department expects to use the WaPOR database exclusively for reporting of results in 2017. In this latest publication (Ministry of Foreign Affairs of the Netherlands, 2017*b*), the IGG department reports to work on a pilot for results with regard to undefined biomass water productivity on crop lands. With the launch of the second phase of the WaPOR database, it is expected to define water productivity and yield scores of wheat, maize and rice. The indicators were formerly based on available statistical data from FAOstat. In the future the data will be provided by WaPOR.

Three different types of indicators are desired by DGIS. First, agricultural yields in kg. In this report the term is labeled as EWU_{DGIS}, efficient water use according to DGIS, referring to agricultural yield. This indicator is averaged for both East- and West Africa and expressed in $kg\ ha^{-1}$. The second type is crop specific water productivity, expressed in $kg\ m^{-3}$. In this report the term is labeled as WP_{DGIS_1}, water productivity according to DGIS for a specific crop. Over the 6 target countries together, this indicator is averaged for both maize and rice and expressed in $kg\ m^{-3}$. It is assumed in this report that the the nominator represents yield but this could also be biomass production. Neither information is given on the source of the water volume. The third type is biomass water productivity assessed with WaPOR in $kg\ m^{-3}$. In this report the term is labeled as WP_{DGIS_2}, water productivity according to DGIS for biomass production. This indicator is equal to the WP_{WaPOR_2}, presented in eq. (3.3). This indicator is averaged for both East- and West Africa. It is not indicated whether the gross or net biomass water productivity from WaPOR is used, see eq. 3.2 and 3.3 in this report. It is assumed in this report that the net biomass water productivity is used, since this is a valuable indicator of how effectively crops and other vegetation use water to develop biomass and subsequent yield.

$$EWU_{DGIS} = \sum Y_y \tag{3.13}$$

$$WP_{DGIS_1} = \frac{\sum Y}{Water} \tag{3.14}$$

$$WP_{DGIS_2} = \frac{\sum B_{act,y}}{\sum T_{act,y}} \tag{3.15}$$

In the above equations Y_y is the yearly crop yield $[kg\ ha^{-1}]$. The term 'Water' is the used volume of water expressed in m^3, its source and scale is not further clarified. $\sum Y\ [kg]$ is the obtained yield for the same scale. $\sum B_{act,y}\ [kg\ ha^{-1}\ y^{-1}]$ is the yearly accumulated above ground dry matter biomass production. $\sum T_{act,y}\ [m^3\ ha^{-1}\ y^{-1}]$ is the accumulated actual transpiration water volume. The DGIS reportages concern yearly evaluations and averages over large areas. The quantities are therefore expressed per ha per year.

Strategies DGIS does not promote or provide strategies for improvement of efficient water use, its vision is that building a strong Community of Practice in the Netherlands with experts from various disciplines will contribute to the development of applicable strategies.

Terminology DGIS strongly promotes water productivity to be used as an indicator of efficient water use. The term *efficiency* is not used by DGIS, hence the confusion of efficiency and productivity observed by other key actors is not present with the directorate. However, *water productivity* is not always clearly defined. The concept 'crop per drop' leaves room for different interpretations.

Conclusions Regarding efficient water use in agriculture, the Dutch government including DGIS and IGG is clearly focused on water productivity, expressed in kg yield or biomass production per m^{-3} water used. The definition of *water used* is not further defined, in one of the equations this represents the actual evapotranspiration. With the currently ongoing development of the WaPOR portal and the use of this data for monitoring of the funded programs, the definitions used in this database will likely to become leading in the general approach towards improvement of efficient water use. DGIS is actively promoting both in the Netherlands and abroad the concept of water productivity and the possibilities provided with the WaPOR database.
A selection of the suggested indicators is used for further analysis using model simulation.

3.1.3. Influential international research

Evaluation of water use in irrigated agriculture started with the definition by Israelsen (1950) and has been subject to research and development since, suggesting various approaches for evaluation and indicators to be used. Research on agricultural water use mostly originates either from the (irrigation) engineering domain or from the (hydrological) earth sciences.

Introduction Research is often intended for a practical application and motivated by a question or lack of knowledge encountered in the field. Research can be commissioned, important research has been driven by the International Committee on Irrigation and Draiange (ICID) in the past (Bos & Nugteren, 1990). Research is not directly responsible for improvement of efficient water use but does influence the perception and level of knowledge of key actors that are directly involved.

The evaluated international research does not have a connection with the observed agricultural fields.

Terminology and indicators Several researchers (Allen et al., 1997; Jensen, 2007) have noted that using the term *efficiency* often leads to confusion. Perry in 2007 published an article on terminology used in the debate on water use in irrigation (Perry, 2007), this article was also referred to during personal interviews with a key actor from a company in the Netherlands. Perry states that the currently used terminology in the current debate is poorly defined and that literature shows widespread confusion about what constitutes 'water use'. Also the term *water use efficiency*, often known as WUE, he reports is in itself confusing and used in different ways. It is interchanged with *irrigation efficiency* or misquoted, Perry gives a series of examples which confirms that the meaning of water use efficiency is not well agreed on or applied in the context of irrigation. He suggests that getting the terminology right should be a high priority. Perry lists various examples of perverse practical outcomes of insufficient or misplaced terminology. He stresses that the current nomenclature related to how irrigation interacts with hydrology, in particular terms such as efficiency and loss, produces confusing results for planners and policymakers involved in addressing issues of water scarcity. Perry states that the terminology for the basic parameters should be common. Also Burt (Burt et al., 1997) stresses the necessity of standardized definitions because of current confusion in terminology. In that time there was no issue of food security and efficient water use, irrigation was applied to ensure human physical survival and the main concern was the production of crop. There was only local competition for water among neighboring users sharing the same water source. Problems to deliver water from source to crops were solved technically with ever more and bigger hydraulic structures (Burt et al., 1997). As an explanation on the observed confusion (Perry, 2007) explains that the science of hydrology and the practice of irrigation engineering have developed through history at different scales. In irrigation system design, economy of design has implied that expensive facilities should be of the minimum necessary size. Thus, much attention was paid to the ratios between: the volume of water available at the diversion point or storage reservoir; the volume of water actually delivered to the crop; the volume of water utilized by the crop. In engineering, dimensionless ratios of inputs to desired outputs are routinely assigned the title of *efficiencies*. Evaluating efficiency in irrigation water use started with Israelsen (1950) who defined *irrigation efficiency* as the ratio of irrigation water consumed by the crops through transpiration in an irrigation farm or project during their growth period, over the water diverted from a river of other natural source into the farm or project canal or canals during the same period of time (Israelsen, 1950). In this report the term is labeled as WUE_{1932}, representing irrigation efficiency according to the definition of Israelsen (1950).

$$WUE_{1932} = \frac{\sum T_i}{\sum W_i} \tag{3.16}$$

In this equation, T_i is the transpiration water volume from irrigation water in m^3 and W_i is the irrigation water volume withdrawn in m^3. In the definition of Israelsen (1950) the spatial scale is the farm or irrigation system and the temporal scale a crop growing season. This definition was developed for use in the design of physical structures of irrigation systems and during the following 40 years this definition was maintained without undergoing much changes.

Standardization of irrigation performances is a relevant issue for the International Committee on Irrigation and Draiange (ICID) (Bastiaanssen & Bos, 1999). In 1967 with later refinements, a joint effort of the ICID, the University of Agriculture in Wageningen, and the International Institute for Land Reclamation and Improvement (ILRI) in Wageningen resulted in a definition of efficiency terms with various figures at appropriate scales providing measures of efficiency at at field, farm, tertiary, scheme and district level (Bos & Nugteren, 1990). In this definition, the overall or project efficiency can be simplified as the product of the conveyance efficiency, the field canal efficiency and the field application efficiency: Ep = Ec x Eb x Ea and is thus the efficiency of the water diverted for irrigation from a river body to meet the crop water requirement that exists because of lack of precipitation. In this report the term is labeled as WUE_{1967_1}, representing irrigation efficiency according to the definition of (Bos & Nugteren, 1990) for the overall system or project. Ec and Ed are related to efficiency of distribution. The field application efficiency Ea is the relation between the quantity of water furnished at the field inlet and the crop water requirement to avoid water stress. In this report the term is labeled as IE_{1967_2}, irrigation efficiency according to the definition of (Bos & Nugteren, 1990) for field application.

$$WUE_{1967_1} = \frac{\sum (ET_{crop,pot} - P_e)}{\sum W_i} \tag{3.17}$$

$$WUE_{1967_2} = \frac{\sum (ET_{crop,pot} - P_e)}{A_i} \tag{3.18}$$

In these equations for a certain scale in time and space, $ET_{crop,pot}$ is the volume of potential crop evapotranspiration or crop water requirement for evapotranspiration in m^3, this is the depth of water required to maintain soil moisture so that plant growth or crop yield is unlimited. P_e is the effective precipitation in m^3, this is the volume of the precipitation that is available for evapotranspiration. The volumes are accumulated for a certain time span. $\sum W_i$ $[m^3]$ is the irrigation water withdrawn and $\sum A_i$ $[m^3]$ is the irrigation water volume applied. The volumes apply to the cropped area. (Perry, 2007) states that the enhancements by Bos & Nugteren (1990), the original definition of efficiency by Israelsen (1950) relating the water used by the crop to the water diverted at some point remained the underlying accounting basis in irrigation. The term *efficiency* is still used at this time, (Perry, 2007) reports that unrelated to context the use of this term is worse than meaningless and can cause wrong decisions to be made economically, hydrologically and ecologically. He explains how in irrigation the purpose of water use is consumption: the removal of water from the hydrological cycle through evaporation and transpiration. Thus an increase in efficiency indicating the service to more precisely and uniformly match the need of the crop results in an increase of crop consumption. A higher efficiency can be expected to cause an increase in consumption and demand. Also the US Interagency Task Force (US Interagency Task Force, 1979), endorsed by (Jensen, 1993), warns that it is frequently assumed that because irrigation efficiency is low, much irrigation water is 'wasted' while this is not necessarily so. Burt et al. (1997) adds that irrigation efficiency does not necessarily make more water available for other uses. In these years it is frequently stated that the 'classical' efficiency term is outmoded (Willardson et al., 1994; Allen et al., 1997; Willardson & Allen, 1998). The same publications suggest to to divide or partition the water diverted to irrigation schemes into the following components: *Consumed* including *beneficial* and *non-beneficial*, *non-consumed* including *recoverable* and *non-recoverable*. Non-consumed recoverable flow is also known as (irrigation) return flow (van Heeswijk, 2016). Perry (2007) approves these suggested terminology stating that this focuses attention on what is really a loss. He recommends using this terminology because it is consistent with hydrology, meeting the criterion of continuity of mass and distinguishing carefully between stocks and flows. He states that ICID recommends that this terminology be used in the analysis of water resources management at all scales and to form the basis for future publications. Perry states that this presented framework is a step forward in clarity but not at all a simplification of the issue. He warns that decisions to be made in the dividing of the water volumes can be challenging and clearly site-specific. Burt et al. (1997) also adds the partitioning of *reasonable* use. In his definition reasonable uses include all beneficial uses but also non-beneficial uses in situations with uncertainties. In this report the terminology presented by (Burt et al., 1997) and (Perry, 2007) is combined in the following overview for partitioning of applied or withdrawn water for agriculture:

- Consumed, always non-recoverable
  - Beneficial, always reasonable: Supporting the production of crops: crop production and maintaining soil quality
    - ◇ ET_{crop}
    - ◇ θ_{crop}
    - ◇ $Qh_{percolation\ for\ leaching}$
  - Non-beneficial, can be reasonable when uncertain: Not contributing to crop production
    - ◇ $ET_{non-crop}$
    - ◇ $\theta_{non-crop}$
- Non-consumed, always non-beneficial
  - Recoverable
    - ◇ $Qh_{percolation,\ excess\ to\ fresh\ water\ aquifer}$
    - ◇ $Qv_{tail\ water,\ collected}$
  - Non-recoverable
    - ◇ $Qh_{percolation,\ excess\ to\ saline\ aquifer}$
    - ◇ $Qv_{tail\ water,\ not\ collected}$

This overview indicates fractions of applied water. ET_{crop} $[m^3]$ is the crop evapotranspiration volume, θ_{crop} $[m^3]$ is water content of vegetation, and Qh $[m^3]$ and Qv $[m^3]$ correspond to horizontal respectively vertical water fluxes. $Qh_{percolation}$ is a horizontal flux of deep percolation to the groundwater, $Qv_{tail\ water}$ is a vertical flux of tail water at the end of the field or system. Using this partitioning, (Burt et al., 1997) presents a whole collection of different performance indicators. This also includes a new efficiency which he called *irrigation efficiency*, IE. This ratio is the volume of irrigation water beneficially used, divided by the total volume of irrigation water that leaves the system. In this report the term is labeled as WUE_{1997}, representing irrigation efficiency according to the definition of (Burt et al., 1997).

$$WUE_{1997} = \frac{\sum U_{B,i}}{\sum A_i - \Delta S_i} \tag{3.19}$$

Here $\sum U_{B,i}$ $[m^3]$ is the irrigation water beneficially used, $\sum A_i$ $[m^3]$ is the applied irrigation water and ΔS_i $[m^3]$ is the irrigation water stored over an observed time span or the positive change of storage. Water naturally applied to the crop is excluded. In the denominator, the stored irrigation water is subtracted from the applied irrigation water, (Burt et al., 1997) states that performance can only be evaluated of water leaves the subject region within the specified time interval. His definition of water use efficiency requires a very clear definition of the frame of reference both in space and time. (Burt et al., 1997) also states that the most common misuse of irrigation efficiency is the improper definition of beneficial uses.

The aforementioned irrigation efficiencies are based on canal flow data (Bastiaanssen & Bos, 1999) and productivity is not evaluated (Bos & Nugteren, 1990). Research by (Bastiaanssen & Bos, 1999) indicated that differences in agricultural performances are to be ascribed rather to the local hydrological setting than to the water delivery performance, demonstrating that using only classical performance indicators based on canal flows a misleading picture can be obtained. Standardization using the classical definitions is problematic.

(Bos & Nugteren, 1990) indicates that the results of the 1967 irrigation efficiencies derived from ICID questionnaires in a large collection of irrigation systems indicate trends only and the individual values of samples are more important than the means. (Wolters, 1992) states that straightforward relationships between characteristics of an irrigation system and the traditional efficiencies do not exist. He proposes that in order to increase the efficiency of irrigation water use in a certain system, it is more useful to regard that system as unique and to use the list of positive and negative effects of increased efficiencies in reaching a decision, rather than to rely on general relationships between the system characteristics and efficiencies. In the 1990s a framework for irrigation performance assessment has been developed covering aspects related to adequacy, equity, reliability and sustainability of the water service (Bos et al., 1991; Wolters, 1992). (Bastiaanssen & Bos, 1999) states that productivity evaluations are more important than issues concerning equity and reliability. In these years also the concept 'water accounting' is introduced where the concept of water productivity is further developed. Water accounting is a procedure for analysis of the uses, depletion and productivity of water in a water basin context (Perry, 2007). (Molden, 1997) developed a conceptual framework for water accounting based on a water balance approach with in- and outflows at different spatial scales. The term *water depletion* is key in this approach. Water depletion including process- and non-process depletion is defined as the use or removal of water from a water basin such that it is permanently unavailable for further use. Within depletion: *process depletion* is the depletion of water to produce an intended good, in agriculture this is transpiration and the water incorporated into plant tissue, the agricultural product. The term *non-process depletion* includes evaporation from soil and water surfaces and non-evaporated components that do not return to the freshwater resource. The term *depleted fraction* is the part of the inflow that is depleted by both process and non-process uses of water.

In this report the terminology presented by (Molden, 1997) and used by (Droogers & Kite, 2001) is structured in the following overview for partioning of water inflow or available water volume at field scale:

- Depleted: Used or removed, permanently unavailable for further use
  - Process: Depleted to produce an intended good
    - T_{crop}
    - θ_{crop}
  - Non-process: Depletion by uses other than intended processs. Sometimes beneficial.
    - $ET_{non-crop}$
    - $\theta_{non-crop}$
    - $Qh_{percolation,\ excess}$
    - $Qh_{percolation,\ for\ leaching}$
    - $Qv_{run-off}$
    - $Qv_{drainage}$
    - $Q_{degraded}$
- Non-depleted: Benefits derived from water without removal. Non-agricultural

In this overview, T_{crop} $[m^3]$ is the crop transpiration water volume, $ET_{non-crop}$ $[m^3]$ is evapotranspiration from other vegetation or soil, $\theta_{non-crop}$ $[m^3]$ is the water content of other vegetation, $Qh_{percolation}$ is deep percolation to the groundwater which can be for leaching (beneficial) or non-beneficial (excess). Vertical fluxes of run off ($Qv_{run-off}$) and drainage ($Qv_{drainage}$) are observed. Percolation, Drainage and run off are depletive at field scale. Quality degradation ($Q_{degraded}$) is also considered a depletion. Water use can be non-depletive for example in case of hydropower generation, but this does not exist in agriculture where water is either removed or degraded in quality. All these fractions of water inflow or available water volume can be expressed in m^3. Molden suggests to measure the productivity of water not only per unit of water consumed in ET but also against gross or net inflow, depleted water, process-depleted water, or available water. Observing the spatial scale of the agricultural field, the following terms are used in this report: WP_{1997_1}, WP_{1997_2}, WP_{1997_3}, WP_{1997_4}, water productivity according to (Molden, 1997) for respectively irrigation water, inflow, depleted water and process depleted water. These terms are also applied by Droogers & Kite (2001).

$$WP_{1997_{irrigated}} = \frac{\sum Y}{\sum A_i} \tag{3.20}$$

$$WP1997_{inflow} = \frac{\sum Y}{\sum Q_{in}} \tag{3.21}$$

$$WP1997_{depleted} = \frac{\sum Y}{\sum Q_{out}} \tag{3.22}$$

$$WP1997_{process} = \frac{\sum Y}{\sum T_{act}} \tag{3.23}$$

In these equations, $\sum Y$ $[kg]$ is the crop yield. All terms apply to the same scale in time and space. $\sum A_i$ $[m^3]$ is the applied irrigation water volume and $\sum T_{act}$ $[m^3]$ is the actual transpiration volume. The terms $\sum Q_{in}$ $[m^3]$ and $\sum Q_{in}$ $[m^3]$ are the total fluxes in and out of the system. What is included in these total fluxes depends on the observed system. These water productivities are thus expressed in $kg\ m^{-3}$. Droogers & Kite (2001) regards these performance indicators as a solution for the main limitations of the classical efficiencies, since this framework includes non-agricultural water uses and the interaction of irrigation with other water users is more explicit.

Also (Burt et al., 1997) states that at the heart of any irrigation performance consideration, a water balance and determination of the fate of various fractions of the total irrigation water applied should be found. (Bastiaanssen & Bos, 1999) states that the accuracy of conventionally gathered data on crop yield, evaporation and soil moisture is low, especially at the regional scale. He suggests to use performance indicators based on several parameters that can be obtained from remote sensing data. The accuracy of measuring these individual parameter ranges between 80% and 90%. The accuracy of the performance indicators based on these parameter is approximated at 75% to 80%. His concern is that usually irrigation managers, consultants and policy makers are not aware of opportunities that can be offered by remote sensing. He states that the corner stone for further refinement of performance analyses and indicators can be found in the interaction between researchers and managers responsible for water division.

Strategies Evans & Sadler (2008) states that there are no universal remedies to improve efficient water use, each area and mix of cropping systems will have unique solutions. Evans & Sadler (2008) presents carefully managed deficit irrigation on agronomic crops as the strategy providing the greatest potential for substantially reducing agricultural water use since large areas of land are involved in the production of staple foods. He also states that managed deficit irrigation requires advanced irrigation methods such as sprinkler irrigation. This main strategy from research is labeled in this report as $Strat_{Research}$.
In regulated deficit irrigation usually mild water deficit is allowed. This reduces the volume of irrigation water used without or only marginally effecting the amount of yield produced. Deficit irrigation can be applied with different irrigation methods and can be enforced constant over the growing season or defined specifically for each growing stage. For maize and winter wheat the advised irrigation method is sprinkler irrigation, and the best results in prior research are obtained with a constant deficit over the growing season (Kirda et al., 2002). Mild water deficit is defined by Chai et al. (2016) as a soil water content remaining at 60-70% of field capacity, in the FAO report by Kirda et al. (2002) 50-70% is used. Also a moderate water deficit can be allowed. Moderate water deficit is defined by (Chai et al., 2016; Li et al., 2010) as a soil water content remaining at 50-60% of field capacity. From maize experiments in prior research is concluded that when soil water content is maintained at 55-65% of its field capacity water, an improvement in efficient water use was observed.

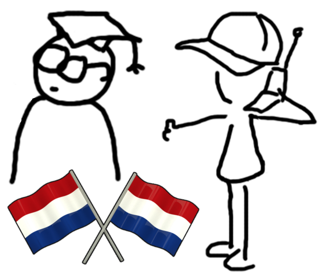
- $Strat_{Research}$ = Regulate mild or moderate soil water deficit by deficit irrigation

Research suggest that in Tadla basin where supplemental irrigation is practiced, deficit irrigation technology can lead to substantial saving in irrigation water, up to an average of 644 cubic meters per ha. It is expected that at least 20% of the cereal cropped area in Tadla will be covered by the deficit supplemental irrigation technology in the coming 2 years. The resulting saving in water is expected to be in the average of 1.5 million cubic meters and can be used to irrigate an additional 400 ha using the deficit irrigation technology. Hence at a yield level assumed at 7.40 t/ha, an additional production of 3000 tons of wheat is expected. At the current wheat price in Morocco the additional production of wheat is worth 1.1 Million US dollars annually (Shideed, 2017).

Concluding In research the variety of perceptions and present confusion in the debate on efficient water use can be observed. Where UN-Water desires a global methodology to evaluate water use in agriculture using the term *efficiency* which is strongly linked to the classical evaluation of irrigation systems using canal flow data, prominent researchers on this subject suggest to make distinctions regarding to *beneficialness*, *consumption* and *depletion* of water. Research suggests to utilize remote sensing data in stead of the less accurate conventionally collected field data. The presented equations show a shift from the engineering focus on efficient water use in irrigation to a hydrological approach including other physical processes involved. The first group observes (the effect of) irrigation water only and excluding the present natural water. The second group includes natural water sources and does not make this distinction.
A selection of the suggested indicators and strategies is used for further analysis using model simulation. For the suggested partitioning of used water into beneficial, consumed and depleted fractions, site-specific decisions are necessary.

3.1.4. Companies and research institutes in the Netherlands

In the Netherlands, Delft University of Technology, Unesco IHE institute for Water Education and Wageningen university are research institutes involved in studies on agricultural water use. Dutch companies related to the issue are consultancies and various non-profit organizations and for-profit corporations. Fourteen interviews were conducted with key actors from companies and research institutes in the Netherlands.



Introduction Statistics Netherlands (CBS) is a Dutch governmental institution that collects statistical information about the Netherlands. In the Netherlands, measurements of SDG indicators are conducted through CBS. CBS in cooperation with other Dutch companies and supported by the Ministry of Foreign Affairs and the Ministry of Infrastructure and Environment, produced a memo in support of SDG 6.4 (Graveland et al., 2016). This is part of the Dutch effort as PoC country for SDG 6.
The Netherlands National IHP-HWRP Committee is a platform connecting Dutch scientists, policy-makers and practioners. The committee aims at contributing to both UNESCO (IHP) and WMO's (HWRP) water programs, based on the input of its members. The IHP-HWRP members are leading Dutch scientists, policy-makers and practitioners and connects academic, governmental, operational, and research institutes focused on water.

Dutch companies and research institutes can be directly involved when responsible for projects in the African continent where improvement of efficient water use is the target. Another option is involvement in roles that contribute to the Netherlands' responsibility as Proof of Concept (PoC) country for SDG 6. Also directed from FAO, Dutch companies are involved in the development of the WaPOR database. All research groups, small medium enterprises and NGO's that are somehow related to the issue are the subject of DGIS striving to develop a stong Community of Practice (CoP) around the theme of water productivity. Thus, multiple companies and institutes are involved in the current development of the discussion around efficient water use. Attendance at the water productivity masterclass sessions from DGIS, published documents and multiple personal interviews have contributed to an overview of these Dutch key actors and their perception regarding efficient water use in agriculture.

Indicators Dutch companies and research institutes contribute to meet the UN Sustainable Development Goals in 2030. This also includes SDG indicator 6.4.1 known as *water use efficiency*, see eq. (3.1).
IHP-HWRP facilitated in September 2016 a workshop in the Netherlands to discuss the monitoring process SDG 6 in the GEMI framework (FAO, 2016*b*; ter Horst & de Vries, 2016). Present were the Dutch indicator coordinators, representatives of GEMI-Target Teams from UN organizations and from all PoC countries and experts from both the Netherlands and abroad. Key actors from different PoC countries consider SDG indicator 6.4.1 to be highly relevant. Main remarks given during the workshop concerned terminology and

definitions, the problem of not knowing how often to report and in what fashion, and the concern that indicators give only little feedback to policymakers. Also responsibility distribution is apparently unclear and most countries encounter challenges in measurements and data gathering. It was commented by workshop participants that widely used efficiency calculations in agriculture are based on the volume of water consumed instead of the in SDG indicator 6.4.1 volume of water withdrawn. Since the agricultural sector uses the largest water volume of all sectors, attendances suggested to incorporate the volume of water consumed in the indicator. Water withdrawn exceeds the consumptive use of irrigation because of losses in distribution. Also concern was expressed on how the ecosystem as a water user is being dealt with, since efficiency is considered to be also a matter of water allocation. Another important remark given on indicator 6.4.1 is the risk that it can stimulate countries to move from basic food crops to more money-making-crops because a higher price results in a larger efficiency according to the currently used definitions. This can possibly result in food scarcity. Where food security is the ultimate target, yield is suggested to be more suitable than added financial value. These two proposed change of the SDG 6.4.1 results in a new term labeled in this report as $WP_{SDG6.4.1_{PoC}}$, representing the SDG 6.4.1 indicator for irrigated agriculture with suggested changes from the professionals in the PoC countries.

$$WP_{SDG6.4.1_{PoC}} = \frac{\sum Y_i}{Consumed_i} \tag{3.24}$$

In this equation $\sum Y$ $[kg]$ is the amount of yield from irrigated agriculture and $\sum U_{C,i}$ $[m^3]$ is the consumed irrigation water. After the implementation of the suggestions, the term is still not dimensionless and therefore technically not an efficiency but remains a productivity.

Interviewees report that a commonly used indicator is 'water saving', referring to a decrease of the amount of water used and withdrawn for agriculture. The term water saving is labeled in this report as EWU_{saving}, efficient water use represented by quantity of water saved.

$$EWU_{saving} = -\sum W_i \tag{3.25}$$

In this equation, $\sum W_i$ $[m^3]$ is the amount of water volume withdrawn for irrigation. The term is negative since a smaller amount of water withdrawn is desired. Interviewees report that *water productivity increase* and *water saving* are two perceptions on improving efficient water use that cannot be combined in water scarce areas, since diminishing applied irrigation water results in crop failure and thus a decrease in water productivity.

From the obtained interviews, division is observed between interviewees in their opinion on the authority of the term *water productivity* and the data required for quantification. The majority of interviewees believes that water productivity should be the focus in improving efficient water use. It is also stated that this should be followed by analysis on the reason of water productivity values.
A minority of the interviewed key actors in this group regards this as political terminology which is not applicable in practice. Alongside DGIS' determination regarding the use of *water productivity*, some Dutch companies involved in the practical implementation of actual projects are skeptical. Remote Sensing analysis of agricultural performance is seen as a diagnostic instrument developed in research. Interviewees state that knowledge is lacking for a translation of this data to practice and to actual products or services that can improve water management. An interviewee reproaches key actors at research level for not presenting something that can directly be applied in practice. Key actors involved in the practical side of the issue see models developed at research level as an academic play ground where the fun is over when the tool 'works' and no attention is given to real-life added value. An interviewee expresses distrust in databases as long as this does not help in the development of technical products that can be applied in practice. The FAO project delivered WaPOR database is regarded very technical and too little focused on water management. Key actors in practice are very pragmatic, implementation is seen as most important and analysis from research level is only considered relevant when it can be directly used as tool or instrument. The use of *water productivity* according to these critical key actors from Dutch companies, is not indisputable but rather a discussion point. There is a division between Dutch key actors since some interviewees state that the SDG indicators are indeed useful tools to support decision making.
According to interviewees the term *water productivity* is used in projects because of influence from DGIS as funding party. The indicator is used in projects as official target, off the record other goals are regarded more

important. Interviewees report that they do not know what to do with water productivity. Currently they do not have insight in what are the most influential factors or parameters.

Strategies Among the interviewees, division is observed regarding a strategies for improvement of efficient water use. This concerns on-farm storage facilities and improved technology like sprinkler and drip irrigation. Some interviewees are wholeheartedly promoting and developing these solutions. Others do not believe this will lead to improvement. Mentioned alternative approaches concern management of a shallow ground water level, agrarian solutions including soil treatment, fertilizers, seed quality and sowing dates, or irrigation timing.

Strategies often suggested by companies involved in practice, are related to improvement is the introduction or upscaling of technologies at farms of small scale farmers. Proposed solutions: on-farm storage of water, increase soil water retention, drip irrigation, on-farm storage and efficient irrigation systems like drip, sprinkler and sub-soil irrigation. Other interviewee mentioned local solutions on system scale like the layout of irrigation and drainage canals. A strategy at field scale that can be implemented in SWAP/WOFOST is sprinkler irrigation. This first strategy from companies is labeled in this report as $Strat_{Companies_1}$.
For multiple interviewees, technical interventions including sprinkler irrigation are the key to improvement. They regard the funding of the investment and the design of simple technology the greatest challenge. Others decline these ideas and are critical with regards to technical improvements in African countries, implemented through Western projects. Technical products and interventions are seen as a symbol of development and being modern. This includes systems of drip and sprinkler irrigation. Interviewees also state that the involved systems only result in improvement of efficient water use when correctly implemented, operated and maintained. Technique is also locally used to obtain more rights in discussions and conflicts between head- and tail end users. The disapproval of technical interventions like drip irrigation and on-farm storage is expressed by multiple interviewees. Some suggest that improved technology is only effective when farmers are trained.

- $Strat_{Companies_1}$ = Change of irrigation method from field irrigation to sprinkler irrigation

Less conflict among key actors in this group seems to exist with regard to sensor technology and optimization of timing and amount of water applied. Installation of sensors in the soil monitor the soil moisture content, irrigation applications (depth and timing) can be decided on based on a soil moisture content criterion. This second strategy from companies that can be applied at the field is labeled in this report as $Strat_{Companies_2}$.
Another strategy is deficit irritation, which is mostly mentioned by key actors involved in research. An interviewer states that with just a little bit of stress, T is reduced but the decrease in biomass production is relatively smaller. Thus, irrigation depth and timing is based on the relative transpiration. This third strategy from companies that can be applied at the field is labeled in this report as $Strat_{Companies_3}$. Interviewees state that flying sensors can be used to monitor potential and actual transpiration. Water logging is seen as loss, attention should be given to the distribution of percolation over the growing season. This also can be obtained by change of watering schedule.

- $Strat_{Companies_2}$ = Irrigation based on soil moisture content, monitored with sensors in the soil
- $Strat_{Companies_3}$ = Irrigation based on relative transpiration, monitored with flying sensors

Multiple interviewees involved both in research and in practice state that in case of shallow ground water table, management of this level is most important in efficient water use. An interviewee states that this can prevent the need for irrigation. In some cases, the combination of precipitation and seepage needs to be sufficient for agricultural production. Control of soil water drainage should prevent flooding in wet seasons and maintain water for periods of precipitation shortage. An interviewee states that irrigation is valuable only when drainage is optimal controlled. This strategy from companies that can be applied at the field is labeled in this report as $Strat_{Companies_4}$.

- $Strat_{Companies_4}$ = Management of the shallow ground water level

Some interviewees state that increasing water productivity is obtained most easily by increasing the amount of production, not reducing the amount of water consumed. As an example an interviewee states that drip irrigation is focused on *water saving* without much result. Another states that the soil should be the focus. An interviewee states that water can only be as productive as its environment allows it to be. A proposed strategy for improvement is to enhance the water holding capacity of the soil by placing water pads that facilitate water buffering, saving both water and nutrients. This strategy labeled in this report as $Strat_{Companies_5}$. Other mentioned strategies are the use of fertilizers, the moment of sowing, land preparation and good seed quality. These strategies are suggested by key actors in both research and practice. Fertilizers are not included in the SWAP/WOFOST simulation, fertile soil is assumed. Strategies for change of sowing date and use of optimal seed quality are labeled as $Strat_{Companies_6}$ and $Strat_{Companies_7}$.

- $Strat_{Companies_5}$ = Installation of pads in plant root zone, increasing soil water retention capacity
- $Strat_{Companies_6}$ = Change of sowing date results in an increase of yield without increase of water used
- $Strat_{Companies_7}$ = Change of used seed to optimal quality.

Several water management experts that are known with the practical implementation of projects and targets mention communication and social structures as being very important and challenging in the technical complexity. Also, when an area is not a priority to the local government then improvement is difficult. An interviewee with experience in projects that have the target to improve water productivity reports that in at policy and management level in the concerning countries there is not much interest in efficient water use in agriculture, no one want to be responsible for existing problems. However, it is also stated that the focus of increase of water productivity should be a policy level since individual farmers are not interested issue, often the fees for water use are low and the farmers are more concerned about income. Other interviewees add that farmers generally do not know how much water is consumed, at best they know how much water is applied.

The subject on which the interviewees are most undivided is the importance of communication and connection with local key actors including both local governments and farmers. An interviewee states that for implementation of research results, evaluation should be conducted in terms used by local key actors. It is important to look for connecting factors. Utility functions should be developed from the field, not from research. Interviewee states that research is valuable only when it connects to local actors. This is also a point of criticism toward the involvement of the Dutch government. Some regard the involvement and effort of the Dutch government in projects in water scarce areas useless since there is no connection to the local actors. Many of the interviewees in the Netherlands mention the need for intensive training and support of local key actors including farmers and think this is crucial for obtaining actual improvement at the field. Farmers' access to knowledge and communication platforms are sometimes actual measures taken in projects concerning the improvement of efficient water use.

- $Strat_{Companies_8}$ = Eliminate irrigation

One of the masterclasses on water productivity initiated by DGIS was focused at rain fed agriculture. To stop irrigation and change is sometimes seen as effective where in rain fed agriculture still significant yield is obtained and the water not withdrawn or applied can serve other uses. This strategy is found in general perceptions, it has not been mentioned by interviewees for the fields observed in this research.

Terminology Statistics Netherlands (CBS) delivered a report on the first measurements of the SDGs for the Netherlands (CBS, 2016). In this publication, SDG indicator 6.4.1 is provided with a clarification that *water productivity* is meant, expressed in € m^{-3}. This illustrates the general preference of Dutch companies and research institutes to use the term *productivity* when a dimensional term is concerned. Multiple interviewees also disapprove the use of the term *efficiency* or the indicator *water saving*.
Disapproval of the term *efficiency* is motivated by their experience that this term is being used often so differently or because they see the term being often only used probabilistically and not actually measured.
In general speaking and publications the term *water productivity* is not further specified. Sometimes interviewees mention the amount of water consumed to be relevant, 'yield' and 'ET' is also mentioned. People in managing positions of the hydrological part of a large funded project use terms *water efficiency* and *water productivity* interchangeably without providing clarification. The term *water productivity* is sometimes seen as the currently common used expression for *water use efficiency* while insight in its actual meaning is lacking. Some companies fully acclaim the focus on water productivity but are involved with donor organizations that have other perceptions of efficient water use.

Concluding Dutch companies are involved in the improvement of efficient water use in agriculture, at the level of data collection and practical implementation. On these subjects, conflicts are encountered with the terminology of SDG indicator 6.4.1. The Dutch sector generally follows the methodologies proposed in research, where different scales and terms are used than those in the methodology proposed by UN-Water. Dutch key actors are also led by the target of the Directorate-General for Development Cooperation of the Netherlands (DGIS) which aims at improving *water productivity* although on this topic division is observed between the interviewed key actors. The majority embraces *water productivity* as an indicator for efficient water use and disapproves of the use of the terms *efficiency* and *water saving*. Another group is critical or skeptical about the use of *water productivity*, not trusting it to be useful in practice. A large variety of perceptions is observed concerning strategies for improvement of efficient water use. This can be summarized observing one group that promotes technical interventions and improvements, and the other group distrusting these strategies. As an alternative to technical interventions, it is suggested to look at more agrarian solutions such as seed quality and sowing date.
A selection of the suggested indicators and strategies is used for model simulation in this research.

3.1.5. Farmers in Mozambique

Four farmers are interviewed personally in the Fidel Castro irrigation/drainage system near Xai-Xai Mozambique, in the same area where the observed field is located. Additionally a group discussion was held with 12 farmers of the same block. The farmers in the machongos are historically seen as the 'family sector' in the drainage area(Ganho, 2013).

Introduction The farmers are smallholders, production is mainly used for home consumption. The plots are part of a system which is sensitive and dependent on good maintenance. The farmers contribute to preserving the system. Farmers decide on what is done at the field, but do not have control at the larger system. The system is the responsibility of the Regadio do Baixo Limpopo (RBL). RBL communicates with the farmers through the farmer organizations: Casas Agrarias (CA). The CA has a president and each agricultural block and subblock is managed by a chief. The president and chiefs are instructed by RBL. Farmers pay a fee to RBL of 500 mt per year per ha. This is a tax for land, water and operation and maintenance of the system. However, most farmers do not pay and RBL has no information on the individual users.

Obviously the farmers are strongly connected to the fields. In this area a shallow ground water table is observed, which is managed by storage in and drainage from the system with channels, valves and a pumping station. The observed seepage is known as sub surface irrigation.

Indicators Farmers state that water scarcity is a problem in their fields. Water should contribute to yield production. They are concerned about the yield from the field. The indicator 'yield' resulting from efficient water use according to the farmers is labeled in this report as $EWU_{farmers}$. This equation is equal to eq. (3.13). In this equation, $\sum Y$ is the amount of agricultural yield in $kg\ ha^{-1}$, accumulated over an observed time span.

$$EWU_{farmers} = \sum Y \tag{3.26}$$

Strategies Farmers mention use of fertilizers, pesticides and better seed quality as strategies for improvement at the field. From these strategies, seed quality can be applied in the used simulations. This is labeled in the report as $Strat_{Farmers_1}$. This strategy is also proposed by key actors from Dutch companies and research institutes presented in Paragraph 3.1.4. Additionally, farmers state that the system is not functioning well and that better management of the ground water table could allow them to make better use of the land and obtain higher productions. At system scale for this purpose it is suggested to increase the amount of channels and to better maintain and clean the channels and valves. Also better operation of the pumping station and valves is mentioned. The strategy to optimally manage the ground water table is labeled in the report as $Strat_{Farmers_2}$. This strategy is related to the strategy in Paragraph 3.1.4 suggesting optimal ground water management to decrease the amount of irrigation water needed. Farmers indicate that crop water shortage should be prevented, this is labeled in the report as $Strat_{Farmers_3}$

- $Strat_{Farmers_1}$ = Change of used seed to optimal quality
- $Strat_{Farmers_2}$ = Good management of the ground water table
- $Strat_{Farmers_3}$ = Prevent crop water shortage

Terminology During the interviews a translator was needed, this might have biased the exact terminology used by the farmer. It was clearly however that farmers do not know or use the term *water productivity*.

Concluding Local farmers are not known with water productivity. Farmers are mostly concerned about yield production. Farmers see sub surface irrigation by management of the water table as something that is operated and decided upon at system scale. Furthermore, farmers see optimal seed quality as an effective strategy.

3.1.6. Governmental organizations in Mozambique

Policy regarding water management in Mozambique can be found from national level to the local water board. Interviews in Xai-Xai and Maputo Mozambique were conducted in May 2017. A total of 17 key actors were interviewed who either work in governmental organizations or work as specialists consulted by governmental organizations.

Introduction At national level, the government of Mozambique is responsible for food security and water management. Mozambique is located along the coast and receives fresh water from several surrounding countries. An agreement with upstream countries is established in the Southern African Development (SADC) protocol. The Direcção Nacional de Gestão de Recursos Hídricos (DNGRH) is the National Directorate of Water and Resource Management, which is part of the Direcção Nacional de Águas (DNA), translated the National Directorate for Water. DNA is an institute that is subordinate to the Ministério das Obras Públicas, Habitação e Recursos Hidricos (MOPH), translated the Ministry of Public Works, Housing and Water Resources. Instituto Nacional de Irrigação (INIR) is the irrigation institute which is part of the Ministério da Agricultura e Segurança Alimentar (MASA), translated the Ministry of Agriculture and Food Security. Mozambique is divided over five Administração Regional de Águas (ARAs), these are Regional Water Authorities. The area of focus is located in the Southern region which is within the authority of the Administração Regional de Água do Sul (ARA-Sul). Locally, water boards are responsible for relatively small regions. The field of focus belongs to the Regadio do Baixo Limpopo (RBL), the water board for the Lower Limpopo.

The observed field in Mozambique is part of a wetland area locally known as *machongos*, characterized by fertile soil with high organic content and a shallow water table. The areas are traditionally cultivated by smallholder farmers. The Mozambican interviewees are known with the machongos and their agricultural potential.

Of the aforementioned governmental organizations, the local water board Regadio do Baixo Limpopo (RBL) is the one closely connected to the observed field near Xai-Xai, in the Fidel Castro irrigation/drainage block. RBL is responsible for management of water, land and infrastructure for an area of 11,787 ha including this block. RBL's largest challenge in the machongos to prevent flooding of the agricultural fields and thus maintain the proper ground water level (Mugabe, 2015*a*,*b*). Under Portuguese rule in the years 1956 - 1975, RBL employees including extension officers and engineers lived close to the area to control the system for which specified people were available. With the Massingir Dam and Smallholder Agricultural Rehabilitation project (MDSAR) in 2003 a pumping station was build downstream along the Limpopo River, from which the whole RBL area is regulated. Water drainage is required for the machongos and this pumped fresh water can be used to irrigate rice cultivation in the lowlands. However, literature suggests that the smallholder model proposed in the initial MDSAR plan was merely donor-led and not owned by Mozambican elites (Ganho, 2013). Multiple interviewed local experts state that the system is now lacking proper coordination from RBL who is the responsible entity. Current extension officers assist each up to 1,000 individual farmers (Mugabe, 2015*b*) and pump operation is said to be often too late. RBL reports to the Instituto Nacional de Irrigação (INIR), who decides on water allocation for irrigation. To the Administração Regional de Água do Sul (ARA-Sul), the water board for Southern Mozambique, water users are clients, how water is used has never been of interest to ARA-Sul. However, water has become more limited because of drought in the last years. Interviewees from ARA-Sul now question whether users use the amount of allocated water or more. There is no monitoring system and thus no information on how much water is used in the irrigation schemes. Also INIR interviewees report that quantification is a problem, data on both water fluxes and land productivity is desired but not available. INIR regards the machongo area in the Lower Limpopo basin to be an important area for food production, it is seen as an example of irrigation by controlled water table. The Direcção Nacional de Gestão de Recursos Hídricos (DNGRH) has three objectives, the third objective concerns water for development including agriculture, where water is seen as crucial. The vision of DNGRH is to build more dams to create hydropower and to decrease their dependency on upstream countries for fresh water. Water shortage has increased in the past few years. This has resulted in national campaigns on the radio, encouraging people to reduce car washing and tap use. Concerning agricultural water use DNGRH has no plans or strategy, this is seen as the responsibility of the Instituto Nacional de Irrigação (INIR). Literature reports that there are no national strategies to support the use of wetlands for agricultural purposes in Mozambique as these ecosystems are viewed as sensitive zones that should not be disturbed, although the wetlands in Mozambique do not have a conservation status (Frenken & Mharapara, 2001).

Indicators Interviewees from RBL report that RBL does not use water productivity in their monitoring and evaluation of projects within the RBL region. Also at ARA-Sul water productivity is unknown. By an interviewee from INIR, water productivity is well-known, seen as important and interpreted as the amount of production and financial gain produced with a certain amount of water applied at the field. In a publication from the Instituto Nacional de Gestão de Calamidades (INGC) or National Institute for Disaster Management, is stated that water management remains key and water-use efficiency must be improved to cope with increasing water scarcity. Improving water-use efficiency is illustrated as 'more crop per drop' (Van Logchem & Queface, 2012). The majority of the key actors in Mozambican governmental organizations does not use water productivity. Individuals are found who are familiar with this indicator, often these key actors have close connections to international consultants or research.
Interviewed ARA-Sul employees interpret efficient water use initially as efficiency applicable on the management of the dam. Efficient water use in the machongos is defined by interviewees as maintaining soil moisture by proper management of the ground water level. This definition of efficient water use is labeled in this report as EWU_{MozGov_1}, efficient water use according to key actors in governmental organizations in Mozambique, representing the of resulting in optimal water content of the soil. Other interviewees explain efficient use of water in this area to be optimal management of the water table in order to preserve the present organic matter. This definition of efficient water use is labeled in this report as EWU_{MozGov_2}, a second indicator for efficient water use according to key actors in governmental organizations in Mozambique, representing the result of optimal preserving of the organic content of the soil.

$$EWU_{MozGov_1} = 1 - |(SM_{opt} - SM_{act})| \tag{3.27}$$

$$EWU_{MozGov_2} = 1 - (O_{pot} - O_{act}) \tag{3.28}$$

In these equations, SM_{opt} is the optimal soil moisture content and SM_{act} is the actual soil moisture content during a growing season. Soil moisture content can be expressed in $cm^3 cm^{-3}$. Similarly, O_{pot} is the potential organic content of the soil and O_{act} is the actual organic content. Both can be expressed as a fraction or percentage of the total soil content.

Strategies Interviewees suggest management of the water table to obtain an increase in efficient water use. Interviewees report that this would require optimal management and maintenance of the system and that also system improvements and investments might be necessary. This includes an increase in the amount of channels and installation of sensors for soil moisture. This strategy is labeled as $Strat_{MozGov_1}$, the first strategy suggested by interviewees from governmental organizations in Mozambique. Currently, the system is not performing optimally. According to multiple interviewed local experts, there is potential for improvement.

- $Strat_{MozGov_1}$ = System investment allowing optimal management of the water table

Additionally for an increase of efficient water use in the machongos, INIR thinks training of farmers, monitoring and communication of monitoring results is seen as most important. INIR is interested in data on the production from this subsurface irrigated area. Interviewees think that when data is available, water management policy can be strongly motivated and obliged. This strategy is labeled as $Strat_{MozGov_2}$, the second strategy suggested by interviewees from governmental organizations in Mozambique. Interviewees also state that farmers should be better educated and advised in cultivation of their land. This third strategy is labeled as $Strat_{MozGov_3}$

- $Strat_{MozGov_2}$ = Monitoring of water use and agricultural performance
- $Strat_{MozGov_3}$ = Education and advise to farmers

Also included in this section is the strategy to eliminate irrigation. This perception is observed in prior local research (Ganho, 2013). When seepage is prevented and all water is drained from the machongos, it can be used in a large downstream irrigation system where rice is cultivated. This perception is related to the priorities of the key actor within the area where the observed field in Mozambique is located.

- $Strat_{MozGov_4}$ = Eliminate irrigation

Terminology Most interviewees have never heard of the term *water productivity*. The term *efficiency* is initially linked to distribution losses.

Concluding The majority of key actors from these governmental organizations in Mozambique related to agricultural water use, is not familiar with the concept of water productivity. However, awareness of the need for *efficient water use* has grown over the last few years when droughts increased. Currently, there is a lack of data. At higher hierarchical levels there is no insight in how much water is actually used. An RBL interviewee reports that there has never been any research by RBL in the machongos, there are no measurements of the seepage or spring water flow that originates from the surrounding hills. The current system where the observed field in Mozambique is located, is not optimally maintained and operated. The suggested indicators are not specific and require information on what is seen as potential and optimal. Thus, these indicators can also be seen as strategies serving the ultimate target of agricultural performance. The proposed strategies for system investment, monitoring and education are very general and are prerequisites for other more specific strategies. These strategies apply to a larger scale and a social domain which is not the focus of the current research.

3.2. Observed agricultural fields

Two African regions are selected where The Netherlands is involved in the improvement of efficient water use. The selected areas and crop types are roughly indicated in Fig. 3.1(b). The first region is Tadla Basin in Morocco which is part of the larger Oum Er Rhiba Basin. Surface irrigated winter wheat is observed for the season 2015/2016 in Tadla basin. The second region is the Lower Limpopo Basin in Mozambique, part of the larger Limpopo Basin. Smallholder maize cultivation is observed for the 2016 season in Lower Limpopo basin. In each area a single fields is observed for a single growing season. The observed field and season is representative for the area and a typical season were efficient water use is desired. The field is observed as a system with seasonal accumulated quantities for production and fluxes in and out of the system, visualized in Fig. 3.2. Water depths are expressed in meter for The baseline scenarios of the observed fields are simulated using the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST), calibrated against Surface Energy Balance Algorithm for Land model (SEBAL) results.

In the following sections the selected fields in each region are introduced. First, an introduction of t preserving a threefold focus. First, presenting the characteristics relevant for the simulation in the SWAP and WOFOST. Second, revealing the similarity and distinctiveness of the two fields. Thirdly, indicating aspects relevant for the simulation of strategies and computation of indicators for efficient water use. The paragraphs includes the geographic location of the field, meteorology and characteristics of the area and the local farming system and general performance.

The regions are distinct in geographical area, meteorological circumstances, crop type, water management practices and other field characteristics such as soil type and ground water level.

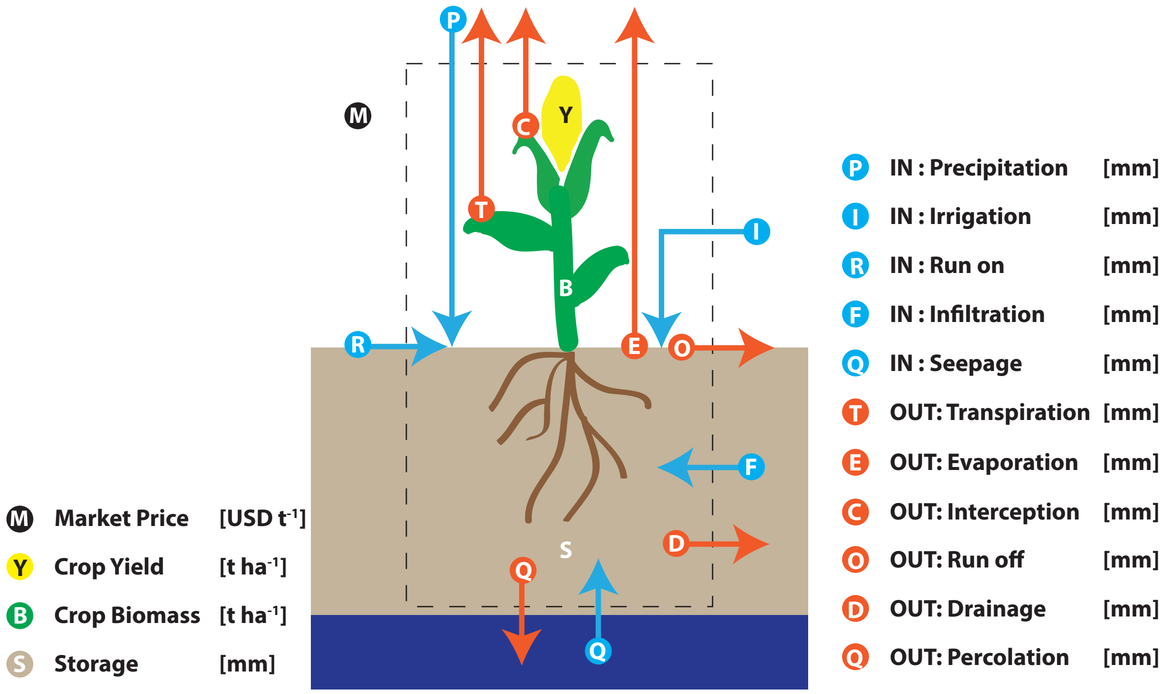


Fig. 3.2: Observed system with seasonal accumulated in and out fluxes observed for each simulation. Apart from the market price each parameter is an output from SWAP/WOFOST. Blue arrows indicate incoming fluxes, red arrows indicate outgoing fluxes.

3.2.1. Irrigated winter wheat in Tadla Basin Morrocco, 2015/2016

Morocco is the first North African country with which the Netherlands established bilateral relations. Morocco is not a Dutch partner country for development cooperation but the Netherlands does support activities in Morocco concerning agriculture and the environment (Government of the Netherlands, 2017*b*).
Government policy in the agricultural sector in Morocco has favored investments in irrigation since the 'million hectares policy' of King Hassan II in 1968, ordering to have a million ha irrigated by the end of the 20th century (Molle & Berkoff, 2007). Currently water resources supply and management is one of the most important national issues and is incorporated in recent policy and national action plans (Martin et al., 2013). Agricultural production and processing makes up 85% of the country's water use and employs 40% of the workforce. Morocco's large-scale irrigation systems are government planned and financed, managed by semi-autonomous, regional public institutions under the responsibility of the Ministry of Agriculture. Morocco's water resources are unevenly distributed and unreliable. Under a changing climate, the country's water resources are predicted to become even more scarce. The natural reductions of water supply are exacerbated by increasing demands from Moroccan economic development and from a growing urban population. In the national strategic plan for agriculture the importance of agriculture and the direct correlation between the amount and seasonality of rainfall and the national Gross Domestic Product (GDP) (Martin et al., 2013; Ministry of Agriculture Morocco, 2008).

Geographical location: Tadla Basin in Morocco is a sub basin with an area of 3440 km^2 within the larger Oum Er Rhiba Basin. The conducted land use classification for the period September 2015 to August 2016 revealed winter wheat to be the most common crop type. Validation indicated an accuracy of 83% for the identification of winter wheat fields. The total area of cultivated winter wheat is 345 km^2 represented by 21,920 polygons, polygon area varying from 0.1 to 184 ha. The field selected from this collection is a general performing field with characteristics representative for the majority of fields in the area. The selection procedure is described in Appendix H. This selection procedure diminished the collection of polygons to a set of 217 polygons representing a total area of 592 ha. This collection of wheat polygons is indicated in the center map in Fig. 3.3, in the left map the position of this collection within Oum Er Rhiba Basin is indicated.
For the selection of a single field the collection of wheat field polygons is further diminished by removal of fields with an area below 5 ha. Based on visual inspection with Google Satellite imagery, individual fields are defined within a polygon. This has resulted in a selection of 11 general performing and relatively large fields with a total area of 72 ha. The field averages of a series of the Surface Energy Balance Algorithm for Land model (SEBAL) results are analyzed for this collection, to select a field that is representative for this specific collection. This resulted in a selected field which has an area of 5.5 ha. In Fig. 3.3 in the center map the position of this field within the collection of wheat polygons is indicated, the right map shows the position of this field.

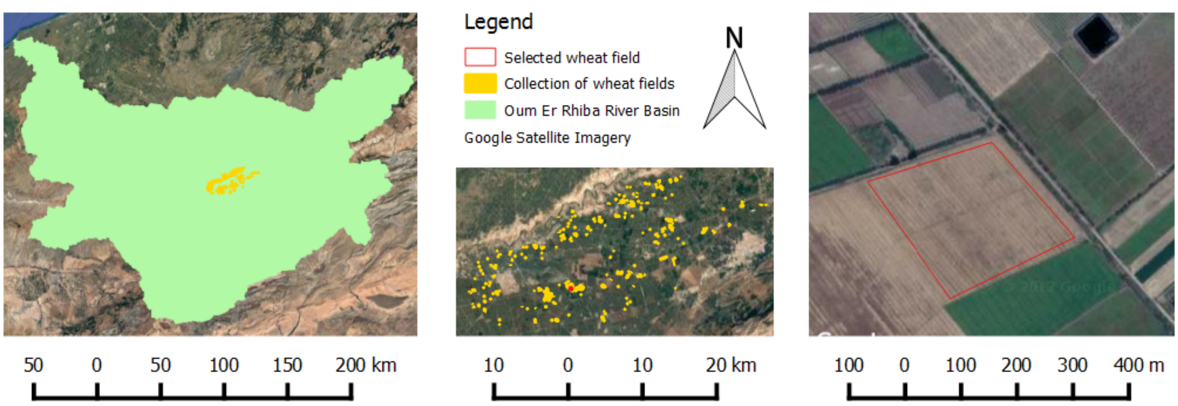
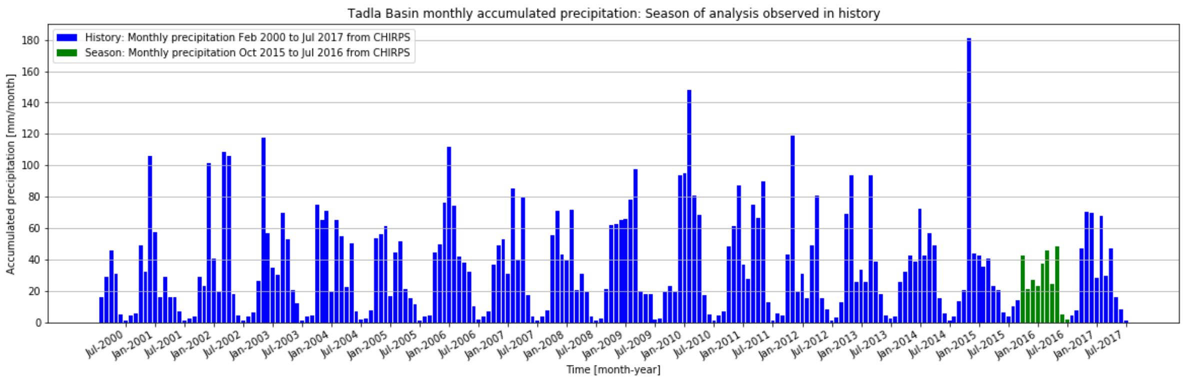


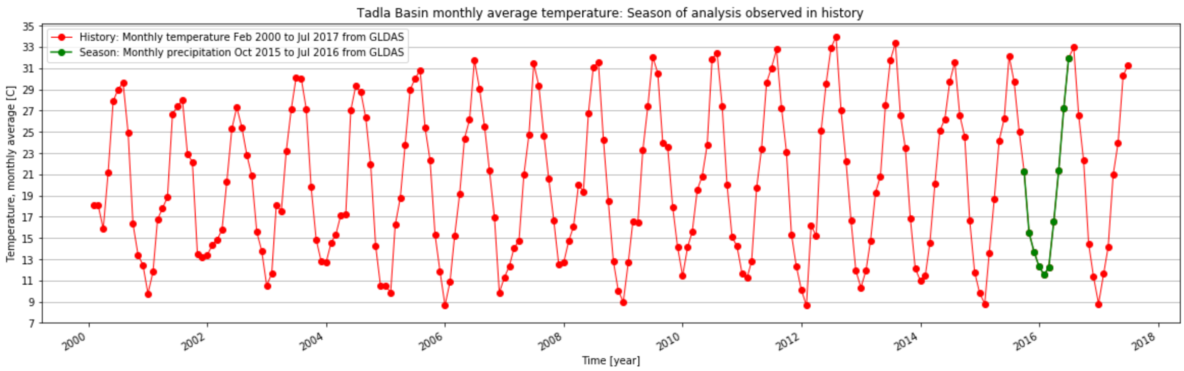
Fig. 3.3: Research site Morocco. Left: Oum Er Rhiba basin. Middle: Collection of wheat polygons after restrictions of salinity, soil type and field performance estimation. Right: Selected field for simulation, relatively large, general performing and representative wheat field

Meteorology and area characteristics The climate in Tadla basin or Tadla plain is Mediterranean or continental semi-arid (Barakat et al., 2015, 2016). In the basin the groundwater aquifer is confined and distance from surface to top of the aquifer exceeds 100 m (Ettazarini, 2006). The elevation of the field is 450 m (U.S. Department of the Interior & U.S. Geological Survey, 2010). An electrical conductivity (EC) of 1.0 $dS\ m^{-1}$ is assumed based on local analysis by Ormva-Tadla (2017), corresponding to a Total Dissolved Solids (TDS) of 640 $mg\ L^{-1}$ or a solute concentration of 0.64 $mg\ cm^{-3}$.

Typical rainy seasons last from November to March and the yearly dry season is observed from April to October. Average annual precipitation is mostly irregular and varies between 170 and 540 mm with an average of 280 mm. The average annual temperatures are about 18 $°C$ with a peak of 40 $°C$ in August and minimum 3 $°C$ in January. The annual potential evaporation is about 1800 mm (Barakat et al., 2015, 2016). In Fig. 3.4 the precipitation and temperature in the observed season in proportion to seasons from February 2000 to current date can be observed. Relative to other years the selected season is relatively dry (see Fig. 3.4(a)) and high temperatures are observed (see Fig. 3.4(b)). The Mediterranean is expected to be one of the world's regions most affected by future climate change, with increasing temperature and decreasing availability of water resources (Hulme, M.; Wigley, T: Barrow, E.; Raper, 2000; Ragab & Prudhomme, 2002). Recent decreases in precipitation have reduced water available for irrigation across the country, particularly in the Oum Er Rbia basin (Martin et al., 2013). A season with relatively low precipitation values and high temperatures is therefore a reasonable selection in the discussion on efficient water use in agriculture in Tadla Basin.



(a)



(b)

Fig. 3.4: Temperature and precipitation in Tadla basin in the observed season compared with other seasons in recent history. (a) Precipitation in Tadla basin: monthly total values from February 2000 to July 2017 including observed season in 2015-2016. Data obtained from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) archive by USGS (Funk et al., 2014). (b) Temperature in Tadla basin: monthly mean values from February 2000 to July 2017 including observed season in 2015-2016. Data obtained from the Global Land Data Assimilation System (GLDAS) by NASA/GSFC/HSL (Rodell et al., 2015)

For simulation with the SEBAL and Soil-Water-Atmosphere-Plant model (SWAP), daily weather data is used. In Fig. 3.5 the data used in SWAP corresponding to the growing season of the wheat field in Tadla Basin is given. In Fig. 3.10 this is presented for the smallholder maize field in the Lower Limpopo basin in 2016. In the graphs for both fields, the same dimensions for the y-axis are used, enabling easy comparison of the meteorological circumstances at the two observed fields. Also variation during the growing season can be observed from these charts. Also total received quantities for radiation and precipitation are computed and indicated in the graphs. For temperature, vapor pressure and wind speed the season mean value and standard deviation are provided. The wheat field receives about 3 $GJ\ m^{-2}$ incoming shortwave radiation and 180 mm precipitation. The average daily minimum and maximum temperature is 7 and 24 $°C$, the average vapor pressure is 0.8 kPa and the average wind speed is 1.3 $m\ s^{-1}$.

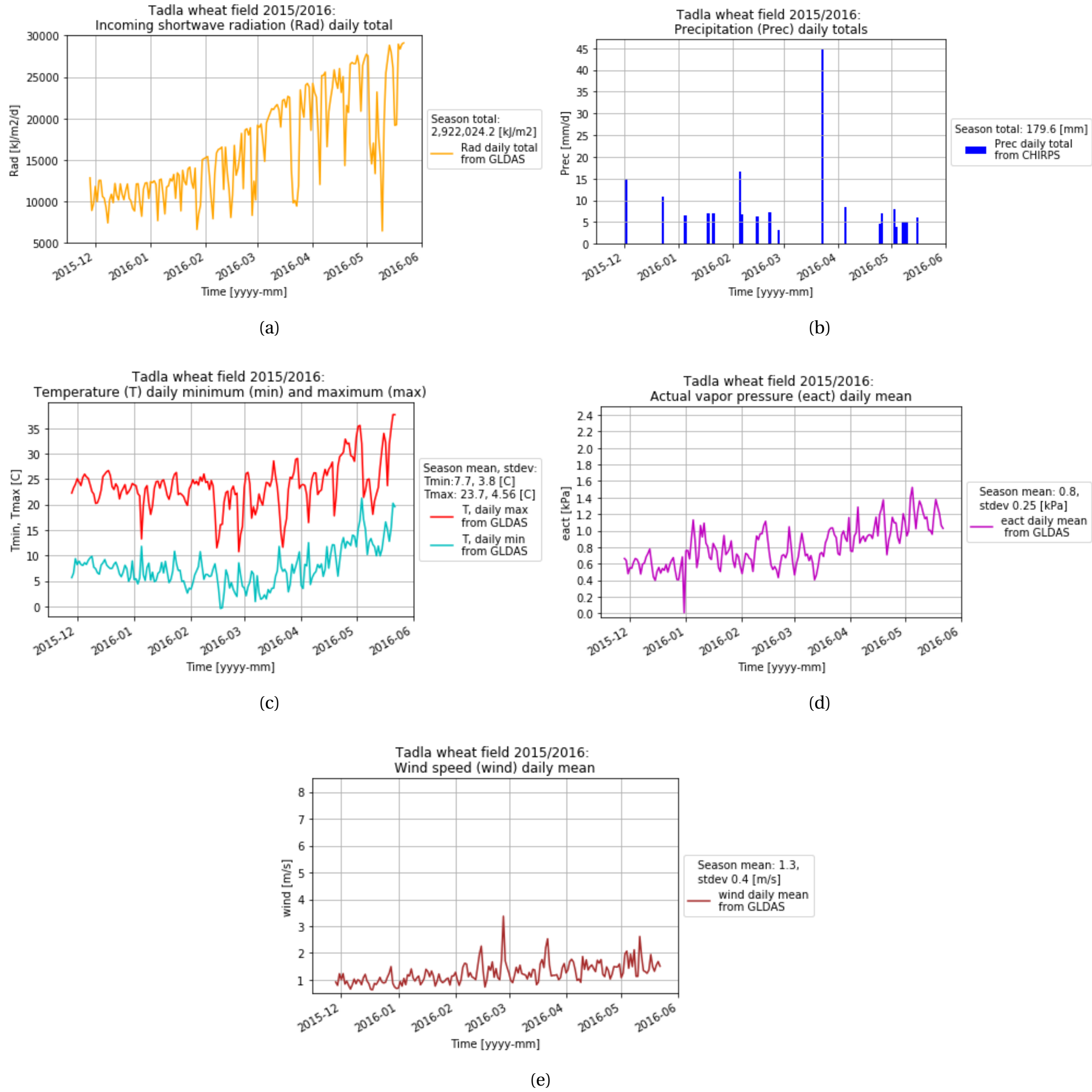


Fig. 3.5: Daily meteorological data from Tadla basin for observed season of winter wheat, obtained from the Global Land Data Assimilation System (GLDAS) by NASA/GSFC/HSL (Rodell et al., 2015) and from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) archive by USGS (Funk et al., 2014). (a) Incoming shortwave radiation, daily total, from GLDAS. (b) Precipitation, daily total, from CHIRPS. (c) Temperature, daily minimum and maximum, from GLDAS. (d) Actual vapor pressure, daily mean, from GLDAS. (e) Wind speed, daily mean, from GLDAS.

Farming system and field performance Traditionally in the Oum Er Rhiba Basin, the agriculture is characterized by the production of wheat, barley and corn. In the Tadla plain more variation is found where modern methods of irrigation and fertilization are used (Ettazarini, 2006) but wheat remains the main crop in Tadla Basin. Agriculture is a major activity in the area (Barakat et al., 2015). The cultivated area includes 137,500 ha of rain-fed land and 117,500 ha of irrigated land. The Tadla irrigation system is the oldest large-scale scheme in Morocco and is divided in two large-scale areas. Networks of open canals receive water by gravity from two dams. The observed field is located on the left bank of the river Oum Er Rhiba known as Beni Moussa, where 69,600 ha irrigated area receives water from the Bin el Oidane dam. The original official allocation since the project design in 1929 is 1.30 $Bm^3\ y^{-1}$. Since the 1980s, considerably less water has been allocated to the scheme. In 2003, 350 Mm^3 was available for Beni Moussa, 49% of the original allocation. As a result of this deficit, private groundwater development is widespread (Molle & Berkoff, 2007). In addition to the two irrigated areas with open canals, 18,600 ha of private irrigation is fed by tube wells and 9,100 ha of traditional small-scale areas are found at the bottom of the surrounding Atlas Mountains. Prior research suggests that currently an annual volume of 500–600 Mm^3 water is used from groundwater which exceeds the volume supplied by the surface. About 50% of the farmers have access to this ground water resource (Lahlou et al., 2013), farmers who do not have access are mainly the small-scale farmers cultivating plots below 2 ha (Kuper et al., 2012). The number of (tube-) wells in the large-scale irrigation systems in Morocco increased from a few hundred in the early 1980s to about 8,300 in 2008 (Hammani et al., 2009).

Water use is regulated by supply instead of by demand and managed through quotas. Farmers in the large-scale irrigation systems in Morocco pay a fixed minimum fee which entitles them to use 3,000 $m^3\ ha^{-1}$. This water charge is based primarily on cost-recovery rather than on conservation criteria (Petieguyot, 2003; Molle, 2009). In most cases, farmers are obliged to pay for their quotas even if they do not use the full amount. However, this is rarely observed since most farmers supplement canal supply with groundwater which is more costly (Molle, 2009).

The Harvest Index (HI) is a crop specific parameter defining the weight of a harvested product or yield as a fraction of the total production of the crop. Actual yield in $kg\ ha^{-1}$ is the product of the crop specific HI with the accumulated dry matter production during the growth season, corrected for the fraction of water present

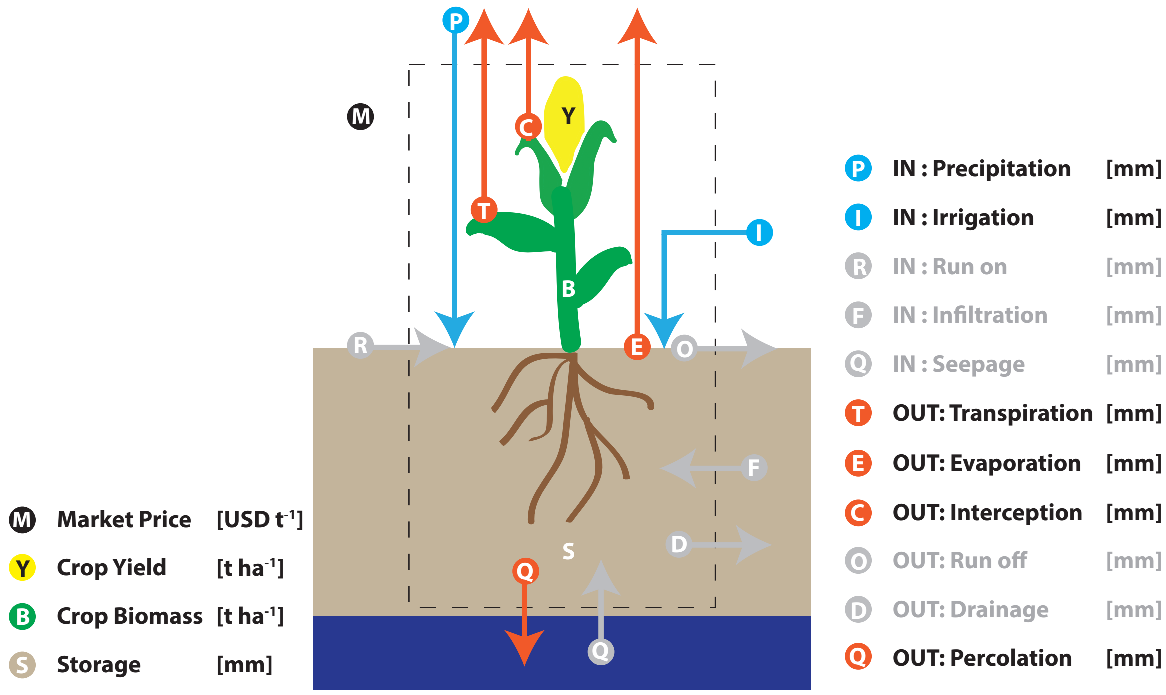


Fig. 3.6: Observed system with seasonal accumulated in and out fluxes observed for each simulation. Apart from the market price each parameter is an output from SWAP/WOFOST. Blue arrows indicate incoming fluxes, red arrows indicate outgoing fluxes. Grey arrows are negligible in the baseline simulation of the winter wheat field in Tadla basin 2015/2016.

in the harvested component of the crop θ_{crop}. According to (Van-Gastel et al., 2002), the seed moisture content is among the most critical factors during the harvest. For combine harvesting the seed moisture content must be between 16-19% to reduce mechanical damage. Field and seed standards standards for wheat in Morocco are given, the standard seed moisture content is 14%. (Bouthiba et al., 2008) described harvest indices of 0.33-0.39 under various irrigation schemes in Algeria. FAO report 66 states the HI for wheat under favorable conditions to vary between 0.45 and 0.55 for modern wheat cultivars (Steduto, Hsiao, Fereres & Raes, 2012). However, according to prior research when there is water stress after flowering or when the cultivar is poorly matched to the production environment HI can fall to as low as 0.2 to 0.3, for wheat in Doukalla Morocco a harvest index of 0.35 [-] is assumed (Goudriaan & Bastiaanssen, 2013). In this research a harvest index of 0.35 is used and a seed moisture content of 0.14.
The wheat market is regulated by the Moroccan Government, to mitigate the impact of changes in international prices on domestic prices (FAO, 2017*a*). Farmers can sell to government licensed traders at the preset price per mega ton wheat, which is set in March 2017 at US $ 264 . This price is representative for the last 10 years (Fardaoissi, 2017).

In Fig. 3.6 a schematization of the observed wheat field in Tadla Basin is given. The field baseline scenario is calibrated in SWAP/WOFOST against SEBAL data. In this baseline simulation, lateral drainage and infiltration and fluxes run off and run on are negligible. Because of the deep ground water table, no seepage is observed. An overview of the calibration result and baseline performance is given in Paragraph 4.2.

3.2.2. Smallholder maize in Lower Limpopo Basin Mozambique, 2016

The Netherlands and Mozambique have maintained since the 1970s cordial ties for development cooperation. Although the discovering of major oil and gas reserves in 2010 means tremendous economic opportunities for Mozambique, the country is still one of the poorest countries in the world. In the period up to 2017, food security is among the main priorities in Dutch development cooperation (Government of the Netherlands, 2017*b*).

The agricultural sector is crucial to the development of Mozambique and agriculture is seen as the engine to reach food security (Gomes & Famba, 1999). The Mozambique Government's strategic plan for the period from 2011 to 2020 calls for an average annual increase in crop production of 7%. Analysis reveals that climate change poses a threat, as the impacts of climate change will demand significantly more effort to attain the targeted levels of yield (Van Logchem & Queface, 2012). Agriculture employs 84% of the active population and contributes to 40% of the Gross Domestic Product (GDP) (DEA, 1997). The actual cultivated area in the country is around 50,000 km^2. Smallholders cultivate about 95% of the total area of which the majority practices rain fed agriculture, mainly for subsistence and with low level of input.
Irrigated agriculture is the largest water consumer, using about 510 Mm^3 per year which represents 80% of the country's total water consumption (Gomes & Famba, 1999). Despite the fact that Mozambique is quite often referred to as abundant in water resources, an increasing and apprehensive aggravation of the scarcity of water in certain regions of the country is observed. Mozambique is extremely dependent on fresh water flows from upstream countries. Despite the increasing scarcity, water is usually available at no cost or at heavily subsidized price. Neither water managers nor water users have the motivation to conserve water, resulting in water being overused instead of considered as a scarce and finite natural resource Gomes & Famba (1999). Interviewees working at governmental organizations reported in May 2017 that droughts in the last few years have been an incentive for increasing efficient water use.

The following sections present the observed field. In Appendix I more background information is included, obtained from literature, field measurements and information provided by interviewees.

Geographical location The observed area is a smallholder farming system in the Fidel Castro irrigation and drainage block in the Lower Limpopo basin Mozambique where the Dutch company FutureWater operates the ThirdEye project aiming at an increase of local water productivity, partly funded by the Dutch Government. This farming system is part of the area of the Regadio do Baixo Limpopo (Water Board in the Lower Limpopo Basin) (RBL) near Xai-Xai city, close to the estuary of Limpopo river. In Fig. 3.7 in the left map the location of the farming system in the basin is indicated. This area is part of what is known as the 'family sector' where small plots are cultivated by smallholders (Ganho, 2013). Maize is the main cultivated crop, the main growing season is April to September. A land use classification is conducted for the area revealing plots with high likelihood of maize cultivation in the observed season. Farmers have small plots, a general field has an area of 0.20 ha (45 by 45 m). The collection is restricted to polygons exceeding 0.20 ha. The resulting collection contains 75 polygons, representing a total area of 8.5 ha. This collection of maize fields is indicated in the center map in Fig. 3.7.

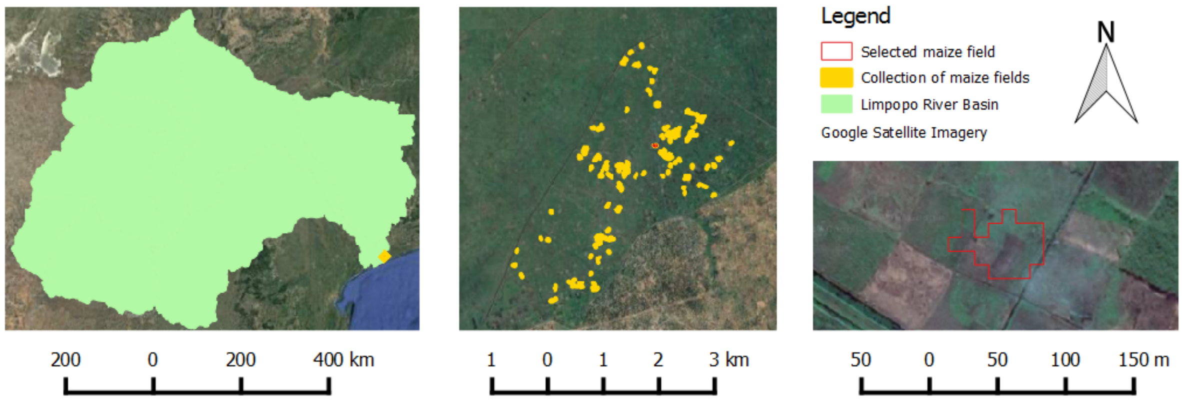


Fig. 3.7: Research site Mozambique. Left: Limpopo River Basin. Middle: Collection of maize polygons after restrictions of area dimensions. Right: Selected field for simulation, well performing and representative maize field

The area is known to be poor performing and crop cultivation often fails (Mugabe, 2015*a*). From the Surface Energy Balance Algorithm for Land model (SEBAL) results for July 2016 in the middle of the growing season, field averages were observed for the Leaf Area Index (LAI). Polygons are removed from the collection where the field average LAI is below 2.0. This results in a collection of 18 fields representing a total area of 7.6 ha. A single field having an area of 0.22 ha is selected which is representative for this well performing collection. In Fig. 3.7 in the center map the position of this field within the collection of maize polygons is indicated, the right map shows the position of this field.

Demarcation of the marshy, rich soils in the RBL area started in 1951. By 1967, about 11,300 ha had been reclaimed and most was under cultivation (Torres, 1967). Currently, RBL's 11,787 ha are organized in 12 blocks. Two distinct areas are recognized. First, the lowlands with large irrigated blocks, intended for commercial agriculture. Secondly, the irrigation/drainage blocks at the foot of the sand hills used by the family sector.

Meteorology and area characteristics In Mozambique the mean annual rainfall decreases from 800-1000 mm near the coast to less than 400 mm in the interior, mainly concentrated during the rainy period between October and April (Reddy, 1986). Mozambique's tropical to sub-tropical climate is moderated by its mountainous topography and influenced by the movement of the Intertropical Convergence Zone (ITCZ), El Niño and surface temperatures in the Indian Ocean. Variability between years is high due to variations in patterns of atmospheric and oceanic circulation. Mozambique's long coastline facing the Indian Ocean places the country in the path of increasingly more intense cyclones (Dyoulgerov et al., 2011).
The observed area near to Xai-Xai city is prone to extreme events such as drought and flooding. Facing these adverse conditions, the traditional family sector smallholder farmers in the RBL area turned to the fertile regions indicated as *swamp area, wetlands, spring zone* or in the local designation: *zonas verdes* or *machongos*. Gomes et al. (1997) states the areas play a very important role for food security and household income of thousands of families when subject to drainage. In the machongos, organic (peat) soils are present, generally very fertile and continuously wet. This is a palustrine wetland ecosystem, occurring in a form of seepage or springs from the surrounding dune areas known as *encostas*. The machongos are associated to water availability all year round. The soil has high infiltration and high recharge rates. In Fig. 3.8 a map of the observed area by Hassing (2017) is shown. The green colored area indicates the present machongos, in between the higher sand dunes and the clayey lowland near the river. The seepage is is generally year round and often referred to as irrigation (Van Der Zaag et al., 2010).

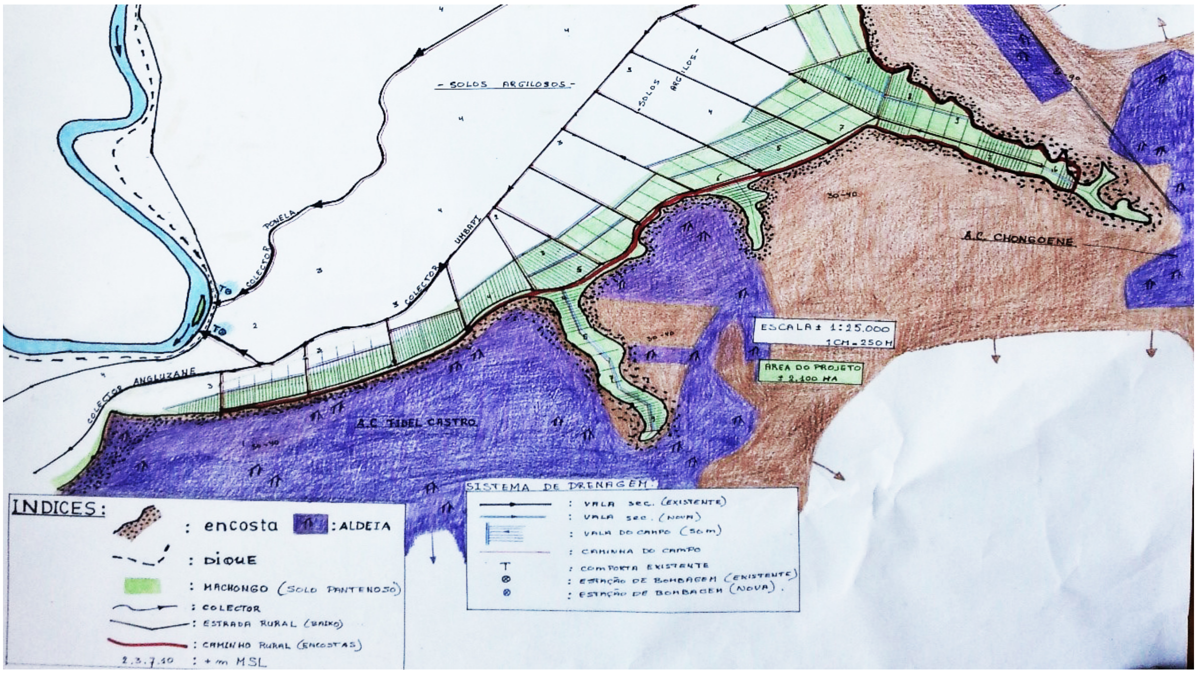
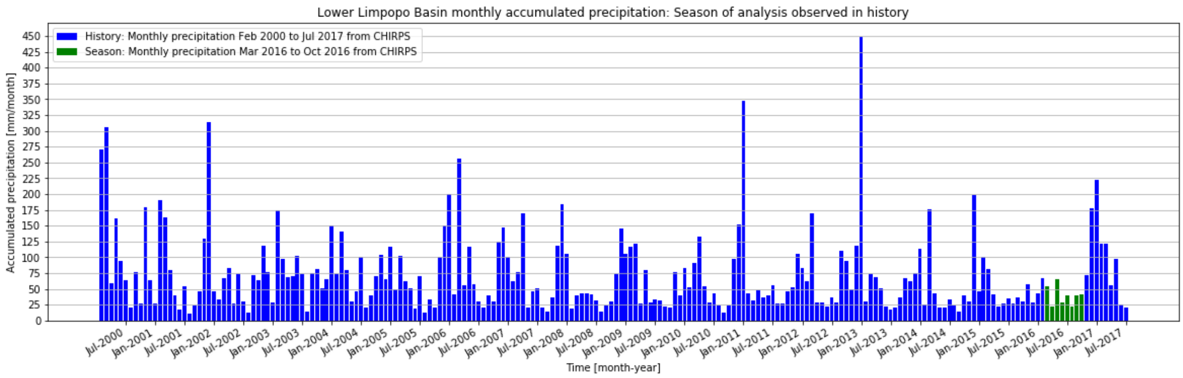


Fig. 3.8: Section of palustrine wetland ecosystem in area of Regadio de Baixo Limpopo (RBL) near Xai-Xai city, including Fidel Castro draiange block. Map by Hassing (2017), indicating machongos in green color, in between sandy dunes and clayey lowland.

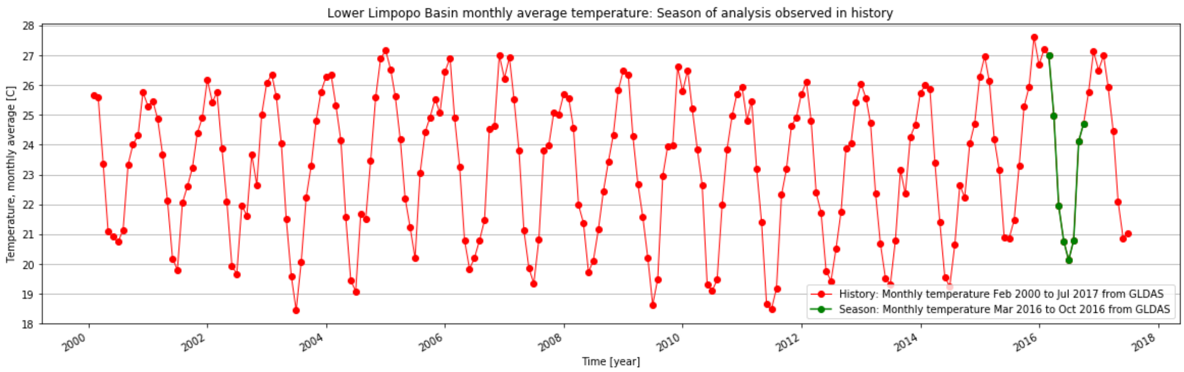
Most peat soils in Mozambique occur under poorly drained and swampy conditions in the vicinity of the coast and in some delta areas. Peat clay and clayey peat, alternating with one or more mineral horizons are typical. Within one soil profile it is often possible to find individual peat layers in various stages of decomposition. These soils are moderately to high permeable and the run-off is absent. Water table is found between the surface and 0.5 m depth (Gomes et al., 1997). This corresponds with field measurements. In the selected field a clayey peat soil is observed with a heavy clay layer starting from 100 cm depth. Using a CTD-diver, shallow ground water solute concentration was measured 615.665 $mg\ cm^{-3}$ in the field. With a double ring infiltrometer test, for the top soil layer a saturated hydraulic conductivity K_{sat} of 19 $cm\ d^{-1}$ was estimated. The other soil hydraulic parameters are determined from the staring series after Wösten et al. (2014), by interpolation using K_{sat} between peat type O17 and O18. The deeper heavy clay layer is characterized according to clay type O13.

The growing season April-September 2016 is selected for being a relatively dry, recent and representative season in between periods of severe drought (2015) and flooding (2017). According to the Oceanic Niño Index (INO) which is the standard used by the National Oceanic and Atmospheric Administration (NOAA) to identify the effects of the El Niño Southern Oscillation (ENSO) effects in the tropical Pacific, the years 2015-2016 are categorized as a very strong ENSO period (NOAA, 2017). In Fig. 3.9 the precipitation and temperature in the observed season in proportion to seasons from February 2000 to current date can be observed. The season 2016 is relatively dry compared to other seasons in recent history. Heavy rainfall is usually observed in December-January, where February is known as 'inundation month' after which sowing starts in March/April. In the months previous to the observed season this heavy rainfall is not observed, see Fig. 3.9(a). As can be observed in Fig. 3.9(b), the temperature in the selected season is relatively high compared to the previous few years but not extreme as similar temperatures were observed in the year 2006.

For simulation of the SEBAL and Soil-Water-Atmosphere-Plant model (SWAP), daily weather data is used. In Fig. 3.10 the data used in SWAP corresponding to the growing season of the maize field in the Lower Limpopo basin is given. In Fig. 3.5 this is presented for the winter wheat field in Tadla basin Morocco in 2015/2016. In the graphs for both fields, the same dimensions for the y-axis are used, enabling easy comparison of the meteorological circumstances at the two observed fields. Also variation during the growing season can be observed from these charts. Also total received quantities for radiation and precipitation are computed and indicated in the graphs. For temperature, vapor pressure and wind speed the season mean value and standard deviation are provided. The maize field receives about 2.4 $GJ\ m^{-2}$ incoming shortwave radiation and 125 mm of precipitation. The average daily minimum and maximum temperature is 18 and 26 $^{\circ}C$, the average vapor pressure is 1.7 kPa and the average wind speed is 1.2 $m\ s^{-1}$.



(a)



(b)

Fig. 3.9: Temperature and precipitation in Lower Limpopo basin in the observed season compared with other seasons in recent history. (a) Precipitation in Lower Limpopo basin: monthly total values from February 2000 to July 2017 including observed season in 2016. Data obtained from the Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) archive by USGS (Funk et al., 2014). (b) Temperature in Lower Limpopo basin: monthly mean values from February 2000 to July 2017 including observed season in 2016. Data obtained from the Global Land Data Assimilation System (GLDAS) by NASA/GSFC/HSL (Rodell et al., 2015)

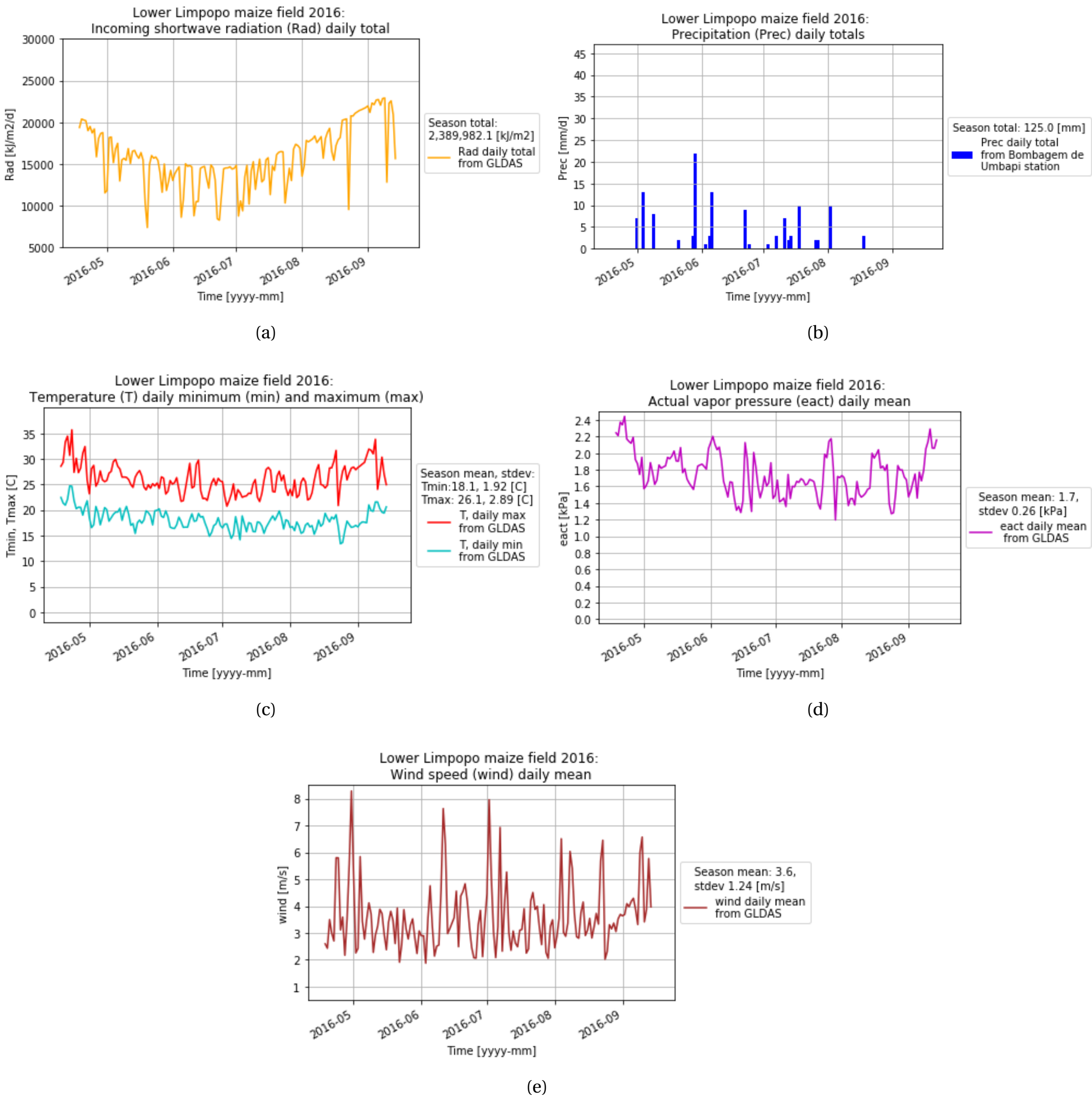


Fig. 3.10: Daily meteorological data from Lower Limpopo basin for observed season of maize, obtained from the Global Land Data Assimilation System (GLDAS) by NASA/GSFC/HSL (Rodell et al., 2015) and from ground truth measurements by the Regadio do Baixo Limpopo at the pumping station Bombagem de Umbapi (Direccao de operacao - Regadio do Baixo Limpopo, 2017), 6.7 km downstream of the observed field. (a) Incoming shortwave radiation, daily total, from GLDAS. (b) Precipitation, daily total, ground measurements from the RBL pumping station Bombagem de Umbapi. (c) Temperature, daily minimum and maximum, from GLDAS. (d) Actual vapor pressure, daily mean, from GLDAS. (e) Wind speed, daily mean, from GLDAS.

Farming system and field performance Prior research reports main local limitations of cultivation of the machongos being high investments to realize drainage and prevent floods, unfavorable soil structure associated to low infiltration rates and risks of salt intrusion due to tidal fluctuation and lowering of the water table. Yield losses are mainly due to flooding and excessive soil water during the rainy season. (Gomes et al., 1997). It is reported that only 5% of the machongos is used, due to malfunctioning of the drainage system which causes the soil to remain flooded (Marques et al., 2006*a*).

A schematization of the current irrigation and drainage system is presented in Fig. 3.11. The canals function both as storage bodies and drainage canals. With the valves and downstream pumping station the ground water level is managed to maintain favorable soil moisture levels for agricultural production. From the downstream pumping station, water is pumped into a storage tower to flow gravity wise into the lower irrigated rice schemes. Excess water is pumped into the Limpopo River. Currently the system is not optimal functioning. Canals are blocked, valves are broken and operation is not well managed. Interviewed experts state that the system is very tardy, it is only manually conducted and there is no plan or structure for the operation. However, local experts state that with proper management it will be very cheap to cultivate in this area.

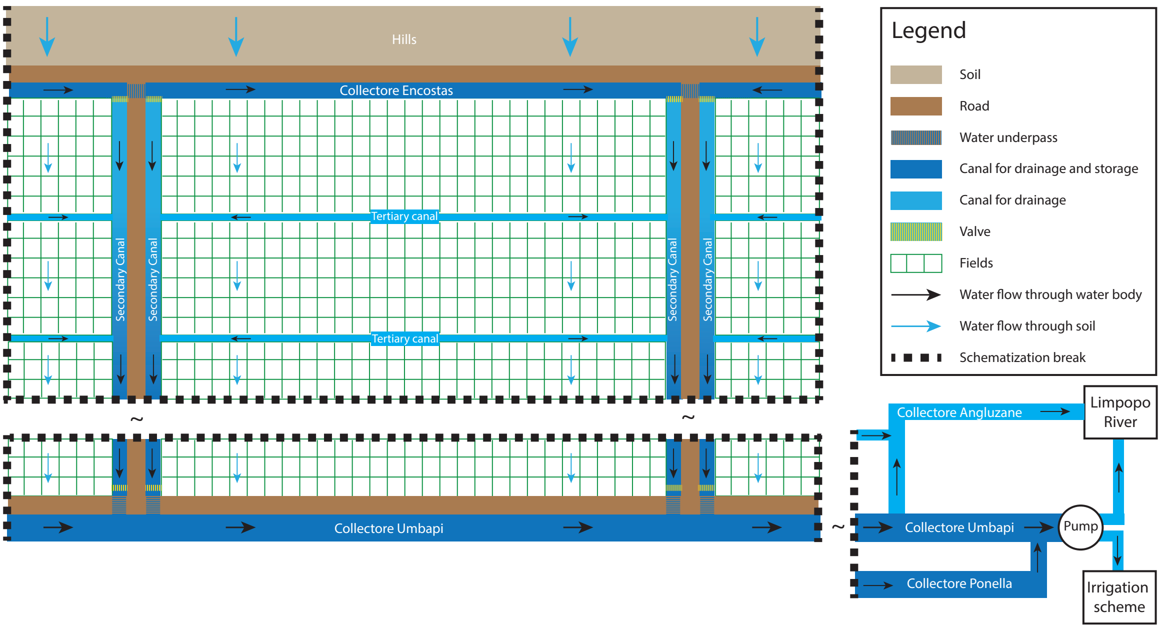


Fig. 3.11: Schematization of the agricultural system in the Fidel Castro irrigation/drainage block near Xai-Xai Mozambique, within the area of the Regadio do Baixo Limpopo (RBL). The observed field is located in this area.

The constant seepage flow from the shallow ground water level is naturally present. This application of sub soil irrigation water can be managed by management of the ground water table. Water that is drained from the system can be used in the large downstream irrigation systems. With optimal drainage the area can be accessed earlier after the rainy season. The naturally present reed vegetation starts to grow after the rains. Removal is manually done, because this heavy work farmers currently only cultivate small plots. If the area is earlier accessible this will be easier. This would also allow farmers to plant earlier. For optimal management of the ground water level, water should be stored in the system to be available in dry periods. Currently the Collectore Encostas (see Fig. 3.11) functions as a storage body. Collectore Umbapi and Ponella are storage bodies for the downstream irrigation scheme. Interviewed local experts state that more drainage canals and storage capacity is required for the system to function optimally. Additionally, interviewees report that the system with the current infrastructure used to function better in earlier times when the system was better maintained and operated and farmers received clear instructions in the cultivation of their plots.
It is thus expected that for optimal functioning of the system, investments are be required. This concerns the operation, maintenance and management of the current system including clear communication and responsibilities of the local key actors. It might also concern extension of the current infrastructure. This is observed at system scale, outside the scope of the current research. In simulation of strategies for the ob-

served smallholder maize field in this area, management of the ground water table is assumed to be possible. This research therefore indicates the potential improvement of efficient water use at field scale when proper management of the ground water table is realized.

Yield rates in the area are low, reported to be 900-1000 kg/ha for crops like maize (Marques et al., 2006*a*). In a group interview in 2016 farmers in the ThirdEye project indicate maize yield of 1.5-2 t/ha (van den Akker, 2016). For computation of yield from biomass in this research therefore a low Harvest Index (HI) of 0.25 is assumed and a seed moisture content of 0.25 is used for maize based on expert knowledge. Most farmers use their production mainly for home consumption, surplus is sold to a middleman, prior research and conducted interviews reveals that farmers are not market oriented (van den Akker, 2016). Maize is the staple food for the poor, with maize meal most often used as a substitute. The average market price in Gaza province in 2017 is 30 MZN/kg (Famine Early Warning System Network, 2017), or 491 USD/Mt.

In Fig. 3.12 a schematization of the observed maize field in Lower Limpopo Basin is given. According the the baseline scenario calibrated with SEBAL data, lateral drainage and infiltration and fluxes run off and run on are negligible. No above ground irrigation is applied. Irrigation is applied subsurface in management of the ground water table. An overview of the calibration results and baseline performance is given in Paragraph 4.3.

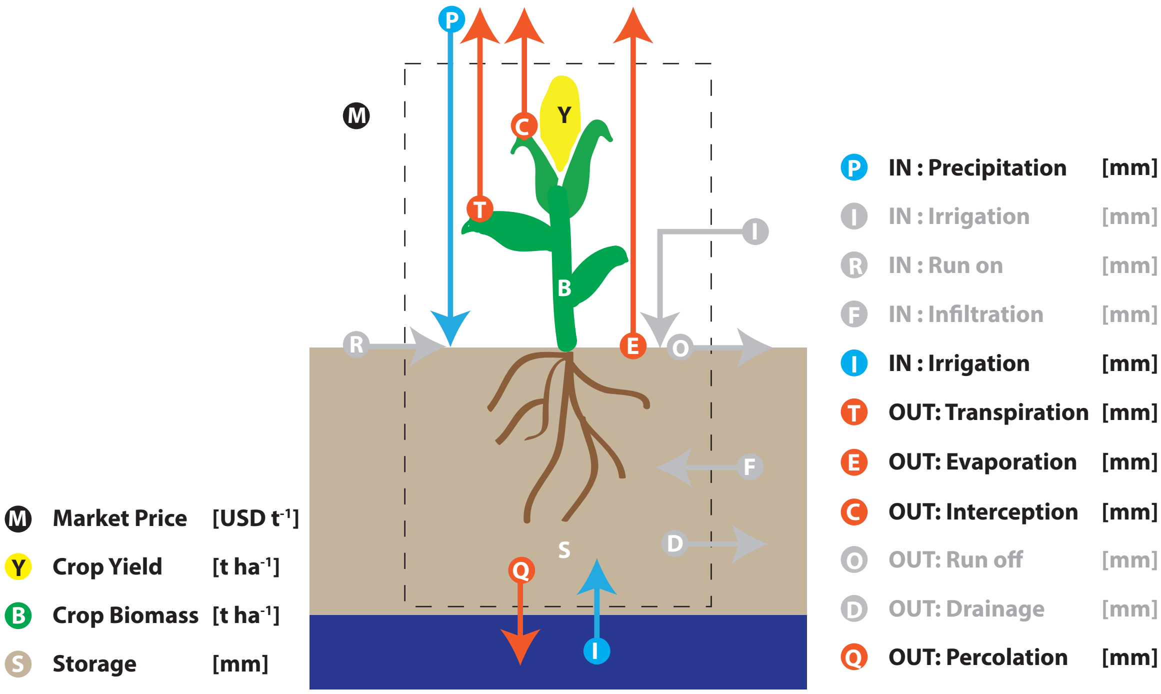


Fig. 3.12: Observed system with in and out flows observed for the simulated maize field in Lower Limpopo Basin. Apart from the market price each parameter is an output from SWAP/WOFOST.

3.3. Observed strategies to obtain improvement of efficient water use at the agricultural field

The previous paragraphs presented the observed fields and the perceptions of the key actors regarding efficient water use in agriculture. A selection is made of strategies seen as most relevant in the current discussion of efficient water use at the agricultural field. The actual fields are simulated in the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST), calibrated against data from the Surface Energy Balance Algorithm for Land model (SEBAL), resulting in a simulated baseline scenario for each field. The addition of a strategy results in a simulated strategy scenario.
To observe general perceptions of the observed key actors and to allow comparison of the two different fields, the formulated strategies are general. Reasonable choices are made concerning the strategies on the different fields. Optimization of strategies for the specific site of application is not within the scope of this research. The first observed field is a 5.5 ha winter wheat field in Tadla basin Morocco in the season 2015/2016 where irrigation is applied at the surface from a field inlet. The second observed field is a 0.2 ha smallholder maize field in the Lower Limpopo basin Mozambique, where sub surface irrigation is applied by management of the shallow ground water table. The fields are introduced in Paragraph 3.2. In Paragraph 4.2 and 4.3 the baseline scenarios of the observed fields are introduced. In the current paragraph, the selected strategies are presented and provided with a brief explanation on the simulation in SWAP and WOFOST.

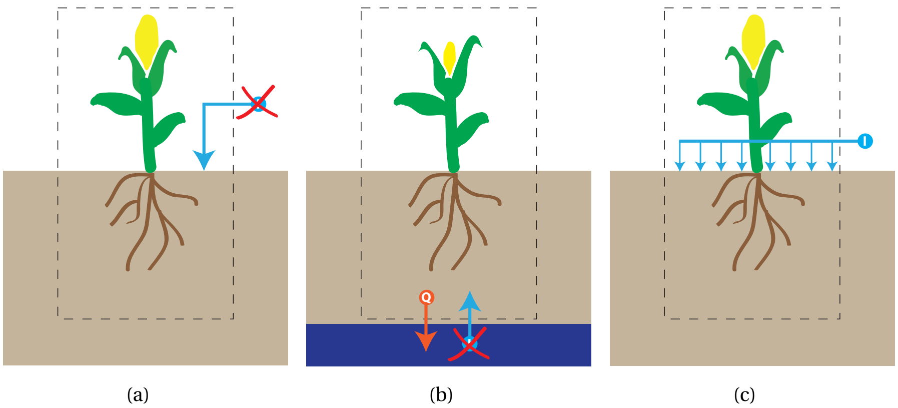


Fig. 3.13: Strategies 1 and 2 illustrated. Strategy 2 does not apply at the maize field in the Lower Limpopo basin. (a) Strategy 1 at winter wheat field in Tadla basin: elimination of surface irrigation. (b) Strategy 1 at smallholder maize field in Lower Limpopo basin: elimination of sub-surface irrigation. (c) Strategy 2 at winter wheat field in Tadla basin: change from field to sprinkler irrigation.

3.3.1. Strategy 1: Irrigation Eliminate

Eliminating irrigation means that no irrigation is applied and the field is rain fed, the water not used for irrigation is used for other purposes. This strategy is observed in general perception concerning efficient water use. The strategy is observed with key actors involved in a larger area who have concerning water use other priorities than the observed field. It is expected that the effect of elimination on the observed fields is not beneficial. In this case the strategy can be used to see if indicators give a misleading representation of improvement of efficient water use.

Irrigation eliminated at the winter wheat field in Tadla Basin: Strategy 1 for the winter wheat field in Tadla basin is illustrated in Fig. 3.13(a). The field is part of a large gravity forced open canal irrigation system. When irrigation is eliminated, the water is not withdrawn from the system. Hence this water can be subtracted from the allocation to the system or it can be used for irrigation of downstream fields within the system. In SWAP, the calibrated surface irrigation is an input which can be switched off for simulation of irrigation elimination.

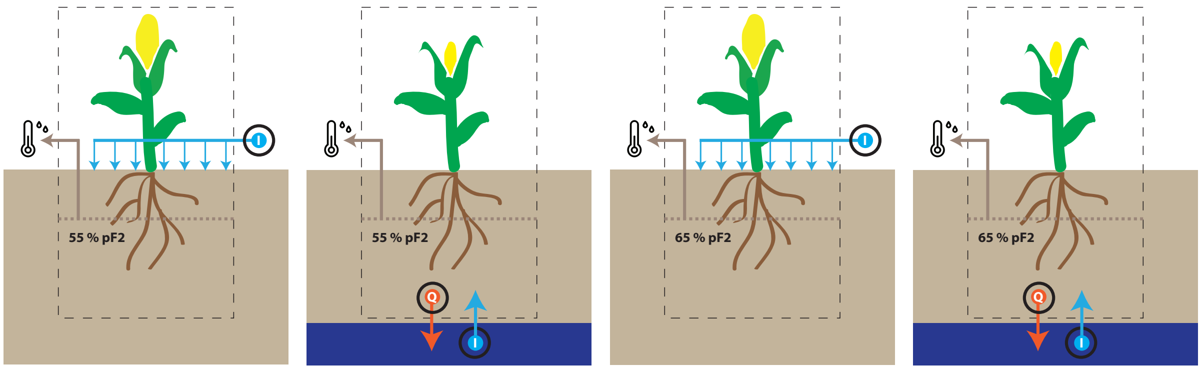
Irrigation eliminated at the maize field in Lower Limpopo Basin: Strategy 1 for the smallholder maize field in Lower Limpopo basin is illustrated in Fig. 3.13(b). The maize field is part of an irrigation/drainage system, sub surface irrigation and is applied by management of the ground water table. When irrigation is eliminated, the water is completely drained and inflow from seepage is prevented. This means that the water can instead be used at the end of the system where it is pumped into a gravity based irrigation system. In SWAP, sub surface irrigation is simulated with a calibrated horizontal bottom flux. Simulating elimination of irrigation, this is changed to free drainage of the soil profile.

3.3.2. Strategy 2: Sprinkler Irrigation

The change of surface or field irrigation to sprinkler irrigation means that instead of an irrigation water depth furnished at a field inlet it is distributed to the field with a sprinkler installation. This strategy is suggested by multiple key actors. This strategy is observed in the perceptions of the Food and Agriculture Organization (FAO), in international research and with involved Dutch companies and research institutes. The strategy only relates to the timing of irrigation and depth of individual applications. With application of this second strategy, the amount of seasonal irrigation water is not changed. When surface irrigation is applied, use sprinkler irrigation is necessary for strategies involving deficit irrigation.

Sprinkler irrigation at the winter wheat field in Tadla Basin: Strategy 2 for the winter wheat field in Tadla basin is illustrated in Fig. 3.13(c). The winter wheat field in Tadla Basin is part of a large gravity open canal irrigation system, surface or field irrigation is applied. Field irrigation requires large water depths to reach every part of the field from the field inlet, in Tadla basin a minumum water depth of 6 cm is applied. Within the growing season, a total of 570 mm water deph is applied at the field. When sprinkler irrigation is applied, the same total water depth is applied in weekly applications of 22.8 mm water depth. In SWAP, the calibrated surface irrigation applications are replaced by these weekly sprinkler irrigation applications.

Sprinkler irrigation at the maize field in Lower Limpopo Basin: The maize field in Lower Limpopo Basin is part of an irrigation/drainage system, sub-surface irrigation and is applied by management of the ground water table. A change to sprinkler irrigation does not apply.



(a) (b) (c) (d)

Fig. 3.14: Strategies 3 and 4 illustrated. (a) Strategy 3 at winter wheat field in Tadla Basin: regulation of moderate soil water deficit. (b) Strategy 3 at smallholder maize field in Lower Limpopo Basin: regulation of moderate soil water deficit. (c) Strategy 4 at winter wheat field in Tadla Basin: regulation of mild soil water deficit. (d) Strategy 4 at smallholder maize field in Lower Limpopo Basin: regulation of moderate soil water deficit.

3.3.3. Strategy 3: Moderate Soil Water Deficit

In regulated deficit irrigation usually mild water deficit is allowed, a moderate water deficit can also be allowed and is a more drastic measure. Deficit irrigation is suggested by key actors from the FAO, international research and Dutch companies and research institutes. Moderate water deficit is defined by (Chai et al., 2016; Li et al., 2010) as a soil water content remaining at 50-60% of field capacity pF2. In the current research, moderate deficit irrigation is applied where irrigation timing and depth is determined according to criteria of soil moisture content at 55% of pF2, constant during the growing season. This is measured with soil moisture sensors in the field within the crop root zone. From maize experiments in prior research is concluded that when soil water content is maintained at 55-65% of its pF2, an improvement in efficient water use was observed. The use of soil moisture sensors for deficit irrigation is suggested specifically by observed key actors from Dutch companies and research institutes.

Moderate soil water deficit at the winter wheat field in Tadla Basin: Strategy 3 for the winter wheat field in Tadla basin is illustrated in Fig. 3.14(a). Implementation of regulated soil water deficit at the winter wheat field in Tadla basin includes irrigation using a sprinkler installation and measurement of soil moisture content with soil sensors at 40 cm depth in the root zone. The field capacity pF2 of this soil layer is 0.369. At 55% of pF2 the soil moisture content is 20.3%. Irrigation timing and depth is determined from this criterion which is a setting in SWAP.

Moderate soil water deficit at the maize field in Lower Limpopo Basin: Strategy 3 for the smallholder maize field in Lower Limpopo basin is illustrated in Fig. 3.14(b). Implementation of regulated soil water deficit at the maize field in Lower Limpopo basin includes measurement of soil moisture content with soil sensors at 40 cm depth in the root zone. Sprinkler irrigation does not apply, sub surface irrigation water is applied with management of the ground water table. Field capacity pF2 of peat soils can be estimated at 0.56 (Innovyze, 2017). At 55% of pF2 the soil moisture content is 30.8%. Vertical ground water flux at the bottom of the simulated soil profile is calibrated according to this criterion. The result is visualized in Fig. 3.15(a) and Fig. 3.15(f).

3.3.4. Strategy 4: Mild Soil Water Deficit

Deficit irrigation is suggested by key actors from the FAO, international research and Dutch companies and research institutes. In regulated deficit irrigation usually mild water deficit is allowed. This reduces the volume of irrigation water used without or only marginally effecting the amount of yield produced. Deficit irrigation can be applied with different irrigation methods and can be enforced constant over the growing season or defined specifically for each growing stage. For maize and winter wheat the advised irrigation method is sprinkler irrigation, and the best results in prior research are obtained with a constant deficit over the growing season (Kirda et al., 2002). Mild water deficit is defined by (Chai et al., 2016) as a soil water content remaining at 60-70% of field capacity pF2, in the FAO report by (Kirda et al., 2002) 50-70% is used. In the current research, mild deficit irrigation is applied where irrigation timing and depth is determined according to criteria of a soil moisture content of 65% of pF2, constant during the growing season. This is measured with soil moisture sensors in the field within the crop root zone. The use of soil moisture sensors for deficit irrigation is suggested specifically by observed key actors from Dutch companies and research institutes.

Mild soil water deficit at the winter wheat field in Tadla Basin: Strategy 4 for the winter wheat field in Tadla basin is illustrated in Fig. 3.14(c). Implementation of regulated soil water deficit at the winter wheat field in Tadla basin includes irrigation with sprinkler installation and measurement of soil moisture content with soil sensors at 40 cm depth in the root zone. The field capacity pF2 of this soil layer is 0.369. At 65% of pF2 the soil moisture content is 24.0%. Irrigation timing and depth is determined from this criterion which is a setting in SWAP. International research expects that deficit irrigation technology can lead to substantial saving in irrigation water, up to an average of 644 cubic meters per ha.

Mild soil water deficit at the maize field in Lower Limpopo Basin: Strategy 4 for the smallholder maize field in Lower Limpopo basin is illustrated in Fig. 3.14(d). Implementation of regulated soil water deficit at the maize field in Lower Limpopo basin includes measurement of soil moisture content with soil sensors at 40 cm depth in the root zone. Sprinkler irrigation does not apply, sub surface irrigation water is applied with management of the ground water table. Field capacity pF2 of peat soils can be estimated at 0.56 (Innovyze, 2017). At 65% of pF2 the soil moisture content is 36.4%. Vertical ground water flux at the bottom of the simulated soil profile is calibrated according to this criterion. The result is visualized in Fig. 3.15(b) and Fig. 3.15(g).


```
* BASELINE
  DATE2 QBOT2
 01-jan-2016 -0.6
 01-mar-2016 -0.3
 01-may-2016  0.0
 01-jun-2016  0.4
 10-jun-2016  0.7
 01-jul-2016  0.7
 12-jul-2016  0.5
 01-aug-2016  0.3
 01-sep-2016  0.2
 01-nov-2016  0.0
* End of table,
* maximum MABBC records
```

(e)

```
* STRATEGY 3
  DATE2 QBOT2
 01-jan-2016 -0.15
 01-mar-2016 -0.1
 01-may-2016  0.0
 15-may-2016  0.55
 20-may-2016 -0.35
 01-jun-2016 -0.1
 05-jun-2016  1.5
 20-jun-2016  0.1
 01-jul-2016  0.3
 12-jul-2016  0.5
 01-aug-2016  0.5
 01-sep-2016  0.6
 01-nov-2016  0.0
* End of table,
* maximum MABBC records
```

(f)

```
* STRATEGY 4
  DATE2 QBOT2
 01-jan-2016 -0.0
 01-mar-2016 -0.0
 01-may-2016  0.05
 15-may-2016  0.35
 20-may-2016 -0.1
 01-jun-2016  0.0
 05-jun-2016  1.0
 20-jun-2016  0.3
 01-jul-2016  0.45
 12-jul-2016  0.5
 01-aug-2016  0.5
 15-aug-2016  0.65
 01-sep-2016  0.6
 01-nov-2016  0.0
* End of table,
* maximum MABBC records
```

(g)

```
* STRATEGY 5
  DATE2 QBOT2
 01-jan-2016 -0.6
 01-mar-2016 -0.3
 01-may-2016  0.18
 05-may-2016  0.6
 20-may-2016  0.2
 01-jun-2016  0.0
 10-jun-2016  0.2
 15-jun-2016  0.5
 25-jun-2016  0.2
 01-jul-2016  0.3
 05-jul-2016  0.5
 15-jul-2016  0.0
 05-aug-2016  0.4
 01-sep-2016  0.4
 01-nov-2016  0.0
* End of table,
* maximum MABBC records
```

(h)

```
* STRATEGY 6
  DATE2 QBOT2
 01-jan-2016 -0.0
 01-mar-2016 -0.0
 01-apr-2016  0.15
 01-may-2016  0.15
 15-may-2016  0.15
 20-may-2016 -0.1
 01-jun-2016  0.0
 05-jun-2016  1.0
 20-jun-2016  0.3
 01-jul-2016  0.4
 12-jul-2016  0.55
 01-aug-2016  0.5
 15-aug-2016  0.7
 01-sep-2016  0.6
 01-nov-2016  0.0
* End of table,
* maximum MABBC records
```

(i)

Fig. 3.15: Simulation of strategies 3-6 with calibration of bottom flux for maize field in Lower Limpopo basin Mozambique 2016. Presented: verification of criteria and records of bottom flux. (a) Verification of strategy 3 criteria: Soil moisture content of 30.8% in root zone. (b) Verification of strategy 4 criteria: Soil moisture content of 36.4% in root zone. (c) Verification of strategy 5 criteria: Relative transpiration at 75%. (d) Verification of strategy 5 criteria: Relative transpiration at 100%. (e) Records of bottom flux calibrated for baseline scenario. (f) Records of bottom flux calibrated for strategy scenario 3. (g) Records of bottom flux calibrated for strategy scenario 4. (h) Records of bottom flux calibrated for strategy scenario 5. (i) Records of bottom flux calibrated for strategy scenario 6.

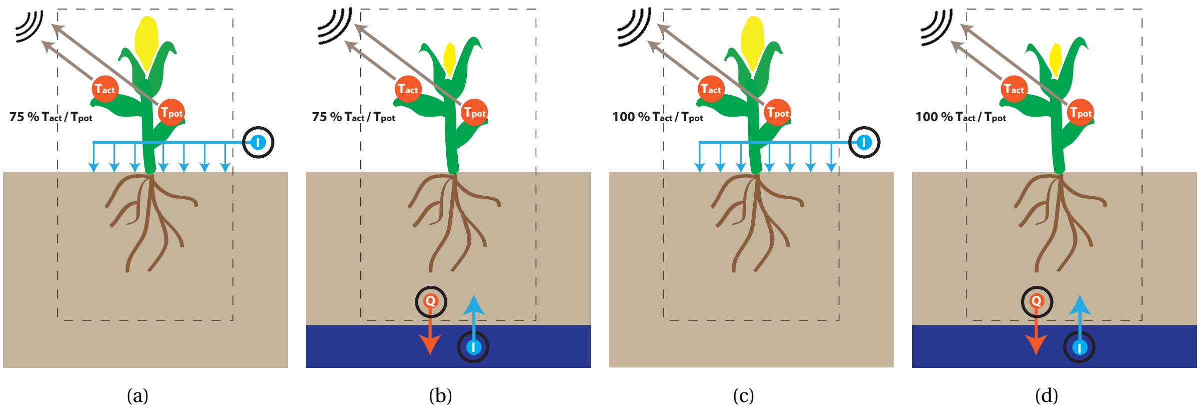


Fig. 3.16: Strategies 5 and 6 illustrated. (a) Strategy 5 at winter wheat field in Tadla Basin: regulation of transpiration deficit. (b) Strategy 5 at smallholder maize field in Lower Limpopo Basin: regulation of transpiration deficit. (c) Strategy 6 at winter wheat field in Tadla Basin: regulation of transpiration optimum. (d) Strategy 6 at smallholder maize field in Lower Limpopo Basin: regulation of transpiration optimum.

3.3.5. Strategy 5: Transpiration Deficit

Transpiration deficit is regulated with deficit irrigation. Deficit irrigation is suggested by key actors from the FAO, international research and Dutch companies and research institutes. Interviewees from companies and research institutes from the Netherlands mentioned regulation of transpiration deficit specifically. When crops do not experience stress, actual crop transpiration T_{act} can be equal to potential crop transpiration T_{pot} and thus the relative transpiration T_{rel}, being T_{act} / T_{pot}, is equal to 1. T_{rel} is reduced with crop stress. A regulated reduction of transpiration or evaporation is obtained with deficit irrigation. A general value of regulated relative evapotranspiration used by FAO is 75%. Prior research suggests that with regulation of this deficit, using sprinkler irrigation, an improvement in efficient water use can be obtained for both maize and wheat (Kirda et al., 2002).

Transpiration deficit at the winter wheat field in Tadla Basin: Strategy 5 for the winter wheat field in Tadla basin is illustrated in Fig. 3.16(a). Implementation of regulated transpiraton deficit at the winter wheat field in Tadla basin requires daily monitoring of the crop transpiration rate which is obtained with flying sensors. A sprinkler installation is used for irrigation. Irrigation timing and depth is determined from the criterion that the relative transpiration is 75% throughout the growing season, which is a setting in SWAP.

Transpiration deficit at the maize field in Lower Limpopo Basin: Strategy 5 for the smallholder maize field in Lower Limpopo basin is illustrated in Fig. 3.16(b). Implementation of regulated transpiraton deficit at the winter wheat field in Tadla basin requires daily monitoring of the crop transpiration rate which is obtained with flying sensors. Sub surface irrigation water is applied with management of the ground water table. Vertical ground water flux at the bottom of the simulated soil profile is calibrated according to the criterion of relative transpiration T_rel of 75% throughout the growing season. The result is visualized in Fig. **??** and Fig. 3.15(h).

3.3.6. Strategy 6: Transpiration Optimum

Interviewed farmers suggested that crops should not experience water shortage. In the current research this is interpreted as a strategy to optimize transpiration. When crops do not experience stress, actual crop transpiration can be equal to potential crop transpiration and relative transpiration being actual / potential transpiration is 1. The transpiration optimum can be regulated such that the relative transpiration is 100%.

Transpiration optimum at the winter wheat field in Tadla Basin: Strategy 6 for the winter wheat field in Tadla basin is illustrated in Fig. 3.16(c). Implementation of regulated transpiraton optimum at the winter wheat field in Tadla basin requires daily monitoring of the crop transpiration rate which is obtained with flying sensors. A sprinkler installation is used for irrigation. Irrigation timing and depth is determined from the criterion that the relative transpiration is 100% throughout the growing season, which is a setting in SWAP.

Transpiration optimum at the maize field in Lower Limpopo Basin: Strategy 6 for the smallholder maize field in Lower Limpopo basin is illustrated in Fig. 3.16(d). Implementation of regulated transpiraton optimum at the winter wheat field in Tadla basin requires daily monitoring of the crop transpiration rate which is obtained with flying sensors. Sub surface irrigation water is applied with management of the ground water table. Vertical ground water flux at the bottom of the simulated soil profile is calibrated according to the criterion of relative transpiration $T_r el$ of 100% throughout the growing season. The result is visualized in Fig. **??** and Fig. 3.15(i).

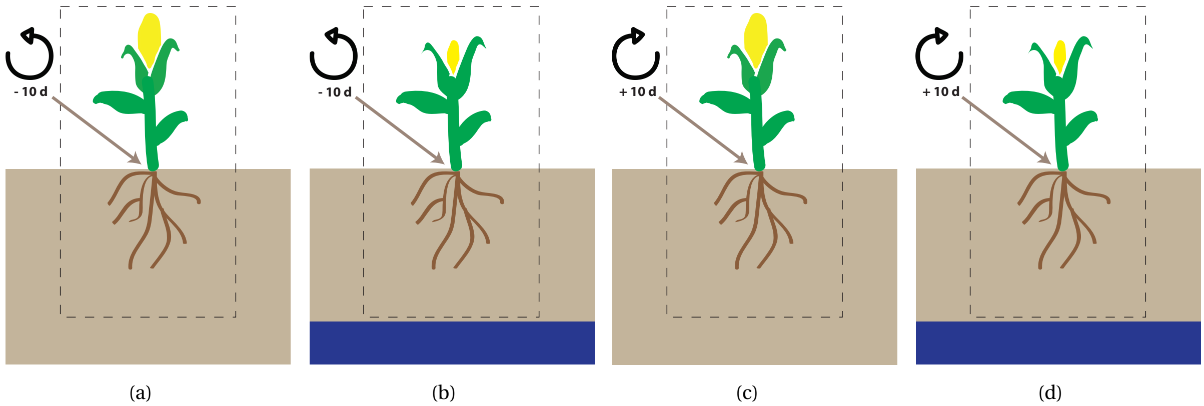


Fig. 3.17: Strategies 7 and 8 illustrated. (a) Strategy 7 at winter wheat field in Tadla Basin: advancing sowing date. (b) Strategy 7 at smallholder maize field in Lower Limpopo Basin: advancing sowing date. (c) Strategy 8 at winter wheat field in Tadla Basin: postponing sowing date. (d) Strategy 8 at smallholder maize field in Lower Limpopo Basin: postponing sowing date.

3.3.7. Strategy 7: Sowing Date Advance

Change of sowing date is mentioned by key actors companies and research institutes in the Netherlands. In this research the sowing date is advanced with 10 days for both the simulated agricultural fields.

Sowing date advanced at the winter wheat field in Tadla Basin: Strategy 7 for the winter wheat field in Tadla basin is illustrated in Fig. 3.17(a). Advancing the sowing date at the simulated wheat field in Tadla basin means that the date of crop emergence is November 18th 2015.

Sowing date advanced at the maize field in Lower Limpopo Basin: Strategy 7 for the smallholder maize field in Lower Limpopo basin is illustrated in Fig. 3.17(b). Advancing the sowing date at the simulated maize field in Lower Limpopo basin means that the date of crop emergence is April 8th 2016.

3.3.8. Strategy 8: Sowing Date Postpone

Change of sowing date is mentioned by key actors companies and research institutes in the Netherlands. In this research the sowing date is postponed with 10 days for both the simulated agricultural fields.

Sowing date postponed at the winter wheat field in Tadla Basin: Strategy 8 for the winter wheat field in Tadla basin is illustrated in Fig. 3.17(c). Postponing the sowing date at the simulated wheat field in Tadla basin means that the date of crop emergence is December 9th 2015.

Sowing date postponed at the maize field in Lower Limpopo Basin: Strategy 8 for the smallholder maize field in Lower Limpopo basin is illustrated in Fig. 3.17(d). Postponing the sowing date at the simulated maize field in Lower Limpopo basin means that the date of crop emergence is April 28th 2016.

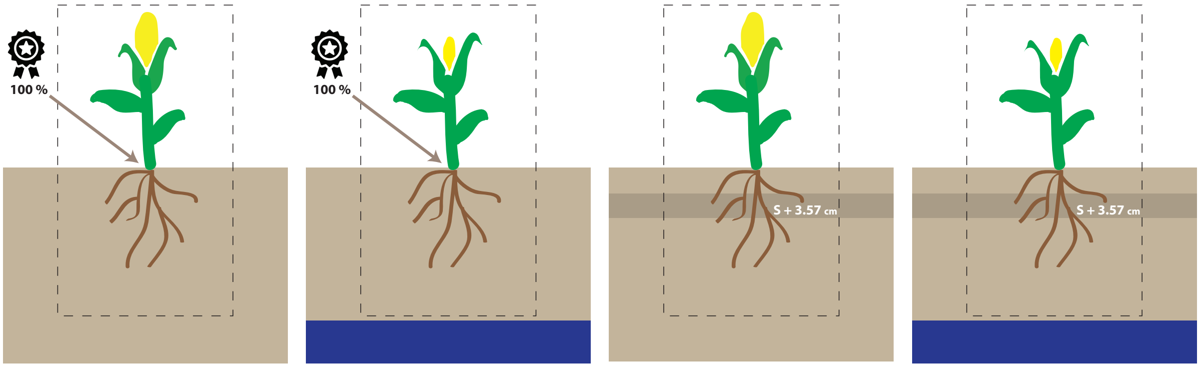


Fig. 3.18: Strategies 9 and 10 illustrated. (a) Strategy 9 at winter wheat field in Tadla Basin: optimal seed quality. (b) Strategy 9 at smallholder maize field in Lower Limpopo Basin: optimal seed quality. (c) Strategy 10 at winter wheat field in Tadla Basin: increase of soil water retention capacity. (d) Strategy 10 at smallholder maize field in Lower Limpopo Basin: increase of soil water retention capacity.

3.3.9. Strategy 9: Seed Quality Optimum

The strategy to change from the currently used seed to a seed with optimum quality is suggested both by interviewed farmers and key actors from Dutch companies and research institutes. Crop types have different varieties and qualities. Use of seed with optimal quality for a crop type represents a crop variety with optimal crop characteristics. This involves leave light extinction and use efficiency, development of leaf area, CO2 assimilation, efficiency of conversion of assimilates into biomass and partitioning of biomass over the crop elements. Optimal characteristics are selected from prior research.

Seed quality optimum at the winter wheat field in Tadla Basin: Strategy 9 for the winter wheat field in Tadla basin is illustrated in Fig. 3.18(a). Optimizing the seed quality for the simulated wheat field in Tadla basin means that for the mentioned crop characteristics, parameters are used from the WOFOST calibrated input file for winter wheat in Southern Spain and Southern Greece (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014).

Seed quality optimum at the maize field in Lower Limpopo Basin: Strategy 9 for the smallholder maize field in Lower Limpopo basin is illustrated in Fig. 3.18(b). Optimizing the seed quality for the simulated maize field in Lower Limpopo basin means that for the mentioned crop characteristics, parameters are used from the calibrated input file for maize by Van Heemst included in the WOFOST 7.1.7 calibrated input files (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014).

3.3.10. Strategy 10: Soil Water Retention Increase

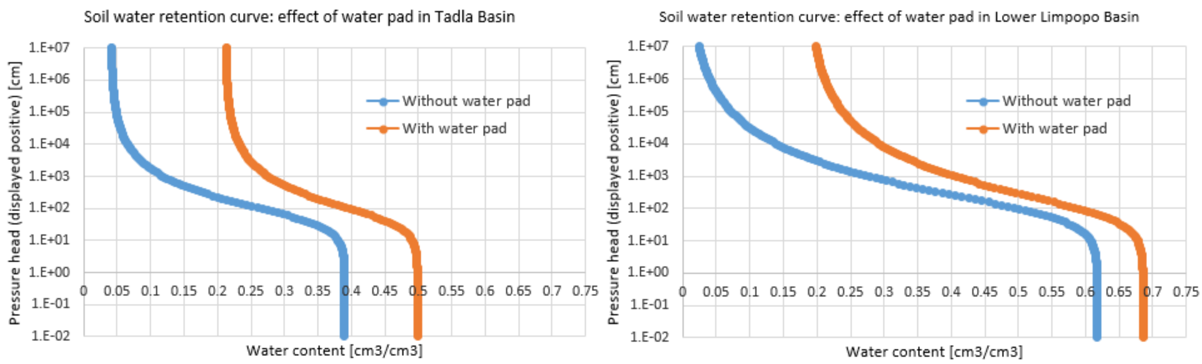
An increase of the soil water retention capacity was suggested by key actors from Dutch companies and research institutes. Increasing the capacity of the soil to retain water against percolation downward or evaporation upward can be realized in the field by installation of polymere waterpads into the soil. These pads are biodegradable and contribute in soil retention capacity for 3 years. The pads contain polymers in between a sandwich of hessian and paper, 1 gram of polymers absorb and buffers 1 liter water. Results from research in agriculture using water pads is reported by (Chevalking, 2017). In Ufra Turkey April 2017, research indicated that the distribution of polymers obtaining the best results is 250 g polymers per m^2. This layer of polymers can contain a 3.57 cm water depth. With the installation of this water pad layer at 20 cm depth from top soil, the saturated water content and residual water content of the surrounding soil from 10 to 30 cm depth from top soil is changed according to the following equation:

$$\theta_{new} = \frac{16.43 * theta_{old} + 3.57 * 1}{20} \tag{3.29}$$

Where θ is either the saturated or residual water content in $cm^3\ cm^{-3}$. In Fig. 3.19 soil retention curves are visualized for the root zone of the observed fields, both with and without the water pad.

Soil water retention increase at the winter wheat field in Tadla Basin: Strategy 10 for the winter wheat field in Tadla basin is illustrated in Fig. 3.18(c).For an increase in soil water retention capacity, a water pad layer is installed. This changes the saturated water content and residual water content of the 20 cm surrounding soil layer. In the baseline scenario this layer has a residual water content of 0.041 and a saturated water content of 0.390 $cm^3\ cm^{-3}$. According to the above equation, the new residual and saturated water content of the soil layer effected by the water pad are 0.2122 respectively 0.4989 $cm^3\ cm^{-3}$. In Fig. 3.19(a) the effect of the water pad for the soil root zone is visualized with soil water retention curves.

Soil water retention increase at the maize field in Lower Limpopo Basin: Strategy 10 for the smallholder maize field in Lower Limpopo basin is illustrated in Fig. 3.18(d). For an increase in soil water retention capacity, a water pad layer is installed. This changes the saturated water content and residual water content of the 20 cm surrounding soil layer. In the baseline scenario this layer has a residual water content of 0.010 and a saturated water content of 0.6858 $cm^3\ cm^{-3}$. According to the above equation, the new residual and saturated water content of the soil layer effected by the water pad are 0.1867 respectively 0.6858 $cm^3\ cm^{-3}$. In Fig. 3.19(b) the effect of the water pad for the soil root zone is visualized with soil water retention curves.



(a) (b)

```
* WINTER WHEAT BASELINE
ISOILLAY1  ORES    OSAT    ALFA    NPAR    KSAT   LEXP  ALFAW  H_ENPR  KSATEXM
    1     0.0410  0.4200  0.0200  1.5000  50.00   1.5   0.025  -40.00   50.0
    2     0.0410  0.3900  0.0700  1.0300  15.00   1.5   0.040  -14.29   15.0
*
* WINTER WHEAT STRATEGY 10
ISOILLAY1  ORES    OSAT    ALFA    NPAR    KSAT   LEXP  ALFAW  H_ENPR  KSATEXM
    1     0.0410  0.4200  0.0200  1.5000  50.00   1.5   0.025  -40.00   50.0
    2     0.2122  0.5235  0.0200  1.5000  50.00   1.5   0.025  -40.00   50.0
    3     0.0410  0.3900  0.0700  1.0300  15.00   1.5   0.040  -14.29   15.0
```

(c)

```
* SMALLHOLDER MAIZE BASELINE
ISOILLAY1  ORES    OSAT    ALFA    NPAR    KSAT   LEXP  ALFAW  H_ENPR  KSATEXM
    1     0.0100  0.6176  0.0136  1.3155  19.01  -2.13  0.0136 -40.00   19.01
    3     0.0000  0.5700  0.0194  1.0890   4.37  -5.96  0.0194 -40.00    4.37
*
* SMALLHOLDER MAIZE STRATEGY 10
ISOILLAY1  ORES    OSAT    ALFA    NPAR    KSAT   LEXP  ALFAW  H_ENPR  KSATEXM
    1     0.0100  0.6176  0.0136  1.3155  19.01  -2.13  0.0136 -40.00   19.01
    2     0.1867  0.6858  0.0136  1.3155  19.01  -2.13  0.0136 -40.00   19.01
    3     0.0000  0.5700  0.0194  1.0890   4.37  -5.96  0.0194 -40.00    4.37
```

(d)

Fig. 3.19: Increase of soil water retention capacity by water pad in the observed fields. Visualized soil retention curve and SWAP input values. (a) Soil water retention curves for soil with and without water pad at the winter wheat field in Tadla basin Morocco. (b) Soil water retention curves for soil with and without water pad at the smallholder maize field in Lower Limpopo basin Mozambique. (c) Soil hydraulic input parameters for winter wheat field in Tadla basin Morocco, for baseline and strategy 10 simulation. (d) Soil hydraulic input parameters for smallholder maize field in Lower Limpopo basin Mozambique, for baseline and strategy 10 simulation.

```
*WINTER WHEAT BASELINE
 SLATB  = DVS   SLA
          0.00 0.0047
          1.00 0.0009
 KDIF   = 0.72
 AMAXTB = DVS    AMAX
          0.39  13.000
          0.50  21.000
 CVS    = 0.7620
 RFSETB = DVS    RFSE
          0.00   1.00
          0.95   1.00
          1.05   0.80
          2.00   0.50
 FLTB =   DVS    FL
          0.00   0.65
          0.10   0.65
          0.25   0.70
          0.50   0.50
          0.70   0.25
          0.95   0.25
          1.05   0.25
          1.95   0.25
          2.00   0.25
 FSTB =   DVS    FS
          0.00   0.35
          0.10   0.35
          0.25   0.30
          0.50   0.50
          0.70   0.75
          0.95   0.75
          1.05   0.20
          1.95   0.00
 FOTB =   DVS    FO
          0.00   0.00
          0.95   0.00
          1.05   0.55
          1.95   0.75
          2.00   0.75
```

(a)

```
*WINTER WHEAT STRATEGY 9
 SLATB  = DVS   SLA
          0.00  0.00212
          2.00  0.00212
 KDIF   = 0.75
 AMAXTB = DVS    AMAX
          1.30   35.83
          2.00   4.48
 CVS    = 0.6620
 RFSETB = DVS    RFSE
          0.00   1.00!
          0.95   1.00!
          1.05   1.00!
          2.00   1.00!
 FLTB =   DVS    FL
          0.00   0.65
          0.10   0.65
          0.25   0.70
          0.50   0.50
          0.646  0.30
          0.950  0.00
          1.050  0.00
          1.950  0.00
          2.000  0.00
 FSTB =   DVS    FS
          0.00   0.35
          0.10   0.35
          0.25   0.30
          0.50   0.50
          0.646  0.70
          0.950  1.00
          1.000  0.00
          2.000  0.00
 FOTB =   DVS    FO
          0.00   0.00
          0.95   0.00
          1.00   1.00
          1.95   1.00
          2.00   1.00
```

(b)

```
*MAIZE BASELINE SCENARIO
 SLATB  =  DVS   SLA
           0.00  0.00240
           0.10  0.00140
           1.00  0.00140
 KDIF   =  0.05
 EFF    =  0.05
 AMAXTB = DVS    AMAX
           0.00 76.000
           1.00 35.000
           1.75 10.000
           2.00 10.000
 CVL    =  0.810
 CVO    =  0.600
 CVR    =  0.920
 CVS    =  0.790
 FRTB   =  DVS    FR
           0.00   0.40
           0.10   0.37
           0.20   0.34
           0.30   0.31
           0.40   0.27
           0.50   0.23
           0.60   0.19
           0.70   0.15
           0.80   0.10
           0.90   0.06
           1.00   0.00
           2.00   0.00
 FLTB   =  DVS    FL
           0.00   0.70
           0.33   0.70
           0.88   0.15
           0.95   0.10
           1.05   0.10
           2.00   0.10
  FSTB  =  DVS    FS
           0.00   0.30
           0.33   0.30
           0.88   0.85
           0.95   0.90
           1.05   0.45
           2.00   0.35
  FOTB  =  DVS    FO
           0.00   0.00
           0.95   0.00
           1.05   0.45
           2.00   0.55
```

(c)

```
*MAIZE STRATEGY 9
 SLATB  =  DVS    SLA
           0.00   0.0035
           1.00   0.0016
           2.00   0.0016
 KDIF   =  0.60
 EFF    =  0.50
 AMAXTB = DVS     AMAX
           0.00    70.00
           1.25    70.00
           1.50    63.00
           1.75    49.00
           2.00     0.00
 CVL    =  0.720
 CVO    =  0.720
 CVR    =  0.720
 CVS    =  0.690
 FRTB   =  DVS     FR
           0.00   0.40
           1.10   0.00
           2.00   0.00
 FLTB   =  DVS     FL
           0.00    0.62
           0.48    0.62
           0.90    0.28
           1.25    0.00
           1.37    0.00
           2.00    0.00
 FSTB   =  DVS    FS
           0.00   0.38
           0.48   0.38
           0.90   0.72
           1.25   0.24
           1.37   0.00
           2.00   0.00
 FOTB   =  DVS    FO
           0.00   0.00
           0.48   0.00
           0.90   0.00
           1.25   0.76
           1.37   1.00
           2.00   1.00
```

(d)

Fig. 3.20: SWAP/WOFOST crop input parameters adjusted for optimal seed quality in strategy 9. (a) Calibrated baseline parameters for winter wheat field in Tadla basin Morocco 2015/2016. (b) Parameters for optimal seed quality for winter wheat field in Tadla basin Morocco 2015/2016, obtained from the WOFOST calibrated input file for winter wheat in Southern Spain and Southern Greece (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014). (c) Calibrated baseline parameters for smallholder maize field in Lower Limpopo basin Mozambique 2016. (d) Parameters for optimal seed quality for smallholder maize field in Lower Limpopo basin Mozambique 2016, obtained from calibrated input file for maize by Van Heemst included in the WOFOST 7.1.7 calibrated input files (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014).

3.4. Observed indicators to measure improvement of efficient water use at the agricultural field

Perceptions of the key actors and the observed fields are presented in previous paragraphs. A selection is made of indicators seen as most relevant in the current discussion of efficient water use at the agricultural field. The actual fields are simulated in the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST), calibrated against data from the Surface Energy Balance Algorithm for Land model (SEBAL), resulting in a simulated baseline scenario for each field. Application of a strategy generates a simulated strategy scenario. From the output of a baseline or strategy scenario, efficient water use is quantified using an indicator. The difference between this indicator for the baseline scenario and for a strategy scenario is the improvement of efficient water use from a strategy, according to an indicator.
In the current paragraph, each of the used indicators is presented. The method for quantification is described in Paragraph 2.6. In Fig. 3.21 the observed system for both fields is visualized. Observing the spatial scale of a single agricultural field and the temporal scale of single growing season and limited to the output of SWAP/WOFOST, adjustments are made to the indicators suggested by the key actors in Paragraph 3.1. The adjustments are described in Paragraph 2.6 are the following:

- $\sum W_i = \sum A_i = \sum I$
- $\sum U_C = \sum ET_{act}$
- $\sum U_{crop,C} = \sum U_B = \sum U_{BC} = \sum T_{act}$
- $Output_i = Output - Output_{rf}$

Distribution losses between water withdrawal and water application at the field are not observed, volume or depth of water withdrawn $\sum W_i$ is equal to the volume or depth of water applied $\sum A_i$. For both the irrigation water depth or volume $\sum I$ is used. For $\sum U_C$ $[m^3]$ which is the volume of water consumed, actual evapotranspiration ET_{act} from the simulated crop is used. This means that ET_{act} other than from the simulated crop and also the crop moisture content θ_{crop} is neglected. The water volumes or depths for crop consumption $\sum U_{C,crop}$, beneficial use $\sum U_B$ and beneficial consumption $\sum U_{BC}$ are assumed to be equal to the actual transpiration $\sum T_{act}$. Also here the crop moisture content θ_{crop} is neglected and it is assumed that salt leaching is not necessary. For quantification of an output or effect of irrigation water $Output_i$ specifically, the output of the natural present water obtained by simulation of the rain fed scenario $Output_{rf}$ is subtracted from the output of the simulated baseline scenario $Output$. For convenience the $\sum$ symbol is discarded in the rest of this chapter.

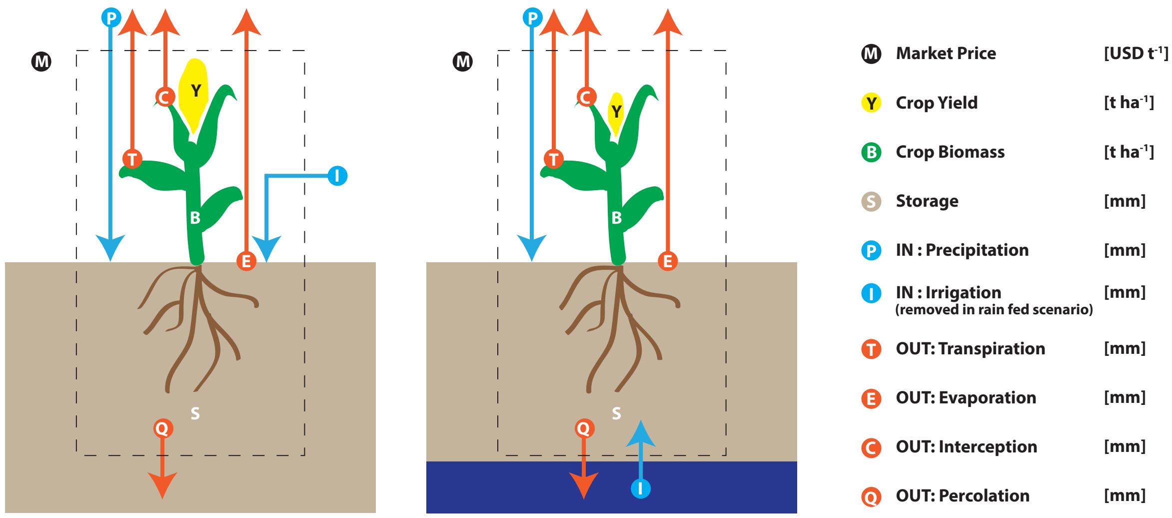


Fig. 3.21: Visualization of the observed system (within dotted lines) simulated in SWAP/WOFOST, representing a single field for a single growing season. Arrows indicate the incoming and outgoing seasonal fluxes. These quantities of agricultural performance and water use are output values from the simulation.

3.4.1. Indicator 1: Water Use Efficiency from SDG indicator 6.4.1

Indicator 1 represents the equation for water use efficiency for irrigated agriculture used in Sustainable Development Goal (SDG) indicator 6.4.1, presented in eq (3.1). It corresponds to a conceptual definition of water productivity from the Food and Agriculture Organization (FAO) presented in eq (3.11). Assumptions for computation of this indicator from SWAP/WOFOST output are visualized in Fig. 3.22(a) and defined in the following equation:

$$Indicator_1 = \frac{GVA}{W_i} = \frac{Y*M}{10*I} \; [USD\ m^{-3}] \tag{3.30}$$

Instead of water volume withdrawn for irrigation W_i $[m^3\ ha^{-1}]$, seasonal depth of irrigation water applied I $[mm]$ is used. GVA $[USD]$ is the Gross Value Added (GVA) of the produced crop, equal to the product of the seasonal yield Y $[t\ ha^{-1}]$ and market price M $[USD\ t^{-1}]$. The factor 10 in the denominator is included for the change of $mm\ ha^{-1}$ to m^3. Without the market price, this indicator is equal to the eighth indicator presented in eq (3.4.8). Since yield is related to actual biomass production B_{act} through the crop water content θ_{crop} and the Harvest Index (HI), the first indicator is expected to relate to the sixth indicator presented in eq (3.4.6).

3.4.2. Indicator 2: Water Use Efficiency from SDG indicator 6.4.1 adjusted

Indicator 2 represents the equation for water use efficiency used in SDG indicator 6.4.1 with changes proposed by water experts from Proof of Concept (PoC) countries, presented in eq (3.24). This indicator represents the yield from irrigation water per consumed irrigation water. Assumptions are made in order to compute this indicator from SWAP/WOFOST output, visualized in Fig. 3.24(a) and defined in the following equation:

$$Indicator_2 = \frac{Y_i}{U_{C,\,i}} = \frac{Y_i}{10*ET_{act,\,i}} = \frac{Y-Y_{rf}}{10*(ET_{act}-ET_{act,\,rf})} \; [t\ m^{-3}] \tag{3.31}$$

For the volume of irrigation water consumed $[m^3\ ha^{-1}]$, actual evapotranspiration from irrigation water $ET_{act,\,i}$ $[mm]$ is used. To quantify the specific outputs from irrigation water, the values from the rain fed scenario Y_{rf} $[t\ ha^{-1}]$ and $ET_{act,\,rf}$ $[mm]$ are subtracted from the values from the observed baseline or strategy scenario Y $[t\ ha^{-1}]$ and ET_{act} $[mm]$. The factor 10 in the denominator is included for the change of $mm\ ha^{-1}$ to m^3. Two important differences are observed between this second indicator and tenth indicator presented in 3.4.10. In the second indicator only the output of the irrigation water is observed, natural water is not incorporated. Additionally, in this second indicator only depletion by evapotranspiration ET_{act} is observed, other depletions are not incorporated.

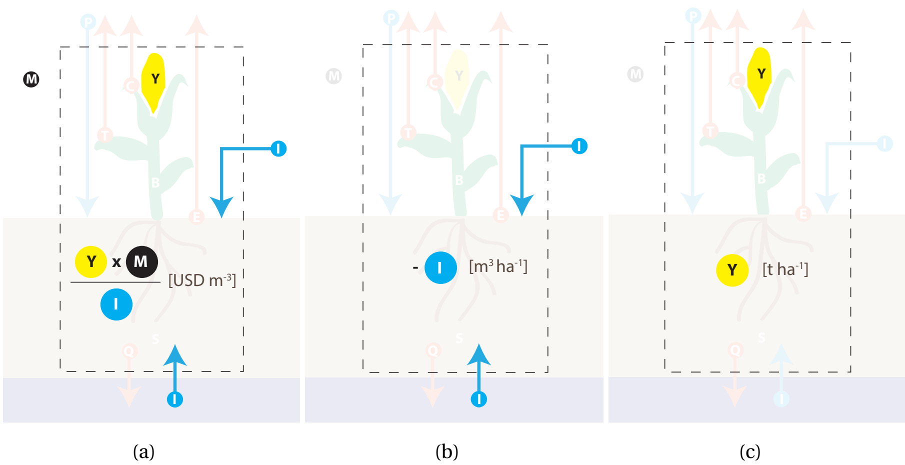


Fig. 3.22: Indicators expressed in units other than seasonal $t\ m^{-3}$, visualized as computed in SWAP/WOFOST. Conversion factors not included. No subscript indicates actual values. Irrigation (I) is applied either on the surface or trough bottom flux, both are visualized. (a) 1: Water Use Efficiency from SDG indicator 6.4.1 (b) Indicator 12: Water Saving. (c) Indicator 13: Agricultural yield.

3.4.3. Indicator 3: Irrigation Efficiency from 1932

The third indicator represents the historical equation for irrigation efficiency from Israelsen (1950), presented in eq (3.16). Because of the made assumptions, the equation represents the amount of irrigation water consumed through transpiration per applied irrigation water. The indicator also represents a general definition for irrigation efficiency from the FAO presented in eq (3.7). Assumptions are made in order to compute this indicator from SWAP/WOFOST output. This is visualized in Fig. 3.23(a) and defined in the following equation:

$$Indicator_3 = \frac{T_{act,\,i}}{W_i} = \frac{T_{act} - T_{act,\,rf}}{I} \; [-] \tag{3.32}$$

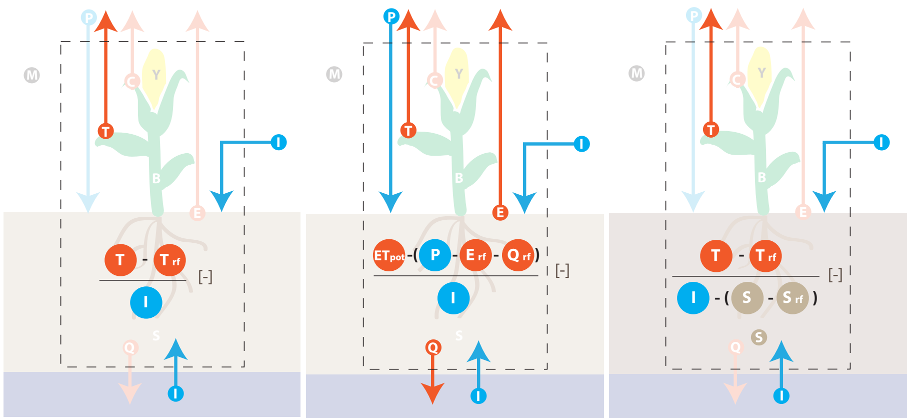
Instead of water volume withdrawn for irrigation W_i $[m^3\ ha^{-1}]$, irrigation water depth I $[mm]$ is used. $T_{act,\,i}$ $[m^3\ ha^{-1}]$ is the seasonal transpiration water depth from irrigation specifically. To obtain this value for a baseline or strategy scenario, the seasonal transpiration water depth for the rain fed scenario $T_{act,\,rf}$ $[mm]$ is subtracted from the value from the observed baseline or strategy scenario T_{act} $[mm]$. Conversion factors are not required in the equation. This third indicator is related to the seventh indicator presented in eq (3.4.7), which is different because of the subtraction of the stored irrigation water from the denominator.

3.4.4. Indicator 4: Irrigation Efficiency from 1967

The fourth indicator is the application irrigation efficiency by Bos & Nugteren (1990), representing the relation between the quantity of water applied at the field and the crop water requirement to avoid water stress. This indicator also represents a definition of irrigation efficiency from the FAO presented in eq (3.8) where the Irrigation Water Requirement (IWR) is used. Assumptions are made in order to compute this indicator from SWAP/WOFOST output. This is visualized in Fig. 3.23(b) and defined in the following equation:

$$Indicator_4 = \frac{IWR}{A_i} = \frac{ET_{pot} - P_{eff}}{I} = \frac{ET_{pot} - (P_{act} - E_{act,\,rf} - Qh_{percolated,\,rf})}{I} \; [-] \tag{3.33}$$

The IWR = $[m^3\ ha^{-1}]$ or the crop water requirement to avoid water stress is defined as the potential evapotranspiration ET_{pot} $[mm]$ minus the effective precipitation water depth P_{eff} $[mm]$. For the water depth applied A_i $[[m^3\ ha^{-1}]$, irrigation water depth I $[mm]$ is used. P_{eff} is defined by Bos et al. (2009) as the part of the total actual precipitation water depth P_{act} $[mm]$ which is available in the rain fed scenario to meet the potential transpiration requirement through root water uptake. Not available for root uptake is the water depth evaporated from the soil $E_{act,\,rf}$ $[mm]$ or the vertical water flux depth percolated to the ground water $Qh_{percolated,\,rf}$ $[mm]$. These values are subtracted from P_{act} to obtain P_{eff}. Conversion factors are not required in the equation.



(a) (b) (c)

Fig. 3.23: Non dimensional seasonal indicators or efficiencies, visualized as computed in SWAP/WOFOST. No subscript indicates actual values. Irrigation (I) is applied either on the surface or trough bottom flux, both are visualized. (a) Indicator 3: Irrigation Efficiency from 1932. (b) Indicator 4: Irrigation Efficiency from 1967. (c) Indicator 7: Irrigation Efficiency from 1997.

3.4.5. Indicator 5: Net Biomass Water Productivity from FAO and DGIS

The fifth indicator is the Net Biomass Water Productivity used in the WaPOR database from the FAO. The equation is given in eq (3.3). This water productivity is also used by the Directorate-General for International Cooperation (DGIS) and presented in eq (3.15). This productivity represents the quantity of biomass production in relation to the actual transpiration. No distinction is made in consumption of irrigation or natural water. The indicator is computed directly from SWAP/WOFOST output. This is visualized in Fig. 3.24(b) and defined in the following equation:

$$Indicator_5 = \frac{B_{act}}{10 * T_{act}} \; [t\ m^{-3}] \qquad (3.34)$$

In this equation, B_{act} $[t\ ha^{-1}]$ is the seasonal above ground dry matter biomass production. T_act $[mm]$ is the actual transpiration water depth accumulated over the same growing season. The factor 10 in the denominator is included for the change of $mm\ ha^{-1}$ to m^3. Since yield is related to actual biomass production B_{act} through the crop water content θ_{crop} and the HI, the fifth indicator is expected to relate to the eleventh indicator presented in eq (3.4.11).

3.4.6. Indicator 6: Water Use Efficiency from FAO

The sixth indicator is an equation for water use efficiency defined by the FAO, also known as 'irrigation water-use efficiency' in eq (3.5). With the applied assumptions, the indicator represents the amount of biomass produced per amount of irrigation water applied. This indicator can also represent the conceptual definitions of water productivity by the FAO presented in eq (3.10) and (3.12). Assumptions are made in order to compute this indicator from SWAP/WOFOST output. This is visualized in Fig. 3.24(c) and defined in the following equation:

$$Indicator_6 = \frac{B_{act}}{A_i} = \frac{B_{act}}{10 * I} \; [t\ m^{-3}] \qquad (3.35)$$

Instead of water volume withdrawn for irrigation W_i $[m^3\ ha^{-1}]$, irrigation water depth I $[mm]$ is used. B_{act} $[t\ ha^{-1}]$ is the above ground dry matter biomass production accumulated over the growing season. The factor 10 in the denominator is included for the change of $mm\ ha^{-1}$ to m^3. Since yield is related to actual biomass production B_{act} through the crop water content θ_{crop} and the HI, the sixth indicator is expected to relate to the eighth indicator presented in eq (3.4.8).

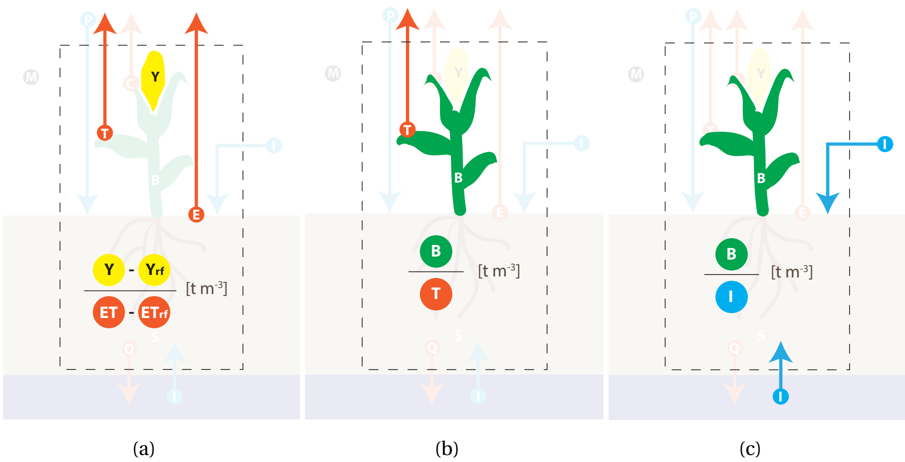


Fig. 3.24: Indicators expressed in seasonal $t\ m^{-3}$ or productivities, visualized as computed in SWAP/WOFOST. Conversion factors not included. No subscript indicates actual values. Irrigation (I) is applied either on the surface or trough bottom flux, both are visualized. (a) Indicator 2: Water Use Efficiency from SDG indicator 6.4.1 adjusted. (b) Indicator 5: Net Biomass Water Productivity from FAO and DGIS. (c) Indicator 6: Water Use Efficiency from FAO.

3.4.7. Indicator 7: Irrigation Efficiency from 1997

The seventh indicator represents the definition of irrigation efficiency by Burt et al. (1997) presented in eq (3.19), evaluating the beneficial use of the applied irrigation water that leaves the system, irrigation water remaining in the system is subtracted from the applied volume. Assumptions are made in order to compute this indicator from SWAP/WOFOST output. This is visualized in Fig. 3.23(c) and defined in the following equation:

$$Indicator_7 = \frac{U_{B,\,i}}{A_i - S_i} = \frac{T_{act,\,i}}{I - S_i} = \frac{T_{act} - T_{act,\,rf}}{I - (\Delta S - \Delta S_{rf})} \quad [-] \tag{3.36}$$

For irrigation water beneficially used $[m^3\ ha^{-1}]$, actual crop transpiration water depth from irrigation water $T_{act,\,i}$ $[mm]$ is applied. Instead of water depth withdrawn for irrigation W_i $[m^3\ ha^{-1}]$, irrigation water depth I $[mm]$ is used. ΔS_i $[mm]$ is the irrigation water stored in the system. The actual transpiration and storage of irrigation water $T_{act,\,i}$ and ΔS_i are obtained by subtraction of these values from the rain fed scenario $T_{act,\,rf}$ and ΔS_{rf} from these values in the simulated strategy or baseline scenario T_{act} and ΔS. ΔS $[mm]$ is equal to the sum of all the seasonal incoming fluxes water depths minus the sum of all the seasonal outgoing fluxes water depths. Conversion factors are not required in the equation. Without subtraction of stored irrigation water, this seventh indicator is equal to the third indicator presented in eq (3.4.3).

3.4.8. Indicator 8: Irrigation Water Productivity from 1997

The eighth indicator is the irrigation water productivity by Molden (1997), presented in eq (3.20). This indicator represents the productivity of irrigation water, where the produced good is the crop yield. This indicator also represents a definition from the FAO for water use efficiency, presented in eq (3.6). This eighth indicator can also represent the conceptual definitions of water productivity from the FAO presented in eq (3.10) and (3.12). The indicator is computed directly from SWAP/WOFOST output. This is visualized in Fig. 3.25(a) and defined in the following equation:

$$Indicator_8 = \frac{Y}{10 * I} \quad [t\ m^{-3}] \tag{3.37}$$

In this equation, Y $[t\ ha^{-1}]$ is the agricultural yield accumulated over the growing season. I $[mm]$ is the irrigation water depth applied during the growing season. The factor 10 in the denominator is included for the change of $mm\ ha^{-1}$ to m^3. This eighth indicator can be compared with the first indicator presented in eq (3.4.1) where with the market price the GVA is computed. Since yield can be computed from actual biomass production B_{act} using the crop water content θ_{crop} and the HI, the eighth indicator is expected to be related to the sixth indicator presented in eq (3.4.6).

3.4.9. Indicator 9: Inflow Water Productivity from 1997

The ninth indicator is the inflow water productivity by Molden (1997) presented in eq (3.21). This is the productivity of the inflow water depth. The produced good is the crop yield. This indicator can represent the conceptual definitions of water productivity from the FAO presented in eq (3.10) and (3.12). Assumptions are made in order to compute this indicator from SWAP/WOFOST output. This is visualized in Fig. 3.25(b) and defined in the following equation:

$$Indicator_9 = \frac{Y}{Q_{in}} = \frac{Y}{10 * (I + P_{act})} \quad [t\ m^{-3}] \tag{3.38}$$

In this equation, Y $[t\ ha^{-1}]$ is the agricultural yield accumulated over the growing season. Q_{in} $[m^3\ ha^{-1}]$ is the inflow water volume into the system which typically contains fluxes of irrigation water, precipitation, run on, infiltration and seepage from the ground water. In the observed systems indicated in Fig. 3.21 the observed incoming fluxes are the irrigation water depth applied during the growing season I $[mm]$ and the totally received actual precipitation depth P_{act} $[mm]$ during the same period. The factor 10 in the denominator is included for the change of $mm\ ha^{-1}$ to m^3.

3.4.10. Indicator 10: Depleted Water Productivity from 1997

The tenth indicator is the depleted water productivity by Molden (1997), presented in eq (3.22). This is the productivity of depleted water depth. The produced good is the crop yield. This indicator can represent the conceptual definitions of water productivity from the FAO presented in eq (3.10) and (3.12). Assumptions are made in order to compute this indicator from SWAP/WOFOST output. This is visualized in Fig. 3.25(c) and defined in the following equation:

$$Indicator_{10} = \frac{Y}{Q_{out}} = \frac{Y}{10*(ET_{act}+C_{act}+Qh_{percolated})} \quad [t\ m^{-3}] \tag{3.39}$$

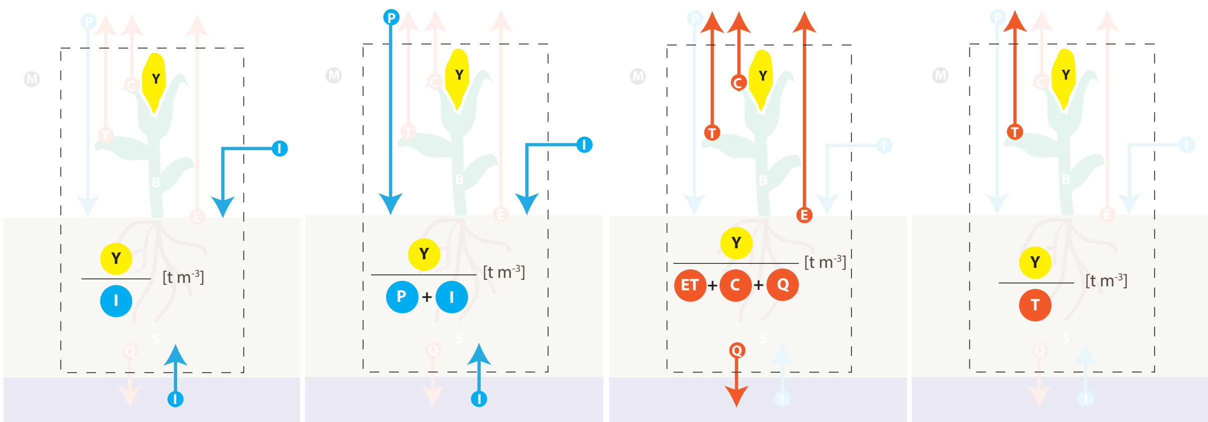
In this equation, Y $[t\ ha^{-1}]$ is the agricultural yield accumulated over the growing season. Q_{out} $[m^3\ ha^{-1}]$ is the depleted water volume from the system which typically contains fluxes of evapotranspiration, interception, run-off, drainage and percolation to the ground water. In the observed systems indicated in Fig. 3.21 the observed depleted fluxes include the actual evapotranspiration water depth ET_{act} $[mm]$, the actual interception water depth C_{act} $[mm]$ and the water depth of the vertical flux percolated to the ground water $Qh_{percolated}$ $[mm]$. The factor 10 in the denominator is included for the change of $mm\ ha^{-1}$ to m^3.

3.4.11. Indicator 11: Process Depleted Water Productivity from 1997

The eleventh indicator is the process depleted water productivity by Molden (1997) presented in eq (3.23). This is the productivity of the process depleted water depth. The produced good is the crop yield. This indicator can represent the conceptual definitions of water productivity from the FAO presented in eq (3.10) and (3.12). The indicator is computed directly from SWAP/WOFOST output. This is visualized in Fig. 3.25(d) and defined in the following equation:

$$Indicator_{11} = \frac{Y}{10*T_{act}} \quad [t\ m^{-3}] \tag{3.40}$$

In this equation, Y $[t\ ha^{-1}]$ is the agricultural yield accumulated over the growing season. The process depleted water in the observed system is the seasonal actual crop transpiration water depth T_{act} $[mm]$. The factor 10 in the denominator is included for the change of $mm\ ha^{-1}$ to m^3. Since yield is related to actual biomass production B_{act} through the crop water content θ_{crop} and the HI, the eleventh indicator is expected to relate to the fifth indicator presented in eq (3.4.5).



(a) (b) (c) (d)

Fig. 3.25: Indicators expressed in seasonal $t\ m^{-3}$ or productivities, visualized as computed in SWAP/WOFOST. Conversion factors not included. No subscript indicates actual values. Irrigation (I) is applied either on the surface or trough bottom flux, both are visualized. (a) Indicator 8: Irrigation Water Productivity from 1997. (b) Indicator 9: Inflow Water Productivity from 1997. (c) Indicator 10: Depleted Water Productivity from 1997. (d) Indicator 11: Process Depleted Water Productivity from 1997.

3.4.12. Indicator 12: Water Saving

The twelfth indicator represents the quantity of water saved which is frequently used as reported by key actors from Dutch companies and research institutes, see eq (3.25). The term water saving is also found at the FAO. Assumptions are made in order to compute this indicator from SWAP/WOFOST output. This is visualized in Fig. 3.22(b) and defined in the following equation:

$$Indicator_{12} \quad = \quad -W_i \quad = \quad -10 * I \quad [m^3\ ha_{-1}] \tag{3.41}$$

Instead of water volume withdrawn for irrigation W_i $[m^3\ ha_{-1}]$, seasonal irrigation water depth I $[mm]$ is used. The equation is negative since a decrease of irrigation water depth is desired. The factor 10 is included for the change of mm to $m^3\ ha^{-1}$. In this indicator a product from water use is not involved.

3.4.13. Indicator 13: Agricultural Yield

The thirteenth indicator is the agricultural yield, used by DGIS in monitoring of projects and mentioned by interviewed farmers to be a relevant indicator. This is presented in eq (3.13) and (**??**). The indicator is computed directly from SWAP/WOFOST output. This is visualized in Fig. 3.22(c) and defined in the following equation:

$$Indicator_{13} \quad = \quad Y \quad [t\ ha^{-1}] \tag{3.42}$$

In this indicator Y $[t\ ha^{-1}]$ is the agricultural yield accumulated over the growing season. Water use is not involved in this indicator.

4

Results

This research analyzes leading perceptions regarding efficient water use at the agricultural field. From key actors' perceptions (see Paragraph 3.1), a deduction an selection procedure resulted in 10 strategies to obtain improvement of efficient water use (see Paragraph 3.3) and 13 indicators to quantify improvement (see Paragraph 3.4). On two simulated actual fields for a single growing season (see Paragraph 3.2), the 10 strategies for improvement are implemented separately. Analysis is done using the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST), calibrated against the Surface Energy Balance Algorithm for Land model (SEBAL), as described in Chapter 2. Calibration results in a simulated baseline scenario representing an actual field during a growing season in the recent past. High accuracy of SEBAL data is demonstrated in prior research. Hence, a simulation is assumed to be a plausible representation of reality when in the simulation output a high level of similarity with the SEBAL data is observed. Strategy scenarios are obtained by adjustment of the baseline model input data and simulated for the same growing season, thus effects of climate variability are excluded. SWAP/WOFOST model output allows for the computation of indicators for efficient water use for both baseline and strategy scenarios. Thus, improvement of efficient water use from baseline to strategy scenario is quantified. The analyzed collection of strategies and indicators is presented to a group of key actors. Individual key actors evaluated the potential effectiveness of each strategy and the potential relevance of each indicator. For this frequency analysis of the support of perceptions by key actors, an on-line survey is used. The survey and a list of participants is included in Appendix K and L.

In this Chapter the results are presented, summarized in the list below. Paragraph 4.1 presents relevant observations in the calibration process and the computed reference evapotranspiration rate ET_{ref} by SEBAL and SWAP which has a fundamental position in both models. In the following Paragraphs 4.2 and 4.3, the calibration result both actual fields is presented. This demonstrates whether the simulated fields are plausible representations of actual fields. The calibrated input files for SWAP/WOFOST simulation of the observed fields' baseline scenarios are included in Appendix J. In Paragraph 4.4 values for efficient water use of the fields' baseline scenario are presented, according to the collection of indicators. This result quantifies the efficient water use at the two fields, before implementation of strategies for improvement. In Paragraph 4.5 values for improvement of efficient water use from the fields' baseline to strategy scenarios is presented, for which the same indicators are used and the strategy scenarios according to the collection of strategies. This is the desired simulation result, the quantification of improvement of efficient water use at the agricultural field. In Paragraph 4.6 the result of the evaluation of the different strategies and indicators by key actors is presented. This demonstrates the frequency distribution of support for the analyzed strategies and indicators. It has revealed for the observed key actor levels of involvement which strategies are seen as most effective and which indicators are seen as most relevant. This is compared with the simulation results.

Par. 4.1 Calibration setup and reference evapotranspiration rate ET_{ref}
Par. 4.2 Calibration result for winter wheat field in Tadla basin Morocco 2015/2016
Par. 4.3 Calibration result for smallholder maize field in Lower Limpopo basin Mozambique 2016
Par. 4.4 Efficient water use at the baseline scenarios
Par. 4.5 Improvement of efficient water use from baseline to strategy scenario
Par. 4.6 Evaluation of key actor levels compared to simulation results

4.1. Setup of SWAP/WOFOST calibration against SEBAL

Calibration of Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST) against Surface Energy Balance Algorithm for Land model (SEBAL) is obtained by first calibrating SWAP with the simple crop module according to a series of iteration steps presented in Table 2.2. This resulted in calibrated input parameters for salinity, soil characteristics and critical pressure heads. In both simulations, no salt stress is observed. These parameters are used as fixed input in the calibration of SWAP with the detailed crop module WOFOST, according to a series of iteration steps presented in Table 2.3. Representative initial input parameters are important in the process of calibration. Parameters are obtained from prior research:

For the winter wheat field in Tadla basin Morocco:

- SWAP main input example file for Hupsel area in the Netherlands (Kroes et al., 2009)
- WOFOST crop input file for winter wheat in the Netherlands (Boons-Prins et al., 1993)
- Simple module crop input file for wheat in the Netherlands (Boons-Prins et al., 1993)
- WOFOST crop input file for winter wheat WWH107 in southern Spain and central and southern Greece (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014)
- WOFOST crop input parameters for durum in Morocco (Pagani et al., 2013)
- Crop specific pressure heads from an on-farm study in Haryana India (Bastiaanssen et al., 1997)
- Spatial maps of HiHydroSoil data, modeled soil hydraulic parameters in Tadla basin (de Boer, 2016)
- Leaf Area Index (LAI) data from SEBAL analysis for the observed area and time span, for the simple crop module in SWAP.
- Meteorological input data from Global Land Data Assimilation System (GLDAS), precipitation data from Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS), see Paragraph 2.8.2.

For the smallholder maize field in Lower Limpopo basin Mozambique:

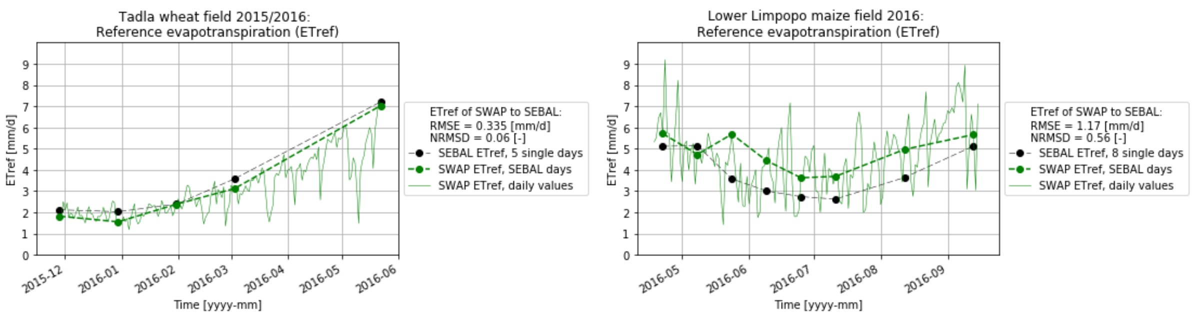
- SWAP main input example file for Hupsel area in the Netherlands (Kroes et al., 2009)
- WOFOST crop input file for maize in the Netherlands (Boons-Prins et al., 1993)
- Simple module crop input file for maize in the Netherlands (Boons-Prins et al., 1993)
- WOFOST crop input file for maize W41 (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014)
- WOFOST crop input parameters for maize in Zambia (Boogaard, Ceccaralli, Wijngaart, Imala, Patricio, Tauacale & Diop, 2014)
- Crop specific pressure heads from an on-farm study in Haryana India (Bastiaanssen et al., 1997)
- Soil hydraulic parameters from field experiments and literature, see Paragraph 3.2.2
- LAI data from SEBAL analysis for the observed area and time span, for the simple crop module in SWAP.
- Canal distances for lateral drainage simulation from visual inspection of Google Satellite images.
- Meteorological input data from GLDAS, precipitation from local station, see Paragraph 2.8.2.

In selection of parameters from prior research, site-specific and crop-specific parameters are taken into account. Some parameters are assumed representative for the observed field and not changed in calibration. Meteorological data is not adjusted. Some parameters are varied upon satisfactory model output or selected based on expert knowledge. In Appendix J the calibrated input files for both fields are presented. The files indicate for each parameter whether it is obtained from prior research or calibrated. In the following paragraphs 4.2 and 4.3 the calibration result for both fields is presented. This is provided with an overview of the parameters that are during calibration most significantly adjusted from their initial values.

4.1.1. Reference Evapotranspiration using Penman Monteith in SWAP and SEBAL

In both the SWAP and the SEBAL, the reference evapotranspiration rate ET_{ref} $[mm\ d^{-1}]$ has a significant role. As described in Chapter 2, both models compute ET_{ref} using Penman Monteith with daily meteorological data and the general Penman-Monteith equation known as the combination equation, standardized by the Food and Agriculture Organization (FAO) (Allen et al., 1998). In this equation the energy balance and the mass transfer method are combined. Using the combination equation, potential evapotranspiration can be calculated for a cropped surface using standard climatological records of sunshine, temperature, humidity and wind speed and crop resistance factors. With computation of ET_{ref} a fully covered grass surface is assumed. SWAP and SEBAL should generate the same output for ET_{ref}. When the level of similarity is low, it can be questioned whether calibration of SWAP against SEBAL is possible.

Values of ET_{ref} from SWAP and SEBAL for both simulated fields are visualized in Fig. 4.1. Both models generate the same trend in ET_{ref} along the growing season. Larger differences are observed for the field in Lower Limpopo basin, see Fig. 4.1(b). This suggests that more difficulty can be encountered in calibration of this field and that the resulting calibrated simulation might not exactly represent the actual field. In Paragraph 5.2 a discussion is provided on ET_{ref} computation in SWAP and SEBAL.



(a) (b)

Fig. 4.1: Reference Evapotranspiration assuming grass coverage, computed using the general combination equation from Penman Monteith. Output from SEBAL and SWAP for the observed growing season is presented for the two simulated fields. For each field, the Root Mean Square Error (RMSE) of SWAP to SEBAL is given. (a) Winter wheat field in Tadla Basin, Morocco 2015/2016 where 5 days of SEBAL analysis are observed. (b) Maize field in Lower Limoppo Basin, Mozambique 2016 where 8 days of SEBAL analysis are observed.

4.2. Calibrated Baseline simulation of General Winter Wheat field in Tadla Basin 2015/2016

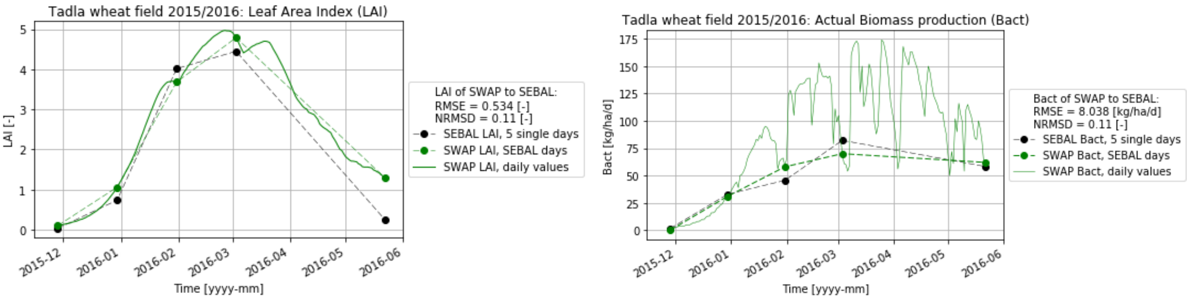
A general performing winter wheat field in Tadla Basin Morocco in 2015/2016 is simulated in the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST), calibrated against output from 5 days of Surface Energy Balance Algorithm for Land model (SEBAL) analysis. In this paragraph the calibration result for this winter wheat field is presented. The growing season is observed from crop emergence to crop harvest, respectively November 15^{th} 2015 to May 23^{rd} 2016. Length of growing season is 190 days, crop anthesis occurred at March 4^{th} 2016. The 5.5 ha field is located on the left bank of the Oum Er Rhiba river and is part of the large Beni Moussa irrigation system. A deep ground water table is observed and field irrigation is applied from a field inlet.

During the calibration process, initial parameters obtained from prior research are adjusted. The calibrated input parameters are presented in Appendix J. The files required for this simulation are the general .swp input file, the detailed .crp input file, and the .015 and .016 meteorological input files. From the calibration process can be observed that the surface irrigation application, soil characteristics and biomass partitioning is most characteristic compared to prior research.

Data on irrigation application is not available. According to the calibration, irrigation depths of 60 to 110 mm are applied, assuming 60 mm to be the minimum depth in surface irrigation. Soil hydraulic parameters are adjusted in the simple crop module simulation for saturated hydraulic conductivity and parameters alpha and n. Crop characteristics are adjusted within feasible ranges for winter wheat. A deep groundwater table is observed in the area, in the SWAP simulation free drainage is assumed at the bottom profile and no lateral drainage occurs. In general WOFOST calibrations, it is assumed that from anthesis to maturity all biomass is used for storage organs. This is adjusted in the current calibration where after anthesis a maximum of 75% of daily produced above ground dry matter biomass is partitioned to storage organs and in every stage of the growing cycle a minimum of 25% is partitioned to the leaves.

4.2.1. Winter Wheat Morocco: Leaf Area index and Biomass Production

In Fig. 4.2 the calibration result for the Leaf Area Index (LAI) and actual biomass production rate B_{act} $[t\ d^{-1}\ ha^{-1}]$ is visualized. These two characteristics are considered highly relevant aspects of crop performance. The LAI has a crucial role in the physical processed by which crop development is defined in WOFOST. Biomass and the closely related crop yield are important products from agriculture and have a crucial role in evaluation of field performance. Output from SEBAL and SWAP visualized in Fig. 4.2 shows large similarity with the results of the SEBAL analysis which indicates a successful calibration of SWAP/WOFOST against SEBAL. The five records of biomass production from SEBAL are relatively low compared to the daily values from SWAP/WOFOST. This is interesting since SEBAL records will correspond to clear sky conditions, where daily shortwave incoming radiation $R_{s,day}$ $[KJ\ m^{-2}]$ is expected to be relatively high. Since solar radiation enables biomass growth, it would be expected that B_{act} is relatively high on these days. As can be seen in Fig. 4.2(b) this is contrary to the prediction by SWAP/WOFOST. In development of LAI over the season a normal trend is observed. The maximum value of 5 is below what is normally observed for winter wheat.



(a) (b)

Fig. 4.2: Leaf Area index and Actual Biomass Production at the simulated winter wheat field in Tadla Basin, Morocco 2015/2016. Output from SEBAL and calibrated SWAP/WOFOST for the observed growing season is presented with the Root Mean Square Error (RMSE) of SWAP to SEBAL using 5 days of SEBAL analysis. Dates between November 15^{th} 2015 and May 23^{rd} 2016 are observed. (a) Leaf Area Index (LAI). (b) Actual Biomass Production B_{act}.

4.2.2. Winter Wheat Morocco: Crop Transpiration

In Fig. 4.3 the calibration result for crop transpiration is visualized. Decrease of relative transpiration T_{rel} or difference between potential transpiration T_{pot} and actual transpiration T_{act} is caused by reduction of transpiration from crop stress. In the simulated field stress from drought is observed. Crop transpiration is a relevant aspect of crop performance and agricultural water use. Output from SEBAL and SWAP visualized in Fig. 4.3 shows large similarity on the days of SEBAL analysis which indicates a successful calibration of SWAP/WOFOST against SEBAL. The last day of SEBAL analysis is an exception where the SWAP/WOFOST output largely exceeds the SEBAL output. Variability of both T_{pot} and T_{act} increases along the growing season. Daily variability is caused by daily meteorological circumstances. This is intensified along the season by increasing variability of transpiration reduction from dryness and the increase of the crop green area. The maximum transpiration rate exceeds 10 $mm\ d^{-1}$. In the second phase of the growing season from anthesis to maturity, an average transpiration rate of 5 $mm\ d^{-1}$ is observed. Except from the first two months, transpiration reduction because of dryness is observed throughout the season.

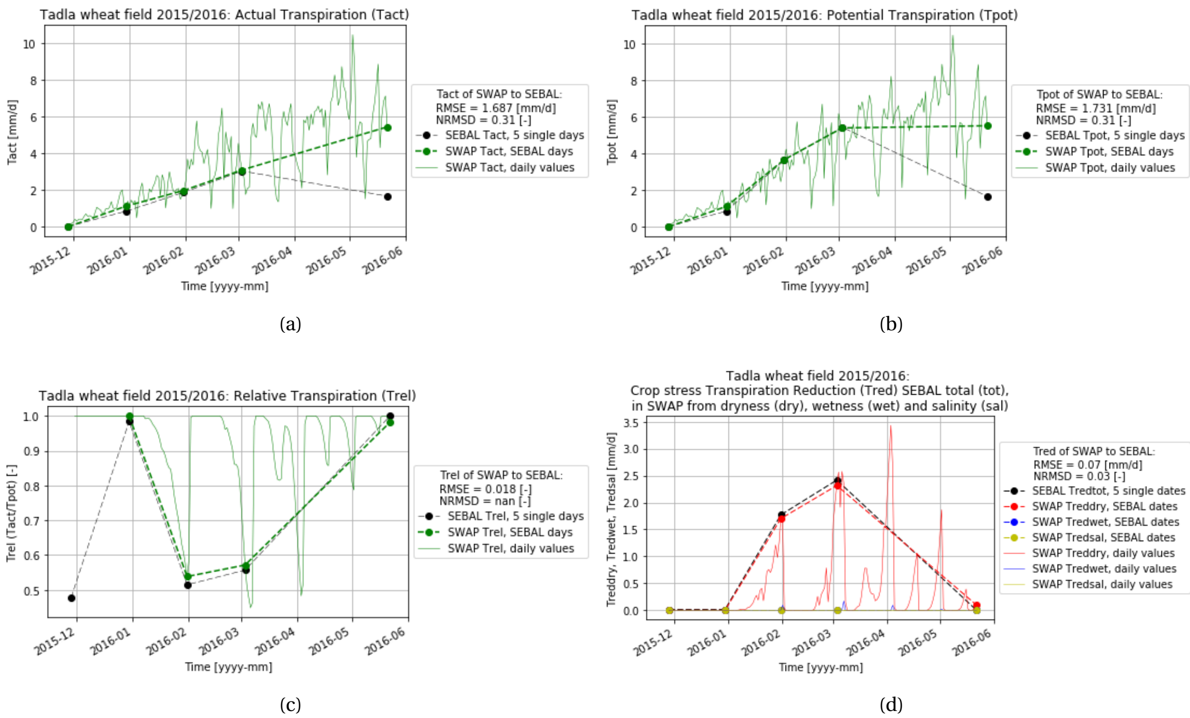
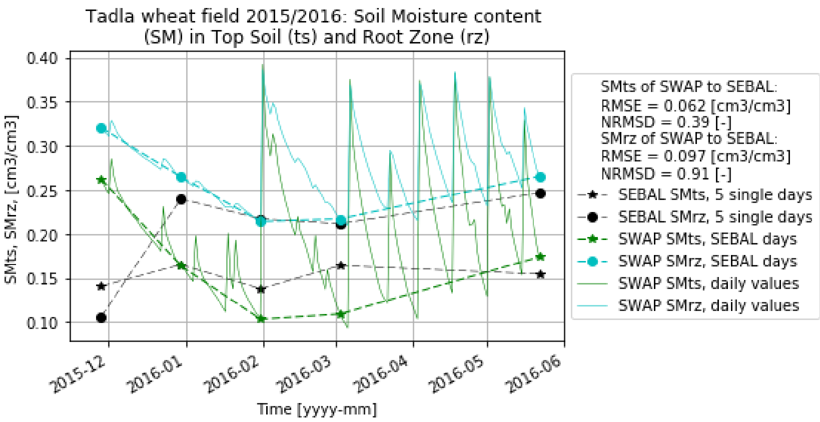


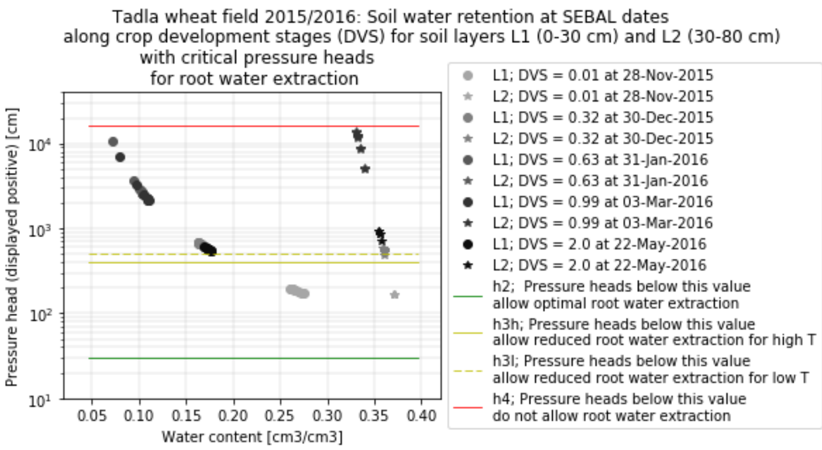
Fig. 4.3: Actual, Potential and Relative Transpiration and observed Transpiration Reduction at the simulated winter wheat field in Tadla Basin, Morocco 2015/2016. Output from SEBAL and calibrated SWAP/WOFOST for the observed growing season is presented with the Root Mean Square Error (RMSE) of SWAP to SEBAL using 5 days of SEBAL analysis. Dates between November 15^{th} 2015 and May 23^{rd} 2016 are observed. (a) Actual Transpiration T_{act}. (b) Potential Transpiration T_{pot}. (c) Relative Transpiration T_{rel}. (d) Transpiration Reduction T_{red} total and from drought, wetness and salinity.

4.2.3. Winter Wheat Morocco: Soil Moisture Content

In Fig. 4.4 the calibration result for soil moisture is visualized. In simulation of SWAP/WOFOST two soil layers are used as suggested by this initially used HiHydroSoil maps. The first layer is found from 0 to 30 cm soil depth. The second layer from 30 to 300 cm soil depth. In SEBAL, soil moisture content of top soil and root zone are generated. Top soil in SWAP/WOFOST is defined from the average over 0 to 5 cm depth, root zone in SWAP/WOFOST is defined from the average over 10 to 80 cm depth. The soil retention curves for the two soil layers and the critical pressure head h_2, $h_{3,low}$, $h_{3,high}$ and h_4 indicate when water is available for root water uptake. Output from SEBAL and SWAP visualized in Fig. 4.4(a) shows large similarity on the days of SEBAL analysis, especially for the root zone, which indicates a successful calibration of SWAP/WOFOST against SEBAL. The first day of SEBAL analysis is an exception where the SWAP/WOFOST output largely exceeds the SEBAL output. This deviation is expected to be due to initial conditions in SWAP, of which the simulation started at August 1^{st} 2015. In the root zone more wetness can be observed compared to the top soil. A low moisture content in the top soil prevents high evaporation rates. Apart from the first months, throughout the growing season low pressure heads are observed, reducing root water extraction rates. This corresponds with the reduction in transpiration observed in the previous section.



(a)



(b)

Fig. 4.4: Soil Moisture Content, Water Retention Capacity and Critical Pressure Heads at the simulated winter wheat field in Tadla Basin, Morocco 2015/2016. (a) Soil Moisture Content in both top soil SM_{ts} and root zone SM_{ts} from November 15^{th} 2015 to May 23^{rd} 2016. Output from SEBAL and calibrated SWAP/WOFOST for the observed growing season is presented with the Root Mean Square Error (RMSE) of SWAP to SEBAL using 5 days of SEBAL analysis. (b) Soil Water Retention Curve for two soil layers in SWAP/WOFOST simulation from November 15^{th} 2015 to May 23^{rd} 2016. Averages both soil layers at several dates along the growing season are visualized. Horizontal lines indicate critical pressure heads h_2, $h_{3,low}$, $h_{3,high}$ and h_4 for crop root water uptake.

4.2.4. Winter Wheat Morocco: Agricultural Yield

In Fig. 4.5 the calibration result for yield production is visualized. SWAP/WOFOST computes both $\sum B_{act}$ $[t\ ha^{-1}]$ and the total dry mass partitioned to storage organs $\sum B_{SO,act}$ $[t\ ha^{-1}]$. Actual yield can be computed from total biomass production $\sum B_{act}$ using the crop seed water content θ_{seed} and Harvest Index (HI) as presented in the equation below (FAO and DWFI, 2015).

$$Y = \frac{HI * \sum B_{act}}{(1-\theta_{seed})} \tag{4.1}$$

HI is the ratio between the mass of storage organs and the weight of total above ground crop. Yield can also be computed from $\sum B_{SO,act}$, using the crop seed water content θ_{seed}. Assuming $\theta_{seed} = 0.14$ and HI = 0.35 as presented in paragraph 3.2.1, yield values computed from total actual biomass $\sum B_{act}$ and from total mass of dry storage organs $\sum B_{SO,act}$ show large similarity. This indicates that that the partitioning of biomass to storage organs is successfully calibrated. From the calibrated SWAP/WOFOST simulation, harvested seasonal yield is 6.6 $t\ ha^{-1}$. This is relatively high for a general performing field, other research in Morocco reports 3.4 $t\ ha^{-1}$ (Goudriaan & Bastiaanssen, 2013).

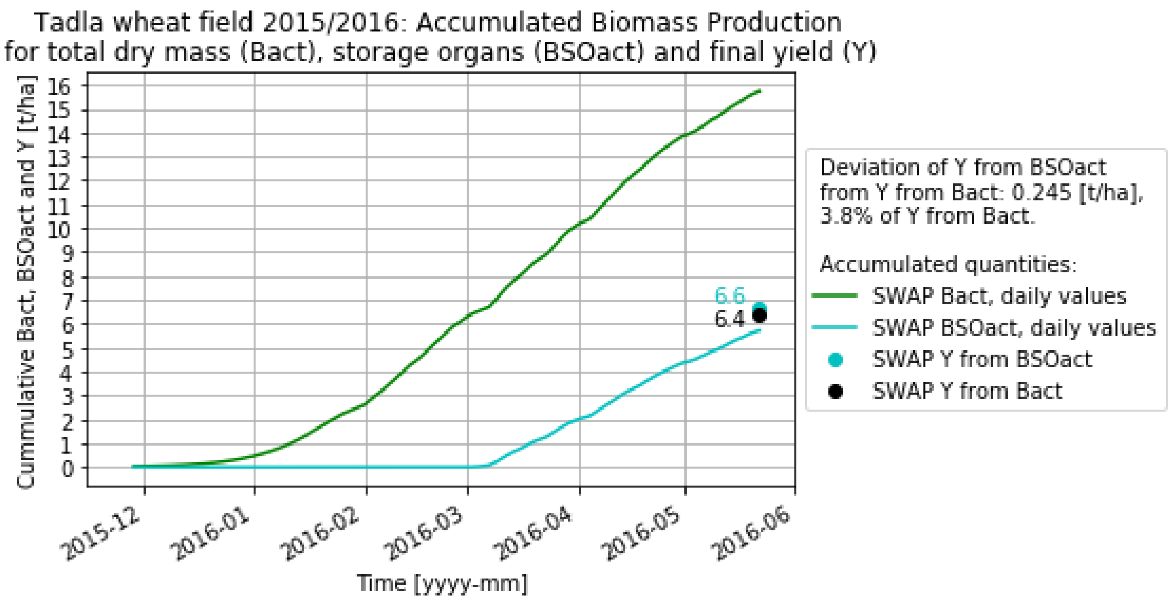


Fig. 4.5: Accumulated biomass and yield production at the simulated winter wheat field in Tadla Basin, Morocco 2015/2016. Accumulated dry mass B_{act} and dry mass of storage organs $B_{SO,act}$ is generated by SWAP. Actual total yield is computed directly with the crop seed water content θ_{seed} from $\sum B_{SO,act}$ and when computed from B_{act} additionally using the Harvest Index (HI). Total accumulated biomass and yield is defined at date of harvest, May 23rd 2016.

4.2.5. Winter Wheat Morocco: Water Balance

In Fig. 4.7 the water balance of the calibrated simulation of the winter wheat field in Tadla Basin Morocco 2015/2016 is visualized. It can be observed from Fig. 4.7(c) that no run on, infiltration, seepage, run off or drainage is observed. No observation of seepage corresponds with the deep ground water table. Lateral drainage is not simulated. The absence of horizontal flows of run on and run off can be explained with the relatively dry situation. The applied irrigation water depth of 570 mm equals over three times the amount of received precipitation depth (180 mm). Crop transpiration is the largest outgoing flux. A negative storage change is observed in the system, this value is close to the water depth that left the system by percolation to the ground water. In Fig. 4.6 the rounded quantities of the seasonal water balance and other elements of agricultural performance are visualized. These elements of the observed system are used in computation of indicators for efficient water use, presented in Paragraph 4.4 and **??**.

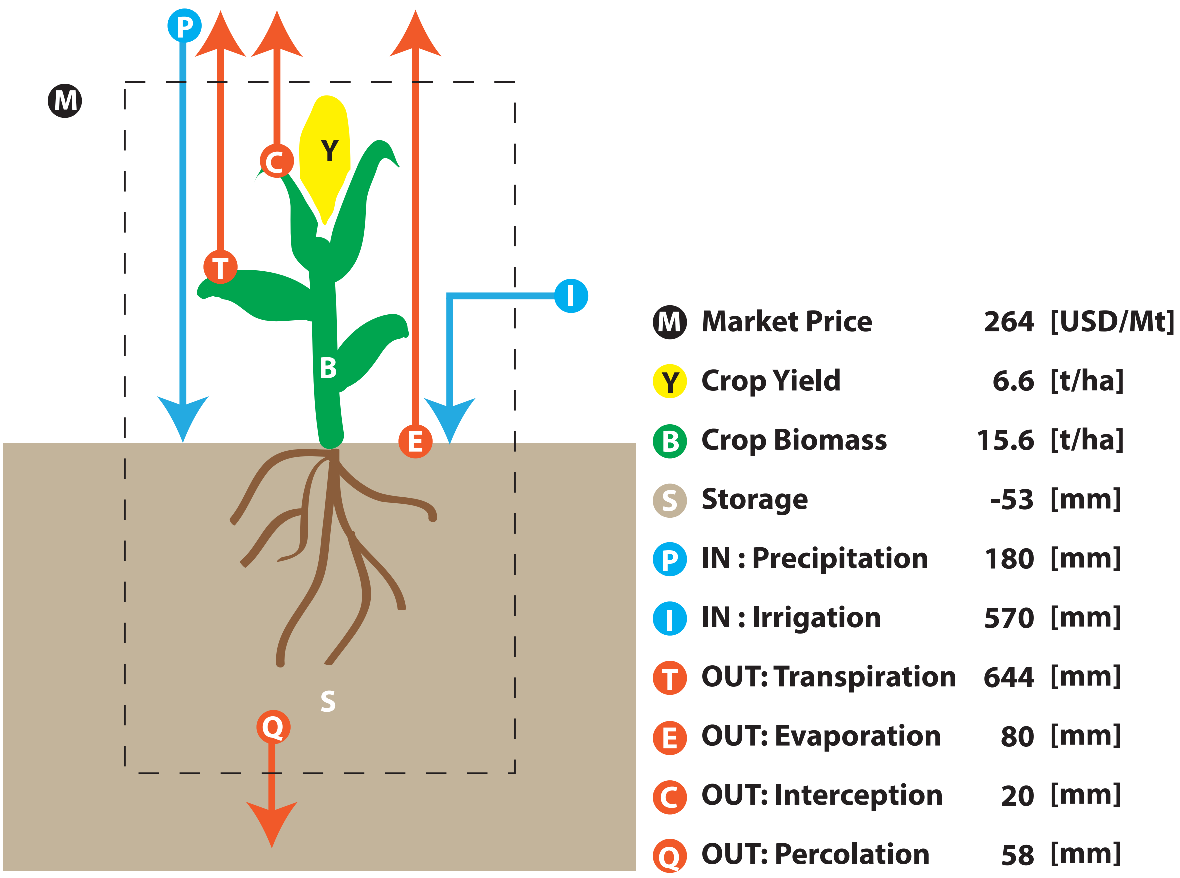
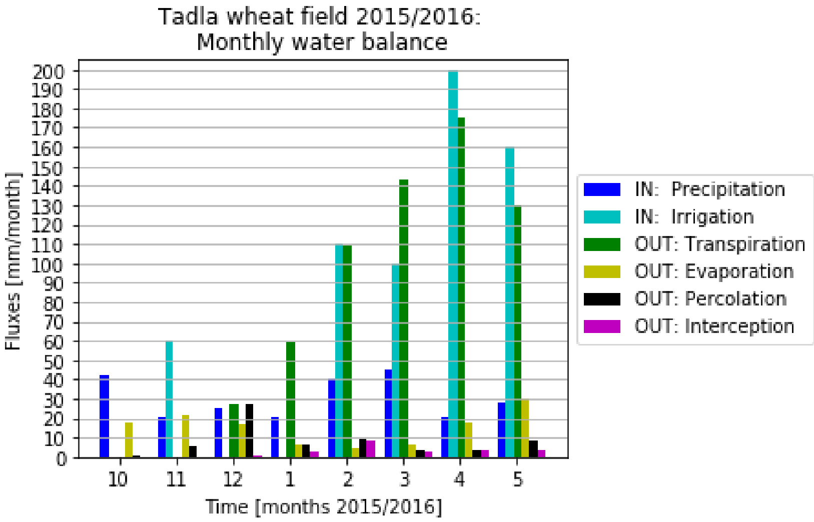
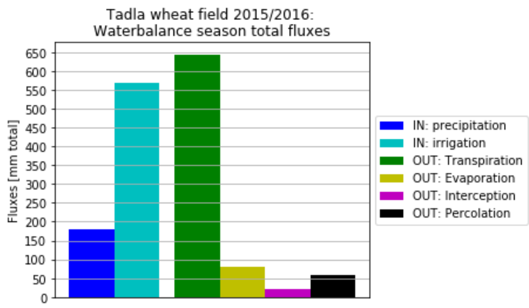


Fig. 4.6: Overview for winter wheat field in Tadla basin 2015/2016: the seasonal water balance and other elements of agricultural performance are visualized with rounded quantities. Seasonal totals are obtained from November 28th 2015 and May 23rd 2016. These elements are used in the computation of efficient water use for the field baseline performance.



(a)



(b)

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Tadla basin wheat field 2015/2016:
WATER BALANCE FOR CROP GROWTH CYCLE
From 28-Nov-2015 until 23-May-2016
---------------------------------------
IN:
  Precipitation  179.58
  Irrigation     570.00
  Runon            0.00
  Infiltration     0.00
  Seepage          0.00
  TOTAL IN       749.58  [mm]
---------------------------------------
OUT:
  Transpiration  644.09
  Evaporation     80.06
  Interception    20.10
  Runoff           0.00
  Drainage         0.00
  Percolation     58.39
  TOTAL OUT      802.64  [mm]
---------------------------------------
Change in storage
  (IN - OUT) is  -53.06  [mm]
---------------------------------------
```

(c)

Fig. 4.7: Water balance for the simulated winter wheat field in Tadla Basin Morocco 2015/2016. (a) Monthly totals for November 2015 to May 2016. Observed fluxes include precipitation, irrigation, transpiration, evaporation, percolation and interception. (b) Seasonal totals from November 28th 2015 to May 23rd 2016. Observed fluxes include precipitation, irrigation, transpiration, evaporation, percolation and interception. (c) Seasonal totals from November 28th 2015 to May 23rd 2016. Total fluxes in and out and change of storage over the growing season is indicated.

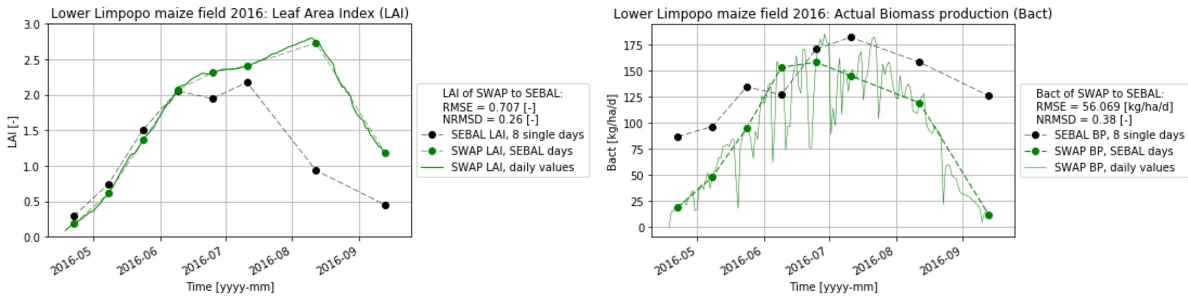
4.3. Calibrated Baseline simulation of Smallholder Maize field in Lower Limpopo Basin 2016

A smallholder maize field in Lower Limpopo Basin Mozambique in growing season April - September 2016 is simulated in the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST), calibrated against data from 8 days of Surface Energy Balance Algorithm for Land model (SEBAL) analysis. In this paragraph the calibration result for this maize wheat field is presented. The growing season is observed from crop emergence to crop harvest, respectively April 18^{th} to September 15^{th} 2016. Length of growing season is 150 days, crop anthesis occurred at July 2^{nd} 2016. The 0.22 ha field is located in the Fidel Castro irrigation/drainage system near Xai-Xai in the 'Machongos'. In this area a year round spring flow and shallow water table is observed. Management of the water table in the system is crucial for preserving the organic soils and enabling agricultural practices. Sub-surface irrigation is applied by management of the ground water.

During the calibration process, initial parameters obtained from prior research are adjusted. The calibrated input parameters are presented in Appendix J. The files required for this simulation are the general .swp input file, the detailed .crp input file, the .dra input file for lateral drainage, and the .016 meteorological input file. From the calibration process can be observed that the sub-surface irrigation application and bottom boundary condition, crop characteristics and biomass partitioning is most characteristic compared to prior research.
No data on irrigation is available. No surface- or sprinkling irrigation is applied, irrigation is applied subsurface by management of the ground water table. The soil column bottom flux is calibrated upon satisfactory results of actual transpiration T_{act} and soil moisture content in the root zone SM_{rz}. The applied bottom boundary condition in SWAP is a prescribed bottom flux for which 10 records are used between January 1^{st} and November 1^{st} 2016. The initial soil moisture content is calibrated using a deep ground water table which is not representative for the local situation but allowed the simulation of plausible soil moisture content values. The simulated bottom flux represents the managed water table by which sub surface irrigation is applied. Crop characteristics are adjusted within feasible ranges for maize and represent poor seed quality. Adjustment from initial values is required in the calibration to obtain high values for actual biomass production rate B_{act} and low values for Leaf Area Index (LAI) along the growing season. In general WOFOST calibrations, it is assumed that from anthesis all biomass is used for storage organs. This is adjusted in the current calibration where after anthesis a maximum of 55% of daily produced above ground dry matter biomass is partitioned to storage organs and in every stage of the growing cycle a minimum of 45% is partitioned to the leaves and stems together.

4.3.1. Smallholder Maize Mozambique: Leaf Area index and Biomass Production

In Fig. 4.8 the calibration result for the LAI and actual biomass production B_{act} is visualized. These two characteristics are considered highly relevant aspects of crop performance. LAI has a crucial role in the physical processed by which crop development is defined in WOFOST. Biomass and the closely related crop yield are important products from agriculture and have a crucial role in evaluation of field performance. Output from SEBAL and SWAP visualized in Fig. 4.8 shows partly satisfying similarity on the days of SEBAL analysis. The period from anthesis to harvest, LAI is overestimated by SWAP/WOFOST. Especially the LAI at the 7^{th} SEBAL date shows a large difference between the SEBAL and SWAP/WOFOST output. The records of biomass production from SEBAL are relatively high compared to the daily values from SWAP/WOFOST, especially at the beginning and end of the season biomass production is underestimated in SWAP/WOFOST. Except for the 7^{th} SEBAL date, development of LAI over the growing season shows a normal trend. Without the exceptional date, a maximum LAI of 2.5 is observed. This is low which corresponds to the reported poor performance in the region. A maximum biomass production rate is observed mid-season, this value exceeds 175 $kg\ ha^{-1}\ d{-}1$.



(a) (b)

Fig. 4.8: Leaf Area index and Actual Biomass Production at the simulated maize field in Lower Limpopo Basin, Mozambique 2016. Output from SEBAL and calibrated SWAP/WOFOST for the observed growing season is presented with the Root Mean Square Error (RMSE) of SWAP to SEBAL using 8 days of SEBAL analysis. Dates between April 18^{th} and September 15^{th} 2016 are observed. (a) Leaf Area Index (LAI). (b) Actual Biomass Production B_{act}.

4.3.2. Smallholder Maize Mozambique: Crop Transpiration

In Fig. 4.9 the calibration result for crop transpiration is visualized. Decrease of relative transpiration T_{rel} or difference between potential transpiration T_{pot} and actual transpiration T_{act} is caused by reduction of transpiration from crop stress. In the simulated field stress from drought is observed. Crop transpiration is a relevant aspects of crop performance and agricultural water use. Output from SEBAL and SWAP visualized in Fig. 4.3 shows large similarity on most days of SEBAL analysis and similarity in trends is observed, which indicates a successful calibration of SWAP/WOFOST against SEBAL. The 7th day of SEBAL analysis is an exception where a large deviation is observed. T_{rel} is slightly underestimated in SWAP/WOFOST and reduction of transpiration from drought $T_{red,dry}$ is overestimated at several days of SEBAL analysis. Except for the first two months, large fluctuations of T_{pot} and T_{act} are observed throughout the season. Daily variability is caused by daily meteorological circumstances. This is increased along the season by variability of transpiration reduction from dryness and the increase of the crop green area. After anthesis, fluctuations are observed between 0.5 and 6.5 $mm\ d^{-1}$, with an average T_{pot} of 3.5 $mm\ d^{-1}$. Reduction of transpiration from dryness is observed especially in the first half of the season.

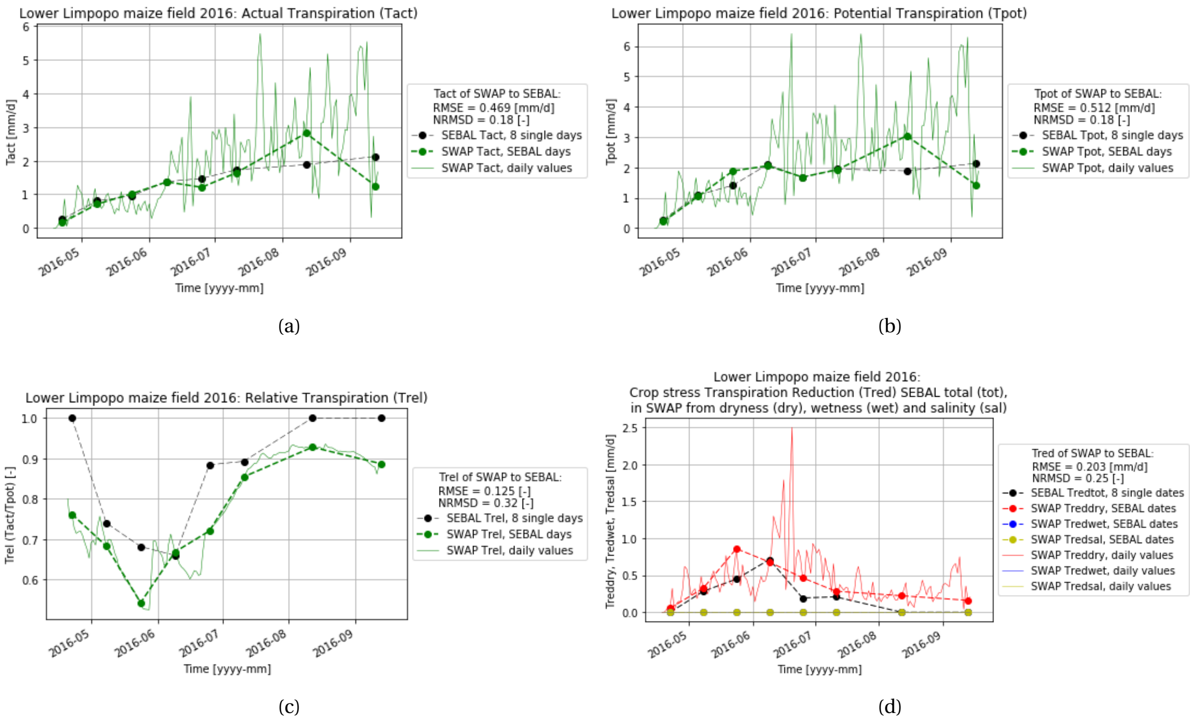
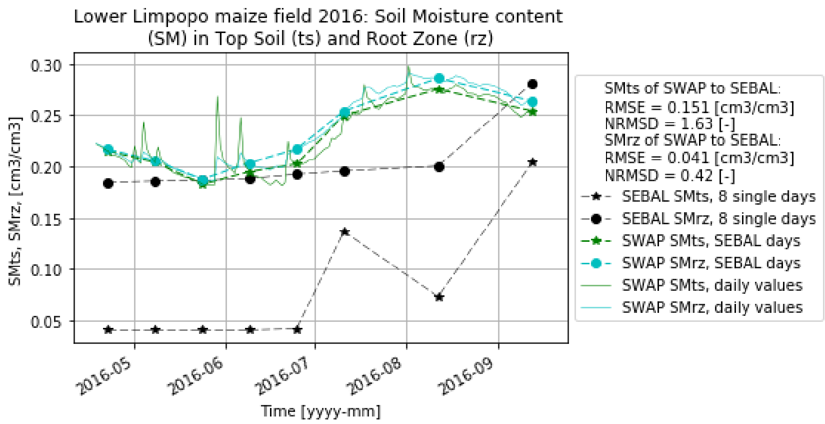


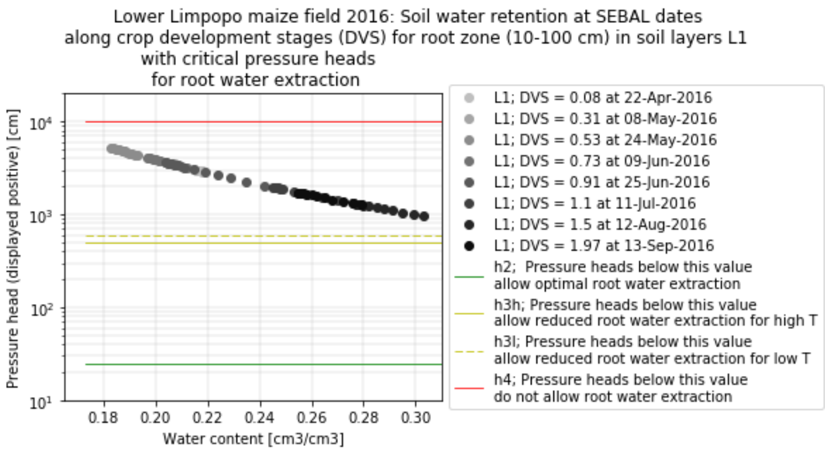
Fig. 4.9: Actual, Potential and Relative Transpiration and observed Transpiration Reduction at the simulated maize field in Lower Limpopo Basin, Mozambique 2016. Output from SEBAL and calibrated SWAP/WOFOST for the observed growing season is presented with the Root Mean Square Error (RMSE) of SWAP to SEBAL using 8 days of SEBAL analysis. Dates between April 18^{th} and September 15^{th} 2016 are observed. (a) Actual Transpiration T_{act}. (b) Potential Transpiration T_{pot}. (c) Relative Transpiration T_{rel}. (d) Transpiration Reduction T_{red} total and from drought, wetness and salinity.

4.3.3. Smallholder Maize Mozambique: Soil Moisture Content

In Fig. 4.10 the calibration result for soil moisture is visualized. In simulation of SWAP/WOFOST two soil layers are used as is observed from measurements in field work. The first layer is found from 0 to 100 cm soil depth. The second layer from 100 to 300 cm soil depth. Rooting depth is found in the first soil layer only, soil moisture content or retention capacity of the deeper soil layer is not observed. In SEBAL, soil moisture content of top soil and root zone are generated. Top soil in SWAP/WOFOST is defined from the average over 0 to 5 cm depth, root zone in SWAP/WOFOST is defined from the average over 10 to 100 cm depth. The soil retention curves for the two soil layers and the critical pressure head h_2, $h_{3,low}$, $h_{3,high}$ and h_4 indicate when water is available for root water uptake. Output from SEBAL and SWAP visualized in Fig. 4.10(a) shows similarity on the days of SEBAL analysis for the root zone but a large overestimation of soil moisture content for the top soil. Both for the top soil and root zone a large deviation is observed for the 7th SEBAL day. In the simulated root zone, a slightly higher water content is observed compared to the top soil, which is close to the water content of the root zone according to SEBAL data. The initial soil water pressure heads visualized in Fig. 4.10(b) are very low, corresponding to the simulated deep initial ground water level. Along the growing season, low pressure heads are observed resulting in a reduction of root water extraction. This corresponds to the observed reduction in transpiration presented in the previous section.



(a)



(b)

Fig. 4.10: Soil Moisture Content, Water Retention Capacity and Critical Pressure Heads at the simulated maize field in Lower Limpopo Basin, Mozambique 2016. (a) Soil Moisture Content in both top soil and root zone from April 18^{th} to September 15^{th} 2016. Output from SEBAL and calibrated SWAP/WOFOST for the observed growing season is presented with the Root Mean Square Error (RMSE) of SWAP to SEBAL using 8 days of SEBAL analysis. (b) Soil Water Retention Curve for two soil layers in SWAP/WOFOST simulation from April 18th to September 15th 2016. Averages of both soil layers at several dates along the growing season are visualized. Horizontal lines indicate critical pressure heads h_2, $h_{3,low}$, $h_{3,high}$ and h_4 for crop root water uptake.

4.3.4. Smallholder Maize Mozambique: Agricultural Yield

In Fig. 4.11 the calibration result for yield production is visualized. SWAP/WOFOST computes both $\sum B_{act}$ $[t\ ha^{-1}]$ and the total dry mass partitioned to storage organs $\sum B_{SO,act}$ $[t\ ha^{-1}]$. Actual yield can be computed from total biomass production $\sum B_{act}$ using the crop seed water content θ_{seed} and Harvest Index (HI) as presented in the equation below (FAO and DWFI, 2015).

$$Y = \frac{HI * \sum B_{act}}{(1-\theta_{seed})} \tag{4.2}$$

HI is the ratio between the mass of storage organs and the weight of total above ground crop. Yield can also be computed from $\sum B_{SO,act}$, using the crop seed water content θ_{seed}. Assuming $\theta_{seed} = 0.25$ and HI = 0.25 as presented in paragraph 3.2.2, yield computed from total actual biomass B_{act} and from storage organs mass $B_{SO,act}$ show large similarity. This indicates that that the partitioning of biomass to storage organs is successfully calibrated. From the simulation in SWAP/WOFOST a total seasonal yield of 4.7 $t\ ha^{-1}$ is obtained. This is very high compared to the locally reported 1-2 $t\ ha^{-1}$.

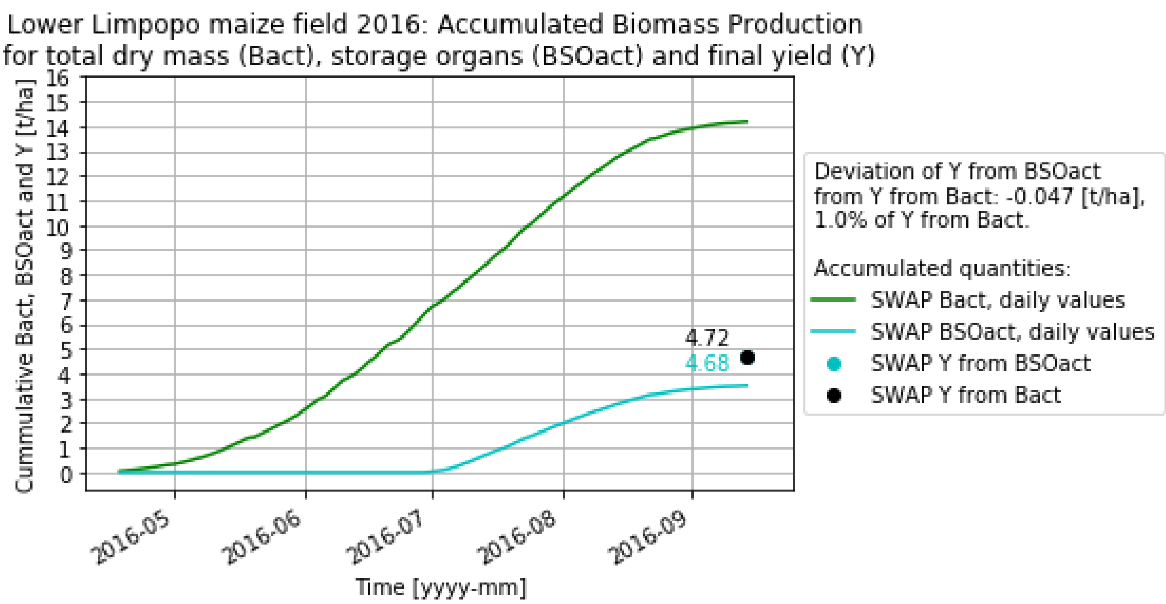


Fig. 4.11: Accumulated dry mass B_{act} and dry mass of storage organs $B_{SO,act}$ is generated by SWAP. Actual total yield is computed directly with the crop seed water content θ_{seed} from $\sum B_{SO,act}$ and when computed from B_{act} additionally using the Harvest Index (HI). Total accumulated biomass and yield is defined at date of harvest, September 15th 2016.

4.3.5. Smallholder Maize Mozambique: Water Balance

In Fig. 4.13 the water balance of the calibrated simulation of the maize field in Lower Limpopo Basin, Mozambique 2016 is visualized. It can be observed from Fig. 4.13(c) that no run on, infiltration, above ground irrigation, run off or drainage is observed. No observation of irrigation corresponds with the sub-surface irrigation by management of the ground water table, represented by the seepage flux. No observation of lateral drainage is assumed to be caused by large distance to canals and the dryness of the season. Also the absence of horizontal flows of run on and run off can be explained with the relatively dry local situation. Preceding the growing season, large monthly fluxes of percolation to the ground water are observed. With the start of the growing season, the ground water level is managed such that seepage occurs, providing sub-soil irrigation water. The amount of applied irrigation water (507 mm) exceeds 4 times the amount of received precipitation (125 mm). Crop transpiration is the largest outgoing flux. However, it is relatively low. The change of storage is large and positive, over 200 mm water depth is stored in the soil along the growing season. In Fig. 4.12 the rounded quantities of the seasonal water balance and other elements of agricultural performance are visualized. These elements of the observed system are used in computation of indicators for efficient water use, presented in Paragraph 4.4 and **??**.

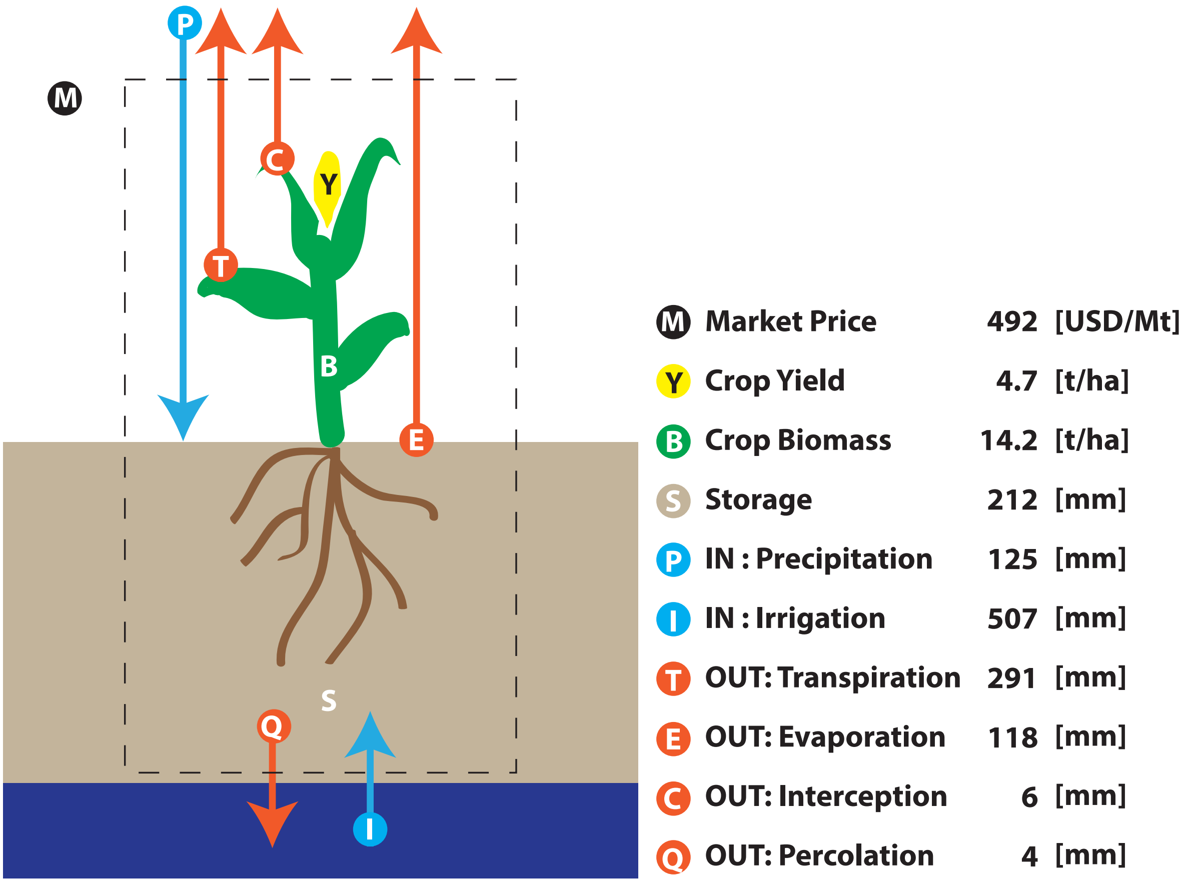
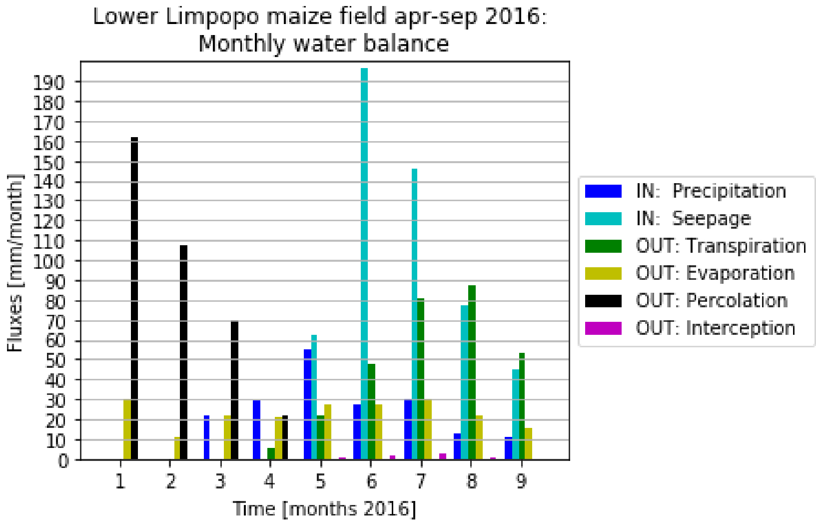
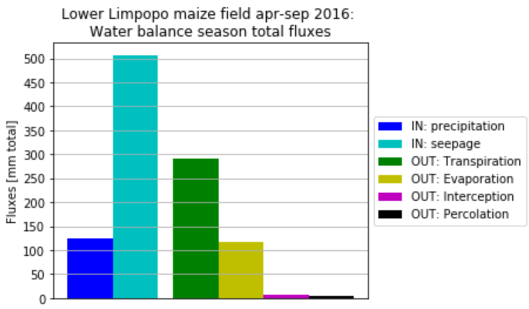


Fig. 4.12: Overview for smallholder maize field in Lower Limpopo basin 2016: the seasonal water balance and other elements of agricultural performance are visualized with rounded quantities. Seasonal totals are obtained from April 18th to September 15th 2016. These elements are used in the computation of efficient water use for the field baseline performance.



(a)



(b)

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Lower Limpopo maize field 2016:
WATER BALANCE FOR CROP GROWTH CYCLE
From 18-Apr-2016 until 15-Sep-2016
-----------------------------------
IN:
  Precipitation  125.00
  Irrigation       0.00
  Runon            0.00
  Infiltration     0.00
  Seepage        506.83
  TOTAL IN       631.83   [mm]
-----------------------------------
OUT:
  Transpiration  291.23
  Evaporation    118.20
  Interception     5.77
  Runoff           0.00
  Drainage         0.00
  Percolation      4.15
  TOTAL OUT      419.35   [mm]
-----------------------------------
Change in storage
  (IN - OUT) is  212.48   [mm]
---------------------------------------
```

(c)

Fig. 4.13: Water balance for the simulated maize field in Lower Limpopo Basin, Mozambique 2016. Seepage represents the sub-surface irrigation. Where irrigation is indicated to be zero, this represents above ground irrigation. (a) Monthly totals for January to September 2016. Observed fluxes include precipitation, seepage, transpiration, evaporation, percolation and interception. (b) Seasonal totals from April 18th to September 15th 2016. Observed fluxes include precipitation, seepage, transpiration, evaporation, percolation and interception. (c) Seasonal totals from April 18th to September 15th 2016. Total fluxes in and out and change of storage over the growing season is indicated.

4.4. Efficient water use, baseline scenario

Simulation output allows for computation of multiple indicators for efficient water use. Hence, efficient water use at the baseline scenarios can be quantified. Table 4.1 contains computed indicators for the single season baseline scenario of both fields. The first field is the simulated winter wheat field in Morocco, see Paragraph 4.2. The second field is the simulated maize in Mozambique, see Paragraph 4.3. In Fig. 4.14 the same data is presented, normalized according to the highest value for each unit of expression. In table and chart the indicators are ordered according to units of expression. The indicators expressed in $t\ m^{-3}$ are *water productivities*, commonly referred to as 'crop per drop'. The non-dimensional indicators are *water efficiencies*.
The data reveals that *water productivity* can correspond to different values for the same field, the same is observed for *water efficiency*. The chart also reveals that for the two observed fields, there is no consensus between the different indicator concerning which field is most efficient in water use at the baseline scenario. Baseline *water productivity* according to 7 different indicators is 7-28 10^{-4} $[t\ m^{-3}]$ at the winter wheat field and 5-49 10^{-4} $[t\ m^{-3}]$ at the maize field, where 49 10^{-4} $[t\ m^{-3}]$ for indicator 5 is an exceptional high value compared to the other baseline water productivity values. The observed ranges of water productivity values and water efficiency values is larger for the maize field than for the winter wheat field. The relative range of water productivity values is larger than observed with the water efficiency values.

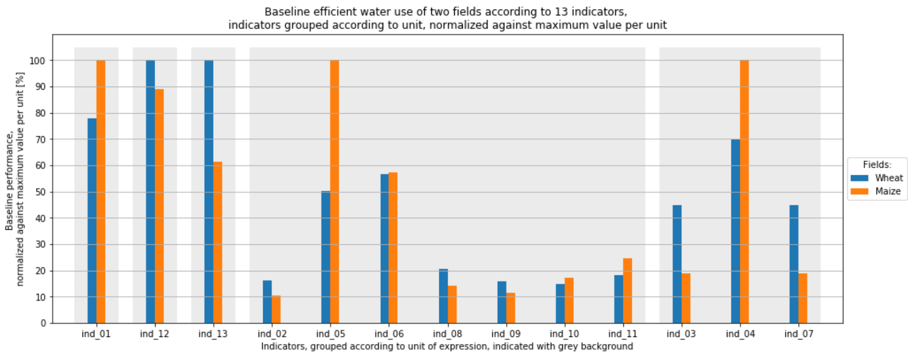


Fig. 4.14: Values for baseline efficient water use performance also presented in Table 4.1. Indicators in chart are normalized against the maximum value of a similar unit, allowing comparison of the observed fields and indicators of similar units.

Table 4.1: Baseline efficient water use according to the collection of indicators, for the two simulated fields: winter wheat in Tadla Basin, Morocco 2015/2016 and maize in Lower Limpopo Basin, Mozambique 2016. Indicators are ordered according to units. Indicators are computed from SWAP/WOFOST output of the simulated winter wheat field for the growing season from November 28^{th} 2015 to May 23^{rd} 2016 and of the simulated maize field for the growing season from April 18^{th} to September 15^{th} 2016.

	Indicator	**Baseline Wheat**	**Baseline Maize**	
01	Water Use Efficiency from SDG Indictor 6.4.1	2.6474 e-07	3.3975 e-07	[USD/m3]
12	Water Saving	-5.7000 e03	-5.0683 e03	[m3]
13	Agricultural Yield	5.7160	3.5070	[t/ha]
02	Water Use Efficiency from SDG Indictor 6.4.1 adjusted	7.8934 e-04	5.0840 e-04	[t/m3]
05	Net Biomass Water Productivity from FAO and DGIS	2.4421 e-03	4.8656 e-03	[t/m3]
06	Water Use Efficiency from FAO	2.7595 e-03	2.7958 e-03	[t/m3]
08	Irrigation Water Productivity from 1997	1.0028 e-03	6.9195 e-04	[t/m3]
09	Inflow Water Productivity from 1997	7.6256 e-04	5.5505 e-04	[t/m3]
10	Depleted Water Productivity from 1997	7.1215 e-04	7.1215 e-04	[t/m3]
11	Process Depleted Water Productivity from 1997	8.8745 e-04	1.2042 e-03	[t/m3]
03	Irrigation Efficiency from 1932	8.4647 e-01	3.5446 e-01	[-]
04	Irrigation Efficiency from 1967	1.3155	1.8868	[-]
07	Irrigation Efficiency from 1997	8.4647 e-01	3.5447 e-01	[-]

4.5. Efficient water use, improvement from baseline to strategy scenario

Two actual fields are simulated in the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST) calibrated against data from the Surface Energy Balance Algorithm for Land model (SEBAL) which resulted in a simulated baseline scenario. When successfully calibrated this is a plausible representation of the actual field for a single growing season. Baseline performance is presented in the previous paragraph. In paragraph the improvement from baseline to strategy scenario is observed. First the field performance of baseline and strategy scenarios is observed, observing water balance components and quantities of field production. Secondly, the increase of efficient water use from baseline to strategy scenario is presented for the collection of strategies, according to the collection of indicators. First the observed 10 strategies and 13 indicators are listed, to which the results presented in the following pages will refer.

Strategies (see Paragraph 3.3) for a single growing season:

1. Irrigation Elimination
2. Sprinkler Irrigation; does not apply at the maize field
3. Moderate Soil Water Deficit; 55% of soil moisture content at field capacity pF2
4. Mild Soil Water Deficit; 65% of soil moisture content at field capacity pF2
5. Transpiration Deficit; T_{pot} = 75%
6. Transpiration Optimum; T_{pot} = 100%
7. Sowing Date Advance; -10 days
8. Sowing Date Postpone; +10 days
9. Seed Quality Optimum
10. Soil Water Retention Increase

Indicators (see Paragraph 3.4) observing seasonal accumulation of quantities:

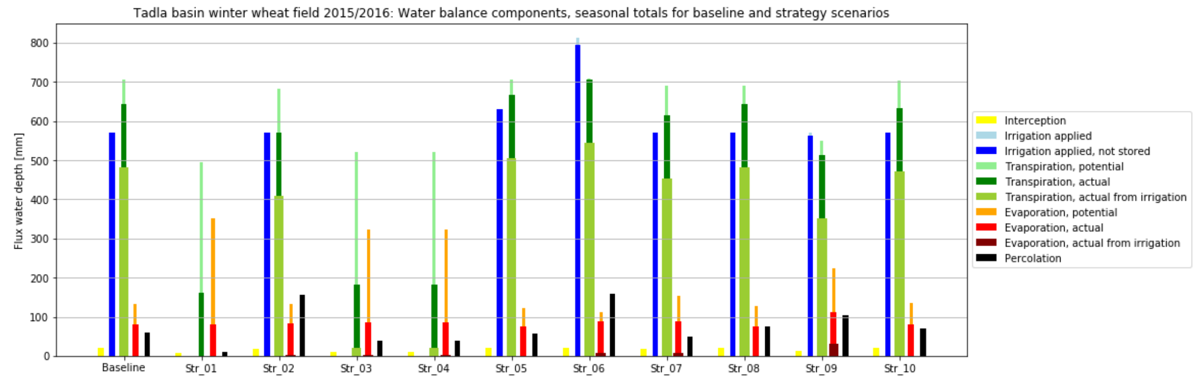
1. Sustainable Development Goal (SDG) indicator 6.4.1, eq (3.4.1)
2. SDG indicator 6.4.1 adjusted, eq (3.4.2)
3. Irrigation Efficiency from 1932, eq (3.4.3)
4. Irrigation Efficiency from 1967, eq (3.4.4)
5. Net Biomass Water Productivity from the Food and Agriculture Organization (FAO) and Directorate-General for International Cooperation (DGIS), eq (3.4.5)
6. Water Use Efficiency from the FAO, eq (3.4.6)
7. Irrigation Efficiency from 1997, eq (3.4.7)
8. Irrigation Water Productivity, eq (3.4.8)
9. Inflow Water Productivity, eq (3.4.9)
10. Depleted Water Productivity, eq (3.4.10)
11. Process Depleted Water Productivity, eq (3.4.11)
12. Water Saving, eq (3.4.12)
13. Agricultural Yield, eq (3.4.13)

4.5.1. Water balance components and field production

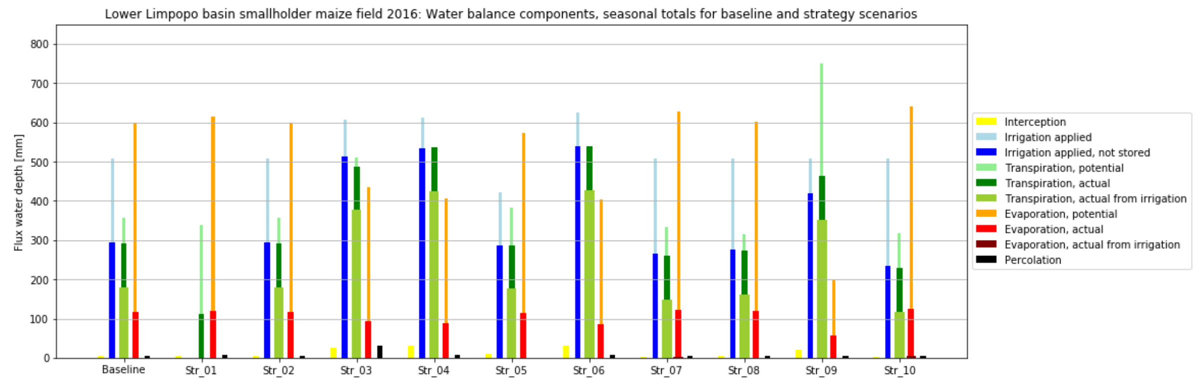
Two fields are observed in this research, a winter wheat field in Tadla basin Morocco and a smallholder maize field in Lower Limpopo basin Mozambique. The fields' baseline scenarios obtained from calibration are presented in Paragraph 4.2 and 4.2. The fields baseline efficient water use according to the observed indicators is presented in Paragraph 4.4. For each field, the baseline scenario and strategy scenarios are simulated.

Observed water balance components for each baseline and strategy simulation are the interception $\sum C$ $[mm]$, irrigation water total $\sum I$ $[mm]$ and not stored $\sum(I-\Delta S_i)$ $[mm]$, transpiration potential $\sum T_{pot}$ $[mm]$, transpiration actual total $\sum T_{act}$ $[mm]$ and from irrigation water $\sum T_i$ $[mm]$, evaporation potential $\sum E_{pot}$ $[mm]$, evaporation actual total $\sum E_{act}$ $[mm]$ and from irrigation water $\sum E_i$ $[mm]$, and percolation to the ground water $\sum Q$ $[mm]$. Water balance components of the observed fields are presented in Fig. 4.15.

The graphs indicate differences between the observed fields. At the winter wheat field (Fig. 4.15(a)) the applied irrigation, percolation and transpiration values are relatively high and the amount of irrigation water stored is negligible. At the maize field (Fig. 4.15(b)) evaporation values are relatively high and a large section of the irrigation water is stored. Significant differences are observed between the different scenarios, however the effect of the strategies appears to be site or crop specific since the pattern observed in the charts is differently for the two observed fields. Most distinct is the effect of strategy 3 and 4. At the winter wheat field, strategy 3 and 4 result in a diminishing of the applied irrigation water and a large reduction in transpiration. At the maize field the opposite effect is observed, where irrigation and transpiration water depths increase significantly. In Paragraph 5.1.1 a discussion is provided on differences between the two observed fields. In Paragraph 5.1.2 a discussion is provided on the definition of strategy 3 and 4.



(a)

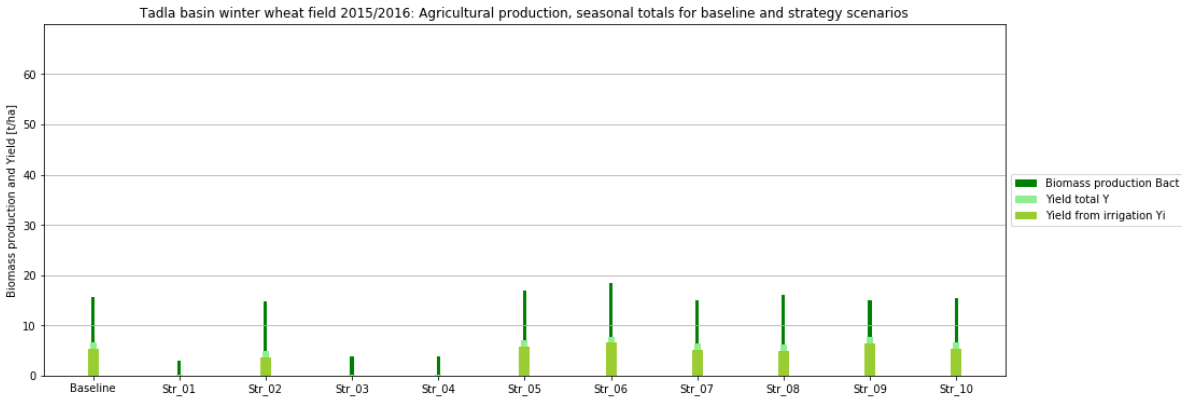


(b)

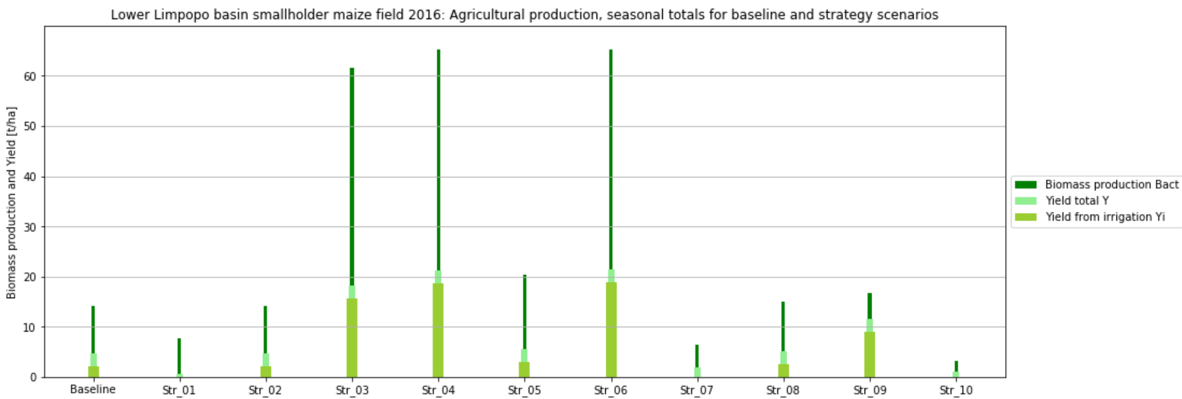
Fig. 4.15: Water balance components for baseline scenario and strategy scenarios for both observed fields, accumulated for the observed season (a) Winter wheat field in Tadla basin Morocco 2015/2016. (b) Smallholder maize field in Lower Limpopo basin Mozambique 2016.

Observed aspects of field production are actual biomass production $\sum B_{act}$ $[t\ ha^{-1}]$ and the actual yield total $\sum Y$ $[t\ ha^{-1}]$ and from irrigation water $\sum Y_i$ $[t\ ha^{-1}]$.

Field production records for the observed fields are presented in Fig. 4.16. It can be observed from these charts that production totals from strategies are not always exceeding the values of the baseline scenario. Most remarkable is the effect of strategy 3, 4 and 6 on the maize field (Fig. **??**) where large seasonal biomass production and total yields exceeding 20 $[t\ ha^{-1}]$ are observed. Inspection of the SWAP/WOFOST output for strategy 4 and 6 at the maize field reveals that in these simulations the actual biomass and yield production equals the potential production rates throughout the growing season. Where strategy 3 and 4 result in increases in field production values for the maize field, decreases are observed at the winter wheat field. A discussion on the high seasonal biomass and yield production in WOFOST is provided in Paragraph 5.2.1.



(a)



(b)

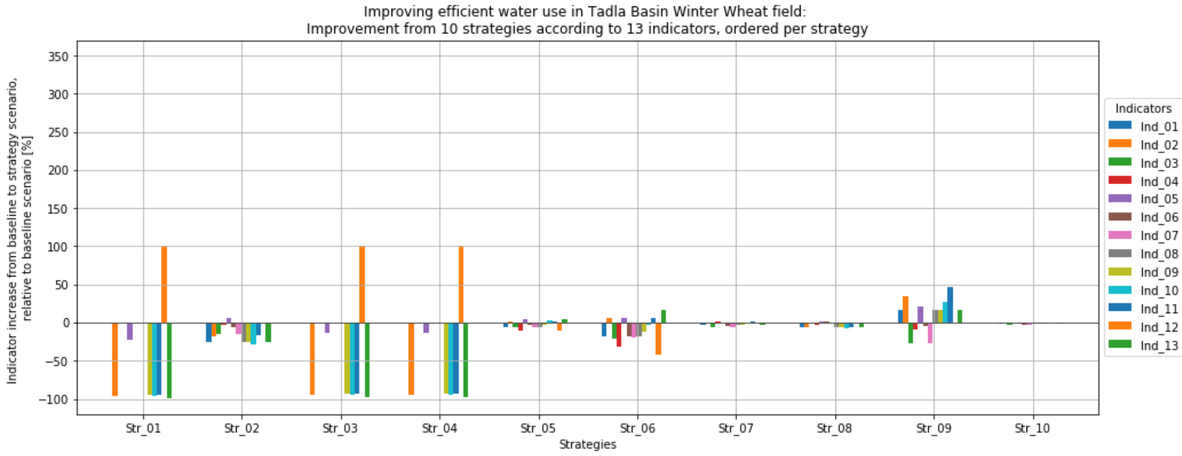
Fig. 4.16: Production of baseline scenario and strategy scenarios for both observed fields. (a) Winter wheat field in Tadla basin Morocco 2015/2016. (b) Smallholder maize field in Lower Limpopo basin Mozambique 2016.

4.5.2. Increases of indicators for efficient water use

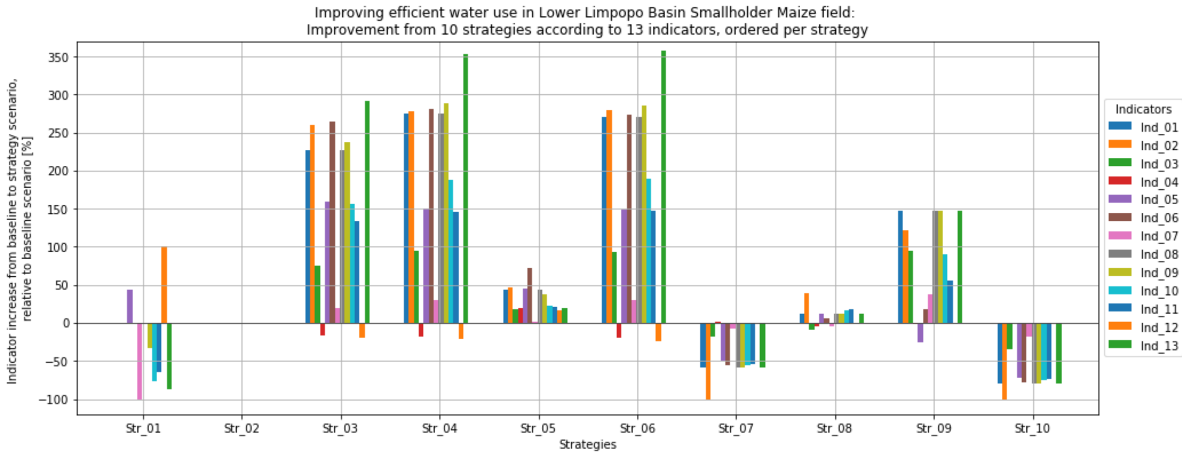
The increases are expressed in percentage of the efficient water use of the baseline scenario. A negative value indicates a decrease. Indicators and strategies are discussed in Paragraph 5.1.2.

In Fig. 4.17 the results are visualized grouped per strategy. Thus for both fields, for each strategy the increase according to all indicators can be observed. This chart indicates that that the effect of strategies on the maize field (Fig. 4.17(b)) is generally larger than the effect on the winter wheat field (Fig. 4.17(a)). Strategy 1 according to most indicators, has a negative effect on both fields. Strategy 2 is nonexistent for the maize field, the effect on the wheat field is mostly negative. Strategies 3 and 4 has large positive effects on the maize field and negative effects on the winter wheat field. Strategy 5 has a positive effect on the maize field, the effect on the winter wheat field is very small and differences in direction are observed between indicators. Strategy 6 has a large positive effect on the maize field. The effect on the winter wheat field is different per indicator but mostly negative. Strategy 7 has only a very small effect on the winter wheat field, the direction is different per indicator. On the maize field this strategy has a negative effect. Strategy 8 has only a very small effect on the winter wheat field, the direction is different per indicator. On the maize field this strategy has a relatively small but mostly positive effect. Strategy 9 has a general positive effect on both fields, the effect on the maize field is larger. Strategy 10 has a negative effect on both fields, on the winter wheat field this is very small.

In Fig. 4.18 the same results are visualized grouped per indicator. Thus for both fields, for each indicator the increase from all strategies can be observed. The indicators are ordered according to unit of expression, highlighted with grey frames.
For the winter wheat field (Fig. 4.18(a)), indicators 1 has relatively small and mostly negative values. The same is observed for indicator 5 and indicator 8 . For indicator 6 and all the *water efficiencies* respectively indicator 3, and indicator 7, only negative increases are observed. For specific strategies, very large increases are observed for indicator 12, indicator 13 and four *water productivities*, respectively indicator 2, indicator 9, indicator 10 and indicator 11. For the wheat field these large increases are negative for all indicators, with an exception for indicator 12. For the maize field, large increases exceeding 200% are observed for several strategies according to indicator 1, indicator 13 and four *water productivity* indicators 2, 6, 8 and 9. Relatively low values below 100% are observed for indicator 12 and for the *water efficiency* indicators 3, 4 and 7. For the maize field there is no indicator with only positive or negative increases. For most indicators, increases from the same strategies are positive or negative.

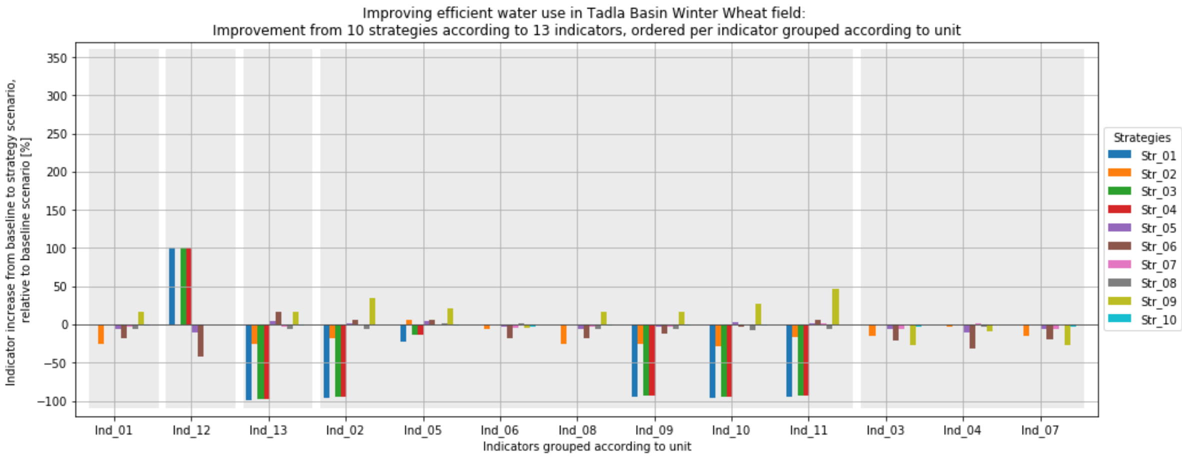


(a)

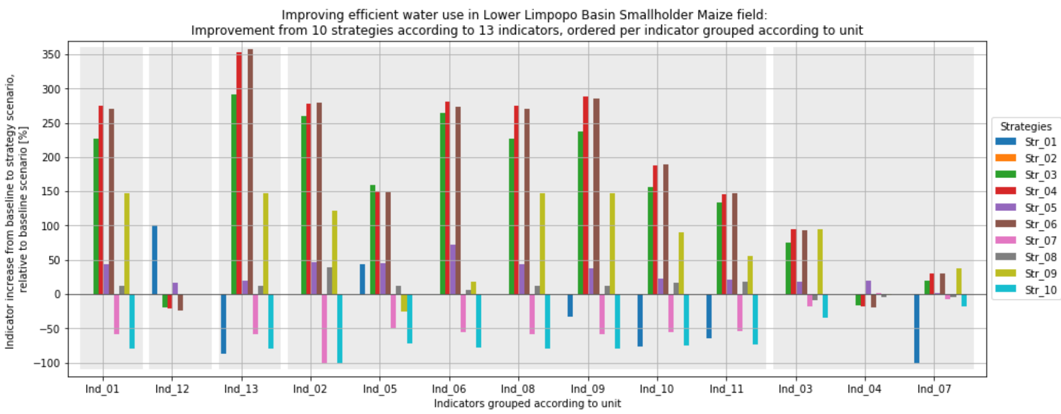


(b)

Fig. 4.17: Evaluation of strategies and indicators at the winter wheat field in Tadla Basin, Morocco 2015/2016. Values are expressed as percentage. Increase of indicator from baseline to strategy scenario is observed relative to the indicator for baseline scenario. Improvements are ordered per indicator. The growing season from November 28th 2015 to May 23th 2016 is observed. (a) Improvement of efficient water use in range of +/- 110% increase relative to baseline scenario. (b) Improvement of efficient water use in range of +/- 8% increase relative to baseline scenario.



(a)



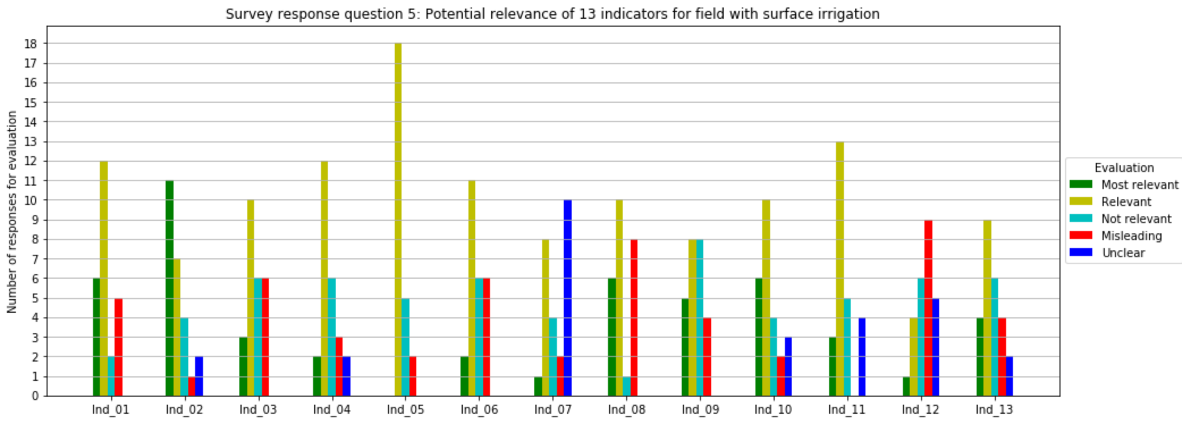
(b)

Fig. 4.18: Evaluation of strategies and indicators at the winter wheat field in Tadla Basin, Morocco 2015/2016. Values are expressed as percentage. Increase of indicator from baseline to strategy scenario is observed relative to the indicator for baseline scenario. Improvements are ordered per strategy, grouped according to units. The growing season from November 28th 2015 to May 23th 2016 is observed. (a) Improvement of efficient water use in range of +/- 110% increase relative to baseline scenario. (b) Improvement of efficient water use in range of +/- 8% increase relative to baseline scenario.

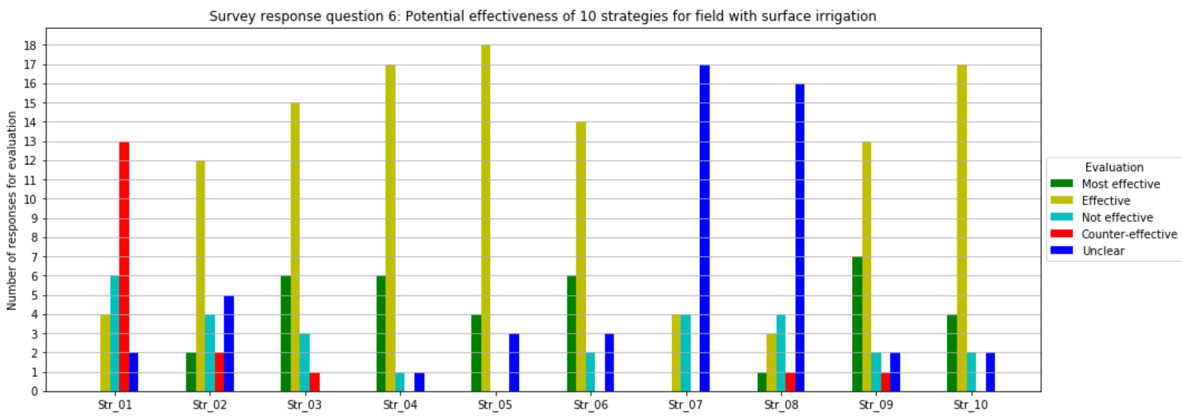
4.6. Efficient water use, evaluation by key actors

The collections of indicators for efficient water use at the agricultural field (Paragraph 3.4), and strategies to obtain improvement of efficient water use (Paragraph 3.3) apply to both observed agricultural fields and correspond to a general agricultural field. The observed fields are simplified and generalized to Case 1: a field with deep ground water table and surface irrigation and Case 2: a field with sub surface irrigation through management of the shallow water table. These two cases are used in an on-line survey. The survey is included in Appendix K. A total of 25 participants responded to the survey, the list of respondents is included in Appendix L. The participants are involved in agricultural water use and/or the discussion on efficient water use in agriculture. Five participants indicated to be involved in practice, six through policy and fourteen in research. The participants evaluated the potential relevance of every indicator (most relevant, relevant or misleading) and the potential effectiveness of each strategy (most effective, effective or counter-effective), for both cases. Evaluation of all indicators and strategies is required, questions cannot be skipped. However, participants were not obliged to finish the survey, 21 participants responded to the last question. Participants also have the option to evaluate a strategy or indicator with 'unclear'. Additionally to the evaluation of each strategy and indicator for both cases, the participants selected for a general field a single most relevant indicator and a single most effective strategy.

In Fig. 4.19 the survey responses for the evaluation of indicators and strategies for Case 1 with surface irrigation are visualized. A total of 25 participants responded to these questions. The response to all questions of the survey is included in Appendix M. From the evaluation of indicators in Fig. 4.19(a) the frequent occurrence of the evaluation 'misleading' is apparent. Indicator 12 was evaluated as 'misleading' by 9 of the 25 participants, corresponding to 36%. Indicator 5 was evaluated by 72% of the participants as 'relevant' but



(a)



(b)

Fig. 4.19: Responses to on-line survey questions 5 and 6, evaluation of all indicators and strategies for Case 1 with surface irrigation. 25 participants responded to these questions. (a) Evaluation of relevance of 13 indicators. (b) Evaluation of effectiveness of 10 strategies.

none of the participants evaluated this indicator as 'most relevant'. Indicator 2 is most often evaluated as 'most relevant', by 44% of the participants. Several indicators are said to be 'unclear', this evaluation was most often received for indicator 7 from 40% of the participants. In Fig. 4.19(b) the evaluation of strategies is visualized. The first strategy is 'counter-effective' according to 52% of the participants. Strategy 7 and 8 are 'unclear' according to 68 and 64%. All other strategies are 'effective' according to 48-72% of the participants. Strategy 9 is most frequently evaluated 'most effective' of all strategies, by 28% of the participants.

4.6.1. Key actors levels of involvement

Responses can also be observed for the key actors involved at different levels in (the discussion on) efficient water use seperately. The controversy between participants is larger for the indicators than for the strategies, therefore more attention is given to the indicators. A total evaluation score for each group of key actors is obtained using weights for the different survey questions and possible responses:

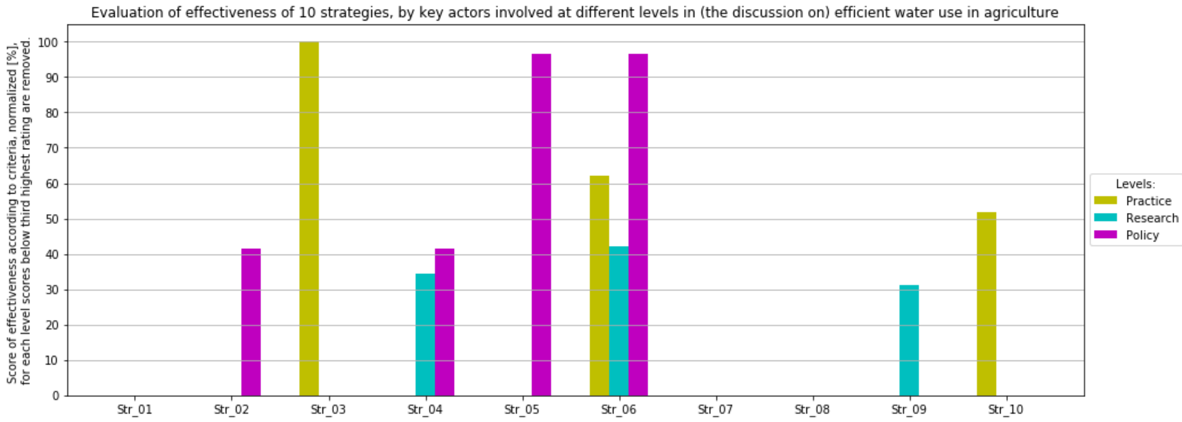
$$Str_{effective} = 0.5 * C1_{Str\ most} + 0.5 * C2_{Str\ most} + 1 * Gen_{Str\ single} \tag{4.3}$$

$$Ind_{relevant} = 0.5 * C1_{Ind\ most} + 0.5 * C2_{Ind\ most} + 1 * Gen_{Ind\ single} - 0.5 * C1_{Ind\ mis} - 0.5 * C2_{Ind\ mis} \tag{4.4}$$

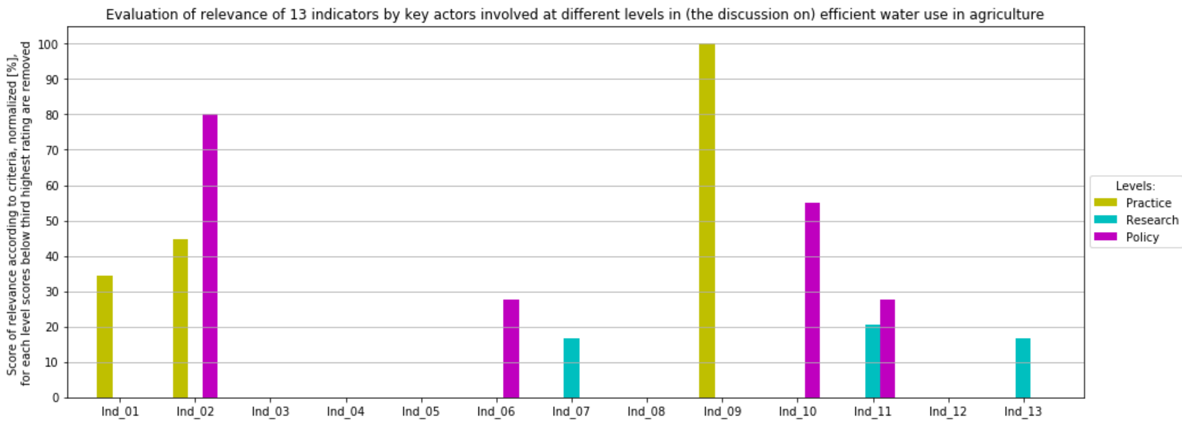
$$Ind_{unclear} = 0.5 * C1_{Ind\ unclear} - 0.5 * C2_{Ind\ unclear} \tag{4.5}$$

Each parameter in the above equations is computed for each level of key actors specifically and normalized according to the total amount participants in this level that responded to the question. C1, C2 and Gen refer to Case 1 with surface irrigation, Case 2 with sub surface irrigation and a general agricultural field. Ind and Str refer to indicators and strategies. The subscripts most, single, mis and unclear refer to most relevant or most effective, single most relevant or effective, misleading and unclear. For each group of key actors, the scores for $Ind_{relevant}$ and $Str_{effective}$ are normalized according to the highest score for an indicator respectively strategy within all groups. Secondly, for each group the scores below the third highest value are removed. The scores for $Ind_{unclear}$ are not normalized or reduced. Hence, for each group of key actors a top three of most effective strategies is obtained, visualized in Fig. 4.20(a). Also, for each group of key actors a top three of most relevant indicators is obtained, visualized in Fig. 4.20(b). Additionally, the evaluated of indicators as 'unclear' by the three groups of key actors can be observed in Fig. 4.20(c).

It is observed from Fig. 4.20 that low scores are observed for the key actors involved at the level of research. This indicates that key actors in research are less eager to evaluate a strategy or indicator as 'most effective' or 'most relevant' or more often evaluate an indicator as 'misleading'. Strategy 6 is preferred by key actors from all levels of involvement. Strategies 1, 7 and 8 are not preferred by any group. This corresponds to the information in the chart in Fig. 4.19(b) which indicates that strategy 1 is seen as counter-effective and strategies 7 and 8 as unclear. There is not an indicator that is preferred by all levels of involvement. It is interesting that indicator 13 representing agricultural yield and strategy 9 representing optimal seed quality is not favored by key actors in practice as would be expected from local farmers. Interviews with multiple farmers near Xai-Xai Mozambique in May 2017 revealed that farmers are primarily concerned about the agricultural yield, the farmers also that better seed quality would contribute to this. The difference with the result from the on-line survey can be explained with the fact that farmers have not responded to the survey. The majority of the survey participants involved in practice are from Dutch companies, involved in the implementation of local projects. A discrepancy can be observed between key actors practically involved at the field. It is also interesting that indicator 1 representing the Sustainable Development Goal (SDG) indicator 6.4.1 is not favored by key actors involved at the level of policy. This is interesting since this is an official indicator from UN-Water and the Food and Agriculture Organization (FAO). This suggest a discrepancy between the official and personal perception of key actors at this level of involvement. The scores in Fig. 4.20(c) indicate that for key actors at the level of research the presented indicators were least unclear. Several survey participants from this level noted on the survey that there was not enough information provided on the cases to evaluate the indicators. However, other survey participants noted that the survey was complex, due to the large amount of information provided. It is apparent that the indicators 7, 10, 11 and 12 are evaluated 'unclear' by 20 to 40% of the participants from all levels of involvement. Apart from indicator 12, these indicators are still favored at some levels of involvement. Very apparent is indicator 11 for which the third highest score in relevance is obtained by key actors in policy, while on average 40% of the respondents from this level evaluates this indicator as 'unclear'.



(a)



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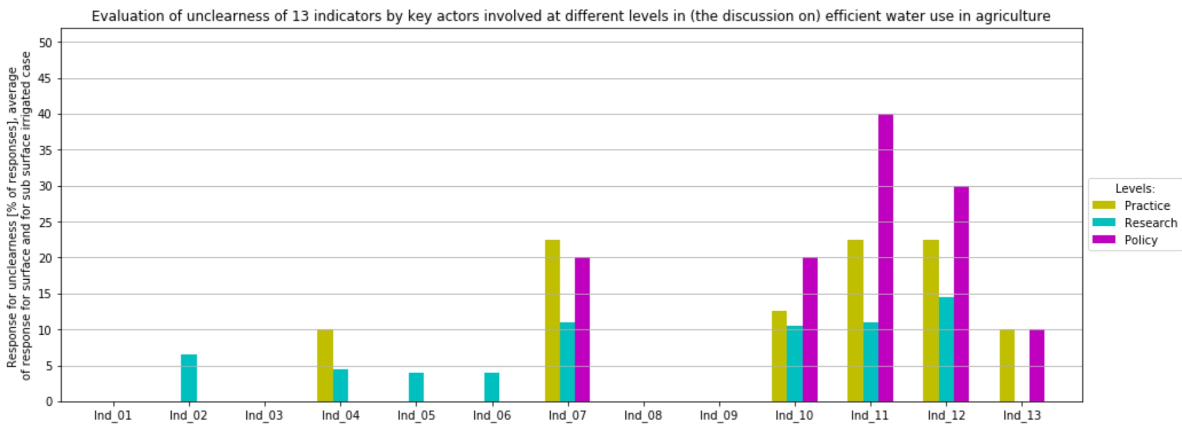


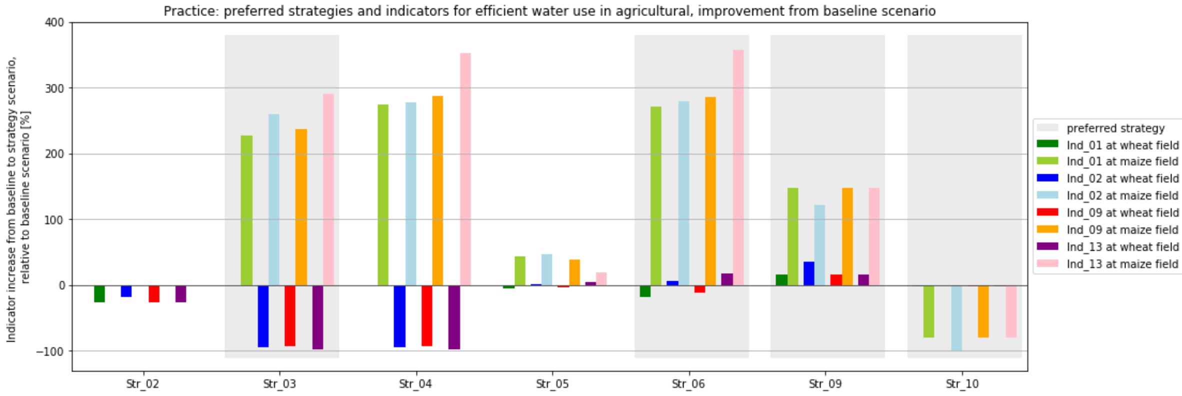
(c)

Fig. 4.20: Evaluation of strategies and indicators by each group of key actors, involved at different levels in (the discussion on) efficient water use in agriculture. Three most relevant indicators and most effective strategies are observed for each group of key actors, according to criteria for survey responses. Scores are normalized according to the highest score in each chart. Response 'unclear' is averaged for both cases and not normalized. (a) Most effective strategies, normalized and low scores removed. (b) Most relevant indicators, normalized and low scores removed. (c) Indicators evaluated 'unclear', mean not normalized.

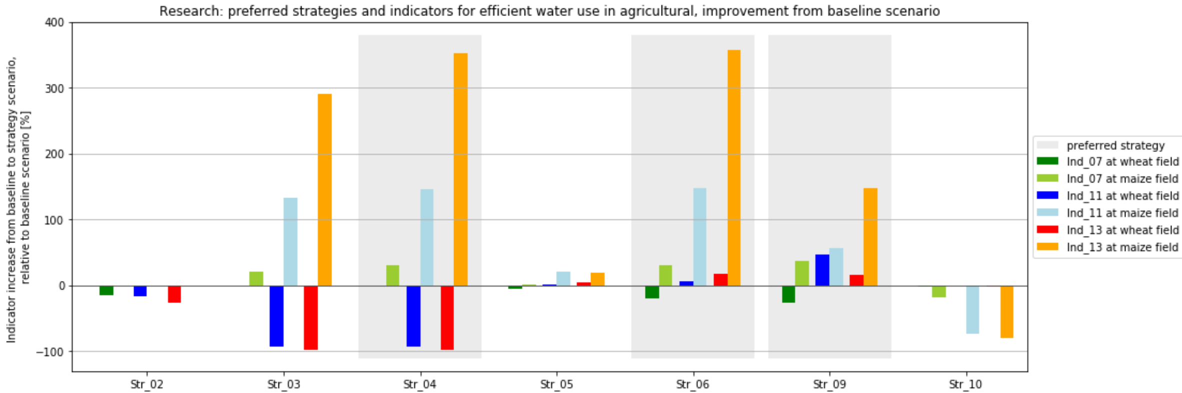
4.6.2. Preferred indicators and strategies

In Fig. 4.21 increases of efficient water use from baseline to strategy scenario are observed relative to the baseline scenario. For the three levels of key actor involvement, the preferred indicators and strategies are used. The preferred strategies and indicators are used as observed from the on-line survey results visualized in Fig. 4.20 and described in the previous section, with four minor adjustments. First, for the level of practice, indicator 13 referring to agricultural yield is used since this indicator is preferred by the farmers who did not participate in the on-line survey. Secondly, strategy 9 representing optimal seed quality is additionally included, for the same reason. Thirdly, for the level of policy indicator 11 is not observed since multiple key actors from this level evaluated this indicator as 'unclear'. Lastly, for the level of policy indicator 1 is observed although this did not appear as a preferred indicator according to policy survey participants. It is included because it has a significant role in the discussion on efficient water use in agriculture and is officially a highly significant indicator at the level of policy. In the figure the increases are visualized for both the winter wheat field in Tadla basin Morocco 2015/2016 and the smallholder maize field in Lower Limpopo basin Mozambique 2016. The first is referred to as 'wheat field', the second 'maize field'. Increases or improvement at the maize field is indicated using light colors, increases or improvement at the wheat field is indicated using darker colors.

It can be observed from the charts in Fig. 4.21(a) that according to the indicators preferred by key actors in practice, the largest improvement at the maize field is obtained using strategy 4. However, this strategy is not evaluated as most effective by key actors involved at this level. For the wheat field, strategy 9 would be most effective. This strategy is preferred by farmers from the observed maize field and was not evaluated as most effective by survey participants. Although strategy 9 does not generate the largest increases, this is the only strategy from which all the observed indicator increases are positive Strategy 10 is evaluated by survey participants from this level as most effective, however at the simulated fields no or a negative increase in efficient water use is observed according to the preferred indicators.
In Fig. 4.21(b) the increases of the indicators preferred by key actors in research are diverse. The largest increases are obtained with indicator 13 using strategy 4 and 6 which are also evaluated as most effective by key actors at this level. However, these strategies generate negative increases for the wheat field according to several indicators. Also strategy 9 is preferred of which the strategies are not the largest but mostly positive. Strategies 2 and 10 generating negative increases and strategy 5 generating very small increases are not preferred by key actors from this level of involvement. This suggest that key actors involved through research are aware of the potential results of strategies at field level and their relation to indicators of efficient water use.
Fig. 4.21(c) visualizes the increases of efficient water use according to indicators preferred by key actors at policy level. Most interesting is strategy 1 which is seen as most effective but has only negative increases according to the preferred indicators. The highest increases according to the observed indicators can be obtained at the maize field using strategy 4 and 6 which are also evaluated as most effective by the survey participants from this level. However, the large positive increases are only observed for the maize field. The largest increases for the wheat field according to the preferred indicators are obtained with strategy 9 which is not evaluated as most effective by the survey participants.



(a)



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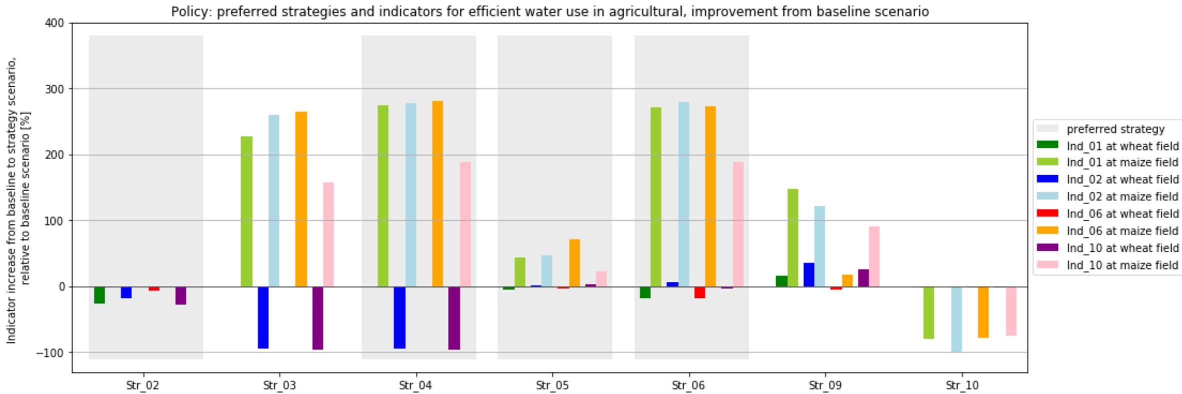


(c)

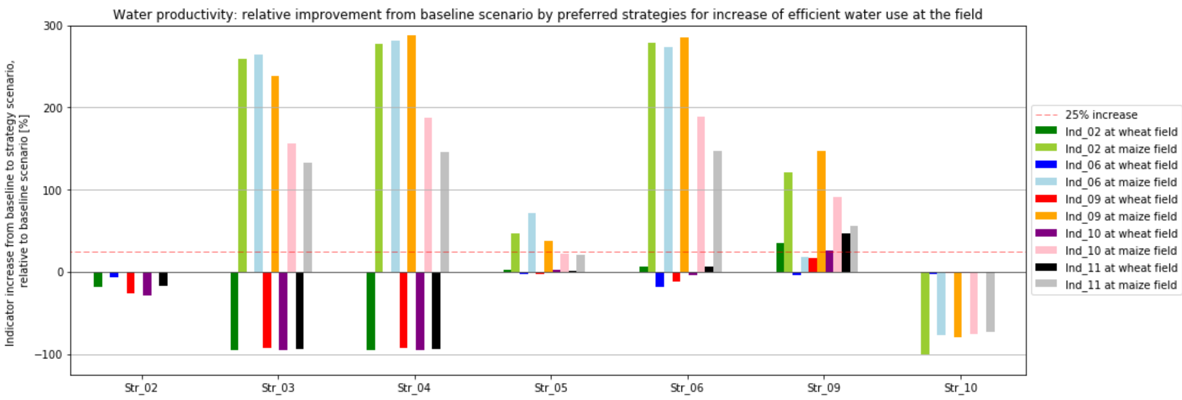
Fig. 4.21: Increases in efficient water use by strategy, relative to baseline scenario. Observed for strategies and indicators preferred by key actors from the three levels of involvement in (the discussion on) efficient water use in agriculture. (a) Increases according to indicators preferred by key actors in practice, preferred strategies are highlighted. (b) Increases according to indicators preferred by key actors in research, preferred strategies are highlighted. (c) Increases according to indicators preferred by key actors in policy, preferred strategies are highlighted.

4.6.3. Water productivity indicators

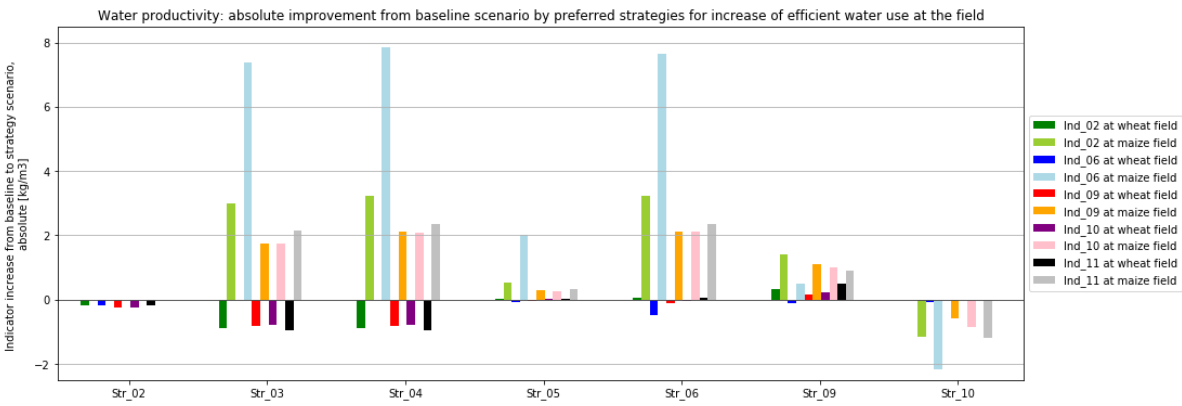
In Fig. 4.22 increases in water productivity are observed for the strategies preferred by survey participants. The indicators evaluated in the on-line survey that are water productivities are indicators 2, 6, 9, 10 and 11. Both the relative and absolute increases are observed. Observing the water productivity indicators specifically, the largest increases are obtained at the maize field, approaching a 300% or 8 $kg\ m^{-3}$ increase.

In Fig. 4.22(a) where the relative increases are visualized, also the 25% target used by the Dutch government is indicated. It is interesting that using strategy 2 and 10, this target is not met for either the wheat or the maize field. The target is met for the wheat field only for some indicators when strategy 9 is used. Using strategy 5, the target is met at the maize field for three of the five observed water productivity indicators. Using strategy 3, 4 and 6, large increases exceeding 100% are obtained at the maize field. It can be observed from this graph that significant differences are observed between the different water productivity indicators. These indicators can all be referred to as 'crop per drop' and can represent conceptual water productivity definitions used by various key actors, while generating different results at field scale.

The same results are observed in Fig. 4.22(b) where the absolute increases from the baseline scenario are observed, expressed in $kg\ m^{-3}$. Most interesting is indicator 6 of which the relative increases are of the same order as indicator 2 and 9 but of which the absolute values significantly exceed all other indicators. The opposite is observed for indicator 9 of which the relative increases are relatively larger than the absolute increases when compared to other water productivity indicators. This suggest the significance of the efficient water use observed at the baseline scenario, presented in Paragraph 4.4.



(a)

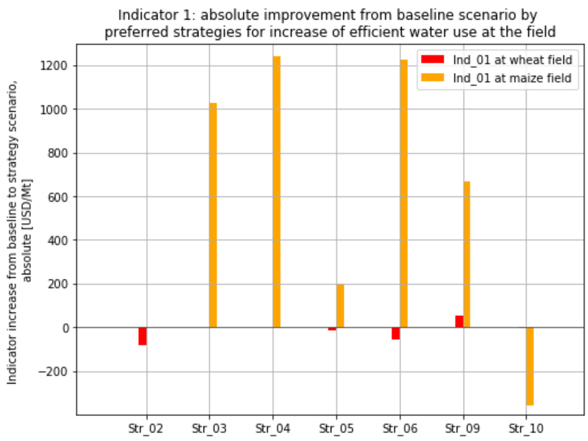


(b)

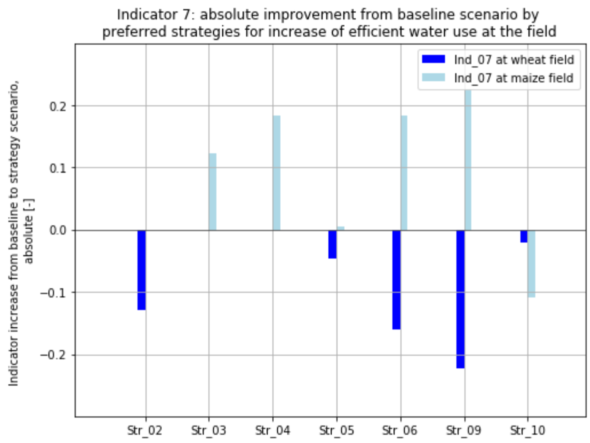
Fig. 4.22: Water productivity indicators evaluated as most relevant by key actors in survey: increases by strategy, relative to baseline scenario and absolute values. Observed for both simulated fields. (a) Relative increases expressed in % of baseline water productivity. Target of 25% increase used by the Dutch government is also indicated. (b) Absolute increase expressed in $kg\ m^{-3}$ increase from baseline water productivity.

4.6.4. Not water productivity indicators

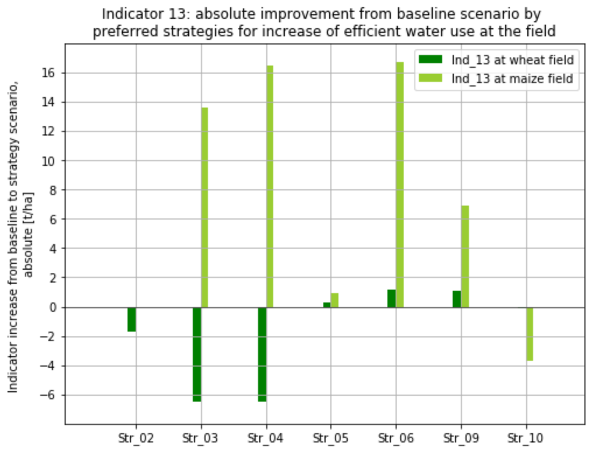
Absolute indicator increases of preferred indicators that are not water productivities, are visualized in Fig. 4.23. These graphs also indicate a large potential improvement for the maize field.



(a)



(b)



(c)

Fig. 4.23: Not water productivity indicators evaluated as most relevant by key actors in survey: absolute increases from baseline to strategy scenario. (a) Indicator 1, absolute increases expressed in $USD\ Mt^{-1}$. (b) Indicator 7, non dimensional absolute increases [-]. (c) Indicator 13, increases expressed in $t\ ha^{-1}$

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5
Discussion

This research analyzes leading perceptions regarding efficient water use at the agricultural field for a single growing season. Key actors perceive different strategies to obtain improvement of efficient water use and different indicators to quantify this improvement. At two different fields, a baseline scenario and strategy scenarios are simulated and the result is quantified according to the collection of indicators. Simulation is done using the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST), calibrated against the Surface Energy Balance Algorithm for Land model (SEBAL). The two collections of strategies and indicators are obtained from literature and from personal interviews with key actors. The achieved collections are coupled back to a large group of key actors who evaluated each strategy and indicators. Key actors are involved in agricultural water use or in the discussion on efficient water use in agriculture at the level of practice, research or policy.

The current chapter provides a discussion of the results. In Paragraph 5.1 the results and aspects of the analysis of efficient water use at the agricultural field in a single growing season is observed. First the representative agricultural fields are discussed. Second, a discussion on the indicators and strategies analyzed in the SWAP/WOFOST simulation is provided. Thirdly, the evaluation of the observed strategies and indicators by the key actors is discussed. In Paragraph 5.2 the used methods are discussed. First the observed benefits and pitfalls of calibration of SWAP/WOFOST with SEBAL are presented. Second, the possibilities and shortcomings of satellite data in this research are discussed. Thirdly, a discussion is provided on the use of an on-line survey for key actors from all levels of involvement, concerning the feasibility and effectiveness of this method.

5.1. Efficient water use at the agricultural field in a single growing season

In two different regions where improvement of efficient water use is desired, a representative agricultural field is selected and simulated for a single growing season. This resulted in a simulated baseline scenario for each field. Additionally for each field, ten strategies are simulated by adjustment of the baseline input data, resulting in 10 strategy scenarios for each observed field. From the output of a simulation, efficient water use is quantified for 13 indicators specifically. The collection of indicators for efficient water use includes *water productivity* indicators [$t\ m^{-3}$], *water efficiency* indicators [-] and *other* indicators expressed in various units. Quantification is obtained for each field, for both the baseline scenario and strategy scenarios. Improvement of efficient water use by a strategy is observed as the increase of an indicator from its baseline to a strategy scenario. Increases can be positive or negative, representing improvement respectively deterioration. Indicator increases can be observed as absolute values using the indicator's unit of expression, or relative to the baseline indicator value and thus expressed in percentage. The used collection of indicators and strategies is evaluated by a group of 25 key actors, involved in practice, through research or at policy level. Results of the simulations are observed specifically for the strategies and indicators evaluated as most effective and most relevant by the key actors from the three levels of involvement.

5.1.1. Representative agricultural fields

The two agricultural fields used in the analysis are most distinct in crop type, field area and production, irrigation method and soil type and storage change. The fields are introduced in Paragraph 3.2.
The first observed field is a winter wheat field in Tadla basin Morocco. The simulation start date is August 1^{st} 2015. The field area is 5.5 ha, the soil is sandy and the ground water table is very deep, seasonal storage change is -53 mm. The field is general performing, producing 6.6 $t\ ha^{-1}$ yield. The plot is part of a large irrigation system. Surface irrigation is applied, a total water depth of 570 mm in 7 applications along the growing season. The growing season is observed from November 28^{th} 2015 to May 23^{rd} 2016. This is a relatively dry season which is expected to be common in the coming decades.
The second observed field is a smallholder maize field in the Lower Limpopo basin Mozambique. The simulation start date is January 1^{st} 2016. The field area is 0.2 ha, the plot is found in a palustrine wetland ecosystem locally known as machongos, the soil is clayey peat. Machongos are characterized by a constant seepage flux from the shallow ground water table, referred to as sub soil irrigation. Hence, irrigation is regulated by management of the ground water table. A total water depth of 507 mm is applied along the growing season, the seasonal storage change is 212 mm. The smallholder plot is relatively good performing, producing 4.7 $t\ ha^{-1}$ yield. The growing season is observed from April 18^{th} to September 15^{th} 2016. This is a relatively dry season caused by a very strong El Niño Southern Oscillation (ENSO) period which is expected to be seen regularly in the coming decades.

Plausibility of baseline scenarios in representing actual fields The field baseline scenario is simulated in SWAP/WOFOST, calibrated against SEBAL data. The baseline scenarios are seen as plausible representations of reality when the output shows large similarity with the SEBAL result. Success of calibration is observed with the values of Root Mean Square Error or Deviation (RMSE) for deviation of SWAP from SEBAL at dates of SEBAL analysis, and the non-dimensional Normalized Root Mean Square Deviation or Error (NRMSD) which is equal to the RMSE divided by the range of the measured data. For simulation of Leaf Area Index (LAI) visualized in Fig. 4.2(a) and Fig. 4.8(a), obtained NRMSD is 0.11 for the wheat field and 0.26 for the maize field. The larger deviation at maize field is mostly caused by a single data point. For actual biomass production rate B_{act} [$t\ d^{-1}\ ha^{-1}$] see Fig. 4.2(b) and Fig. 4.8(b), NRMSD values are 0.11 and 0.38. For crop transpiration rates [$mm\ d^{-1}$], NRMSD values for the wheat field range between 0.03 and 0.31 see Fig. 4.3, for the maize field a range 0.18-0.32 is observed as can be seen from Fig. 4.9. Calibration of soil moisture content [$cm^{-3}\ cm^{-3}$] is less successful, see Fig. 4.4(a) and Fig. 4.10(a) indicating NRMSD values between 0.39 and 1.63.

This suggests that both fields are sufficiently successful calibrated, especially observing LAI, the actual biomass production rate B_{act} [$t\ d^{-1}\ ha^{-1}$] and crop transpiration rates including actual transpiration T_{act} [$mm\ d^{-1}$], potential transpiration T_{pot} [$mm\ d^{-1}$], relative transpiration T_{rel} [$-$] and transpiration reduction T_{red} [$mm\ d^{-1}$]. Less similarity between SWAP and SEBAL is observed for the soil moisture content [$cm^{-3}\ cm^{-3}$]. The winter wheat field is most successfully calibrated.

The seasonal yield on both fields is high compared to prior research and local knowledge, see Fig. 4.5 and Fig. 4.11. No data on ground water level or pressure heads is available. The initial ground water level and vertical water flux at three meter soil depth are calibrated within plausible ranges. No soil ground data is available for the winter wheat field, soil hydraulic parameters are calibrated using initial parameters from the HiHydroSoil dataset. Soil hydraulic parameters for the maize field are determined from field measurements and the Staring Series from Wösten et al. Also for both fields the crop characteristics are calibrated within plausible ranges using representative WOFOST calibrations from prior research. The calibrated biomass partitioning deviates from prior WOFOST calibrations. Commonly after crop anthesis (flowering), 100% of the daily biomass dry mass growth is partitioned to the crop storage organs (seeds). In the current calibrations, between anthesis and maturity, 25-45% of the daily biomass dry mass growth is partitioned not to storage organs but to leaves and stems. In the calibrated baseline scenarios, horizontal fluxes including run on and run off, lateral drainage and infiltration are not observed. No data of these fluxes is available. Their non-existence can be be explained with the relatively dry top soil and soil moisture content, resulting in only horizontal fluxes.

> This suggests that further knowledge on crop physiology including plausible ranges and correlation of the crop characteristics could result in a more plausible simulation of the observed crop growth in WOFOST. Additionally, data on soil characteristics and ground water is expected to allow for a more accurate simulation of the actual fields.

The SWAP bottom boundary for water transport is defined by a calibrated bottom flux. The selected initial ground water depth is deep. Although the simulated season is dry, a deep water table is not common in the observed area. Fig. 4.10(a) shows that the simulated root zone soil moisture shows a satisfactory level of similarity with SEBAL data, NRMSD is 0.42. Since no data is available on ground water levels and hydraulic pressure heads, it cannot be verified whether the selected bottom boundary definition is suitable for the observed maize field in the Lower Limpopo basin.

> This suggests that data on ground water levels, vertical fluxes or hydraulic pressure heads could be a valuable contribution to the applied methodology of calibration of SWAP/WOFOST against SEBAL.

Plausibility of strategy scenarios in representing strategies implemented at actual fields Strategy scenarios are obtained by simulation of SWAP/WOFOST, with adjusted parameters for the calibrated baseline scenario. The observe strategies are presented in Paragraph 3.3.

At the winter wheat field, surface irrigation is applied. Hence, strategies involving criteria for irrigation application are simulated directly, since SWAP allows the use of these criteria and computes the required irrigation timing and water depth. At the maize field, sub surface irrigation is applied for which the bottom flux is calibrated using 10 records between January 1^{st} and November 1^{st}. The strategies involving criteria for irrigation application are also calibrated, resulting in series of 13 to 15 bottom flux records for the same time span. For the strategy of elimination of irrigation to make the water available for other uses, free drainage of the soil profile is simulated in SWAP. The winter wheat field is part of the Beni Moussa irrigation system. When less water is applied for irrigation, this is available for other users in the system or a smaller amount of water can be allocated to the system. The maize field is part of the Fidel Castro irrigation/drainage block, water drained from this area can be used for rice irrigation in a large downstream irrigation system.

> For both fields, the assumption is made that water is used beneficially when not applied for irrigation at the observed field.

A strategy for increase of soil moisture retention which can be obtained using polymere waterpads is simulated with a computed increase of the residual and saturated soil moisture content for a 20 cm soil layer in the crop root zone. This is estimated based on information available on the polymere waterpad characteristics. Other soil hydraulic parameters are assumed to remain unchanged.

> This suggests that more information on the effect of polymere water pads on the soil hydraulic parameters could result in a better simulation of this strategy. Since this strategy is relatively new and data unavailable, this could require field and laboratory measurements.

A strategy for optimizing seed quality is simulated using parameters for crop characteristics from WOFOST calibrations for the same crop type in similar areas, obtained from prior research. The assumption is made that the used calibrations from prior research use optimal seed quality and are representative for the observed areas.

> This suggests that further knowledge on crop physiology including plausible ranges and correlation of the crop characteristics could result in a more plausible simulation of optimal seed quality in WOFOST.

Efficient water use, differences between the observed fields The used indicators for efficient water use at the agricultural field are presented in Paragraph 3.4. For both fields, efficient water use indicators are computed for the baseline scenario, see Fig. 4.14. The observed ranges of water productivity values and water efficiency values at the baseline scenario are larger for the maize field than for the winter wheat field. The highest and lowest values for water productivity and for water efficiency are all observed at the maize field.

> This suggests that ranges observed in baseline efficient water use are specific for a region or a crop or an individual field.

For both fields, the relative increases of indicators from baseline to strategy scenarios are observed, see Fig. 4.18 and Fig. 4.17. According to these results, most of the applied strategies have a larger effect on the maize field than on the winter wheat field. Only the effect of strategy 1 where irrigation is eliminated, generates results in the same order of magnitude. Some strategies including 3, 4 and 6 that result in significant improvement of efficient water use at the maize field according to most indicators, results in a deterioration of efficient water use or small improvements at the winter wheat field according to the same indicators. According to the relative increases of the water efficiency indicators, all strategies at the winter wheat field result in a deterioration of efficient water use.

> This suggests that the potential improvement of efficient water use for different fields is diverse. At the winter wheat field, for some indicators improvement is not even possible with the observed strategies.

For both fields, relative and absolute increases are observed, according to water productivity indicators evaluated by key actors as most relevant, for strategies which are evaluated by key actors as most effective, see Fig. 4.22. The Dutch government uses a 25% water productivity as target in the improvement of efficient water use. At the Dutch Directorate-General for International Cooperation (DGIS), indicator 5 is commonly used. As can be observed from Fig. 4.18, the target of 25% increase of indicator 5 is never met at the wheat field. At the maize field, this target is met using strategies 1, 3, 4, 5 and 6.

> This suggest that the potential increase in water productivity for different fields is diverse. At the winter wheat field, the 25% target of the Dutch government according to their water productivity indicator cannot be met by observed strategies.

Efficient water use at other fields The observed strategies and indicators are simulated for two different fields. This section discusses coherence observed between the two fields and the question whether this is also expected at other fields that are not simulated.

Relative increases with the strategies and indicators evaluated as most effective and most efficient by key actors are observed, see Fig. 4.21. According to this dataset, the best results are obtained using strategies 5 and 6 involving deficit irrigation to criteria of relative transpiration and strategy 9 involving optimal seed quality. For these strategies, most indicators are positive, only for the winter wheat field small negative increases are observed using indicator 1, 7 and 9. This dataset of preferred indicators and strategies reveals that for both fields, strategy 10 involving soil water retention increase, has a marginal or negative effect. Strategy 2 involving sprinkler irrigation only applies at the surface irrigation field and has a small negative effect. Especially strategies 3 and 4 involving deficit irrigation to the criteria of soil moisture content have an opposite effect where at the maize field large improvements of efficient water use is obtained and at the winter wheat field only deteriorations. The large differences described in the previous section indicate that baseline efficient water use and improvement of efficient water use by a strategy is highly field-specific.

> This suggests that it is impossible to predict baseline efficient water use and improvement of efficient water use by a strategy on other fields. Strategies 5 an 6 involving deficit irrigation to the criteria of relative transpiration and strategy 9 representing optimal seed quality, are likely to result in an improvement of efficient water us at other fields.

5.1.2. Indicators and strategies analyzed using SWAP/WOFOST simulation

A collection of 10 different strategies and 13 different indicators are analyzed using a SWAP/WOFOST simulation of two different fields, presented in Paragraph 3.3 and 3.4.

Completeness of selected indicators and strategies The collection of indicators and strategies is obtained from a thorough literature study and multiple interviews. Consulted literature includes both academic research and policy publications. A total of 40 personal interviews were conducted with key actors in the Netherlands and in Mozambique. The key actors are involved at the level of practice, research or policy. No interviews were conducted with key actors from Mozambique. The selected indicators and strategies from the observed perceptions are those that have a prominent role or appear most frequently in the observed groups of key actors. The obtained collection of indicators and strategies represents the variety of perceptions observed with Dutch and Mozambican key actors.

The strategies are confined to the possibilities of simulation in SWAP/WOFOST and the spatial and temporal scale of a single field for a single growing season. This means that long term strategies or strategies at the level of an irrigation system are not observed. In the simulation of SWAP/WOFOST, fertile soil and healthy crops are assumed, corresponding to the general and good performing observed actual fields. The optional detailed chemical transport models PEARL for pesticides and ANIMO for nutrients are not included. Strategies involving pesticides and fertilizers mentioned by key actors are therefore excluded. In interviews, key actors often mentioned social structures, communication, education and operation at system scale to be highly relevant in the improvement of efficient water use. These aspects in water management are prerequisites for the observed strategies, not analyzed in the current research. Feasibility of practical implementation at of strategies at actual fields is not included in the selection process. However, this is expected to be incorporated in key actors' perceptions. Additional research for implementation costs are required for recommendations.

> This suggests that strategies involving presticides and fertilizers excluded from this research could be relevant. Also, implementation of the observed strategies is not necessarily feasible.

The indicators are also confined to the output of SWAP/WOFOST for a single field and growing season. Hence, long-term sustainability is not observed. The SWAP/WOFOST output is are field average values, equity and uniformity within the field cannot be evaluated.

It can be argued that indicators are only relevant when measurement is feasible in practice. This has not been included in the selection of indicators, although it is expected to be incorporated in key actors' perceptions. In order to recommend an indicator for general use, knowledge on feasibility and expected costs is required. Some indicators observe the effect of irrigation water only, for which data is required on both the irrigated and rain fed scenario of the same field for the same growing season. This data cannot be monitored in reality, these indicators are therefore theoretically. This concerns indicator 2, 3, 4, and 7.

> This suggests that there can be other indicators involving equity and uniformity within a field which are not observed in the current research. Also, actual monitoring is not possible for the theoretical indicators 2, 3, 4 and 7.

Sensibility of simulated strategies The observed strategies are general, not optimized for a specific field, in order to allow comparison between different fields. The simulated strategies correspond to perceptions of the observed key actors. Required parameters for implementation of the strategies in SWAP/WOFOST are used from prior research.

With strategy 3 and 4, moderate and mild soil water deficit is observed. for the soil moisture content at 40 cm soil depth the criteria of 55% respectively 65% of the soil moisture content at field capacity pF2 is used. This corresponds to prior research. At the wheat field the pF2 soil moisture content is for the soil layer at 40 cm depth is 0.369 [cm^3 cm^{-3}], at the maize field 0.560 [cm^3 cm^{-3}] is observed at pF2. The soil water retention curve of the winter wheat field soil layer is very steep so that the pressure head at the soil moisture content at 65% of 0.369 [cm^3 cm^{-3}] is below h_4, which is the critical pressure head below which root water extraction is impossible. Hence, this criterion for the soil at 40 cm depth at the winter wheat field will result in a soil moisture content at which is too low to allow root water extraction but too high to allow irrigation application. For a soil moisture content criterion of 55% of the soil moisture content at pF2, this effect is observed to an even greater extent. Indeed with strategies 3 and 4, no irrigation is applied at the winter wheat field while crop transpiration and field production is greatly decreased. The soil water retention curve at the maize field is very flat. The soil moisture contents used for criteria of irrigation correspond to pressure heads where root water uptake is allowed. Hence, these criteria are easily met resulting in irrigation application and crop water stress is small. Indeed, with strategies 3 and 4 at the maize field, 606 and 613 mm is applied which exceeds the maize field baseline application.
This illustrated that using strategies 3 and 4, large differences can be observed between fields with different soil characteristics. An alternative strategy where this difference is expected to be smaller is to use a percentage of the Totally Available Water (TAW) content [cm^3 cm^{-3}] or Readily Available Water (RAW) content [cm^3 cm^{-3}] as criterion for irrigation application. TAW is the water content between field capacity pF2 and wilting point pF4.2. For the winter wheat field at 40 cm soil depth, pF4.2 corresponds to a soil moisture content of 0.324. Hence, criteria of 0.55 and 0.65 % TAW correspond to 0.349 and 0.353 cm^3 cm^{-3}. RAW is the water content between field capacity pF2 and the critical pressure head below which root water extraction is reduced which is h_3h for a high actual transpiration T_{act} rate. For the winter wheat field, h_3h corresponds to a pressure head of -400 cm at which a soil moisture content of 0.357 is found. Hence, criteria of 0.55 and 0.65 % RAW correspond to 0.363 and 0.365 cm^3 cm^{-3}. It is expected that these criteria will result in better performance of the winter wheat field than currently observed by strategies 3 and 4. It is expected that the differences for the maize field will be smaller.

> This suggests that strategies 3 and 4 using a fraction of soil moisture content cm^3 cm^{-3} at field capacity pF2 as criterion for deficit irrigation, are not beneficial for all soil types.

With strategy 5, transpiration deficit is observed throughout the growing season. This is also a criterion for deficit irrigation which is more directly related to crop performance than criteria for soil moisture content. The selected 75% of relative transpiration $T_{rel\ [-]}$ is used from literature. It is expected that crop tolerance for transpiration reduction is crop- and region specific which explains different results for the observed fields.
Using strategies 3, 4 and 6 at the maize field results in large seasonal biomass production, exceeding 60 $t\ ha^{-1}$ and high yield production which exceeds for strategy 4 and 6 20 $t\ ha^{-1}$. In the SWAP/WOFOST simulation

This suggests that strategy 5 using 75% of relative transpiration $T_{rel\ [-]}$ as criterion for deficit irrigation generates different results for various crop types.

of strategy scenario 4 and 6, the actual biomass production rate for total dry mass B_{act} $[t\ d^{-1}\ ha^{-1}]$ and the actual biomass production rate for dry mass of storage organs $B_{SO,act}$ $[t\ d^{-1}\ ha^{-1}]$ representing the yield rate are equal to the potential rates for every day of the growing season. It can be questioned whether these high quantities that are possible in SWAP/WOFOST simulation are physiological feasible.

This suggests that the results obtained for strategies 3, 4 and 6 involving deficit irrigation at the maize field are not representative for the observed strategies.

With strategy 7 and 8, variation of sowing dates is observed. A sowing date postpone and advance of 10 days is used. This is very general and not specific. In the on-line survey these strategies were evaluated 'unclear' by 64% of the survey participants. Instead of these two strategies, it would be interesting to observe the strategy 'best sowing date for highest yield' for each observed field. This would require the simulation of multiple sowing dates for each field and a selection of the best performance. However, the optimization of strategies is not within the scope of this research.

This suggests that the definition of strategies 7 and 8 involving change of sowing dates is too general.

Reliability of computed indicators Indicators are computed directly from the SWAP/WOFOST output files, no measurement errors can be made in copying of the data. The obtained data is assumed to be accurate, since the SWAP/WOFOST computations are known to be very precise and a daily time step is used for water balance computations.
Some indicators involve the effect of irrigation water only. This is not included in the SWAP/WOFOST output, where no distinction is made between applied and naturally present water. Hence, for each observed field also the rain fed scenario is simulated. Output from the rain fed scenario is subtracted from output from a baseline or strategy scenario, in order to obtain the effect of the irrigation water. This is an assumption that cannot be verified with field measurements.

This suggests that the computed indicators are accurate for the WOFOST/SWAP simulations. The assumption is made that for a baseline or strategy scenario where both natural and irrigated water is present, an effect of irrigation water only can be quantified by subtraction of this same output for the rain fed scenario.

Usefulness of indicators Indicator 1 representing SDG indicator 6.4.1. Fig. 4.17 shows that as expected the relative increases of this indicator are equal to indicator 8, the irrigation water productivity from 1997. This strategy results in an increase for SDG indicator 6.4.1 of 148 $USD\ Mm^{-3}$ for the smallholder maize field and 17 $USD\ Mm^{-3}$ for the winter wheat field, see Fig. 4.23(a). No values are computed for strategies where no irrigation water is applied, thus the indicator does not provide information on whether this is an improvement or deterioration of efficient water use. Evaluating the applied irrigation water is relevant when data is available regarding efficient use of water for other purposes than field application. This is outside the scope of this research but expected to be difficult to quantify. Also, the water depth or volume of applied irrigation water is difficult to monitor accurately. An alternative for the use of irrigation water in the denominator is to use seasonal evapotranspiration (ET) or transpiration (T). These water volumes or depths provide information on the consumption of water by the observed system and by the crop. These quantities can also be accurately monitored with remote sensing technologies. Indicator 2, 9, 10 and 11 use T or ET in the denominator. According to these indicators strategy 1 representing elimination of irrigation has a negative effect on the efficient water use at maize field, see Fig. 4.17.

> This suggests that water productivity indicators with the volume or depth of irrigation water applied in the denominator are less favorable than when T or ET is used. Hence, indicators 2, 9, 10, 11 are prefered above 1, 6 and 8. This also suggests that indicators 3, 4, 7 and 12 are less useful since these also use the volume or depth of irrigation water applied.

The DGIS uses indicator 5 representing biomass production divided by transpiration. A 25% increase is desired. At the maize field this target is met by, among other strategies, elimination of irrigation, see Fig. 4.18(b). However, this strategy also results in a 87% decrease of seasonal yield, see Fig. 4.17(b). This chart also demonstrates that the change to optimal seed quality at the smallholder maize field results in a water productivity increase of -26% for this indicator, while all other indicators suggest an improvement of efficient water use. These results reveal that the results from this indicator are misleading. The odd results are caused by the use of biomass production in the nominator of the water productivity definition. Yield production is more representative for the desired field performance.

> This suggests that indicator 5 representing biomass production divided by transpiration and used by DGIS, is not a useful indicator. Model results demonstrate that more representative values for improvement of efficient water use are obtained when agricultural yield is used in the nominator of the water productivity definition.

In Fig. 4.18(a) the effect according to three efficiency indicators (3,4 and 7) at the winter wheat field is observed. These indicators suggest that strategy 9 representing optimal seed quality results in a deterioration of efficient water use. When irrigation is eliminated, only indicator 7 for the maize field indicates a deterioration of efficient water use. Furthermore, the simulation results reveal that according to the efficiency indicators, strategies have different effects at both fields. Only at the winter wheat field, indictor 3 and indicator 7 generate similar results.

> This suggests that efficiency indicators are not useful for quantification of efficient water use. It also suggests that when the term 'water use efficiency' is used, this needs to be clearly defined since it allows multiple interpretations that have very different results at field scale.

Long-term and large-scale analysis In the current research the temporal and spatial scale of a single field and a single growing season is observed. Simulation of multiple years and a larger scale in the Fidel Castro irrigation/drainage system in Mozambique would allow the use of accumulated water storage in the soil to be used in the following season. Maize production rates at system scale are expected to be lower since in the current research a relatively good performing smallholder maize field is simulated. In Tadla basin, simulation of multiple years would allow to compute deep aquifer recharge and depletion, observing also the ground water pumping rates present in the basin. Since the simulated winter wheat field is average performing, production rates at system scale are expected to be comparable. The simulated growing seasons are relatively dry, it would be interesting to simulate the strategy scenarios for other seasons. In the current research, baseline scenario and strategy scenarios are simulated for the same growing season. Observing multiple years would allow to compute year to year indicator increases.

> This suggest that it would be interesting to supplement the current research with long-term and large-scale analysis.

Overlap and discrepancies of efficient water use values For two fields, baseline water productivity is observed according to 13 indicators, see Fig. 4.14. The range of different water productivity values is larger than observed with the water efficiency values. Except for indicator 5, the difference between the fields for each baseline water productivity indicator is smaller than observed with the water use efficiency indicators and the indicators with other units of expression.

> This suggests that baseline water productivity is less field specific than baseline efficient water use according to other indicators.

For two fields, indicator increases are observed according to 13 indicators, from baseline to strategy scenario for 10 different strategies, see Fig. 4.17 and Fig. 4.18. The increases are expressed in % relative to the baseline scenario. Increases from indicator 12 representing 'Water saving' are very different and often opposite of the increases observed according to other indicators. The largest increases are observed at the maize field using strategies 3, 4 and 6. Strategy 5 at the maize field is the only strategy for which all indicator increases are positive. Strategy 10 at both fields is the only strategy for which all increases are negative. There is no indicator which reveals only positive or only negative increases. The increases according to the water efficiency indicators are relatively small compared to the other indicators.

> This suggests that the observed indicator increases which all represent *improvement of efficient water use*, actually indicate improvement of different aspects of water use. The relative increases of these aspects from baseline to strategy scenarios have different maginudes and directions.

See Fig. 4.22, a water productivity increase of 25% is reached with strategy 5 and 9 at the maize field, according to some of the water productivity indicators. Other indicators present an increase below the 25% target. Between the different water productivity indicators, the differences in relative increases and in absolute increases are significant. For strategy 9 at the maize field the relative water productivity increase ranges between 18% according to indicator 6 and 148% according to indicator 9. For strategy 5 at the maize field the absolute water productivity increase ranges between 0.3 $kg\ m^{-3}$ according to indicator 11 and 2.0 $kg\ m^{-3}$ according to indicator 6. For strategy 6 and 9 at the winter wheat field, both positive and negative water productivity increases are observed.

> This suggests that different water productivity indicators, that can all be referred to as 'crop per drop' expressed in $kg\ m^{-3}$, can result in very different results for both absolute and relative increases from baseline scenario. Even both positive and negative increases can be observed for the same field using the same strategy.

5.1.3. Indicators and strategies evaluated by key actors

The collection of indicators and strategies is presented to key actors involved in practice, through research and at policy level. For a case with surface irrigation representing the winter wheat field and a case with sub surface irrigation representing the maize field, survey participants evaluated the potential relevance of each indicator and the potential effectiveness of each strategy. Additionally from the collection a single most effective strategy and single most relevant indicator for a general field was selected. Indicators and strategies could also be evaluated as 'unclear'. A criterion is observed for for most effective strategies and most relevant indicators. At this criterion, responses to different survey questions are combined, where positive weights are used for evaluation 'most important' and negative weights for the evaluation 'misleading'. The top three scores are observed for each key actor level of involvement. This is visualized in Fig. 4.20 and Fig. 4.21.

Indicators evaluated as unclear For the two cases, the mean response rate for the evaluation 'unclear' for each indicator for each level of key actors is observed, see Fig. 4.20(c). This value is for each indicator significantly larger for key actors in practice and in policy compared to key actors in research. The highest mean response rate 'unclear' is obtained for indicator 11, where 40% of the key actors involved at policy level evaluated this indicator as 'unclear'. Indicators 7, 10, 11 and 12 have a mean response rate 'unclear' exceeding 10% for all three levels of involvement.

This suggests that the presented indicators are most common or understandable for key actors involved in research. Also, indicators 7, 10, 11 and 12 are the least clear for all key actors.

Unity and discrepancies within levels In the computed most relevant indicators and most effective strategies, the scores for key actors in research are significantly smaller than for key actors in policy and practice, see Fig. 4.20(a) and Fig. 4.20(b).

This suggests that key actors in research are either less eager to evaluate a strategy or indicator as 'most effective' or 'most relevant' or more often evaluate an indicator as 'misleading'. It could also mean that a larger variety of perceptions is observed between key actors in research than key actors in other levels.

As can be observed from these charts, key actors in research evaluate indicator 7, 11 and 13 as most relevant. Indicator 7 is a non-dimensional efficiency, indicator 11 is a water productivity expressed in $kg\ m^{-3}$ and indicator 13 represents agricultural yield expressed in $t\ ha^{-1}$. Key actors involved at policy level evaluated in the on-line survey indicators 2, 6, 10 and 11 as most relevant. These are all water productivities, expressed in $kg\ m^{-3}$. Key actors involved in practice evaluated in the on-line survey indicators 1, 2 and 9 as most effective. Indicators 2 and 9 are water productivities expressed in $kg\ m^{-3}$, indicator 1 can also be seen as a water productivity, expressed in $USD\ m^{-3}$. A discrepancy can be observed within the perceptions of key actors involved in practice and in policy. In practice, participants in the on-line survey evaluate strategies and indicators differently than the farmers interviewed. In policy, a difference is observed between the official indicators including indicator 1 and indicators evaluated as most relevant by individual survey participants.

This suggest a difference in perception between farmers and other key actors involved at a practical level. It also indicates a difference between official perception and personal perceptions of key actors at a level of involvement. Individual key actors involved in research evaluate four water productivities as most relevant indicators for efficient water use. Only key actors in research evaluate a water efficiency as most relevant indicator for efficient water use.

Overlap and differences between levels As can be seen from Fig. 4.20(a), strategy 6 is evaluated as most effective by all levels of involvement. In the on-line survey, 24% of the survey participants evaluated this strategy as most effective. Strategy 3 has the higest score of all strategies according to the used criterion. Strategies 1, 7 and 8 are evaluated as most effective by none of the three levels.

Two strategies can be seen as evaluated most effective by all key actors. This includes strategy 3 involving moderate soil water deficit as percentage of soil moisture content at field capacity pF2 and strategy 6 which involves optimal crop transpiration are seen by key actors as most effective strategies. Strategies for change of sowing date and elimination of irrigation is not seen as effective.

There is no indicator that is seen as most relevant according to the criterion by all three levels of involvement, see Fig. 4.20(b). Indicators 3, 4, 5, 8 and 12 are evaluated as most relevant by none of the three levels. Indicators 2 and 11 are seen as most effective by two of the three levels of involvement according to the used criterion. In the survey question with with the highest response rate (see Fig. 4.19(a)), 11% of the survey participants evaluated indicator 2 as most relevant, all other indicators were evaluated 'most relevant' by only 0-6% of the survey participants.

This suggests that there is a large variety of perceptions concerning relevant indicators for efficient water use. If any, indicators 2 and 11 are most preferred by all levels of involvement. Indicator 2 is the adjusted Sustainable Development Goal (SDG) indicator 6.4.1 see eq (3.4.2). Indicator 11 is the Process Depleted Water Productivity from 1997 see eq (3.4.11).

Coherence between preferred indicators and strategies In Fig. 4.21 for each key actor level results for the preferred strategies and indicators are visualized. Observed with key actors involved at the level of practice and policy, the strategies that obtain the largest improvement in efficient water use according to the most relevant indicators are not the strategies that evaluated as most effectively. Even more, strategies are seen as most effective that generate negative increases for both the observed fields. For the indicators seen by key actors in research as most relevant, the same key actors also see as most effective strategies 6 and 9 which generate the best result according to these indicators. The same is observed for key actors in practice. However, these key actors also see strategy 10 as most effective which has either none or a large negative effect on the observed fields, according to the indicators seen as most relevant by key actors in practice. For the indicators seen as most relevant by key actors in policy, strategy 9 would be most effective. However, this strategy is not seen as most effective by key actors at this level. Instead, key actors involved at policy level see strategy 2 as most effective which generates only negative increases according to the indicators seen as most relevant. By all levels of involvement either strategy 3 or strategy 4 is seen as most effective. In these strategies, deficit irrigation is defined by the criterion of soil moisture content at a fraction of the soil moisture content at field capacity pF2. These strategies are not beneficial for all soil types, as discussed in Paragraph 5.1.2.

This suggests that key actors involved through research are most aware of the potential results of strategies at field level and their relation to indicators of efficient water use. Key actors at practical and policy level see strategies as most effective that generate only negative increases of indicators seen as most relevant. Key actors from all levels see a strategy as most effective where deficit irrigation is applied by the criterion of soil moisture content at a fraction of the soil moisture content at field capacity pF2. These strategies are not beneficial for all soil types.

At Dutch policy level, the official target in improvment of efficient water use is a 25% increase of water productivity according to indicator 5. As can be seen in Fig. 4.18, this target can only be met at the maize field using strategy 1 and 3-6. Strategy 1 is the elimination of irrigation. Strategy 3-6 involve deficit irrigation based on criteria for soil moisture content or crop relative transpiration. In Fig. 4.17 can be seen that apart for indicator 5 and indicator 12 representing water saving, strategy 1 results in a deterioration of efficient water use at the maize field, including a reduction in agricultural production exceeding 75%.

This suggests that the waterproductivity indicator used by DGIS for evaluation of improvement efficient water use, is not representative when ultimately food security is desired, since this indicator can suggest an improvement when the agricultural production is significantly decreased.

5.2. Applied methods

For the analysis of indicators and strategies at the agricultural field, field simulations in the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST) are used, calibrated against output from the Surface Energy Balance Algorithm for Land model (SEBAL). Model and satellite data is used as input data for SWAP/WOFOST and SEBAL. Strategies and indicators are obtained from interviews and literature study, key actors evaluated the obtained collection through an on-line survey. In this paragraph these methods are discussed.

5.2.1. Benefits and pitfalls of calibration of SWAP/WOFOST with SEBAL

For two different areas, SEBAL analysis is conducted resulting in spatial distributed datasets of daily values for each day of SEBAL analysis. In each area, the data is aggregated to field averages for a single field. Thus, time series are obtained for field characteristics against which SWAP/WOFOST is calibrated. SEBAL output used for this purpose is the Leaf Area Index (LAI) [-], actual and potential transpiration rates T_{act} $[mm\ d^{-1}]$ and T_{pot} $[mm\ d^{-1}]$, soil moisture content for top soil and root zone SM_{ts} $[cm^3\ cm^{-3}]$ and SM_{rz} $[cm^3\ cm^{-3}]$, and actual biomass production rate B_{act} $[kg\ ha^{-1}\ d^{-1}]$. SWAP is first calibrated using the simple crop module where the LAI is forced by the user. Secondly, SWAP is calibrated using the detailed crop model WOFOST where LAI is computed defined by simulated physical processes. For both SWAP with the simple module and SWAP/WOFOST, calibration was obtained step-wise. Each step is an iterative process upon satisfactory result for the desired step output.

Reference Evapotranspiration in SWAP and SEBAL SEBAL and SWAP both use Penman-Monteith according to the method standardized by the Food and Agriculture Organization (FAO) for computation of evapotranspiration (ET) rates. Both models can compute the reference evapotranspiration rate assuming grass coverage ET_{ref} $[mm\ d^{-1}]$. When the same method and input parameters are used, ET_{ref} is identical for both models. However a deviation is observed at both fields which is largest at the maize field, see Fig. 4.1. Deviations are quantified using the Root Mean Square Error or Deviation (RMSE) and the Normalized Root Mean Square Deviation or Error (NRMSD), where NRMSD is defined as the RMSE divided by the range of the measured dataset. Thus, for the wheat and maize field ET_{ref}, RMSE values of 0.34 and 1.17 $mm\ d^{-1}$ and NRMSD values of 0.06 respectively 0.56 are observed.
It is assumed that both models use the same method for computation of Penman-Monteith. The standardized method also provides methods for computation of missing data. SWAP and SEBAL use different elements of the Global Land Data Assimilation System (GLDAS) for meteorological input data, SEBAL uses daily mean air temperature $T_{mean,day}$ $[°C]$ and SWAP uses the minimum and maximum air temperatures $T_{min,day}$ $[°C]$ and $T_{max,day}$ $[°C]$. Hence, RH [%] used in SEBAL is computed using daily mean specific humidity $H_{mean,day}$ $[kg/kg]$, surface pressure $P_{mean,day}$ $[Pa]$ and mean air temperature $T_{mean,day}$. For computation of the actual vapor pressure $e_{act,mean,day}$ $[kPa]$ used in SWAP a more precise method is used where instead of the mean air temperature $T_{mean,day}$, the minimum and maximum air temperatures $T_{min,day}$ and $T_{max,day}$ are used. The daily minimum and maximum temperature are used in SWAP for accurate estimations of the saturated vapor pressure $e_{sat,mean,day}$ $[kPa]$ which has a crucial role in the Penman Monteith equation. The model dynamics of SEBAL concerning computation of $e_{sat,mean,day}$ for Penman Monteith are not investigated.

> This suggests that because of the different temperature data used in SEBAL and SWAP, different components of the Penman Monteith equation are derived, resulting in a deviation of reference evapotranspiration ET_{ref} $[mm\ d^{-1}]$ of both models. The observed deviation is largest at the maize field.

Evaluation of SEBAL In the current research, SEBAL output is assumed to accurately represent actual field parameters. With the obtained parameters, SWAP/WOFOST is calibrated. The latest pySEBAL 3.3.6 beta version for Landsat imagery is used. This is run from Python, input is required in an Excel file. Output is spatially distributed data in raster files.

SEBAL requires input of soil hydraulic parameters, for which spatially distributed HiHydroSoil model data is used. The same soil hydraulic parameters are used as initial parameters in the SWAP/WOFOST calibration.

However, for the wheat field these parameters are adjusted during the calibration and for the maize field other parameters were derived from field measurements. Hence, the soil characteristics for the same field used in SEBAL are different from the calibrated parameters in SWAP.

> This suggests that the observed fields could be more optimally simulated when the SEBAL simulation is repeated using the calibrated soil characteristics, after which the SWAP/WOFOST calibration is repeated with the new SEBAL output. This process can be repeated. It is expected that this additional iteration will converge to a more accurate simulation of the actual fields.

Difficulties were encountered in the use of SEBAL for this research. SEBAL is python based and uses the Geospatial Data Abstraction Library (GDAL) package. At the time of SEBAL simulation for this research, GDAL was updated or instable resulting in difficulties in SEBAL simulation. Python is open source, it is thus free and available for anyone and also permanently under development.

> This suggests that SEBAL is accessible for many users. However, the used Python packages can be unstable, causing difficulties for the current pySEBAL model.

SEBAL output is spatially distributed with a precision of 30 m when Landsat data is used. However, for calibration of SWAP/WOFOST field averages are required. For this purpose, a Python script is developed requiring a time series of SEBAL output and a shapefile with polygons for the observed fields. The generated output is a time series of field averages. Since SEBAL is also Python based, such computations could be included in the SEBAL. SEBAL input is required in a separate Excel file. This is sensitive for errors and time consuming when SEBAL output is desired for multiple dates. To run SEBAL Python is required, hence SEBAL input could be linked directly to the SEBAL python file allowing automation.

> This suggests that at the current pySEBAL version allows several improvements could be made to increase the user friendliness.

Evaluation of land use classifications In this research, in two areas a typical and representative field is simulated. To obtain SEBAL results for a single field, the exact geographical location is required. For this purpose, land use classifications were conducted for both regions using the Google Google Earth Engine code editor (EE). This is an Application programming interface (API) which allows computations with spatial data without downloading the used datasets. For the classificiation methods, Normalized Difference Vegetation Index (NDVI) data is used from Landsat 7 imagery (L7), Landsat 8 imagery (L8) and Sentinel 2 imagery (S2) satellite imagery.

For Tadla basin Morocco, a 1,038 ha ground truth dataset from the observed period was available. In the developed method this dataset is partly used for classification and partly for validation of the land use in the total area of 3440 km^2 of Tadla basin. This method indicated winter wheat to be the most common crop, the obtained accuracy for winter wheat is 83%. For the observed area in the Lower Limpopo basin Mozambique, no ground truth is available, only the local information that maize is the common crop type and that the majority of the area is covered with natural vegetation. Using maize crop phenology data from prior research, pixels with high likelihood of maize cultivation were obtained. This could not be validated with ground data.

> This suggests the significance and difficulty of land use classification in hydrological research. It is possible to obtain a land use classification with NDVI data. With a significantly large ground truth dataset is available, land use of a large area can be both classified and validated. Without ground truth data using local information of the most common crop type, pixels with high likelihood for this crop can be obtained. Google EE is very useful for both methods.

Evaluation of SWAP/WOFOST SWAP and WOFOST are used to simulate actual field baseline scenarios and strategy scenarios and to compute indicators for efficient water use from the model output. To obtain a field baseline scenario, SWAP/WOFOST is calibrated against SEBAL data. In this research SWAP3.2.36 is used. This version of SWAP does not have a Graphical User Interface (GUI) and requires multiple and extensive ASCII input files. Lately a new version of SWAP is published which includes a GUI.

The SWAP/WOFOST output is generated in text files. This is connected to a developed Python scripts that allows visualization of the data and comparison with SEBAL data. The use of the ASCII files for SWAP input data is not user friendly. For calibration, a clear procedure is followed using different steps. For each step, SWAP input parameters in the ASCII are adjusted manually upon satisfactory results, no automation is applied. It is expected that better calibration result could be obtained when the calibrated process is automated and optimized for each separate step. Also the newer SWAP version is expected to be more user friendly. Also, in the SWAP/WOFOST input files, the role of individual parameters and interconnectedness of the different input parameters is not clear.

> This suggests that the current calibration method for SWAP/WOFOST against SEBAL data, can be improved using a Python script to automate the required iterations. From this script, the SWAP input files can be generated and the output can be compared to SEBAL data. This is expected to be more user friendly and generate a better calibration result. Use of SWAP and WOFOST requires knowledge on the equations, parameters and their physical meaning.

The simulated baseline scenarios contain plausible seasonal biomass and yield production for both observed fields. Simulation of several strategies at the maize field results in very high seasonal biomass and yield production. In these simulations (see Fig. 4.16), seasonal biomass exceeds 60 $t\ ha^{-1}$ and seasonal yield exceeds 20 $t\ ha^{-1}$. It is questionable whether this is physiological feasible at an actual maize field. Inspection of SWAP/WOFOST output revealed that for these simulations, the actual biomass and yield production rates are equal to the potential rates on every day of the growing season. This demonstrates optimal production and large optimal production rates allowed by WOFOST. This is not observed for any strategy at the winter wheat field. For both crop types, crop characteristics are determined by calibration of crop input parameters.

> This suggests that the possible potential production rates in WOFOST are higher than what is expected to be feasible at an actual field. Also, this suggests that high actual production rates are obtained by calibration of the crop characteristics. It is expected that with more knowledge on crop physiology and acceptable ranges for parameters related to crop characteristics, more representative actual crop growth can be simulated in SWAP/WOFOST.

5.2.2. Possibilities and shortcomings of model and satellite data

To diminish the need of field measurements in this research, satellite and model data is used. For meteorological data, Global Land Data Assimilation System (GLDAS) and Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) is used. For land use classification, Normalized Difference Vegetation Index (NDVI) data from Landsat 7 imagery (L7), Landsat 8 imagery (L8) and Sentinel 2 imagery (S2) satellite imagery is used. Soil characteristics are obtained from HiHydroSoil.

As described in Paragraph 2.8.2, prior research suggests that GLDAS data overestimates the daily shortwave incoming radiation $R_{s,day}$ $[KJ\ m^{-2}]$, especially during warm seasons. $R_{s,day}$ provides energy for crop growth, hence and overestimation of biomass and yield production is expected. See Fig. 4.5 and Fig. 4.11, at both fields the obtained seasonal yields are high compared to values obtained from prior research and local reports. For SEBAL, instantaneous meteorological data is required for which the most representative GLDAS three-hour average is used. It can be questioned whether these values successfully represent the instantaneous data.

This suggests that use of daily shortwave incoming radiation $R_{s,day}$ $[KJ\ m^{-2}]$ from GLDAS results in an overestimation of biomass production and related yield.

HiHydrosoil data is used for the initial soil hydraulic parameters in SWAP. However, for the simulated fields this data is proven insufficient, the parameters were either changed during calibration or replaced with soil characteristics obtained from field measurements.

This suggests that HiHydroSoil data is not sufficient for accurate estimation of soil hydraulic parameters at field scale. For some fields the data can be used as initial parameters in a calibration procedure.

Landsat imagery is used for SEBAL analysis. This dataset has a precision of 30 m and is generated every 16 days. The optical images are restricted to cloud-free days. This is a significant limitation in areas that are often cloudy. In the observed areas and growing seasons, the number of useful dates of SEBAL analysis for the winter wheat and maie field are 5 respectively 8. Since the best calibration of SWAP/WOFOST using SEBAL data was obtained for the winter wheat field, a large number of SEBAL dates does not guarantee a successful calibration.

This suggests that the number of available and useful SEBAL dates is time and location specific as it is limited by cloud coverage. A successful calibration of SWAP/WOFOST against SEBAL data can be obtained with 5 useful SEBAL dates within a growing season.

A challenging aspect of the calibration of SWAP/WOFOST against SEBAL data is the ground water level, especially at a field where a shallow water table is observed. No ground data on ground water levels or pressure heads was available. Currently there is no satellite or model data available for world wide ground water levels and pressure heads. In the current research, for both the observed areas a land use classification is required. Currently there is no model dataset for world wide land use. Therefore in the current research land use classifications were done for the observed areas.

This suggests that satellite based model data of land use and ground water levels or pressure heads would be very useful in hydrological research.

Use of satellite and model data in the current research prevented the need for time consuming and expensive field or laboratory experiments. Also, use of these datasets allows analysis of periods in the past, where field measurements can only be obtained in the present time. The use of Google Google Earth Engine code editor (EE) allows computations with spatially distributed model or satellite data without the need to download these datasets.

This suggests that the use of satellite data is useful in hydrological research. Also, execution of computations in the Google EE enables research without downloading the required datasets.

5.2.3. Feasibility and effectiveness of an on-line survey with key actors from all levels of involvement

An on-line survey is developed for key actors in agricultural water use involved in practice, through research or at policy level. In the survey, participants evaluate the indicators and strategies of the collection observed in this research. The indicators are evaluated for potential relevance, the strategies are evaluated for potential effectiveness. This is done for two simplified cases representing the fields observed in this research. Participants can also evaluate a strategy or indicator as 'unclear'. Additionally, the participants selected for a general field a single most effective strategy and a single most relevant indicator.

Survey distribution and response rate As described in Paragraph 2.7, the survey is distributed via email and LinkedIn. By these means, the survey is estimated to reach 485 key actors of which a 20% response rate is expected. The on-line survey was available between October 6^{th} and November 2^{nd} 2017 and resulted in 25 responses. If 485 key actors are reached, the obtained response rate is 5%.

This suggests that the willingness to participate in an on-line survey contributing to hydrological research is low, the estimated actual response rate is 5%.

Depth of provided information For evaluation of indicators and strategies, information on the observed system is required. The survey is designed to require 20 minutes for completion. The survey is intended for key actors with various backgrounds. Key actors from the level research, practice and policy are expected to have different levels of knowledge concerning agricultural water use and water balances. The two observed fields are simplified and generalized. Visualizations including symbols and logical color schemes for clarification and to reduce the required amount of text. Survey participants were asked to evaluate the 'potential' relevance and effectiveness of indicators and strategies, suggesting an estimation. Survey participants were also allowed to evaluate a specific indicator or strategy 'unclear'. However, comments from survey participants were received indicating both that the survey was complex and that the amount of information was insufficient. The average time spent for completion of the survey was 27 minutes.

This suggest that it is difficult to design an on-line survey which is comprehensive, not time consuming and suitable for key actors from various background. Presenting the same questions for different key actors might require different information and information depth and different means of communication. This also illustrates the variety of perceptions of efficient water use at the agricultural field among different key actors.

6

Conclusion and recommendations

Different key actors are involved in the improvement of efficient water use in agriculture. This improvement is desired in arid and semi-arid regions to guarantee food security in the coming decades. This thesis demonstrates a variety of possible perceptions held by key actors, regarding the improvement of efficient water use at the agricultural field. There is little agreement between key actors, both regarding the most relevant indicators for quantification of efficient water use, and regarding the most effective strategies to obtain improvement. This thesis analyses 13 different indicators for efficient water use and 10 different strategies that can be applied to obtain improvement of efficient water use.

At international policy level, UN-Water and the Food and Agriculture Organization (FAO) are involved, striving for the improvement of efficient water use according Sustainable Development Goal (SDG) indicator 6.4.1. This indicator is referred to as 'efficiency' while it is not dimensionless. Contradiction and vagueness is obvious in the terminology used in FAO publications. Official FAO water productivity indicators are vague and conceptual, allowing multiple definitions. At the Dutch policy level, the Directorate-General for International Cooperation (DGIS) uses the target of 25% increase in water productivity for improvement of efficient water use. The indicator is commonly referred to as 'crop per drop' without a clear definition. Projects are evaluated by water productivity increase, defined as biomass production per crop transpiration $kg\ m^{-3}$. Individual key actors involved at policy level do not evaluate SDG indicator 6.4.1 or the water productivity used by DGIS as most relevant at the agricultural field. Instead, several other water productivities also expressed in $kg\ m^{-3}$ are seen as most relevant indicators of efficient water use. Local key actors involved at policy level in areas where improvement of efficient water use is desired, are often not familiar with water productivity indicators. With key actors in practice, a difference is observed between uneducated farmers and other key actors involved in agricultural water use at a practical level. Key actors involved through research are more familiar with the indicators and strategies observed in this thesis than key actors in practice or policy. Also, these key actors are most critical concerning relevant indicators for efficient water use. It is also demonstrated in this research that key actors involved at the level of research better understand the relation of strategies and indicators.

This thesis demonstrates that it is possible to simulate typical actual fields in the Soil-Water-Atmosphere-Plant model (SWAP) and WOrld FOod STudies simulation model (WOFOST) for a single and relatively dry growing season, calibrated against data from the Surface Energy Balance Algorithm for Land model (SEBAL). Furthermore, the SWAP/WOFOST simulation allows for the simulation of strategy scenarios according to the observed 10 strategies. Hence, for baseline scenario and strategy scenarios, the 13 observed indicators for efficient water use can be computed from the model output, which allows quantification of improvement of efficient water use by implementation of a strategy. Using this methodology, analysis is conducted for two different fields. The first simulated field is an average performing winter wheat field in Tadla Basin Morocco having an area of 5.5 ha. The growing season is observed from November 2015 to May 2016, length of the season is 190 days. It is located on the left bank of the Oum Er Rhiba river and is part of the large Beni Moussa irrigation system. A deep ground water table is observed and field irrigation is applied from a field inlet. In the observed season, 180 mm precipitation is received. In the field baseline scenario, 570 mm irrigation is applied and the produced yield is 6.6 t/ha. The second simulated field is a relatively good performing small-

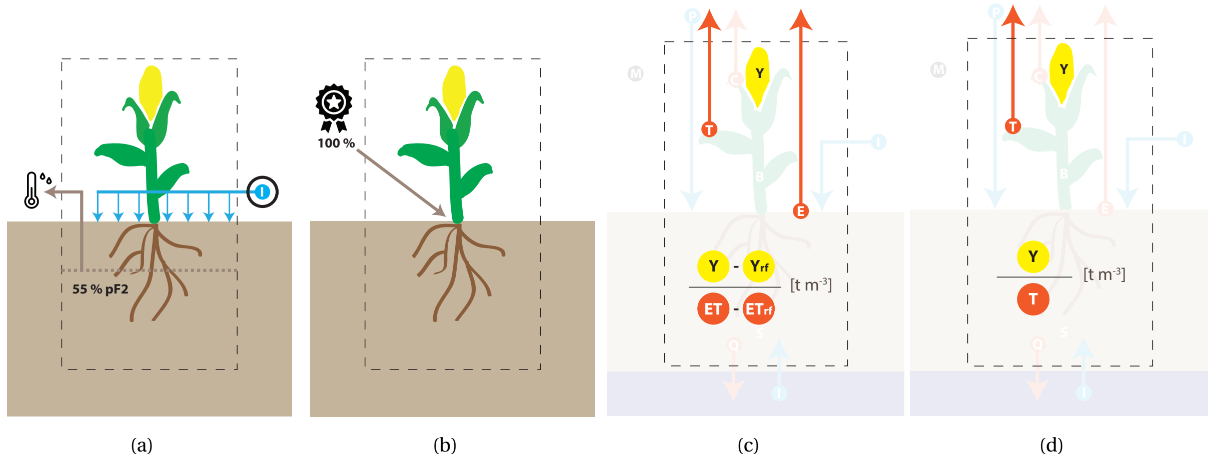

Fig. 6.1: Strategies and indicators from the collection observed in this research. (a) Regulated moderate soil water deficit which can be obtained in the observed fields using sprinkler irrigation (illustrated) or by accurate management of the ground water table. (b) Change to optimal seed quality, agricultural strategy. (c) Water productivity indicator $kg\ m^{-3}$ observing effect of irrigation water only, for agricultural yield (Y) and evapotranspiration (ET). (d) Water productivity indicator $kg\ m^{-3}$ agricultural yield (Y) and crop transpiration (T).

holder maize field in Lower Limpopo Basin Mozambique having an area of 0.22 ha. The growing season is observed from April to September 2016, length of season is 150 days. The field is located in the Fidel Castro irrigation/drainage system near Xai-Xai in an area locally known as machongo. In this area a year round spring flow and shallow water table is observed. Management of the water table in the system is crucial for preserving the organic soils and enabling agricultural practices. Sub-surface irrigation is applied by management of the ground water. In the observed season, 125 mm precipitation is received. In the field baseline scenario, 506 mm irrigation is applied and the produced yield is 4.7 t/ha. For the applied methodology a minimum of ground truth data is required, demonstrating that satellite data and satellite based model data is useful in agro-hydrological research. The obtained baseline scenarios are a plausible representation of the actual fields. However, strategies of deficit irrigation at a sub surface irrigated maize field in the Lower Limpopo river by management of the ground water table results in seasonal biomass production exceeding 60 $t\ ha^{-1}$ and water productivity increases exceeding 100%. It is questionable whether the biomass production rates observed in the SWAP/WOFOST simulation are physiological feasible. For the maize field the bottom boundary for vertical water transport is defined with a calibrated bottom flux. No data on ground water has been available. Against SEBAL data, the simulations are sufficiently calibrated. It is expected that improvement can be made with data for ground water level, pressure heads or vertical fluxes.

A strategy seen as a highly effective by key actors from all three levels of involvement is regulated mild or moderate soil water deficit, illustrated in Fig. 6.1(a). Irrigation is applied when the soil moisture content at a certain depth in the crop root zone declines below a fraction of the soil moisture content observed at the soil field capacity pF2. This can be measured with soil sensors. This thesis demonstrates that the effect of this criterion is highly dependent on the soil characteristics. It is expected that other criteria related to for example the Totally Available Water (TAW) or Readily Available Water (RAW) depth, would result in more consistent results for fields with different soil characteristics. The strategy generating the largest improvement of efficient water use at both fields observed in this thesis, according to indicators seen as relevant by key actors from all levels of involvement, is the change to optimal seed quality. This is an agricultural strategy, visualized in Fig. 6.1(b). This strategy results in an increase for SDG indicator 6.4.1 of 148 $USD\ Mm^{-3}$ for the smallholder maize field and 17 $USD\ Mm^{-3}$ for the winter wheat field. The result of the combination of multiple strategies has not been investigated in the current research.

Multiple commonly used definitions of water productivity are analyzed in this thesis. All are expressed in $kg\ m^{-3}$ and correspond to 'crop per drop' or other vague and conceptual definitions of water productivity. Both 'crop' and 'drop' can refer to different seasonal outputs of an agricultural field. By changing to optimal seed quality at the smallholder maize field in Mozambique, increases of water productivity range between -26

and +148% dependent on the used definition of water productivity. The decrease of 26% is obtained according to the water productivity definition used by DGIS. All other water productivity increases for this strategy at the maize field are positive.
According to the water productivity indicator used by DGIS, the 25% target cannot be met at the winter wheat field in the Tadla basin. The potential increase of water productivity at the winter wheat field is also low according to other water productivity indicators. The 25% target is met at the maize field when irrigation is eliminated. However, this strategy also results in a 87% decrease of seasonal yield. It can thus be concluded that this water productivity indicator does not contribute to food security. Instead of this water productivity currently used by DGIS, it is recommended based on the findings of this thesis to use a water productivity indicator involving yield production instead of biomass production.
In used water productivity indicators, the denominator consists of a water quantity. This can refer to applied irrigation water as observed in the UN SDG indicator 6.4.1, or to other water balance fluxes including evapotranspiration (ET) or transpiration (T). Evapotranspiration and transpiration provide information on the consumption of water by the observed system and by the crop. These quantities can be accurately monitored with remote sensing technologies. Evaluating the applied irrigation water is considered relevant when data is available regarding efficient use of water for other purposes than field application. This is outside the scope of this research but the quantification of this information is expected to be difficult. Accurate monitoring of irrigation application is also difficult. When this quantity is used in the denominator, the indicator does not provide information on the effect of irrigation elimination. For these reasons, indicators using ET or T in the denominator are seen as more useful. Hence, this thesis demonstrates that SDG indicator 6.4.1 is inadequate for quantification of efficient water use in agriculture. This thesis also demonstrates that the use of efficiency indicators is possible but not recommended in the evaluation of improvement of efficient water use.

Seen as relevant indicators are therefore the yield production by irrigation water divided by evapotranspirated irrigation water visualized in Fig. 6.1(c) and yield divided by transpiration in Fig. 6.1(d). Although little agreement is observed between individual key actors, the largest agreement on relevant indicators is found for these two indicators. It is thus expected that these indicators will be most easily accepted by key actors involved at different levels. Since the first indicator observing the effect of irrigation water only is theoretical indicator and not measurable at actual fields, the indicator observing yield divided by transpiration is seen as most suitable. According to this indicator (Fig. 6.1(d)), optimal seed quality (Fig. 6.1(b)) results in a water productivity increase of 56% or 0.9 $kg\ m^{-3}$ at the smallholder maize field, and 47% or 0.5 $kg\ m^{-3}$ at the winter wheat field. In world wide monitoring of this indicator, the greatest challenge is expected in the computation of yield from biomass production. Information of land use is required in order to estimate the Harvest Index (HI) and seed moisture content. This thesis therefore also emphasizes the need for the development of methodologies that allow world wide mapping of agricultural land use.

The simulation results indicate that at the smallholder maize field in the Lower Limpopo basin in Mozambique, the potential improvement of efficient water use at field scale is large and significantly larger than observed for the winter wheat field in Tadla basin Morocco. This thesis demonstrates the relevance of agrohydrological modeling in estimating possible potential improvement which is expected to be relevant to precede investments made to this purpose. The observed strategies at the smallholder maize field require strategic management of the ground water table. Although system scale analysis is not within the scope of this research, based on local observations and reports from local interviewees suggest that the system is currently not optimally operated and maintained. Local experts believe that better water management and investment in the current system infrastructure and monitoring equipment can result in significant improvements.

To conclude, the results in this thesis show that multiple and contradicting perceptions are held by key actors in the improvement of efficient water use at the agricultural field. Official and influential indicators in the Sustainable Development Goals (SDGs) and observed with the Dutch DGIS are seen as insufficient in indicating the most relevant aspects of agricultural water use. Instead of irrigation water used, the volume or depth of water consumed by the system (evapotranspiration) or by the crop (transpiration) is more relevant providing information on what happens with the applied water. Instead of the produced biomass, produced yield is more relevant since this is desired when striving for food security. Thus, the indicator of yield divided by transpiration (Fig. 6.1(d)) is recommended. According to this indicator, improving seed quality is the most effective strategy for improvement of efficient water use.

The used methodology for calibration of SWAP/WOFOST against SEBAL is proven to be useful and is recommended to be used in future agro-hydrological research. For feature research continuing on the applied methodology, it is recommended to improve in the calibration of crop characteristics acceptable ranges and correlations for parameters related to crop characteristics. Also, availability of ground water data is expected to improve the simulation of the system bottom boundary for vertical water transport. As the simulated smallholder maize field revealed large potential improvement of efficient water use, this is also expected to be found at the actual field. Future research is recommended on the necessary and possible system scale interventions that are required for in the Mozambican machongos to obtain the potential improvement. The applied methodology is demonstrated to be useful to compare the potential possible improvement of efficient water use at different fields. Simulation analysis as conducted in this research is recommended in feasibility studies for projects that aim at the improvement of efficient water use on agricultural fields. In this thesis the relevance of accurate land use classifications is underlined. Land use classification is required in the methodology used in this research in order to use the spatially distributed SEBAL data for the calibration of SWAP/WOFOST. Furthermore, world wide spatial data on land use is needed for the use of the recommended indicator involving agricultural yield. Hence, it is recommended to invest in the development of methodologies that allow world wide mapping of agricultural land use. In the current study, combinations of the 10 observed strategies have not been analyzed. This is recommended for further research in further investigation of possible strategies for improvement of efficient water use at the agricultural field. Also, it is recommended to continue in the analysis of different criteria for deficit irrigation. It is expected that criteria involving TAW or RAW, will result in more consistent results for fields with different soil characteristics. The conducted personal interviews, literature study and on-line survey emphasized the differences in used terminology and knowledge present with key actors involved in practice, through research and in policy. The observations and results of this thesis can be used for further research.

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METHODS

A

Personal interviews on the increase of efficient water use at the agricultural field

List of contacts. Conducted interviews and attended presentations. In case of multiple contact moments, the date corresponds to the first meeting or conversation.

Table A.1: Personal interviews with key actors in (the discussion on) efficient water use in agriculture.

Name	Function	Company	Country	Level	Date
Wim Bastiaanssen	Professor of Global Water Accounting	Unesco-IHE /TU Delft	the Netherlands	Research	13-05-2016
Job Kleijn	Senior officer Water, coordinator of monitoring SDG indicator 6.4.1	DGIS	the Netherlands	Policy	26-05-2016
Frank van Steenbergen	Owner	MetaMeta	the Netherlands	Research / Practice	20-06-2016
Abraham Mehari Hailer	Hydrologist	MetaMeta	the Netherlands	Research / Practice	28-07-2016
Michael McClain	Chair Prof. of Ecohydrology, Head of the Hydr. and WR Chair Group	Unesco-IHE	the Netherlands	Research	11-01-2017
Nadja den Besten	Hydrologist	FutureWater	Mozambique	Practice	31-01-2017
Martijn de Klerck	Project manager / Hydrologist	FutureWater	the Netherlands	Research / Practice	01-02-2017
Jos van Dam	Head lecturer Soil Physics and Land Management	WUR/Alterra	the Netherlands	Research	01-02-2017
Wouter Beekman	Director / Expert Agricultural water	Resilience BV	the Netherlands	Research / Practice	01-02-2017
Peter Prins	Advisor Water and Agriculture	NWP	the Netherlands	Research / Policy	02-03-2017
Arie-Jan Broere	Export / Sales / Planning	Broere Hortitech BV	the Netherlands	Practice	02-03-2017
Gijs Simons	Team leader / Hydrologist	FutureWater	the Netherlands	Research / Policy	02-03-2017
Simon Chevalking	Hydrologist	MetaMeta	the Netherlands	Research / Practice	02-03-2017
Peter Raatjes	Agricultural expert	RMA	the Netherlands	Practice	02-03-2017
Sam van Til	Operational manager ThirdEye project	ThirdEye	the Netherlands	Research / Practice	03-03-2017
Peter Droogers	Scientific director / Hydrologist	FutureWater	the Netherlands	Research / Practice	09-03-2017
Jan van Til	Project manager ThirdEye project	ThirdEye	the Netherlands	Research / Practice	18-03-2017
Jos Timmermans	Policy Analyst, focus water management	TU Delft	the Netherlands	Research / Policy	19-03-2017
Paul Hassing	Senior International Cooperation Expert: Climate, Water and Energy	PMC	the Netherlands	Policy / Practice	25-04-2017
Teodomiro Cabral	Hydrologist	ARA-Sul	Mozambique	Policy / Practice	12-05-2017
David Mocambe	Hydrologist	ARA-Sul	Mozambique	Policy / Practice	12-05-2017
João da Costa	Hydrologist	ARA-Sul	Mozambique	Policy / Practice	12-05-2017
Gimo Macaringue	Hydrologist	ARA-Sul	Mozambique	Policy / Practice	12-05-2017
Juan Estrada	Private Consultant in Water Management and Engineering	self-employed	Mozambique	Research / Practice	12-05-2017
Dercio Chissaque	Senior Flying Sensor Operator	ThirdEye	Mozambique	Practice	15-05-2017
Judith Francisco	Smallholder farmer	self-employed	Mozambique	Practice	16-05-2017
Alberto	Smallholder farmer	self-employed	Mozambique	Practice	16-05-2017
Melita	Smallholder farmer	self-employed	Mozambique	Practice	16-05-2017
Antonio Franceso	Smallholder farmer	self-employed	Mozambique	Practice	16-05-2017
Angela Faria	Manager of monitoring and evaluation of ADB projects	RBL	Mozambique	Policy / Practice	17-05-2017
Haider Marmahomer	Manager of monitoring and evaluation of RBL projects	RBL	Mozambique	Policy / Practice	17-05-2017
Celestino Tsimpho	In charge of RBL projects, formerly head irrigation and drainage	RBL	Mozambique	Policy / Practice	17-05-2017
Abilio	Operator of pumping station	RBL	Mozambique	Practice	18-05-2017
David Zimba	Chief Administration construction of irrigation/drainage system 1982	RBL	Mozambique	Practice	18-05-2017
Paiva Munguambe	Chief at INIR / Lecturer in Wetlands	INIR	Mozambique	Policy / Research	19-05-2017
Leovigildo Ferraõ	Chief Technology construction of irrigation/drainage system 1982	RBL	Mozambique	Practice	22-05-2017
Eládio Chambe	Chief agricultural production, formerly extenstionist for 8 years	RBL	Mozambique	Practice / Policy	23-05-2017
Fredrik Huthoff	Consultant Water Resource Management	HKV / DNGRH	Mozambique	Research / Policy	24-05-2017
Justino Marrengula	Hydrologist	DNGRH	Mozambique	Research / Policy	24-05-2017
Wu Bingfang	Head of Division of Digital Agriculture	CAS / DNGRH	Mozambique	Research / Policy	24-05-2017
Ivo Haren	Water Resources Specialist	WE Consult	Mozambique	Research / Practice	24-05-2017

B

Python script to obtain field specific parameters from SEBAL output

The following pages include the developed Python script for aggregation of spatially distributed output data from the Surface Energy Balance Algorithm for Land model (SEBAL) into field averages. The developed function can be compared to the QGIS Zonal Statistics for individual raster bands.

```
# -*- coding: utf-8 -*-
"""
Created on Tue Aug 15 13:59:17 2017
@author: Charlotte van der Leer
"""

####################################################################################################################
##############################                                                          ############################
##############################    SCRIPT OM SEBAL RESULTATEN OM TE ZETTEN               ############################
##############################    NAAR VELDGEMIDDELDES VOOR VELDJES BINNEN              ############################
##############################    HET GEBIED VAN DE SEBAL ANALYSE.                      ############################
##############################                                                          ############################
##############################    NODIG:                                                ############################
##############################    - SEBAL RESULTATEN (.TIF FILES)                       ############################
##############################    - SHAPEFILE MET POLYGONEN (.SHP EN .DBF)              ############################
##############################                                                          ############################
##############################    OUTPUT:                                               ############################
##############################    - GRAFIEKEN MET SEBAL RESULTATEN PER VELD             ############################
##############################    - TXT FILE MET OVERZICHT VAN ALLE VELDEN              ############################
##############################    - TXT FILE PER VELD MET SEBAL RESULTATEN,             ############################
##############################      KAN GEBRUIKT WORDEN BIJ KALIBRATIE VAN              ############################
##############################      SWAP/WOFOST VOOR EEN SPECIFIEK VELD.                ############################
##############################                                                          ############################
####################################################################################################################

import osr
import shapefile
import os
import gdal
import numpy as np
from datetime import datetime, timedelta
from osgeo import ogr
import sys
import subprocess
import matplotlib.pyplot as plt


def main():

    time_now1 = datetime.now()
    print 'Run started at',time_now1.strftime('%c')

    # Lege matrix om te vullen: (NIET AANZITTEN)
    SEBAL = [],[],[]

############################## VOOR NIEUWE TOEPASSING AANPASSEN VANAF HIER ###########################

    # Folder waar shape file staat en waarin mapje met resultaat zal worden geplaatst:
    directory = 'C:\Users\Charlotte\Desktop\THESIS2\SEBAL\ZONALSTATISTICS'

    # Informatie shapefile (.shp en dbf file)
    shapefile_name = 'Tadla_fields_above5ha_local'                    # Name of .shp en dbf file
    shapefile_epsg = '32629'                                 # Projection
    shapefile_attribute = 'area[ha]'                          # Name of attribute defining areas

    # Handmatig rijtje van SEBAL data [yyyy-m-d] geen nullen voor maand of dag plaatsen!
    Dates = [datetime(2015,11,28),datetime(2015,12,30),datetime(2016,1,31),datetime(2016,3,3),datetime(2016,5,22)]
    #Tadla long: Dates =
[datetime(2015,8,24),datetime(2015,9,9),datetime(2015,9,25),datetime(2015,10,11),datetime(2015,11,28),datetime(2015,12,30),datetime(2016,1,31),datetime(201
6,3,3),datetime(2016,4,4),datetime(2016,5,22),datetime(2016,6,23),datetime(2016,7,9),datetime(2016,8,10),datetime(2016,9,11),datetime(2016,10,29)]
    #XaiXai: Dates =
[datetime(2016,3,21),datetime(2016,4,22),datetime(2016,5,8),datetime(2016,5,24),datetime(2016,6,9),datetime(2016,6,25),datetime(2016,7,11),datetime(2016,8,1
2),datetime(2016,9,13),datetime(2016,10,15),datetime(2017,1,3)]

    # Gewenste naam voor subfolder met resultaten
    directory_result = 'ZonalStats_Tadla_above5ha_local'

    # Keuzes voor output:  txt files en/of grafieken
```

```
    SWITCH_txtfiles = 1          # Keuze om resultaten weg te schrijven naar txt files          1=y 0=n
    SWITCH_charts_all = 1        # Keuze om grafiek weer te geven en op te slaan voor alle areas          1=y 0=n
    SWITCH_charts_field = 1      # Keuze om grafiek weer te geven en op te slaan voor specifiek veld          1=y 0=n
    SWITCH_charts_fieldnr = 11   # Keuze voor dit specifieke veld          # = nummer van area

    # Folder waar SEBAL resultaten in staan EN voor rasters de voorvoegsels per dag          CHECK 'input_raster' HIERONDER OF ZELFDE NAAMGEVING
GEBRUIKT IS!
    SEBAL_file = 'C:\Users\Charlotte\Desktop\THESIS2\SEBAL\TADLA_SEBAL\Tadla_'
    #XaiXai: SEBAL_file = 'C:\Users\Charlotte\Desktop\THESIS2\SEBAL\MOZAMBIQUE\RadMethod2_2\Moz_'

    #          WANNEER JE SEBAL ELEMENTEN AANPAST DAN OOK BIJ
    #          WEGSCHRIJVEN ELEMENTEN (ZIE ONDER) AANPASSEN!!
    # Onderdelen van SEBAL die je wilt hebben:
    SEBAL[0].append('ETrf')          # Evapotranspiration, reference
    SEBAL[0].append('LAIn')          # Leaf Area Index
    SEBAL[0].append('Abdo')          # Albedo
    SEBAL[0].append('Tpot')          # Transpiration, potential
    SEBAL[0].append('Tact')          # Transpiration, actual
    SEBAL[0].append('SMts')          # Soil moisture content, top soil
    SEBAL[0].append('SMrz')          # Soil moisture content, root zone
    SEBAL[0].append('BmPr')          # Biomass Production

    # Voor elk onderdeel het specifieke stukje path:
    SEBAL[1].append('\Output_evapotranspiration\L8_L8_ETref_24_30m_')
    SEBAL[1].append('\Output_vegetation\L8_lai_average_30m_')
    SEBAL[1].append('\Output_vegetation\L8_surface_albedo_30m_')
    SEBAL[1].append('\Output_evapotranspiration\L8_L8_Tpot_24_30m_')
    SEBAL[1].append('\Output_evapotranspiration\L8_L8_Tact_24_30m_')
    SEBAL[1].append('\Output_soil_moisture\L8_L8_Top_soil_moisture_30m_')
    SEBAL[1].append('\Output_soil_moisture\L8_L8_Root_zone_moisture_30m_')
    SEBAL[1].append('\Output_biomass_production\L8_L8_Biomass_production_30m_')


############################## EINDE BLOK MET AANPASSINGEN ###########################

############################## VOORBEREIDINGEN ###########################

    # Maak paths en directories compleet voor verder gebruik
    shapefile1_fullname = directory + '\\' + shapefile_name + '.shp'
    shapefile2_fullname = directory + '\\' + shapefile_name + '.dbf'
    output_directory = directory+'\\'+directory_result
    if not os.path.exists(output_directory):
        os.mkdir(output_directory)
    raster_name = directory_result+'\\'+shapefile_name
    raster_path  = os.path.join(directory,raster_name + '.tif')
#    output_file = os.path.join(output_directory,'output.txt')          # om array_output in op te slaan, werkt nog niet

    # Haal shapes uit de shapefile:
    myshp = open(shapefile1_fullname,"rb")
    mydbf = open(shapefile2_fullname,"rb")
    r = shapefile.Reader(shp=myshp, dbf=mydbf)
    rshape=r.shapes()

    # Trek rijtje van areas uit de shapefile:
    reader = ogr.Open(shapefile1_fullname)
    layer = reader.GetLayer(0)
    Areas = []
    for i in range(layer.GetFeatureCount()):
        feature = layer.GetFeature(i)
        Areas.append(feature[shapefile_attribute])

    # Bepaal dimensies:
    amount_SEBAL = len(SEBAL[0])
    amount_Areas = len(Areas)
    amount_Dates = len(Dates)

    # Settings voor progress bar
    streepjes = 16          # HIER LENGTE PROGRESS BAR INSTELLEN!
```

```
    streepjes_deel = np.round(amount_Areas/streepjes)

    # Bepaal afmetingen van shapefile om te gebruiken bij het rasterizen hierna
    array_ave_lat = []
    array_ave_lon = []
    for i in range(0,amount_Areas):

        # Haal lat/lon uit de shapes:
        bbox = rshape[i].bbox
        ave_lat = (bbox[0] + bbox[2])/2
        ave_lon = (bbox[1] + bbox[3])/2
        array_ave_lat.append(ave_lat)
        array_ave_lon.append(ave_lon)

    region_height = np.int(np.ceil(np.max(array_ave_lat) - np.min(array_ave_lat)))
    region_width = np.int(np.ceil(np.max(array_ave_lon) - np.min(array_ave_lon)))

    # Maak raster van de shapefile met gdal_rasterize
    rasterize_Cmd = 'gdal_rasterize -a '+shapefile_attribute+' -ts '+str(region_width)+' '+str(region_height)+' -l '+shapefile_name+' '+shapefile1_fullname+'
'+raster_path
    process = subprocess.Popen(rasterize_Cmd)
    process.wait()

    # Maak matrix (array) van rasterized shapefile
    dest=gdal.Open(raster_path)
    band = dest.GetRasterBand(1)
    data_MASK = band.ReadAsArray()

############################ RESULTATEN GENEREREN ###########################

    # Loop door dagen, SEBAL elementen, areas:
    array_output = np.zeros([amount_Areas,amount_Dates,amount_SEBAL])
    j=0
    for Date in Dates:
        print 'Start date',j+1,' of',amount_Dates,''
        SEBAL[2].append([])
        for k in range(amount_SEBAL):

            element_number = k+1
            element_name = SEBAL[0][k]

            sys.stdout.write('SEBAL element ')
            sys.stdout.write(str(element_number))
            sys.stdout.write(' of ')
            sys.stdout.write(str(amount_SEBAL))
            sys.stdout.write(' which is ')
            sys.stdout.write(str(element_name))
            input_raster =
SEBAL_file+Date.strftime('%Y')+'_'+Date.strftime('%m')+'_'+Date.strftime('%d')+SEBAL[1][k]+Date.strftime('%Y')+'_'+np.str(Date.timetuple().tm_yday)+'.tif'
            input_dest = reproject_dataset_example(input_raster,raster_path,method=1)
            input_data = input_dest.GetRasterBand(1).ReadAsArray()
            SEBAL[2][j].append(input_data)
            sys.stdout.write(', is now reprojected.')

            sys.stdout.write(' Progress through list of areas: ')
            streepjes_count = 0
            for i in range(0,amount_Areas):
                area = Areas[i]
                streepjes_count = streepjes_count+1
                data_check = np.copy(SEBAL[2][j][k])
                data_check[data_MASK != area] = np.nan
                output_value = np.nanmean(data_check)
                array_output[i,j,k] = output_value

                if streepjes_count == streepjes_deel:
                    sys.stdout.write('-')
                    streepjes_count = 0
```

```
            sys.stdout.write(' done!\n')

        j=j+1

############################## RESULTATEN WEGSCHRIJVEN ##########################

    if SWITCH_txtfiles == 1:
        sys.stdout.write('Progress of documenting:  ')

        # Maak algemene textfile met overzicht van alle areas:
        filename_head = os.path.join(output_directory,'Areas.txt')
        textfile_head = open(filename_head,'w')
        textfile_head.write('ID,AREA[ha],LAT[degr],LON[degr]\n')

        # Vul algemene textfile en maak per area textfile aan:
        streepjes_count = 0

        for i in range(0,amount_Areas):
            text1=i+1                          # Nummer van Area
            text2=Areas[i]                     # Oppervlakte van area

            # Raster van shapes omzetten epsg naar WGS84 (epsg 4326) om lan/lon in graden te krijgen:
            epsg_from = int(shapefile_epsg)   # of: epsg_from = Get_epsg(outputname)
            epsg_to = int(4326)
            osng = osr.SpatialReference()
            osng.ImportFromEPSG(epsg_from)
            wgs84 = osr.SpatialReference()
            wgs84.ImportFromEPSG(epsg_to)
            tx = osr.CoordinateTransformation(osng, wgs84)

            # Coordinaten van lat/lon:
            (ulx, uly, ulz) = (tx.TransformPoint(array_ave_lat[i], array_ave_lon[i]))
            text3 = uly
            text4 = ulx

            # Schrijf gegevens van area op regel in textfile:
            textfile_head.write('%s,%s,%s,%s\n' %(text1, text2, text3, text4))

            # Maak textfile per area:
            filename_area = os.path.join(output_directory,'area%s.txt'%text1)
            textfile_area = open(filename_area,'w')

            # Header in textfile van area met algemene informatie:
            textfile_area.write('ID:       %s\n'%(text1))
            textfile_area.write('Area [ha]: %s\n'%(text2))
            textfile_area.write('Lat,Lon:   %s,%s\n'%(text3, text4))
            textfile_area.write('\n')
            textfile_area.write('Date = Date of SEBAL analysis                        [dd-mm-yyyy] \n')
            textfile_area.write('ETrf = Reference evapotranspiration assuming grass     [mm/d] \n')
            textfile_area.write('LAIn = Leaf Area Index (LAI)                         [-] \n')
            textfile_area.write('Abdo = Albedo                                        [-] \n')
            textfile_area.write('Tpot = Transpiration, potential                      [mm/d] \n')
            textfile_area.write('Tact = Transpiration, actual                         [mm/d] \n')
            textfile_area.write('SMts = Soil moisture content in top soil             [cm3/cm3] \n')
            textfile_area.write('SMrz = Soil moisture content in root zone            [cm3/cm3] \n')
            textfile_area.write('BmPr = Biomass Production                            [kg/ha/d] \n')
            textfile_area.write('\n')

            textfile_area.write('Date, ETrf, LAIn, Abdo, Tpot, Tact, SMts, SMrz, BmPr  \n')
            # Vul textfile van area:
            j = 0
            for Date in Dates:
                textfile_area.write('%s,%s,%s,%s,%s,%s,%s,%s,%s\n' %(Date.strftime('%d-%m-%Y'), array_output[i,j,0], array_output[i,j,1], array_output[i,j,2],
array_output[i,j,3], array_output[i,j,4], array_output[i,j,5], array_output[i,j,6], array_output[i,j,7]))

                j = j+1
            textfile_area.close()
            streepjes_count = streepjes_count+1
```

```
            if streepjes_count == streepjes_deel:
                sys.stdout.write('-')
                streepjes_count = 0

        textfile_head.close()

#       output_file = open(output_file,'w')
#       output_file.write(array_output)
#       output_file.close()

        sys.stdout.write(' DONE!')
        time_now2 = datetime.now()
        time_now_lapse = (time_now2 - time_now1).seconds/60
        print 'Run completed at',time_now2.strftime('%c'), 'duration was', time_now_lapse, 'minutes'

#   np.savetxt('savedoutput.txt',array_output)  # WERKT NIET???

############################ GRAFIEKJES ##########################

    if SWITCH_charts_all == 1:

        Fig_text = [['Tadla Basin SEBAL Reference Evapotranspiration rate field average',
                    'Tadla Basin SEBAL Leaf Area Index field average',
                    'Tadla Basin SEBAL Albedo field average',
                    'Tadla Basin SEBAL Potential Transpiration rate field average',
                    'Tadla Basin SEBAL Actual Transpiration rate field average',
                    'Tadla Basin SEBAL Soil Moisture content Top Soil field average',
                    'Tadla Basin SEBAL Soil Moisture content Root Zone field average',
                    'Tadla Basin SEBAL Actual Biomass Production rate field average'],
                    ['ET_ref [mm/d]', 'LAI [-]', 'Albedo [-]', 'T_pot [mm/d]',
                     'T_act [mm/d]', 'SM_ts [cm3/cm3]', 'SM_rz [cm3/cm3]', 'BP_act [kg/ha/d]']]

        for k in range(amount_SEBAL):
            chart = 'Field_all_'+str(k+1)+'_'+str(SEBAL[0][k])
            filename_chart = os.path.join(output_directory,chart + '.png')
            fig = plt.figure()
            ax1 = fig.add_subplot(111)
            #fig_title = 'SEBAL element '+str(k+1)+' of '+str(amount_SEBAL)+' ('+str(SEBAL[0][k])+') for areas in '+str(shapefile_name)+'.shp'
            #fig_ylabel = str(SEBAL[0][k])
            fig_title = Fig_text[0][k]
            fig_ylabel = Fig_text[1][k]
            ax1.set_title(fig_title)
            ax1.set_xlabel('Time [dates of SEBAL analysis]')
            ax1.set_ylabel(fig_ylabel)
            for i in range(amount_Areas):
                fig_label = 'Area nr '+str(i+1)+' of '+str(amount_Areas)
                ax1.plot(Dates,array_output[i,:,k], linestyle='--', linewidth=0.5, marker='o', label=(fig_label))
            leg = ax1.legend()
            ax1.grid(True, which='both')
            box = ax1.get_position()
            ax1.set_position([box.x0, box.y0, box.width * 0.8, box.height])
            ax1.legend(loc='center left', bbox_to_anchor=(1, 0.5))
            fig.autofmt_xdate()
            fig.savefig(filename_chart, bbox_extra_artists=(leg,), bbox_inches='tight')

    if SWITCH_charts_field ==1:
        fieldnumber = SWITCH_charts_fieldnr-1
        for k in range(amount_SEBAL):
            chart = 'Field_'+str(SWITCH_charts_fieldnr)+'_'+str(k+1)+'_'+str(SEBAL[0][k])
            filename_chart = os.path.join(output_directory,chart + '.png')
            fig = plt.figure()
            ax1 = fig.add_subplot(111)
            #fig_title = 'SEBAL element '+str(k+1)+' of '+str(amount_SEBAL)+' ('+str(SEBAL[0][k])+') for area number '+str(SWITCH_charts_fieldnr)+' in
'+str(shapefile_name)+'.shp'
            #fig_ylabel = str(SEBAL[0][k])
            fig_title = Fig_text[0][k]
            fig_ylabel = Fig_text[1][k]
            ax1.set_xlabel('Time [dates of SEBAL analysis]')
```

```
        ax1.set_ylabel(fig_ylabel)
        ax1.set_xlim([datetime(2015,11,15),datetime(2016,6,1)])
        #fig_label = 'Area nr '+str(SWITCH_charts_fieldnr)+' of '+str(amount_Areas)
        ax1.plot(Dates,array_output[fieldnumber,:,k], linestyle='--', linewidth=0.5, color = 'g', marker='o', label=(fig_label))
        #leg = ax1.legend()
        ax1.grid(True, which='both')
        #box = ax1.get_position()
        #ax1.set_position([box.x0, box.y0, box.width * 0.8, box.height])
        #ax1.legend(loc='center left', bbox_to_anchor=(1, 0.5))
        fig.autofmt_xdate()
        fig.savefig(filename_chart, bbox_extra_artists=(leg,), bbox_inches='tight')


############################# FUNCTIES VOOR HERPROJECTEREN VAN TIM HESSELS ##########################

def reproject_dataset_example(dataset, dataset_example, method=1):

    # open dataset that must be transformed
    try:
        if dataset.split('.')[-1] == 'tif':
            g = gdal.Open(dataset)
        else:
            g = dataset
    except:
            g = dataset
    epsg_from = Get_epsg(g)

    # open dataset that is used for transforming the dataset
    try:
        if dataset_example.split('.')[-1] == 'tif':
            gland = gdal.Open(dataset_example)
        else:
            gland = dataset_example
    except:
            gland = dataset_example
    epsg_to = Get_epsg(gland)

    # Set the EPSG codes
    osng = osr.SpatialReference()
    osng.ImportFromEPSG(epsg_to)
    wgs84 = osr.SpatialReference()
    wgs84.ImportFromEPSG(epsg_from)

    # Get shape and geo transform from example
    geo_land = gland.GetGeoTransform()
    col=gland.RasterXSize
    rows=gland.RasterYSize

    # Create new raster
    mem_drv = gdal.GetDriverByName('MEM')
    dest1 = mem_drv.Create('', col, rows, 1, gdal.GDT_Float32)
    dest1.SetGeoTransform(geo_land)
    dest1.SetProjection(osng.ExportToWkt())

    # Perform the projection/resampling
    if method is 1:
        gdal.ReprojectImage(g, dest1, wgs84.ExportToWkt(), osng.ExportToWkt(), gdal.GRA_NearestNeighbour)
    if method is 2:
        gdal.ReprojectImage(g, dest1, wgs84.ExportToWkt(), osng.ExportToWkt(), gdal.GRA_Bilinear)
    if method is 3:
        gdal.ReprojectImage(g, dest1, wgs84.ExportToWkt(), osng.ExportToWkt(), gdal.GRA_Lanczos)
    if method is 4:
        gdal.ReprojectImage(g, dest1, wgs84.ExportToWkt(), osng.ExportToWkt(), gdal.GRA_Average)
    return(dest1)

def Get_epsg(g, extension = 'tiff'):

    try:
```

```
        if extension == 'tiff':
            # Get info of the dataset that is used for transforming
            g_proj = g.GetProjection()
            Projection=g_proj.split('EPSG","')
        if extension == 'GEOGCS':
            Projection = g
        epsg_to=int((str(Projection[-1]).split(']')[0])[0:-1])
    except:
       epsg_to=4326
       print 'Was not able to get the projection, so WGS84 is assumed'
    return(epsg_to)

############################## DAT WAS HET. ############################

if __name__ == '__main__':
    main()
```

C

Soil-Water-Atmosphere-Plant model (SWAP) theoretical background

The simulated system can be seen as a soil column having top- and bottom boundary conditions and a soil profile. Different characteristics of the top, bottom and profile determine the fluxes in and out of the system and the changes in the soil column. The column is visualized in Fig. C.1. In the following section the essential physical processes and corresponding equations for the soil profile and top- and bottom boundary are presented. This is confined to the elements and possibilities in SWAP and that have a crucial role in the calibration of the two simulated fields.

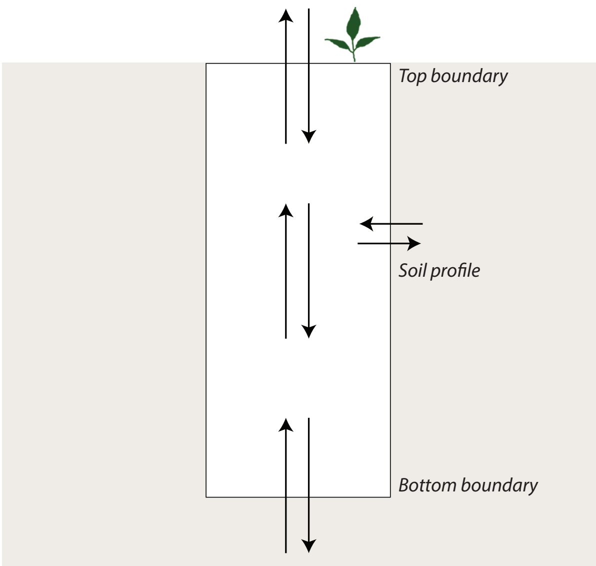


Fig. C.1: Soil column simulated in SWAP, boundaries described for top, bottom and soil profile.

The Soil Profile Vertical water movement is caused by pressure head difference. In SWAP it is Darcy's equation for one-dimensional unsaturated flow which is used combined with the continuity equation for soil water considering infinitely small soil volumes, resulting in the general equation for water flow in variably saturated soils, known as Richards' equation.

$$\frac{\delta \theta}{\delta t} = \frac{\delta \left[K(h) \left(\frac{\delta h}{\delta z} + 1 \right) \right]}{\delta z} - S \tag{C.1}$$

In this equation, θ is the volumetric water content $[cm^3\ cm^{-3}]$, t is time [d], K(h) is the hydraulic conductivity $[cm\ d^{-1}]$, h is the soil water pressure head $[cm]$, z is the vertical coordinate taken positively upward $[cm]$ and S $[cm^3\ cm^{-3}\ d^{-1}]$ is the sink term. This sink term is equal to the soil water extraction rate by plant roots when no exchange with macro pores or drain discharge in the saturated zone are considered, as is done in this analysis. Richards' equation is solved numerically by SWAP, using soil physical relations and soil characteristics. Flow between compartments follows from difference in pressure heads between compartments. The layering of the soil profile and thickness of the individual compartments is essential for the soil water flow computation. Prior research by Dam & Feddes (2000) reports for realistic simulation of matrix infiltration at the soil surface and fluxes of infiltration and evaporation, a required compartment thickness near the soil surface in the order of 1 cm. Deeper in the soil profile, where the soil water is less dynamic, the compartment thickness may increase. In the current research, the first (and top) sublayer consists of 5 compartments of 1 cm thickness. The second sub layer has 5 compartments of 5 cm. These two sub layers are the first soil layer. The third sublayer consists of 7 compartments of 10 cm. The last sub layer consists of 4 compartments that are each 50 cm in thickness. Thus the total column used in this simulation has a height of 300 cm. This is visualized in Fig. C.2.
Different options are possible in SWAP for the numerical solution of Richards' equation for which the default settings are used. The numerical scheme used in the current research to solve Richard's equation is an adapted version of the implicit, backward, finite difference scheme with an explicit linearization of hydraulic conductivities described by Haverkamp et al. (1977); Belmans et al. (1983). The current scheme is described by van Dam et al. (2008). This scheme applied in SWAP complies with an accurate balance and rapid convergence. The combination of this computation with the top boundary procedure in SWAP describes accurately and computational efficiently the process of water movement in the soil during infiltration (Van Dam & Feddes, 2000).

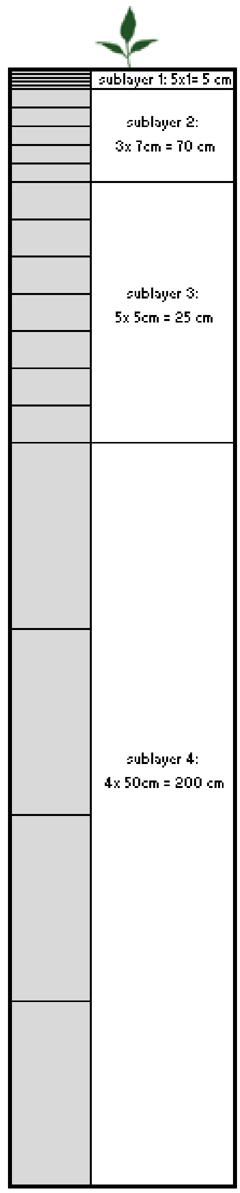


Fig. C.2: Applied soil layering in SWAP

An essential element in the soil profile is the definition of soil characteristics. The soil characteristics and corresponding hydraulic functions are defined by the Mualem - van Genuchten parameters. The van Genuchten analytical θ(h) function (Van Genuchten, 1980) is used to compute the soil water retention curve or soil moisture characteristic. This curve can be used to predict soil water storage, saturation, field capacity and wilting point. This is visualized in Fig. C.3 where an example of the soil water retention capacity for plant root water uptake is indicated for loam soil. Wilting point can vary for different crop types.

$$\theta = \theta_{res} + (\theta_{sat} - \theta_{res}) \left(1 + |\alpha h|^n\right)^{-m} \tag{C.2}$$

In the van Genuchten equation, θ is the actual water content $[cm^3\ cm^{-3}]$, h is the soil water pressure head $[cm]$, θ_{res} is the residual water content $[cm^3\ cm^{-3}]$, θ_{sat} is the saturated water content $[cm^3\ cm^{-3}]$, α is an empirical shape parameter related to the air entry suction $[cm^{-1}]$, n is a measure of pore-size distribution [-] and m [-] is also an empirical shape parameter which can be taken as equal to 1 – (1/n).

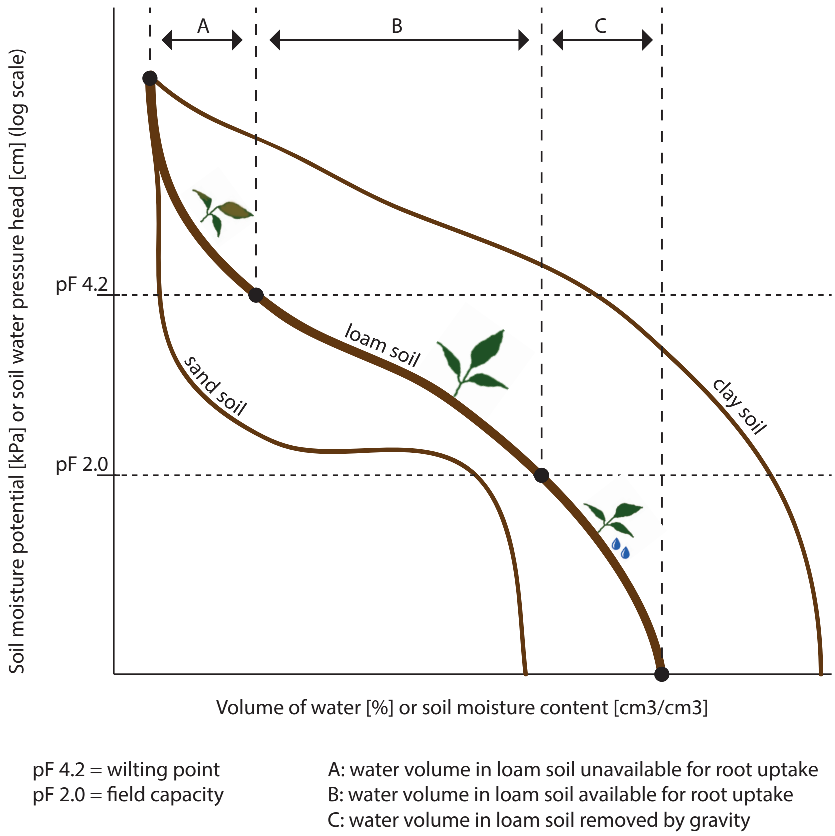


Fig. C.3: Illustration of water retention curves for different soil types, water volumes indicated for loam soil

An approximation of the differential water capacity C [cm-1] can be obtained with the derivative of θ to h. The differential water capacity is required in the numerical solution of Richards' equation. Using the above equation for θ(h), the theory on unsaturated hydraulic conductivity (Mualem, 1976) is applied. Hydraulic conductivity is a measure of ease of movement of a fluid like water through a porous medium like soil.

$$K = K_{sat} S_e^{\lambda} \left[1 - \left(1 - S_e^{\frac{1}{m}} \right) e^m \right]^2 \tag{C.3}$$

In the Mualem equation, K is the unsaturated hydraulic conductivity [cm d-1], K_{sat} is the saturated hydraulic conductivity [cm d-1], λ is a shape parameter [-], S_e [-] is the relative saturation which can be defined as $(\theta - \theta_{res})/(\theta_{sat} - \theta_{res})$. Parameter m [-] is the same shape parameter used in the soil retention curve, related to n. The hydraulic conductivity K describes the ease by which a fluid can move through pore spaces or fractures. For the numerical solution of Richards' equation yielding a steady-state solution the hydraulic conductivity is to be treated implicitly through its derivative to h. In this research, the weighted geometric mean is used for the computation of the hydraulic conductivity and for Richards equation with hydraulic conductivity an explicit solution is applied. Due to the hysteretic effect of water filling and draining soil pores, different wetting and drying curves may be distinguished in the soil water retention curve. Since hysteresis is not considered in this research, the α parameter of the main wetting curve for hysteresis is equal to the α parameter for the main drying curve. The air entry pressure head is known to be equal to -1/α. In this study the measured saturated vertical hydraulic conductivity is assumed to be equal to the fitted saturated vertical hydraulic conductivity Bartholomeus et al. (2015).

Lateral drainage, infiltration or interflow in the soil profile can be simulated but does not apply when a deep ground water table and free drainage at the soil column bottom is observed. When lateral drainage is observed from open channels or drain tubes then resistance of drainage and infiltration, drain spacing and case of open channels water levels in time are defined for each number of the the present drainage levels. In this research, several phenomena are not included in the simulation. This applies to hysteresis, similar media scaling, preferential flow due to macro pores and the computation of heat transport. The initial soil moisture condition is defined by an initial ground water level assuming equilibrium. The conducted simulations include solute transport, as the soil moisture content and actual transpiration can be influenced by solute concentrations. Solute concentration [$mg\ cm^{-3}$] in precipitation and irrigation water is neglected. The initial soil solute concentration in the soil profile needs to be defined for each research site. Solute adsorption is considered as well as solute decomposition and mixed reservoir of saturated zone.

Top boundary The top boundary is strongly determined by the cultivated crop. Date of crop emergence is indicated in the main .swp input file. Crop characteristics are defined in the .crp input file. Either the simple crop module or the detailed crop module WOFOST can be used. In paragraph 2.5 on WOFOST the detailed module is presented. This section applies to the input file for the simple crop module.

Crop phenology in time is highly relevant in SWAP. This is defined in SWAP as the development state (DVS). Two temperature sums for the period from emergence to anthesis (blooming) and from anthesis to maturity define the development stage of the crop, where crop emergence is assumed to occurs at DVS = 0.01, anthesis at DVS = 1.00 and crop maturity (and consequent harvest) at DVS = 2.00. Also a start value of this temperature sum below which no physical activity takes place is defined. The crop development stage is of large significance for crop performance and biomass accumulation. Other crop characteristics are defined as a function of DVS, where a series of DVS records and for each DVS a corresponding parameter can be assigned. SWAP applies linear interpolation for these parameters between the records of DVS.

SWAP applies Penman-Monteith in the computation of potential evapotranspiration. With actual crop data, three evapotranspiration rates [cm/d] are computed for a wet canopy completely covering the soil, for a dry canopy completely covering the soil and for a bare and wet soil. Potential evaporation and transpiration in the simulation is computed from these three rates. SWAP also allows the application of Penman-Monteith with reference crop data and crop factor. When a crop factor of 1.0 and reference crop data is applied, the crop reference evapotranspiration rate assuming grass can be computed, ET_{ref} or ET_0. This is a method standardized by FAO, the general Penman-Monteith equation known as the combination equation (Allen et al., 1998). The elements in the equation are derived in SWAP following the standardized FAO method, from meteorological input data and crop characteristics. SWAP and SEBAL use slightly different meteorological input data for the Penman-Monteith equation. In Paragraph 4.1 output of reference evapotranspiration assuming grass coverage is observed for both models. Appendix **??** elaborates on the use of Penman-Monteith in SEBAL and SWAP.

In the simple .crp input file, the leaf area index is defined along the crop development stage. Thus the leaf area index in this crop module is forced and not defined by physical processes. Following, the crop height along the crop development stage is required. Also the crop reflection coefficient (albedo) and minimum canopy resistance are required for the computation of ET with Penman-Monteith. The canopy resistance of intercepted water is assumed to be negligible for the observed crops. Other crop characteristics involve coefficients for light extinction for diffuse and direct visible light which are used to quantify the decrease of solar radiation within a canopy. The rainfall interception method of Von Hoyningen-Hune and Braden with corresponding coefficient is selected for the observed crops. The rooting depth along the development stage is defined. The relative root density along the rooting depth is unknown for the simulated crops and assumed to be constant along the rooting depth as is applied in may applications of SWAP (Agoshkov & Puel, 2009). Soil water extraction by plant roots is further defined through the microscopic concept (de Jong van Lier et al., 2008). requiring values for critical pressure heads and levels of high and low atmospheric demand. In a SWAP simulation crops can experience water stress resulting in a reduction in transpiration, either from wetness or drought. Reduction in transpiration can also be caused by salt stress. For the relation between ECsat and crop reduction, the ECsat level at which salt stress starts and the decline of root water uptake above this level is required. For the relation between concentration and ECsat, a coefficient and an exponent to convert concentration to EC are needed.

The sink term S [$cm^3\ cm^{-3}\ d^{-1}$] in Richards' equation is equal to the soil water extraction rate by plant roots since no exchange with macro pores or drain discharge in the saturated zone are considered. S_{pot}(z) [d^{-1}] is the potential root water extraction rate at a certain depth. This is determined in SWAP as the product of the potential transpiration rate Tpot and the root length density l_{root}(z) at this depth [$cm^3\ cm^{-3}$] as a fraction of this root length density integrated over the root layer thickness D_{root} [cm]. This method and equation is developed by (Bouten, 1992).

$$S_p(z) = \frac{l_{root}(z)}{\int_{-D_{root}}^{0} l_{root}(z)\,dz} T_p \quad \text{(C.4)}$$

Since for the root density a uniform distribution along the root depth is assumed, the above equation can be simplified as is also suggested by Feddes (1978), resulting in S_{pot} independent of z.

$$S_p(z) = \frac{T_p}{D_{root}} \quad \text{(C.5)}$$

SWAP computes water content in each soil compartment. Within the root zone D_{root}, for the i^{th} compartment the equation above is computed using compartment height H_i [cm] instead of D_{root} Skaggs et al. (2006) argumented that different stress factors can be multiplied to calculate the actual root water flux Sact(z) [d-1]. This is applied in SWAP where the potential root water extraction rate is multiplied with the dimensionless reduction factors due to wetness, drought, salinity stress and frozen soil conditions:

$$S_a = \alpha_{rd} * \alpha_{rw} * \alpha_{rs} * \alpha_{rf} * S_{pot} \quad \text{(C.6)}$$

Frozen soil conditions do not occur so it is assumed that α_{rf} = 1 at any moment during the simulation. Water stress indicated by α_{rw} and α_{rd} is in SWAP described by the function proposed by (Feddes et al., 1978) see the left chart in Fig. C.4. This graph describes the distribution of soil water pressure head against the reduction factor α due to water stress. For soil water pressure heads above h_1 the plant is too wet to extract water. Between h_1 and h_2 the plant experienced stress from wetness (indicated as α_{rw} in above formulas). The crop experiences stress of drought when the soil water pressure head is between h_3 and h_4 (indicated as α_{rd} in above formulas). In case of pressure heads below h_4 no water uptake is possible. For pressure heads between h_2 and h_3, optimal root water uptake is observed so that α_{rw} and α_{rd} are equal to 1. For h_3 two values can be defined, since the crop demand of water is not constant during the crop cycle. Naturally for high rates of transpiration the plant will earlier experience stress of drought since more water is required. A higher pressure head h_{3h} is found for higher transpiration T_{high} and a lower pressure head h_{3l} is found for a lower rate of transpiration T_{low}. Water stress reduction factors α_{rw} and α_{rd} are computed in SWAP for each soil compartment separately as SWAP considers a specific soil water pressure head for each compartment.

Likewise, a graph can be used for salinity stress. SWAP uses the response function of (Maas & Hoffman, 1977) indicated in the right chart of Fig. **??**. Salinity stress is determined using two parameters. EC_{max} [dS m-1] is the salinity concentration below which it is assumed that no salinity stress is experienced by the plant. EC_{slope} [m dS-1] is the rate at which the root water uptake declines at salinity levels above EC_{max}. The chart shows the soil water electrical conductivity (EC) against the reduction factor α_{rs}.

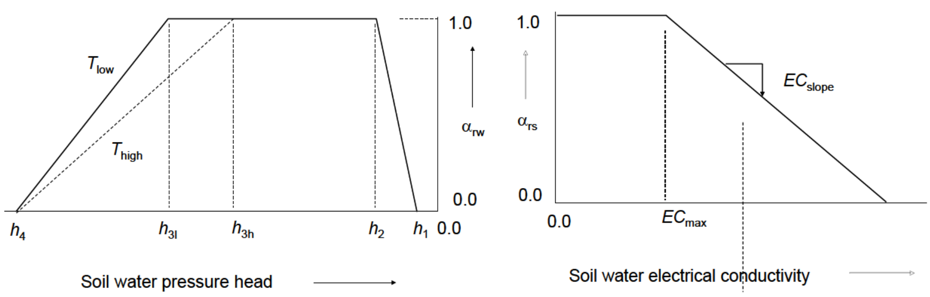


Figure 3.4 Reduction coefficient for root water uptake, α_{rw}, as function of soil water pressure head h and potential transpiration rate T_p (after Feddes et al., 1978).

Figure 3.5 Reduction coefficient for root water uptake, αrs, as function of soil water electrical conductivity EC (after Maas and Hoffman, 1977).

Fig. C.4: Reduction factors from water stress (left) and salinity stress (right) in SWAP (Kroes et al., 2009)

The actual root water extraction rate is determined for each soil compartment. The amount of water extracted in the i^{th} soil compartment in the root zone is computed in SWAP using:

$$S_{act[i]}(z) = \frac{\alpha_{rd[i]} * \alpha_{rw[i]} * \alpha_{rs[i]} * T_{pot[i]}}{H_i} \tag{C.7}$$

Where H_i [cm] is the height of the i^{th} compartment. When a value for S_{act} can be used for each compartment in a soil layer, T_{act} is computed by integrating S_{act} over the height of the root zone D_{root}. Since S_{act} is computed for each compartment specifically, T_{act} can be found using the following equation:

$$T_{act} = \sum_{i=1}^{n} \left(\int_{-D_{root}}^{0} S_{act}(z)\, dz \right) \tag{C.8}$$

Where n is the amount of compartments within the root zone. With the assumed uniform root length density distribution, the above equation can be simplified:

$$T_{act} = T_{pot} * \sum_{i=1}^{n} \left(\alpha_{rd[i]} * \alpha_{rw[i]} * \alpha_{rs[i]} \right) \tag{C.9}$$

Thus T_{act} is equal to the product of T_{pot} with the sum of the reduction factors of all the compartments within the root zone. The reduction factor of each compartment is the product of it's reduction factor for drought, wetness and salinity.

The simple model does not calculate the crop potential or actual yield. Irrigation can be applied both from the general input file .swp or from the crop input file .crp. From the main input file, a time series is required including per day an amount of water, concentration of irrigation water and type of irrigation where sprinkling or surface irrigation can be selected. In the observed fields, irrigation water concentration is assumed to be negligible and surface irrigation is applied. Applying irrigation from the crop input file allows the use of irrigation timing and depth criteria instead of prescribed days and amount of irrigation. Specific dates between which irrigation scheduling is allow are required, as well as the solute concentration of irrigation water and the method of sprinkling or surface irrigation. For timing criteria multiple options are available for which thresholds along the crop development stages are required. This can be defined by daily stress, depletion of readily or totally availably water, depletion of water amount, critical pressure head or soil moisture content, water deficit. Irrigation can also be set weekly or with another fixed interval. For irrigation depth criteria, this can be set back to field capacity or using a fixed irrigation depth. Also minimum and maximum irrigation depths can be set. The settings on irrigation are an important factor in the column top boundary.

The soil column top boundary in SWAP is also determined by daily weather conditions. SWAP requires input data including short wave radiation [kJ m-2], maximum and minimum temperature [$°C$], actual vapor pressure [kPa], wind speed [$m\ s^{-1}$] and precipitation [$mm\ d^{-1}$]. Daily values for reference evapotranspiration ET_{ref} [$mm\ d^{-1}$] are computed with the meteorological data using Penman-Monteith. The latitude and altitude of the meteorological station and the height of the wind speed measurements is required. Since remote sensing data is used for meteorological data, the local latitude and altitude are used. The wind speed measurements height is needed in SWAP to correct when crop heights are different from wind speed height. This is only done for wind speed measurements above 2.0 m since a highly variable wind speed profile is assumed below 2 m. At weather stations wind is typically measured at 10 m height. The remotely sensed wind speed is indicated as near surface wind speed. In SEBAL where the same data is used, a wind speed measurements height of 2.0 m is assumed, also applied in SWAP.

Regarding ponding, runoff and runon the default settings in SWAP are applied. This includes a minimum thickness of 2 cm for runoff in case of ponding, a drainage resistance for surface runoff of 0.5 days and an exponent in the drainage equation of surface runoff of 1.0. For soil evapotranspiration the choice is made to not use the soil factor to calculate Epot from ETref, with this setting SWAP will compute Epot separately with crop characteristics or crop factor. For the reduction of potential soil evaporation, SWAP is set to compute a reduction to maximum Darcy flux and to maximum Boesten/Stroosnijder (Boesten & Stroosnijder, 1986) for which the corresponding soil evaporation coefficient of Boesten/Stroosnijder is used. No snow accumulation and melt or soil water flow reduced by frost is considered. Top soil temperature is said to be computed from air temperature of meteo input file.

Bottom boundary An initial ground water level is defined. SWAP allows several options for the definition of the bottom boundary. It can be prescribed by time series of ground water level, bottom flux, soil water pressure head at the soil profile bottom compartment or hydraulic head in deep aquifers. There is also an option for free drainage or outflow or a bottom flux equal to zero. The different options require different parameters. The selection for the applied method is determined by the local situation and available data.

D

World FOod STudies crop growth model (WOFOST) theoretical background

WOFOST computes absorbed radiation by solar radiation and crop leaf area. WOFOST also takes photosynthetic leaf characteristics and possible water and/or salinity stress into account, when computing the produced carbodydrates (CH2O). CH2O provides energy for living biomass (maintenance respiration) and is converted into structural material during which weight is lost (growth respiration). Produced material is partitioned among roots, leaves, stems and storage organs, determined by partitioning factors depending on the development stage. The fraction partitioned to the leaves determines leaf area development and hence the dynamics of light interception. This is visualized schematically in Fig. D.1. In the simple crop module of SWAP which can be used instead of WOFOST, the Leaf Area Index (LAI) is forced directly by the user as a function of crop development stage, not influenced by physical processes as incorporated in WOFOST. In WOFOST, dry weight of the plant organs is obtained by integrating growth rates over time. During the development of the crop, part of living biomass dies due to senescence. Unlike the simple crop module, WOFOST enables the simulation of actual crop biomass production.

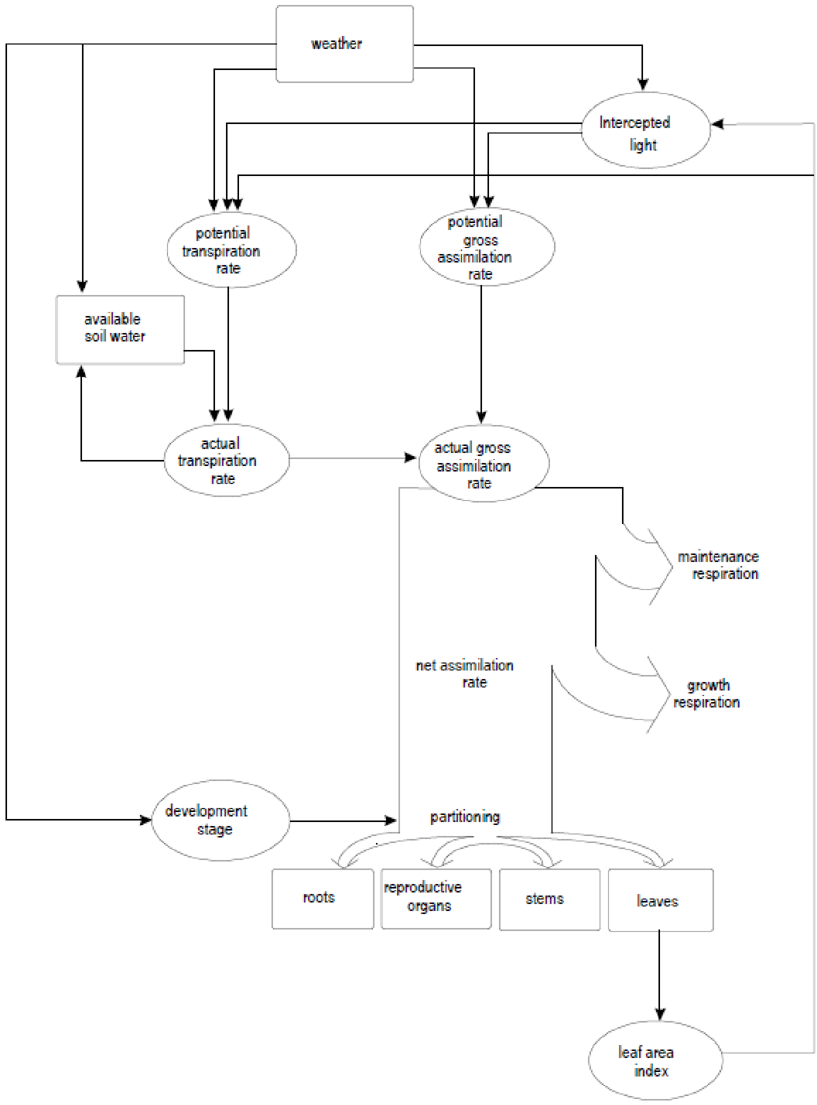


Fig. D.1: Major eco-physiological processes used in the simulation of crop growth in WOFOST (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014)

SWAP employs the TTUTIL library to read the ASCII input files in easy format. Output is generated in ASCII and binary files. SWAP input files like the .crp input file consist of required data and various parameters that can be adjusted by the user. Using WOFOST requires a more detailed .crp input file than where the simple crop module is applied. A description on the general structure of SWAP and use of the simple crop module is given in paragraph 2.4. This section describes the detailed WOFOST .crp input file used in SWAP. Light interception and carbon dioxide (CO2) assimilation are the main crop growth driving processes. Some simulated crop growth processes like the maximum rate of photosynthesis and the maintenance respiration are influenced by temperature. Other processes are a function of the phenological crop development stage (DVS), including the partitioning of assimilates or decay of crop tissue. The parameters are dependent on crop type and the selected sites of research and require calibration.

In the crop input file the definition of the crop phenology development stage (DVS) is very significant. Crop emergence is assumed to occur at DVS = 0.01, anthesis (flowering or heading) at DVS = 1.00 and crop maturity (and consequent harvest) at a user defined stage of 2.00. Two temperature sums for the period from emergence to anthesis and from anthesis to maturity define the actual development stage of the crop during simulation, which decreases with daily temperature. The increase in temperature sum can be defined as a function of daily average temperature. Crop development can also be dependent on length of day light, where a minimum day length for optimum crop development and a shortest day length for any development can be defined. The crop development stage is of large significance for crop performance and biomass accumulation. Other crop characteristics are defined as a function of DVS, where a series of DVS records a corresponding parameter can be assigned. SWAP applies linear interpolation for these parameters between the records of DVS.

The definition of crop characteristics for computation of Penman-Monteith and other characteristics include crop height, light extinction, crop reflection, rainfall interception, canopy resistance, coefficients for light extinction for diffuse and direct visible light, crop reflection coefficient (albedo) and minimum canopy resistance, this is similar to the simple crop module. The crop height is defined along the crop development stage. The canopy resistance of intercepted water is assumed to be negligible for the observed crops and the for the rainfall interception method of Von Hoyningen-Hune and Braden the corresponding coefficient is selected.

Regarding the rooting depth, an initial rooting depth, maximum daily increase and maximum rooting depth is required. The relative root density along the rooting depth is unknown for the simulated crops and assumed to be constant along the rooting depth as is applied in may applications of SWAP (Agoshkov & Puel, 2009). Soil water extraction by plant roots is further defined through the microscopic concept (de Jong van Lier et al., 2008). This is the same as defined in the simple crop module, requiring values for critical pressure heads and levels of high and low atmospheric demand. In a SWAP simulation crops can experience water stress resulting in a reduction in transpiration, either from wetness or drought. Reduction in transpiration is also caused by salt stress, for which the procedure is also equal to the simple crop module. For the relation between ECsat and crop reduction, the ECsat level at which salt stress starts and the decline of root water uptake above this level is needed. For the relation between concentration and ECsat, a coefficient and an exponent to convert concentration to EC are needed. A factor is used to convert concentration to EC per model profile. For the application of irrigation scheduling, the same options are available as given in the simple crop module. Applying irrigation from the crop input file allows the use of irrigation timing and depth criteria instead of prescribed days and amount of irrigation. Specific dates between which irrigation scheduling is allow are required, as well as the solute concentration of irrigation water and the method of sprinkling or surface irrigation. For timing criteria multiple options are available for which thresholds along the crop development stages are required. This can be defined by daily stress, depletion of readily or totally availably water, depletion of water amount, critical pressure head or soil moisture content, water deficit. Irrigation can also be set weekly or with another fixed interval. For irrigation depth criteria, this can be set back to field capacity or using a fixed irrigation depth. Also minimum and maximum irrigation depths can be set. The settings on irrigation are an important factor in the column top boundary.

The crop green area assimilates and respirates carbon dioxide (C02). For CO2 assimilation by leaves, the assimilation-light response method for single leaves is applied, where the gross assimilation rate is determined by a maximum gross assimilation rate at light saturation, the rate of light absorption in the canopy and the light use efficiency. The maximum gross assimilation rate and light use efficiency are determined in the .crp input file. The light use efficiency is a constant parameter, the maximum gross assimilation rate is a function of development stage. The rate of light absorption in the canopy is the derivative over the depth of the canopy of the net light intensity, which is the light intensity adjusted for crop reflection. Light intensity is assumed to decrease exponentially into the canopy with leaf area index. This net light intensity is determined by the incoming Photosynthetically Active Radiation (PAR), the reflection coefficient of a green leaf canopy with a random spherical leaf angle distribution according to (Goudriaan, 1977), the radiation extinction coefficient kappa and the depth of the canopy which is equal to the cumulative Leaf Area Index (LAI). The instantaneous rates per leaf layer are integrated over the canopy leaf area index and over the day, for which the Gaussian integration method is used. So far, assimilation is treated as a function of the intercepted light and photosynthetic crop characteristics such as initial light use efficiency and maximum leaf CO2 assimilation rates. The daily computed assimilation rate in WOFOST can be reduced by unfavorable temperatures. Reduction factors can be defined in the .crp input file as function of average day temperature and as function of minimum day temperature.

Some of the carbohydrates formed are respired to provide energy for maintaining the existing biological structures. This maintenance respiration consumes roughly 15-30% of the carbohydrates produced by a crop in a growing season (Penning de Vries et al., 1979). This underlines the importance of accurate quantification of this process in the model. WOFOST estimates the maintenance costs using the approach proposed by (Penning de Vries & van Laar, 1982), assuming that the reference maintenance requirements are proportional to the dry weights of the plant organs to be maintained. In the .crp input file, relative maintenance respiration rate of leaves, storage organs, roots and stems are required. These maintenance respiration rates are corrected for senescence and temperature. The crop-specific reduction factor for senescence is defined as a function of development stage. Higher temperatures accelerate the turnover rates in plant tissue and hence the costs of maintenance. An increase in temperature of $10°C$ typically increases maintenance respiration by a factor of about 2 (Kaše & Čatský, 1984; Penning de Vries & van Laar, 1982). The increase factor of the respiration rate per $10°C$ temperature increase is defined in the input file.

Dry matter can be partitioned among roots, leaves, stem and storage organs. The primary assimilates that exceed the maintenance costs are available for conversion into structural plant material. In this conversion process CO2 and H2O are released. The magnitude of growth respiration is determined by the composition of the end product formed (Penning de Vries et al., 1974). The weight efficiency of conversion of primary photosynthates into structural plant material varies with the composition of that material. Fats an polymer support tissues (lignin) are produced at high costs; structural carbohydrates and organic acids are relatively cheap. Proteins and nucleic acids form an intermediate group. These efficiencies are incorporated in organ specific conversion factors defined for conversion into leave, storage organs, roots and stems. For each of these four plant organs, crop specific partitioning factors along the crop development stage are defined. In Fig. D.2 an example of a typical assimilation is visualized.

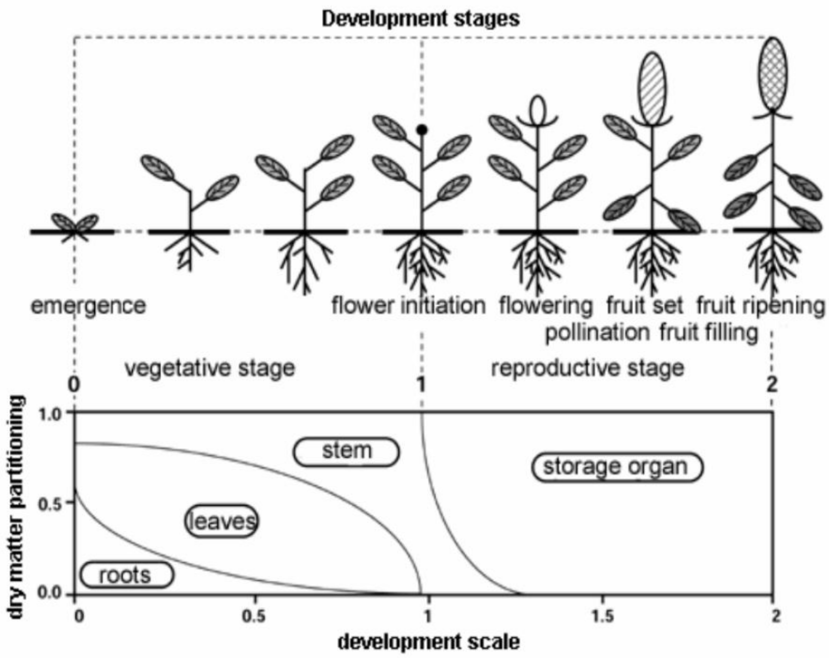


Fig. D.2: Typical partitioning of assimilated dry matter among leaves, stem, roots and storage organs as function of development stage in WOFOST (Boogaard, Van Diepen, Rötter, Cabrera & Van Laar, 2014)

Death rates (senescence) are determined in WOFOST for each plant organ. The death rate of storage organs is assumed to be zero. Death rate for stems and roots is a function of crop development stage. Death rates for leaves are due to water stress, self-shading and exceedance of leave life span. Potential death rate of leaves due to water stress is defined by the leaf dry matter weight, potential transpiration and an in the .crp input file defined maximum relative death rate of leaves due to water stress. Potential death rate of leaves due to self-shading is determined by the leaf dry matter weight and extinction coefficient for the diffuse radiation flux and increases linearly with leaf area index. The maximum value of these two potential death rates is used in WOFOST for the combined effect of water stress and mutual shading. Leaves that escaped from premature death due to water stress or mutual shading, die inevitably due to exceedance of the life span for leaves. Life span is defined in the .crp input file, it is the maximum amount of days a leaf can live at a constant temperature of 35°C. A physiologic aging factor is calculated each day, determined by the average temperature and the defined lower threshold temperature for aging of leaves. The integral over time of this physiological aging factor represents the physiologic age. SWAP daily computes specific leaf area, growth of dry matter leave weight and physiological age. These daily values are added as elements to three arrays. The weight of leaves that has died from water stress or self-shading is subtracted from the weight of the oldest array element, then from the second oldest leaf element, and so on, emptying and thus removing the oldest leaf elements. After removal from water stress and self-shading, WOFOST checks the physiological age and removes the elements that have attained the maximum life span.

The initial amount of dry crop weight and the initial leaf area index at emergence are defined in the .crp input file. The product of the initial dry weight and the initial partitioning factor yield the dry weight at emergence. Daily net growht rate for each plant organ is determined by gross growth rate and senescence. Integration over time yields the dry matter weight for stems, roots and storage organs. For the plant leaves WOFOST applies a different approach. In the initial stage, rather than by the supply of assimilates both the rate of leaf appearance and final leaf area are constrained by temperature because of the effect of temperature on cell division and extension. Prior research reports that for a relative wide range of temperatures the growth rate responds linearly to temperature (Hunt et al., 1985; Causton & Venus, 1981; van Dobben, 1962). The growth rate of the leaf area index w_{LAI} in this initial exponential growth stage is therefore described in WOFOST as the product of the leaf area index, the maximum relative increase of leaf area index defined in the .crp input file and the effective temperature. WOFOST assumes that the exponential growth rate of LAI will continue until it equals the assimilation limited growth rate for this index and thus reaches the growth source limit. When this second, source limited growth stage is reached, wLAI is determined by the product of the daily net growth rate for leaves and the specific leaf area. The specific leaf area is defined in the .crp input file as a function of development stage. The green parts of the stems and storage organs may absorb a substantial amount of radiation in addition to the plant leaves. The corresponding green area index (GAI) is added to the leaf area index. The green area index is computed in WOFOST for both the stems and storage organs as the product of the dry matter weight for the plant organ and its specific green area. The specific green area for the storage organs and stems is indicated in the crop input file. For both the simulated crop types these specific green areas are considered negligible.

E

Method for land use classification in Google Earth Engine using ground truth data

Tadla Basin Morocco Land Use Classification

For September 2015 – August 2016

Charlotte van der Leer
February 17th 2017

Abstract

A landuse classification of Tadla basin (Morocco) for an area of 3,440 km^2 for the time span September 2015 – August 2016 is conducted in Google Earth Engine using a ground truth dataset of 1648 polygons and Normalized Difference Vegetation Index images. After comparison of several combinations of Sentinel-2, Landsat-8 and Landsat-7 images for monthly averages, a classification was selected using all of the mentioned imagery. The ground truth dataset is further complemented based on visual analysis of current Google Satellite imagery. From each of the 21 individual classes, 200 random points are taken in order to obtain a representative training set without exceeding the maximum capacity of the Earth Engine. The selected classification was validated for six most frequently appearing crops using an independent dataset of 773 ha. The obtained accuracy is 80%. Of Tadla basin, 56% of the cultivated area is classified as one of these validated crops. Independent validation for all classes was not possible because of the small amount of ground truth data available for most of the classes. The accuracy for the complete ground truth dataset area including the points used as training data, and therefore not totally independent, is 58% with a large variation between the accuracies of the different classes specifically. In the used ground truth dataset, the four crop types that are the least frequently appearing are represented by an area of less than 0.1 ha. These classes specifically result in a low classification accuracy of 0-2%. As land use classification is an important element of water management and hydrology, it is recommended for further research to determine the necessary minimum area for each present crop in a ground truth dataset in order to obtain significant accuracy. As the training data and independent validation data is taken from the same section of the basin, it is recommended also for further research to validate the result in a different section of the basin.

The classification is used to select and localize frequently appearing crops in the area that can be modelled with the Soil Water Atmosphere Plant model. The selected crops are Sugar Beet (Beta vulgaris L.), classified with an accuracy of 74% and Winter Wheat (Tritium aestivum L.) classified with an accuracy of 83%. Variation of training point collections and analysis of the conversion matrixes for the different classifications suggests that the ground truth dataset is accurate except for two large polygons classified as citrus trees. The total classified area of Sugar Beet is 136 km^2 (4% of the basin) represented by 15,890 polygons having a size of 0.1 to 66 ha. The total obtained area of Winter Wheat is 345 km^2 (10% of the basin) represented by 21,920 polygons having an area of 0.1 to 184 ha. These localized fields of Sugar Beet and Winter Wheat will be used for further analysis not included in this report.

Introduction

This classification is a necessary component of a Water Management MSc thesis at the faculty Civil Engineering and Geosciences at Delft Technical University (The Netherlands) in which different perceptions regarding efficient water use in irrigated agriculture at fields scale are analyzed. Specifically, a field-scale analysis with the Soil-Water-Atmosphere-Plant model (SWAP) is conducted for fields in the Tadla Basin, Morocco, for crops that are commonly present in the area. To verify whether the result is plausible, a comparison is made with output from the Surface Energy Balance Algorithm for Land model

(SEBAL) which generates spatially distributed output. In order to do this comparison, information on the most frequent appearing crops that can be modelled in SWAP and their exact location for a specific time span is needed. In order to obtain this information, this land use classification as described in this report is done for the Tadla basin (3443 km^2), using a set of ground truth data of a section of the basin and Sentinel-2 and Landsat images. From this classification a choice is made for the crops to be modelled in SWAP. Crops that can be modelled in SWAP and that are known to be present in Tadla Basin are Field Bean (Vicia faba L.), Grain maize (Zea mays L.), Sugar Beet (Beta vulgaris L.) and Winter wheat (Tritium aestivum L.).

Method

The classification is conducted in the Google Earth Engine (EE) editor using Java Script and specific Earth Engine code, classifying pixels according to their Normalized Difference Vegetation Index (NDVI) development. It is assumed that NDVI development is crop type specific and will allow to make sufficient distinction between the different crops and other land use in the basin. In prior research, a ground truth land use classification has been conducted for the period September 2015 to August 2016 of an area of roughly 7 by 5 km, classifying 17 different crop types and two tree types (source?? Dataset provided by Wim Bastiaanssen, January 2017). Each class is represented by a collection of polygons that is assigned in EE as a feature collection. The amount of polygons per class is highly variable. It is assumed that the rarely appearing crops in the basin are represented by the classes having a few polygons each and that the frequently appearing crops are represented by the classes having a large collection of polygons. It is also assumed that this ground truth data set covers all appearing crops in the basin. When both assumptions are met the ground truth dataset is indeed representative for the whole Tadla basin. From the provided ground truth dataset, two large polygons classified as citrus trees have been left out of the analysis because an initial study of NDVI development over the observed area and time span indicated significant crop variety within these polygons. These left out areas are shown in figure 2. The crops and tree types are divided into the following groups, also visualized in figure 1.

1. Rarely appearing crops: each having 1-50 polygons and 0.2-40 ha within observed area
2. Frequently appearing crops: each having 80-400 polygons and 50-400 ha within observed area
3. Trees (olives and citrus): both having 30-60 ha within observed area

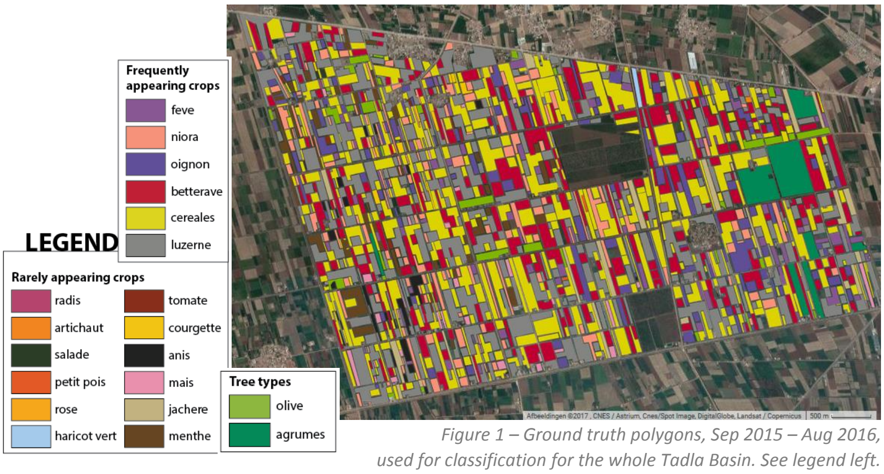


Figure 1 – Ground truth polygons, Sep 2015 – Aug 2016, used for classification for the whole Tadla Basin. See legend left.

Added to this ground truth dataset of crops and tree types is a selection of 10 polygons with urban area and 10 polygons with river water north of the observed area. These polygons have been chosen with visual inspection of the current Google Satellite images, assuming that the location of the urbanized areas and river water at the moment these images were taken is the same as in the period September 2015 – August 2016. The final dataset used for the classification consist of the different crop types, tree types, urban area and water, represented by 21 different land use classes.

Categories and random training points

From the polygons data set, a collection of 200 training points is taken randomly from each class. These points are used to construct a training image collection with monthly average NDVI values. In prior research a limited collection of polygons is used instead of random points from the total collection (Bastiaanssen & …, 2016). The choice for 200 points from the complete collection of polygons for each class instead of choosing a couple of polygons for each class is made in order to get an optimal representation of each class without exceeding the capacity of the classification method. EE has a maximum capacity for its calculations, when polygons are used for this 21 different classes then only a few polygons of each class can be used as training data. The ground truth dataset includes over 400 polygons for some of the crop types. It is expected that variation exists between different fields of the same crop, especially for frequently appearing crops because their frequent appearing suggests that these crops perform good under varying circumstances and treatment in the basin. It is therefore assumed that a random selection of points from the complete set of polygons for a specific crop will result in a better representation of the range of variety within this crop type than the selection of a few specific polygons. As much information as possible is utilized without exceeding the maximum capacity of EE when a random selection of 200 points is taken from its complete set of polygons.

To validate the method and used ground truth dataset, the group with the most frequently present crops is divided in two sets: set A and set B. Using these sets, the classification method is conducted twice for each dataset of NDVI images. Four categories of polygons are used for the analysis, visualized in figure 2:

- River water (bright blue polygons), used for each classification
- Rarely appearing crops, trees and urban area (yellow polygons), used for each classification
- Half of each frequent appearing crop, “A” (red polygons), used for classifications with set A
- Half of each frequent appearing crop, “B” (blue polygons), used for classifications with set B.

For each classification, the classes (00 to21) consist of all rarely appearing crops, the frequent appearing crops either within set A or B, both tree types, urban area and water. From each of these classes 200 points are taken randomly as training points. This means that a total dataset of 4200 points is used, within the engine capacity of 5000 points.

Figure 3 illustrates the points selected for the frequent (red and blue) and rarely appearing crops (yellow). As can be seen, the distribution of points varies significantly. Especially in the yellow category, points can be very close together since some crops within this group are represented by a single field and 200 points are taken within this one polygon.

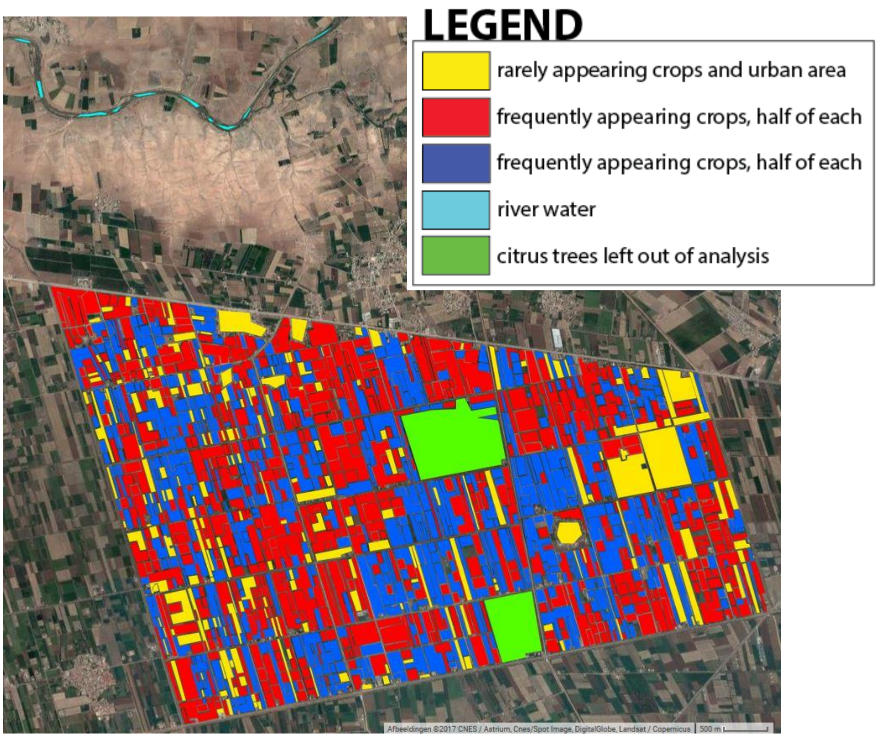


Figure 2 – Categories of polygons used for the classification of Tadla basin.

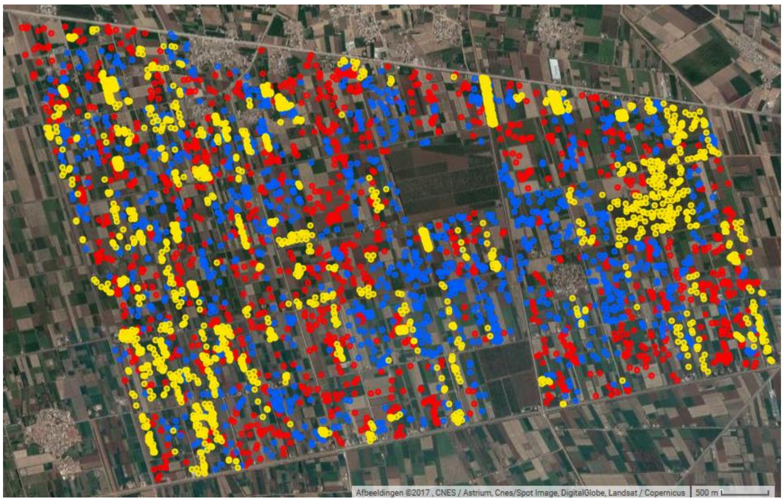


Fig 3 – Illustration of random points taken from different categories, 200 for each class.

NDVI maps

Monthly NDVI maps are generated using Sentinel-2 (S2), Landsat-8 (L8) and Landsat-7 (L7) images. S2 has a precision of 10m and images are produced every 5 days. L8 and L7 have a precision of 30m and are produced both every 16 days, 8 days apart. Parts of images containing clouds are not usable and pixels with cloud coverage have been removed from each image, resulting in gaps in the dataset. Monthly averages are used to solve for most of this problem.

Classifications using S2, L8, L7 or a combination of these are conducted. Graphical overview of the result is shown in Appendix I. With an initial visual analysis no large differences between Set A and Set B of each NDVI dataset are observed at first sight. This implies that the ground truth dataset is accurate. S2 combined with L8 with or without L7 appears to give the best result. Using only S2 images for monthly averages results in too much gaps in the dataset created by clouds. Only L8 and L7 or a combination of both results in a less accurate and more coarse result.

The rest of this analysis and report will focus on two NDVI datasets, each classified with set A and set B:

- S2, L8 and L7 (S2L8L7)
    - Classified with set A
    - Classified with set B
- S2 and L8 (S2L8)
    - Classified with set A
    - Classified with Set B

Although monthly averages of NDVI images are used, clouds still diminish the amount of data points that are usable. For all classes, the minimum amount of training points per month was found in October 2015. The amount of points available varies from 29 (for class 14 using S2L8) to 199 (for class 00 and class 12A using S2L8L7). Table 1 shows for each class its area in the ground truth data set and the monthly minimum number of training points available. The average number of available training points per class is less for the NDVI dataset S2L8 compared to S2L8L7, as could be expected. The largest difference is observed for class 14, having 29 points for S2L8 instead of 95 points for S2L8L7. A lower accuracy is expected for the classification of this class when NDVI from S2L8 is used.

Ground truth classification Tadla area and used training points per class		Rarely appearing crops												Frequent appearing crops: set A and B												Other		
		C15 - Radis	C02 - Artichaut	C17 - Salade	C14 - PetitPois	C16 - Rose	C07 - HaricotVert	C18 - Tomate	C04 - Courgette	C01 - Anis	C10 - Mais	C08 - Jachere	C19 - Menthe	C06A - Feve - A	C06B - Feve -B	C11A - Niora -A	C11B - Niora -B	C12A - Oignon -A	C12B - Oignon -B	C03A - BetteraveASucre -A	C03B - BetteraveASucre -B	C05A - Cereales -A	C05B - Cereales -B	C09A - Luzerne -A	C09B - Luzerne -B	C13 - Olive	C00 - Agrumes	C20 - Paved
Total area of polygons	absolute [ha]	0	0	1	1	1	2	2	6	16	17	39	42	27	20	45	50	49	45	136	114	264	180	253	202	32	64	22
per class	percentage of all classes [%]	0.01	0.02	0.04	0.05	0.07	0.13	0.10	0.38	1.01	1.02	2.40	2.55	2.90		5.85		5.77		15.37		27.23		27.89		1.94	3.90	1.36
Polygons per class	number available per class	1	1	2	2	1	1	7	13	27	32	31	51	43	45	77	75	70	52	124	118	198	211	205	205	38	8	10
S2L8L7 Training points,	number availabe per class	31	49	76	95	125	123	139	166	190	187	195	197	194	195	193	196	199	193	190	192	196	195	198	197	181	199	179
minimum per month	number available per ha	158	135	122	118	103	58	82	27	12	11	5	5	7	10	4	4	4	4	1	2	1	1	1	1	6	3	8
S2L8 Training points,	number availabe per class	31	49	76	29	125	107	139	166	190	187	171	197	180	178	167	177	199	147	149	158	186	174	189	184	174	199	124
minimum per month	number available per ha	158	135	122	36	103	50	82	27	12	11	4	5	7	9	4	4	4	3	1	1	1	1	1	1	5	3	6

Table 1 – Areas of ground truth dataset and comparison of available training points for S2L8L7 and S2L8.

Comparison of classifications

The visual result of the four classifications observing the area of the ground truth dataset, is shown on the following pages in figures 4 to 7.

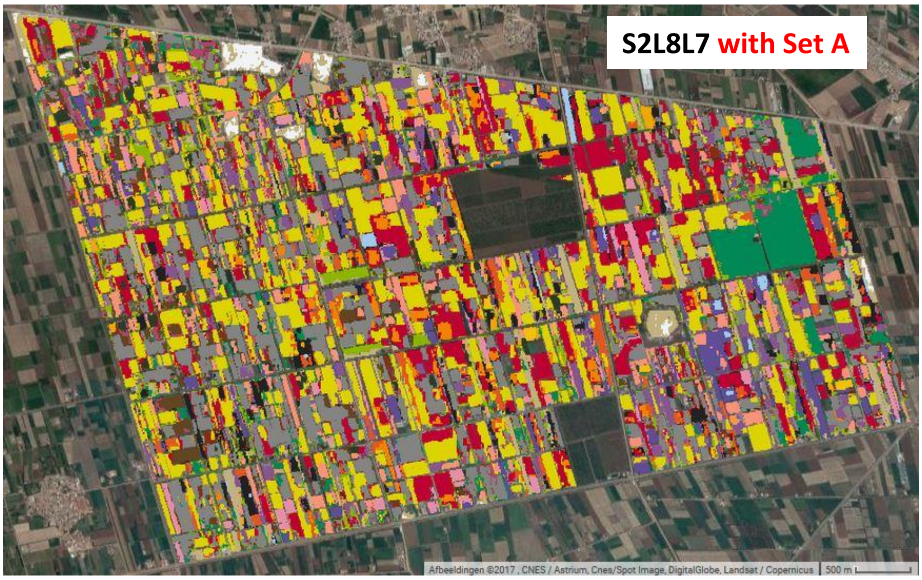


Figure 4 – Classification result for within ground truth areas, for S2L8L7-A.

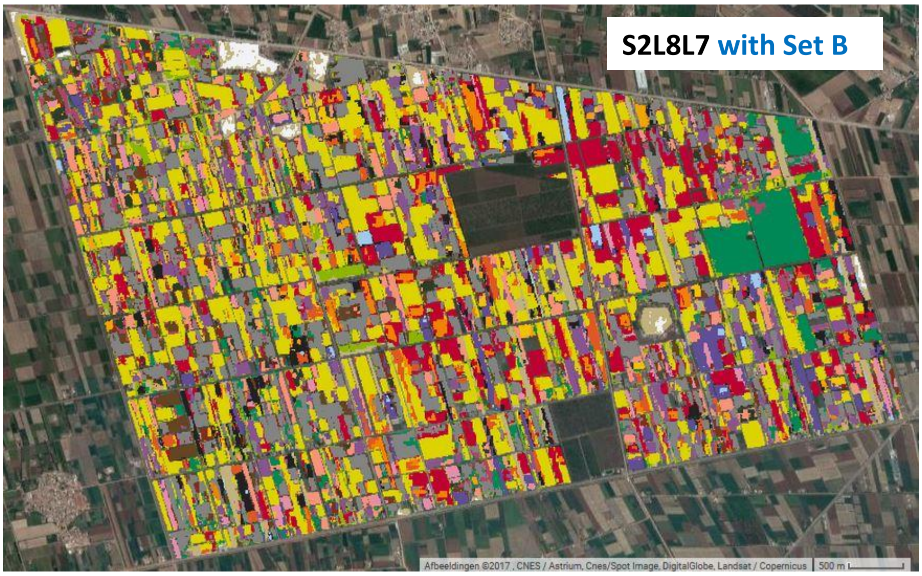


Figure 5 – Classification result for within ground truth areas, for S2L8L7-B.

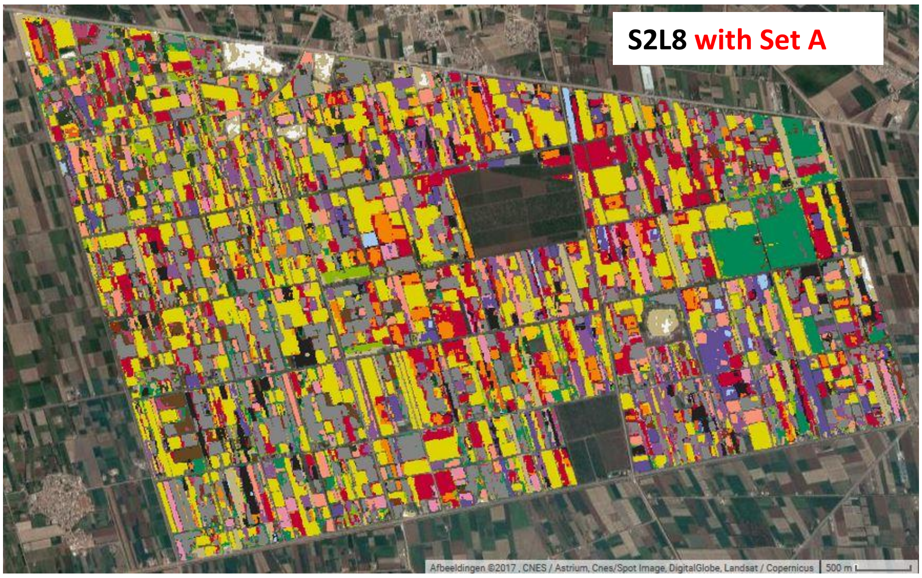


Figure 6 – Classification result for within ground truth areas, for S2L8-A.

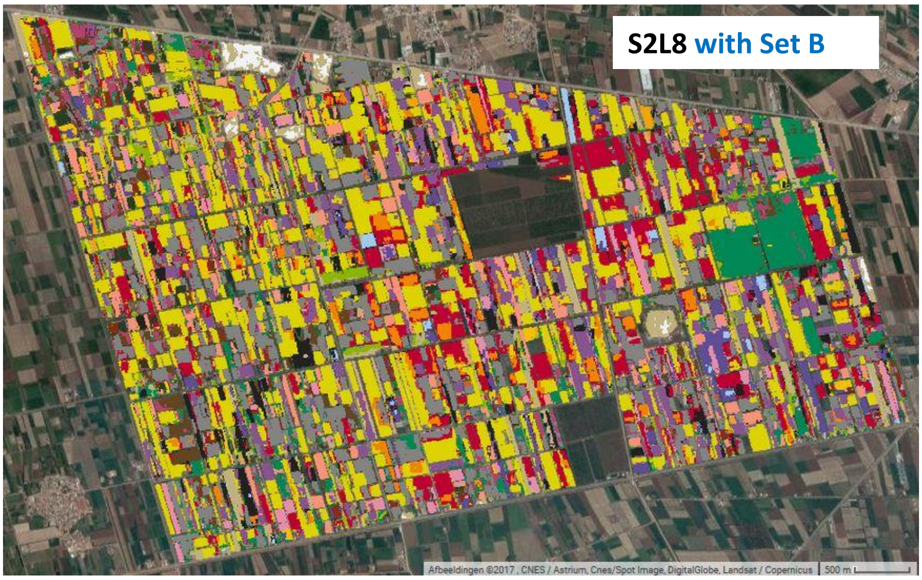


Figure 7 – Classification result for within ground truth areas, for S2L8-B.

In the following section the result of the four different datasets in their classifications of the area of the ground truth dataset will be further analyzed. This allows for a selection of the classification and crops that will be used in the further analysis with SWAP.

In table 2, accuracies for the different classifications are given, both for the complete set of 21 classes and for the four crops that can be modelled in SWAP. The accuracy of the complete set of classes is the area that is correctly classified according to the ground truth data set, as a percentage of the total area of the ground truth data set. The accuracy of a specific crop is the classified area that coincides with the area of this crop determined by the ground truth data set, expressed as the percentage of the total area that is classified as this specific crop. A 100% accuracy for a specific crop means that all the area that is classified as this crop coincides with the polygons of this crop as given in the ground truth dataset. However, if the classification generates only one pixel of a crop which happens to be within a polygon of this crop, then a 100% accuracy is reached for this crop, but the classification of the complete set of fields of this crop is far from the truth. Therefore table 3 is used which contains for the same crops the area of the ground truth polygons of the crop that is correctly classified, as a percentage of the total area of the polygons of this crop. This "completeness" observed for the complete collection of classes, is equal to the accuracy of the complete set of classes since it is the ground truth dataset area that is classified and analyzed. For the crops that have been divide into set A and set B, the completeness is observed for the set that has not been used as training data in the classification. These values show whether set A or set B is the best representation of the variation present within a crop type. The values in table 2 and 3 are given a colored background ranging from low values (white) to high values (green). As high values are desirable for both the accuracy and completeness of a classification, green cells indicate a favorable classification.

NDVI data	**S2L8L7**		**S2L8**	
polygon set	**A**	**B**	**A**	**B**
	Accuracy [% correct of classified area]			
All classes	**58.3**	**57.8**	**57.6**	**55.8**
C03 - Sugar Beet	68	74	65	70
C05 - Wheat	88	83	88	84
C06 - Beans	35	27	31	25
C10 - Maize	22	22	23	21

Table 2 – Accuracy, for total area and for four crops specifically.

NDVI data	**S2L8L7**		**S2L8**	
polygon set	**A**	**B**	**A**	**B**
	Completeness [% of ground truth recognized, for class 03, 05 and 06 observing the set not used for classification]			
All classes	**58.3**	**57.8**	**57.6**	**55.8**
C03 - Sugar Beet	50	52	45	44
C05 - Wheat	58	77	62	77
C06 - Beans	49	51	52	64
C10 - Maize	47	41	48	49

Table 3 – Completeness, for total area and for four crops specifically.

Observing the results presented in tables 2 and 3, clearly the crop types Sugar Beet (class 03) and Wheat (class 05) perform better in the classifications compared to Bean (class 06) and Maize (class 10), having a much higher accuracy. The accuracy of the NDVI dataset including Landsat-7 also performs slightly better than without Landsat-7. Although in the classification with S2L8L7 the accuracy of wheat is the highest (88%) using set A, the completeness using this set is much lower. Also the classification of Sugar Beet is better both in accuracy and completeness when set B is used. Therefore the choice has been made to continue using S2L8L7 with set B, selecting Sugar Beet (74% accuracy) and Wheat (83% accuracy) for simulation and further analysis using SWAP and SEBAL.

Results and discussion

With the chosen dataset of monthly S2L8L7 NDVI maps with set B, a classification has been conducted for the Tadla Basin, over the area of 3440 km^2, with a precision of 10m. The result is visualized in figure 8. In Appendix III the map is shown in more detail. The same color scheme applies as has been used before.

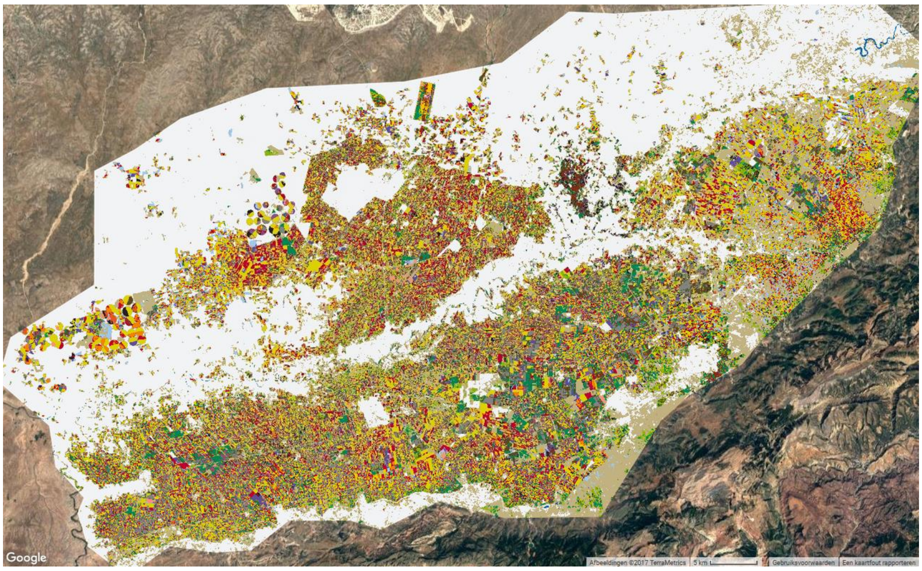


Figure 8 – Land use classification result for Tadla basin (3440 km^2) with S2L8L7-B, for Sep 2015 – Aug 2016.

Conversion matrix

In table 4 the conversion matrix is shown for this classification, observing the area of the ground truth dataset within Tadla basin. For each class both the accuracy and the completeness are given. In the following section the conversion matrix is further explained and analyzed. The conversion matrixes for the classifications S2L8-A, S2L8-B, and S2L8L7-A can be found in Appendix II.

The classes according to the ground truth polygons are structured vertically, first the rarely appearing, then the frequent appearing crops split into set A and set B, and then the non-crop. The first columns provide the total area for each class in the ground truth data set and the number of training points per ha. From the polygons of set A no training points are taken. Horizontally the classified areas are listed. The first few rows represent for each classified class the total area and the percentage of the total area that is falsely classified as the corresponding crop.

Accuracy

Each row representing a crop has two sub-rows for the rarely appearing crops and non-crop and three sub-rows for the frequently appearing crops. The top sub-row values show the accuracy for each crop in percentage, given a colored background ranging from low (white) to high (blue) values. The values on the diagonal should be high and at best 100%, all other values should be low and at best 0%. For each column the sum of the accuracies is 100. Shown in the first column, Radish (class15) has an accuracy of 0%. This means that of all area classified as Radish, 0% is Radish according to the ground truth data set. Observing the rest of the column, high percentages are found: 64% of the area classified as Radish is actually Alfalfa (class09) according to the ground truth data set. The highest accuracy is found for paved or urban area (class 20), showing an accuracy of 85%. Most of the area that is falsely classified as paved (10%) are fallow fields. Simultaneously, 13% of the area classified as fallow land is actually paved. As no vegetation develops on either paved or fallow land, it is can be expected that in a classification based on NDVI development, these classes get confused.

Completeness

The second and third sub-row present the completeness for each ground truth polygon set in percentage, given a colored background ranging from low (white) to high (green) values. Also for these values the diagonal should approach 100% and all other values 0%. For each of these rows the sum is 100. Observing again Radish (class15), a completeness of 82% is found. This means that 82% of the ground truth polygons representing Radish are indeed classified as Radish. The completeness for radish is rather high but to evaluate the performance also the accuracy should be observed. There is only 0.2 ha of Radish available in the ground truth dataset. The 37 ha classified as Radish indeed incorporates 82% of these 0.2 ha but the other 36 ha is falsely classified, hence resulting in a very low accuracy. Observing the completeness is especially relevant for the more frequently appearing crops that are separated in two sets. For each set of a crop the completeness is given. It is interesting to see that there are no large differences between the two sets, which suggests that both sets are a good representation of the complete ground truth dataset.

S2L8L7_B					Small frequency crops: 1 - 50 fields each												Large frequency crops: 100 - 400 fields each, divided into SetA (red) and SetB (blue)						Non-crops: fruit trees and paved area		
Crop class ground truth polygons	Area [ha]	Area [% of total]	Training points per ha	Crop class classified	C15	C02	C17	C14	C16	C07	C18	C04	C01	C10	C08	C19	C06	C11	C12	C03	C05	C09	C13	C00	C20
				Total area classified [ha]	37	39	24	40	12	9	23	21	47	31	79	42	95	76	57	175	380	292	48	91	14
				[% of total area]	2	2	1	2	1	1	1	1	3	2	5	3	6	5	4	11	23	18	3	6	1
				Area overestimated [% of total area]	2	2	1	2	1	0	1	1	2	1	3	2	4	2	1	3	4	3	2	2	0
C15 - Radis	0.2	0.0	158	upper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				lower	82	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	4	0
C02 - Artichaut	0.4	0.0	135	upper	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				lower	0	97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0
C17 - Salade	0.6	0.0	122	upper	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				lower	0	0	76	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	24	0
C14 - PetitPois	0.8	0.0	118	upper	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				lower	0	0	0	98	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
C16 - Rose	1.2	0.1	103	upper	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				lower	0	0	0	0	99	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0
C07 - HaricotVert	2.1	0.1	58	upper	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				lower	0	0	0	0	0	96	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0
C18 - Tomate	1.7	0.1	82	upper	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				lower	3	0	1	0	0	0	59	3	0	0	0	2	0	0	7	0	2	5	1	11	0
C04 - Courgette	6.3	0.4	27	upper	0	0	0	0	0	0	1	12	0	3	0	1	0	0	1	0	0	0	0	1	0
				lower	1	0	1	0	0	0	3	41	0	13	3	5	0	4	10	1	4	4	1	10	0
C01 - Anis	16.4	1.0	12	upper	0	0	0	2	1	2	0	1	22	1	0	2	0	0	2	0	0	0	2	0	0
				lower	1	0	1	4	1	1	1	1	62	2	1	5	2	0	5	2	3	3	5	2	0
C10 - Mais	16.7	1.0	11	upper	0	0	1	0	0	1	8	3	0	22	1	0	0	0	7	0	0	0	1	1	0
				lower	0	0	1	0	0	1	11	4	1	41	4	1	1	1	22	2	1	3	3	4	0
C08 - Jachere	39.2	2.4	5	upper	0	0	0	0	2	9	1	1	1	0	37	0	0	3	1	0	0	0	4	1	10
				lower	0	0	0	0	0	2	0	0	1	0	75	0	1	5	1	0	1	1	5	2	3
C19 - Menthe	41.5	2.5	5	upper	9	1	8	1	11	4	5	6	3	0	1	29	1	2	6	0	0	2	3	3	0
				lower	8	1	4	1	3	1	3	3	3	0	1	30	2	3	8	1	1	15	4	6	0
Feve				upper	1	2	0	6	1	3	0	1	7	1	2	0	27	1	0	1	2	1	2	0	0
C06A	26.7	2.9	0	lower	0	2	0	6	0	1	0	0	8	0	4	0	51	1	0	3	17	5	2	0	0
C06B	20.5		10	lower	1	1	0	4	1	0	0	1	5	2	2	0	57	1	0	2	15	5	2	1	0
Niora				upper	4	0	33	2	9	8	14	11	0	8	9	2	2	66	8	0	1	1	3	3	1
C11A	45.0	5.9	0	lower	2	0	11	0	2	0	4	2	0	4	8	1	3	46	9	1	1	2	1	4	0
C11B	50.4		4	lower	1	0	6	2	0	1	2	3	0	2	6	1	2	59	1	0	4	3	2	3	0
Oignon				upper	0	1	6	3	33	48	28	48	4	40	6	1	3	4	58	1	0	0	5	3	0
C12A	49.0	5.8	0	lower	0	1	2	1	3	5	9	11	2	13	6	0	5	2	32	2	1	1	2	2	0
C12B	45.1		4	lower	0	0	1	1	5	4	4	11	2	14	4	1	1	4	39	1	0	1	3	4	0
BetteraveASucre				upper	5	62	8	8	1	2	4	7	34	5	1	2	21	1	1	74	7	5	7	1	0
C03A	136.3	15.4	0	lower	1	11	1	1	0	0	0	0	7	1	1	0	8	0	0	52	11	4	1	0	0
C03B	114.2		2	lower	1	7	1	2	0	0	0	1	6	1	0	0	7	0	0	51	11	7	2	0	0
Cereales				upper	11	23	14	64	5	0	4	2	9	2	9	5	29	11	1	7	83	5	12	3	0
C05A	263.7	27.2	0	lower	0	2	0	5	0	0	0	0	1	0	1	0	6	1	0	2	77	2	1	0	0
C05B	180.2		1	lower	2	2	1	7	0	0	0	0	1	0	2	1	6	3	0	4	62	6	2	1	0
Luzerne				upper	64	10	27	11	27	2	28	8	18	17	13	54	15	10	6	17	6	84	27	24	4
C09A	252.7	27.9	0	lower	5	1	2	1	1	0	1	0	2	1	3	5	2	2	1	5	4	56	2	6	0
C09B	202.1		1	lower	5	1	1	1	1	0	2	0	2	1	2	6	4	2	1	8	6	52	4	4	0
C13 - Olive	31.7	1.9	6	upper	2	0	1	1	0	0	2	0	1	0	6	2	1	1	2	0	1	1	28	4	0
				lower	3	0	1	1	0	0	2	0	1	0	14	2	3	2	4	3	6	5	43	11	0
C00 - Agrumes	63.6	3.9	3	upper	3	0	0	0	0	0	0	0	0	0	2	2	0	0	8	0	0	1	6	56	0
				lower	2	0	0	0	0	0	0	0	0	0	3	1	0	0	7	0	0	2	5	79	0
C20 - Paved	22.1	1.4	8	upper	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0	0	85
				lower	0	0	0	0	0	0	0	0	0	0	47	0	0	0	0	0	0	0	0	0	53

upper value: accuracy per classified class (white-blue), lower values: correctness per polygons of class (white-green)

Table 4 – Conversion matrix for classification of ground truth dataset area in Tadla basin, using S2L8L7-B

Table 4 reveals highly variable accuracies for the different classes, ranging from 0 to 85%. Especially the rarely appearing crops have small accuracies, other classes in the ground truth dataset area are falsely classified as these rarely appearing crops. It is interesting to see that this is not randomly distributed but that rather high percentages are assigned to specific other crops, for example 64% of the area classified as Radish (class 15) is actually Alfalfa (class 09). Apart from class 08 (fallow), each of the rarely appearing crops has a percentage of 28 to 64 of its classified area that should be a single other crop. This suggests that the ground truth dataset is accurate, otherwise a more distributed result would be observed. As can be seen in table 4, especially Onion (class 12) and Alfalfa (class 09) polygons are classified as one of these rarely appearing crops. This suggests that their NDVI development is comparable to these rarely appearing crops.

The accuracies are determined with ground truth data which is partly also used for training data of the classification itself. An actual validation needs to be done with a separate dataset. This is possible only for the frequently available crop that were split into set A and set B. For the rarely available crop, all ground truth fields are needed as training data. When validating the classification of the six most frequently appearing crops in the area using set A which has a total area of 773 ha, an accuracy of 80% is found, ranging from 27% for class 06 (bean) to 91% for class 09 (alfalfa). An overview of all areas and accuracies is shown in table 5. The selected crops wheat and sugar beet show an accuracy of 78% respectively 86%. These are significantly high.

S2L8L7-B validation of frequently appearing crop with independent set A						Total accuracy:		80 %
Class	Area [ha]	Area classified [ha]	**C06**	**C11**	**C12**	**C03**	**C05**	**C09**
C06A - Feve	27		14	0	0	1	4	1
C11A - Niora	45		1	21	4	0	0	1
C12A - Oignon	49		3	1	15	1	1	1
C03A - BetteraveASucre	136		11	1	0	70	15	6
C05A - Cereales	264		17	3	0	4	202	5
C09A - Luzerne	253		6	4	2	13	11	142
Total area:	773							
Accuracy per crop:		[%]	**27**	**68**	**72**	**78**	**86**	**91**

Table 5 – Validation of S2L8L7-B classification with independent set A

For the frequent appearing crops, the used training points are widespread: only 1-10 points per ha are used from set B. However, wheat still shows a high accuracy (83%) with only 1 point per ha, while Bean (class 06) has a much lower accuracy of 27% with 10 points per ha.

When observing the monthly NDVI averages, averaged over both the collection of polygons or fields and training points of each class, the selection of points appears to be a good representation of the whole selection of polygons. This is shown for the frequently appearing crops in the chart given in figure 9. The values for the polygons or fields of each class are connected with a solid line and the average over the collection of training points for each class are connected with a dashed line. The solid line (fields) and dashed line (training points) for each of the frequent appearing crops show great similarity. This suggests that a random selection of 200 points for each class results in a sufficient representation of the total collection of fields.

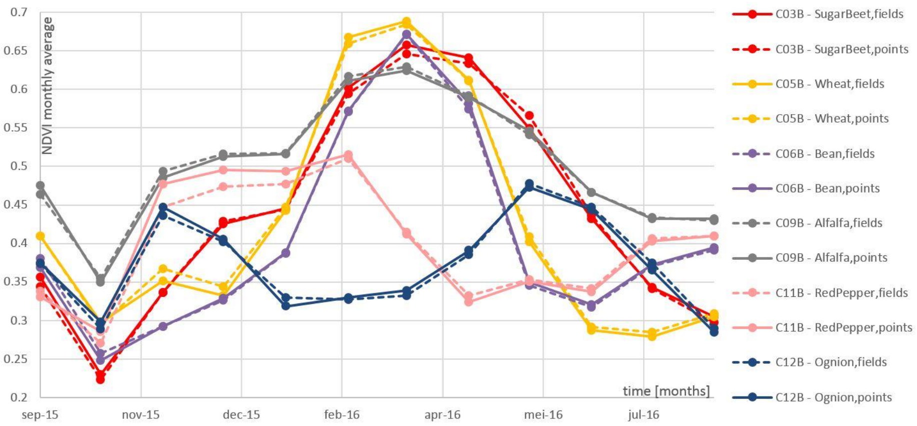


Figure 9 – Chart with NDVI monthly averages for frequent appearing crops. For each class 11 measuring points, connected with solid line for average over polygons and connected with dashed line for average over collection of training points.

Figure 9 shows that four of the frequent appearing crops have a peak in their NDVI development between 0.6 and 0.7 in March-April. Of these crops the Sugar Beet (class 03, red), Wheat (class 05, yellow) and Bean (class 06, purple) show similarity for other months also. It is therefore expected that these crops are confused in the classification.

The same chart can be observed for the rarely present crops, presented in figure 10. The solid line connects the monthly average NDVI values averaged over the available fields in the ground truth data set and the dashed line represents the average over the training points taken from these polygons. Again the average of each collection of points seem to represent the average over the fields of this class sufficiently. Observing the lines representing the NDVI development of Anise (black, class 01), Artichoke (light green, class 02) and Peas (orange, class 14), similarity is seen with the NDVI development of Sugar Beet, Wheat and Bean as presented in figure 9. It can therefore be expected that these crops get confused in the classification, which is confirmed by the conversion matrix.

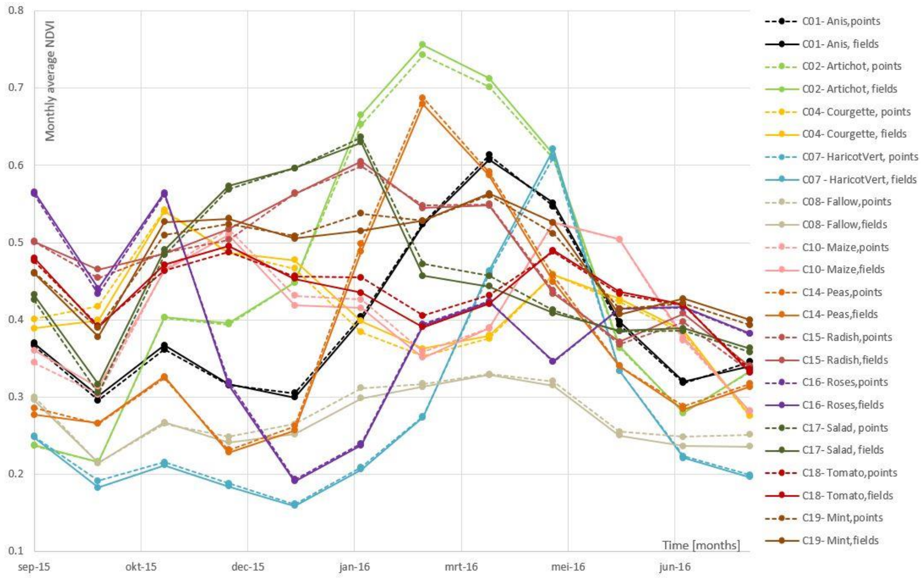


Figure 10 – Chart with NDVI monthly averages for rarely appearing crops. For each class 11 measuring points, connected with solid line for average over polygons and connected with dashed line for average over collection of training points.

Assuming a normal distribution in the variation of monthly average NDVI values per month per class, also percentiles can be evaluated. In figure 11 the distribution within the point collection for the crops of class 01, 02, 03B, 05B, 06B, 09B and 14 is further analyzed by observing the values within one standard deviation (σ) to either side of the mean (μ). This selection of crops is observed since their average values and pattern of development show similarity. The values at one sigma above mean are connected with a solid line, the values at one sigma below the mean are connected with a dashed line. This means that for each class, 68.2% of all points can be found between its solid and dashed line. From figure 11 can be concluded that within each of these classes a significant variation is found and that the ranges between the two standard deviations overlap significantly for the observed crops.

Also the difference between the collection of fields and collection of points for each of these classes was evaluated for the values at one standard deviation at either side of the mean. The result, not included in this document, showed only small differences, comparable to those of the average values as shown in figure 10. This also shows that a collection of 200 random points for each class from the collection of fields is a sufficient representation of the collection of fields. It is therefore assumed that the training points dataset used for the classification cannot be further improved with the data provided in the ground truth dataset.

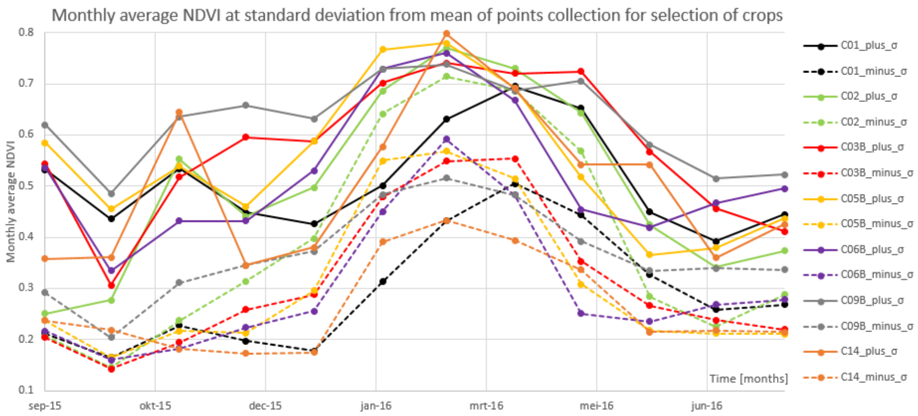


Figure 11 – Monthly average NDVI within point collection at standard deviation from mean

The result presented in figure 11 further questions the accuracy of the classification. The ground truth dataset could be biased, resulting in less distinct NDVI development for the different crops. It is also possible and likely that significant variation in NDVI development within a class is actually present and overlapping for different crop types. This means that the ground truth dataset is accurate but that the method to classify according to this monthly NDVI development is not adequate to distinguish between these crops.

Tadla basin areas

In table 5 the tabular result of the classification of the Tadla basin area is shown. Of each class the area in km^2 and as percentage of the total area is given. The first colored column represents the area per class as a percentage of its category. The next column shows the same, not for the classification result but for the ground truth data set. The last column shows the difference that would be found when using the NDVI dataset without Landsat 7.

While the initial difference in accuracy seemed marginal without L7 (58% for S2L8L7-B vs. 56% for S2L8-B) the result when applying this classification on the whole basin is large. The table shows that without Landsat-7 there would be a decrease of 27% of area with fruit trees, 10% more water and a significant decrease of crop area. Remarkable also in the obtained result is that the most rarely appearing crops are more present in the obtained classification than in the ground truth data set. This corresponds with the accuracies for these classes, in the ground truth dataset area the rarely appearing crops were also largely overestimated. Wheat is the most present crop in the basin according to the classification, while in the ground truth data set Alfalfa was more present. As the ground truth dataset is only a small section of the whole basin, it is possible that in other areas Alfalfa is more present.

Classification result S2L8L7-B

category	class in category	km2	% of total	% of category	% of category in ground truth	when using S2L8_B [%]
Total Tadla Basin		**3440**	**100.0**			**0**
Urban, bare or fallow		**1958**	**56.9**			**-1**
	Bare or urban	1389	40.4	70.9	36.1	-4
	Jachere	569	16.5	29.1	63.9	6
Fruit trees		**236**	**6.9**			**-27**
	Olive	115	3.3	48.9	33.2	-23
	Agrumes	120	3.5	51.1	66.8	-31
Water		**5**	**0.1**			**10**
Crops		**1241**	**36.1**			**5**
	Cereales	352	10.2	28.3	32.1	4
	Luzerne	190	5.5	15.3	32.9	-9
	Betterave A Sucre	150	4.4	12.1	18.1	-10
	Menthe	92	2.7	7.4	3.0	21
	Radis	63	1.8	5.0	0.0	37
	Oignon	54	1.6	4.4	3.5	-33
	Haricot Vert	49	1.4	4.0	0.2	-20
	Feve	48	1.4	3.9	3.4	29
	Anis	48	1.4	3.8	1.2	23
	Petit Pois	36	1.0	2.9	0.1	-2594
	Courgette	31	0.9	2.5	0.5	36
	Niora	30	0.9	2.4	3.6	-10
	Artichaut	28	0.8	2.2	0.0	21
	Tomate	27	0.8	2.2	0.1	9
	Mais	19	0.6	1.5	1.2	21
	Salade	18	0.5	1.5	0.0	46
	Rose	6	0.2	0.5	0.1	-73

Table 6 – Result of classification of Tadla basin, observing areas for each class

Left out citrus polygons

Two large polygons that were classified as agrumes (citrus trees, class 20) according to the ground truth dataset have been left out of the analysis since an initial study of the NDVI development showed large variation within these areas. A classifiscation of these polygons using the S2L8L7 NDVI monthly averages and training set B, gives a result shown in the figure 12. A part of the lower polygon is classified as citrus trees indeed, but the majority is indicated to be olive trees (light green), alfalfa (grey) and fallow (light brown). This could be explained by the following options:

1. The ground truth is not accurate for these two polygons
2. The ground truth classification is conducted for another year than was reported
3. Thee NDVI development of citrus trees is very much comparable to olive crops, alfalfa and fallow fields.

The first option is most likely. The second option would mean that the accuracy of the whole classification as done in this report can be questioned since crop rotation can be conducted. However, this is not likely since quite high accuracies have been found in this classification and crops are more likely to be rotated than trees. The third option is not likely either because the ground truth polygons of citrus trees that are used for the analysis (63.6 ha where 199 training points could be taken) generate a completeness of 79% and only 3% of the area is classified as fallow and 2% as alfalfa.

Concluding that these two polygons are not ground-classified accurately, raises the question whether the other ground-truth polygons are accurate.

Figure 12 – Classification of polygons that were classified as citrus trees (class 00 in the ground truth dataset

Conclusion and recommendations

Including Landsat-7 images in the monthly averages has proven to give better result than only Sentinel-2 and Landsat-8. The classification using polygon dataset B results in the best performance after evaluation of both the accuracy and the completeness regarding the ground truth dataset. For the six most frequently appearing crops, a validation has been conducted with the independent ground truth data set A which has a size of 773 ha. High accuracies were observed using this accuracy, especially for crops most frequently present in the whole basin according to the complete classification. When assuming the same accuracy for the validated crops within the whole basin, then a total accuracy of 81% is found. This applies to an area of 825 km2 which is 56% of all area in the basin containing crops or trees. These values are visualized in table 7. The ground truth dataset used for validation is independent but located in the same section of the basin where the training points are taken. When considering this accuracy valid for the whole basin, the assumption is made that there are no large spatially differences within the basin. As no large differences in elevation or meteorological circumstances are observed, this assumption is considered valid. However, it would be interested to validate the classification in a different section of the basin.

Area classified as validated crops in Tadla basin

	Accuracy within independent set A [%]	Area classified in Tadla basin [km2]
C06A - Feve	27	48
C11A - Niora	68	30
C12A - Oignon	72	54
C03A - BetteraveASucre	78	150
C05A - Cereales	86	352
C09A - Luzerne	91	190

- Accuracy validated crops relative to classified area of validated crops: 81 %

- Area classified as crops and trees in Tadla basin: 1477 km2
- Area classified as validated crops in Tadla basin: 825 km2
-Area of validated crops relative to area of all crops and trees in Tadla basin: 56 %

Table 7 – Validated accuracy and classification result in Tadla basin observed for 6 validated crops

The total accuracy for the ground truth dataset including rarely appearing crops is 58%, showing large variation in the accuracies for the specific classes. Since the difference between set A and set B is not significantly large, the ground truth dataset is regarded accurate. This is further confirmed by the fact that the classes with a low accuracy tend to be structural in the class they falsely classify. If the conversion matrix had shown larger random errors then the accuracy of the dataset would be less likely. Observing the NDVI development trends of both the collection of polygons and training points for each class proves that the selection of training points is a good representation of the variety within the fields of the same class. However, the variation within a class is significant and the ranges of several crop types overlap. This suggests that classification based on NDVI development with a 100% accuracy is not possible. In order to obtain a more accurate result than the 58% that is reached in this study, it is recommended for further research to vary in the amount of training points taken for each class. In this study 200 points are taken for each class, it would be valuable to see if improvement could be made by selecting an amount of points relative to the area of each class. Some crops that are frequently appearing are likely to contain larger variations between fields of the same crops, since their frequent appearance suggest that these crops are easily cultivated in this area under varying treatment and circumstances. The rarely appearing crops suggest to be more vulnerable are more likely to show less variation in their development. For the chosen classification the training points for the frequently appearing crops are taken from Set B. The difference between the result from set A and set B is not large but improvement could be made by further analyzing the variation within a crop type and the selecting the optimal set for trainings data for each crop specifically. Another recommendation involves smaller time steps. However, in order to obtain this it might be necessary to expand the ground truth dataset because occurrence of clouds might force the use of larger time steps. This is especially the case since for some crop types only a single field is provided in the ground truth dataset. The expansion of the used dataset is always a valid recommendation. Land use classification is seen as an important element in water management and hydrology. However, acquiring accurate ground data is expensive and time consuming, therefore it is recommended for further research to determine the minimum amount of area and fields for each crop necessary in order to conduct a classification with sufficient accuracy. This could make future ground truth datasets for classification more efficient and effective. In the current dataset, some crop types are represented by 1 or 2 fields, having a total area of less than 1 ha. As these classes show an accuracy of 0 to 1%, it is suggested that the minimum area for a crop type in the ground truth dataset should be higher.

The goal of this study is to select and localize crops for further analysis is SWAP and SEBAL. A choice is made to use wheat (class 05) and sugar beet (class 06). The dataset containing the areas classified as beet and wheat is further cleaned by removing the single pixels as is assumed that these are outliers or not representative for a specific field. The result concerning beet is a collection of 15,890 polygons each representing a single field or multiple fields of Sugar Beet with a size ranging from 0,1 to 66 ha. The total area of Sugar Beet is 136 km^2, 4% of the total classified area of Tadla basin (3440 km^2). Similarly, for Winter Wheat an amount of 21,920 polygons are found with a size ranging from 0,1 to 184 ha. The total area of Wheat is 345 km^2, corresponding to 10% of the total basin area. This result and the distribution of the beet and wheat fields over the basin is visualized in figure 13.

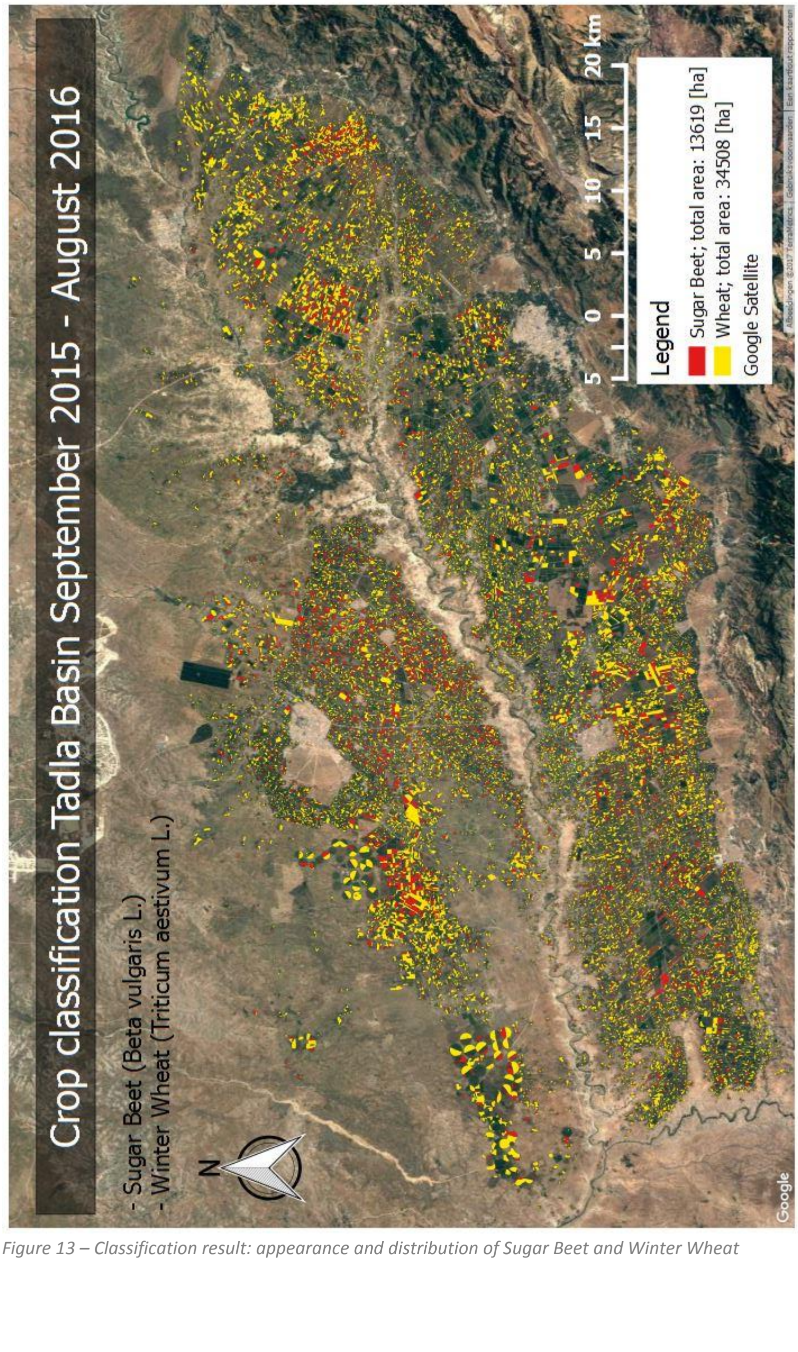


Figure 13 – Classification result: appearance and distribution of Sugar Beet and Winter Wheat

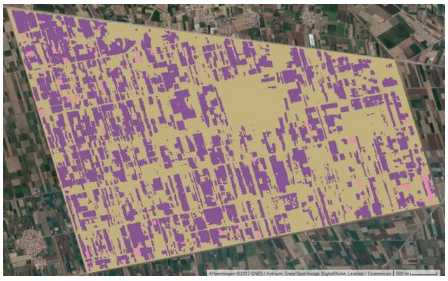
References

- Bastiaanssen & …, *Landuse map from temporal signature*, articel on "Open Geo Blog", published October 21, 2016, last visited at February 16, 2017. URL: https://mygeoblog.com/2016/10/21/landuse-map-from-temporal-signature/
- ………, Land use classification ground truth dataset, September 2015 – August 2016.

Appendix I classifications with combinations of S2, L8 and L7

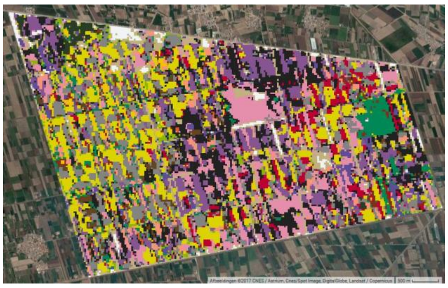
Below the result is shown of classifications using Sentinel-2, Landsat-8, Landsat-7, single or combined, of the same area as the ground truth dataset that is used for the classification. The color for each class remains constant over the whole analysis. The best result should be similar to the ground truth dataset as figure 1 of this report. The last four images shown below are the ones that are further discussed in this documents. The other classifications have been regarded as less accurate based on visual inspection.

Sentinel-2, Set A

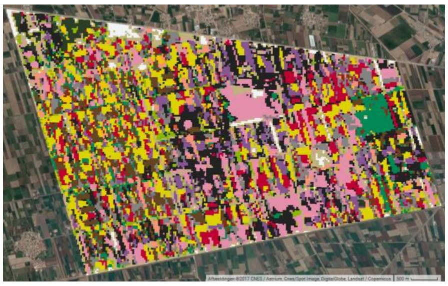


Sentinel-2, Set B

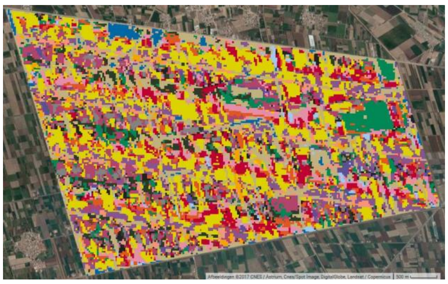
Landsat-8, Set A



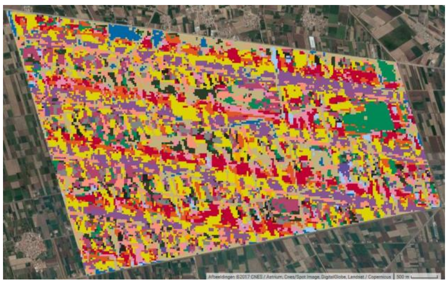
Landsat-8, Set B



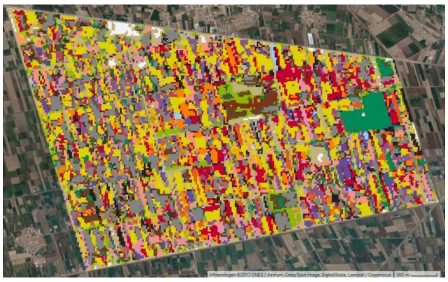
Landsat-7, Set A



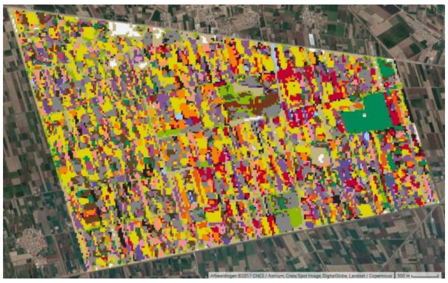
Landsat-7, Set B



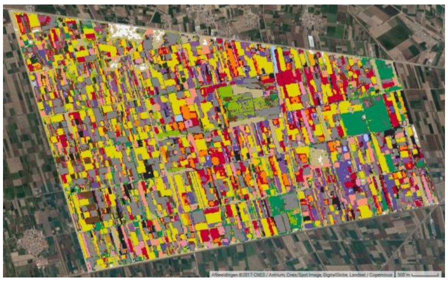
Landsat-7 and -8, Set A



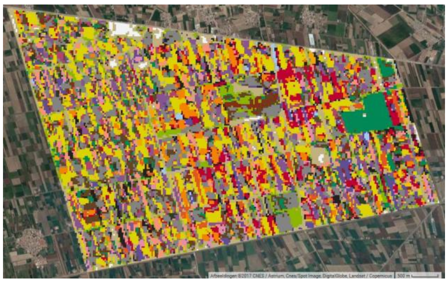
Landsat-7 and -8, Set B



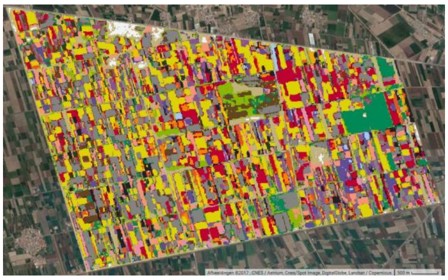
Sentinel-2 and Landsat-8, Set A



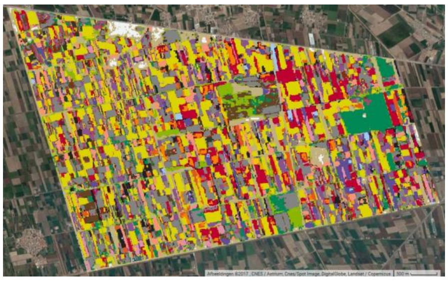
Sentinel-2 and Landsat-8, Set B



Sentinel-2, Landsat-8 and -7, Set A



Sentinel-2, Landsat-8 and -7, Set B



Appendix II Conversion matrixes

Below the conversion matrixes are given from the classifications S2L8-A, S2L8-B, and S2L8L7-A. For these tables the same explanation applies as has been given with table 4 containing the conversion matrix of S2L87_B.

S2L8L7_A

S2L8L7_A				Small frequency crops: 1 - 50 fields each												Large frequency crops: 100 - 400 fields each, divided into SetA (red) and SetB (blue)						Non-crops: fruit trees and paved area		
Crop class classified				C15	C02	C17	C14	C16	C07	C18	C04	C01	C10	C08	C19	C06	C11	C12	C03	C05	C09	C13	C00	C20
Total area classified [ha]				33	40	27	41	10	8	18	24	53	35	70	45	77	81	58	202	346	310	56	84	14
[% of total area]				2	2	2	3	1	0	1	1	3	2	4	3	5	5	4	12	21	19	3	5	1
Area overestimated [% of total area]				2	2	2	2	1	0	1	1	3	2	3	2	3	2	2	4	2	3	3	2	0
Crop class ground truth polygons	Area [ha]	Area [% of total]	Training points per ha																					
C15 – Radis	0.2	0.0	158	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				82	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	4	0
C02 – Artichaut	0.4	0.0	135	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0
C17 – Salade	0.6	0.0	122	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	95	0	0	0	0	0	0	0	0	0	3	0	0	0	1	1	0	0
C14 – PetitPois	0.8	0.0	118	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	95	0	0	0	0	0	0	0	0	0	3	0	0	0	1	1	0	0
C16 – Rose	1.2	0.1	103	0	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	0	98	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0
C07 – HaricotVert	2.1	0.1	58	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	0	0	94	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0
C18 – Tomate	1.7	0.1	82	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				1	0	1	0	0	0	58	5	0	4	1	1	0	0	2	0	0	8	3	11	0
C04 – Courgette	6.3	0.4	27	0	0	0	0	0	0	2	11	0	3	0	1	0	0	1	0	0	0	0	1	0
				1	0	1	0	0	0	5	42	0	16	1	4	0	5	7	2	3	5	1	9	0
C01 – Anis	16.4	1.0	12	1	0	0	2	2	2	1	1	19	1	0	2	0	0	2	0	0	0	1	0	0
				1	0	1	4	1	1	1	1	63	2	1	5	2	0	6	2	1	3	5	2	0
C10 – Mais	16.7	1.0	11	0	0	1	0	0	1	11	3	0	22	1	0	0	0	5	0	0	0	1	1	0
				0	0	1	0	0	0	12	4	1	47	3	1	2	2	17	1	0	3	4	4	0
C08 – Jachere	39.2	2.4	5	0	0	0	0	2	11	1	1	1	0	41	0	1	3	1	0	0	0	4	1	10
				0	0	0	0	0	2	0	1	1	0	73	0	1	5	2	0	0	1	5	2	3
C19 – Menthe	41.5	2.5	5	10	1	7	0	11	1	6	7	2	0	0	28	1	3	6	0	0	2	3	3	0
				8	1	4	0	3	0	3	4	3	0	1	30	1	5	9	1	1	16	4	5	0
Feve				1	2	0	5	1	3	0	0	5	1	1	0	35	1	0	1	2	1	2	0	0
C06A	26.7	2.9	7	0	1	0	5	0	1	0	0	6	0	2	0	63	0	0	2	12	5	2	0	0
C06B	20.5		0	2	1	0	3	0	0	0	0	6	2	1	0	49	3	1	4	17	7	3	1	0
Niora				5	0	35	2	8	8	10	16	0	6	6	2	4	62	8	0	1	1	3	4	1
C11A	45.0	5.9	4	2	0	6	0	1	0	2	2	0	4	4	1	4	57	9	1	1	2	1	4	0
C11B	50.4		0	1	0	13	2	0	1	1	6	0	1	5	1	3	50	2	0	3	4	2	4	0
Oignon				1	1	5	6	27	45	23	45	4	42	5	1	4	6	54	1	0	0	4	3	0
C12A	49.0	5.8	4	0	1	2	1	2	4	5	12	2	14	4	0	5	5	35	2	1	1	1	2	0
C12B	45.1		0	1	0	1	4	4	3	3	12	3	18	3	1	1	6	31	1	0	1	3	4	0
BetteraveASucre				5	61	12	16	2	1	5	6	40	7	1	3	11	1	2	68	4	6	9	1	0
C03A	136.3	15.4	1	0	11	1	2	0	0	0	0	8	1	0	0	3	0	0	59	5	5	2	0	0
C03B	114.2		0	1	8	2	3	0	0	0	1	9	1	0	1	4	0	1	50	6	10	2	1	0
Cereales				15	24	11	56	6	0	4	2	9	2	7	4	31	11	1	11	88	6	14	3	0
C05A	263.7	27.2	1	0	2	0	4	0	0	0	0	1	0	1	0	5	1	0	4	76	2	1	0	0
C05B	180.2		0	2	2	1	6	0	0	0	0	1	0	2	1	6	3	0	7	58	7	3	1	0
Luzerne				56	11	24	11	29	2	30	8	17	15	14	55	11	12	8	18	4	83	28	18	4
C09A	252.7	27.9	1	4	1	1	1	1	0	1	0	2	1	2	5	2	2	1	6	3	60	3	4	0
C09B	202.1		0	4	1	1	1	1	0	1	0	2	1	2	7	2	2	1	11	4	51	5	3	0
C13 – Olive	31.7	1.9	6	3	0	2	1	0	0	2	0	1	0	6	2	1	1	2	1	0	1	26	4	0
				3	0	1	1	0	0	1	0	2	0	14	3	2	2	4	3	3	6	46	10	0
C00 – Agrumes	63.6	3.9	3	3	0	0	0	0	0	0	0	0	0	3	2	0	0	8	0	0	1	5	60	0
				1	0	0	0	0	0	0	0	0	0	3	1	0	0	7	0	0	3	5	79	0
C20 – Paved	22.1	1.4	8	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	85
				0	0	0	0	0	0	0	0	0	0	47	0	0	0	0	0	0	0	0	0	53

upper value: accuracy per classified class (white-blue), lower values: correctness per polygons of class (white-green)

S2L8_A

upper value: accuracy per classified class (white-blue), lower values: correctness per polygons of class (white-green)

Crop class ground truth polygons	Area [ha]	Area [% of total]	Training points per ha	C15	C02	C17	C14	C16	C07	C18	C04	C01	C10	C08	C19	C06	C11	C12	C03	C05	C09	C13	C00	C20
Crop class classified				Small frequency crops: 1 - 50 fields each												Large frequency crops: 100 - 400 fields each, divided into SetA (red) and SetB (blue)						Non-crops: fruit trees and paved area		
Total area classified [ha]				37	69	28	3	7	8	17	22	62	35	72	42	89	81	66	186	361	303	46	87	11
[% of total area]				2	4	2	0	0	0	1	1	4	2	4	3	5	5	4	11	22	19	3	5	1
Area overestimated [% of total area]				2	4	2	0	0	0	1	1	3	2	3	2	4	2	2	4	3	3	2	2	0
C15 – Radis	0.2	0.0	158	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				86	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	4	0
C02 – Artichaut	0.4	0.0	135	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0
C17 – Salade	0.6	0.0	122	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				3	0	76	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	19	0
C14 – PetitPois	0.8	0.0	36	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	21	0	25	0	0	0	0	0	1	0	0	48	1	2	0	0	1	0	0	0
C16 – Rose	1.2	0.1	103	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	0	101	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C07 – HaricotVert	2.1	0.1	50	0	0	0	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	0	0	95	0	0	0	0	2	0	0	0	3	0	0	0	0	0	0
C18 – Tomate	1.7	0.1	82	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				4	0	1	0	0	0	59	2	0	5	0	2	0	0	3	0	0	5	2	12	0
C04 – Courgette	6.3	0.4	27	0	0	0	0	0	0	2	13	0	2	0	0	0	0	1	0	0	0	0	0	0
				2	0	1	0	0	0	5	46	0	13	1	2	0	6	8	2	3	5	1	6	0
C01 – Anis	16.4	1.0	12	1	0	1	0	2	2	1	1	18	1	0	2	0	0	1	0	0	0	1	0	0
				2	0	1	0	1	1	1	1	69	2	1	5	2	0	6	2	1	3	2	2	0
C10 – Mais	16.7	1.0	11	0	0	0	0	0	1	12	4	0	23	0	0	0	0	4	0	0	0	1	1	0
				0	0	1	0	0	1	12	5	1	48	2	1	2	2	16	1	1	3	2	5	0
C08 – Jachere	39.2	2.4	4	0	0	0	0	5	11	0	0	1	0	40	0	1	3	2	0	0	0	4	1	11
				0	0	0	0	1	2	0	0	1	0	74	0	1	5	3	0	0	1	4	2	3
C19 – Menthe	41.5	2.5	5	12	1	10	7	8	0	10	7	2	0	0	25	0	2	7	0	0	2	3	2	0
				11	1	7	1	1	0	4	4	3	0	1	25	1	4	11	1	1	17	3	5	0
Feve				1	2	1	0	2	1	0	0	4	1	1	1	31	1	0	1	2	1	2	1	0
C06A	26.7	2.9	7	0	3	0	0	0	0	0	0	6	0	3	1	65	0	0	2	14	4	1	1	0
C06B	20.5		0	1	2	1	0	1	0	0	0	5	1	1	0	52	3	0	4	17	7	2	3	0
Niora				4	0	36	0	9	10	9	14	0	6	6	2	4	63	8	0	1	1	3	5	0
C11A	45.0	5.9	4	1	0	8	0	1	0	2	2	0	3	4	1	4	55	10	1	1	1	1	4	0
C11B	50.4		0	2	1	13	0	0	1	1	4	0	2	5	1	4	52	2	1	3	3	2	4	0
Oignon				0	1	5	75	20	46	22	44	5	44	5	2	4	5	52	1	0	0	3	3	0
C12A	49.0	5.8	4	0	1	2	2	1	5	5	11	1	15	4	1	5	5	36	2	2	1	1	1	0
C12B	45.1		0	0	0	1	4	1	3	2	9	5	18	3	1	1	5	38	1	0	1	2	4	0
BetteraveASucre				5	64	9	2	1	0	4	6	41	7	1	2	12	1	2	65	4	6	9	1	0
C03A	136.3	15.4	1	0	20	1	0	0	0	0	0	10	1	0	0	4	0	0	50	5	5	1	0	0
C03B	114.2		0	1	14	1	0	0	0	0	1	11	1	0	0	4	1	1	45	6	10	2	1	0
Cereales				10	21	8	0	3	0	4	2	10	2	6	4	36	11	2	12	88	5	17	4	0
C05A	263.7	27.2	1	0	3	0	0	0	0	0	0	1	0	1	0	7	1	0	3	78	2	1	1	0
C05B	180.2		0	2	3	1	0	0	0	0	0	1	0	1	1	7	3	0	8	62	6	3	1	0
Luzerne				59	11	27	10	32	2	24	9	17	14	13	55	11	12	9	20	5	83	30	21	1
C09A	252.7	27.9	1	5	2	2	0	0	0	1	0	2	1	3	5	2	2	1	6	3	59	2	4	0
C09B	202.1		0	5	2	2	0	0	0	1	0	3	1	1	6	3	2	1	11	4	50	4	4	0
C13 – Olive	31.7	1.9	5	2	0	1	0	0	0	3	0	1	0	6	3	1	1	4	1	0	1	26	5	0
				2	0	1	0	0	0	1	0	3	0	14	4	2	2	8	5	3	6	37	14	0
C00 – Agrumes	63.6	3.9	3	5	0	0	0	0	0	3	1	0	0	3	4	0	0	7	0	0	1	3	55	0
				3	0	0	0	0	0	1	0	0	0	4	3	0	0	8	0	0	4	2	76	0
C20 – Paved	22.1	1.4	6	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	88
				0	0	0	0	0	0	0	0	0	0	57	0	0	0	0	0	0	0	0	0	42

S2L8_B

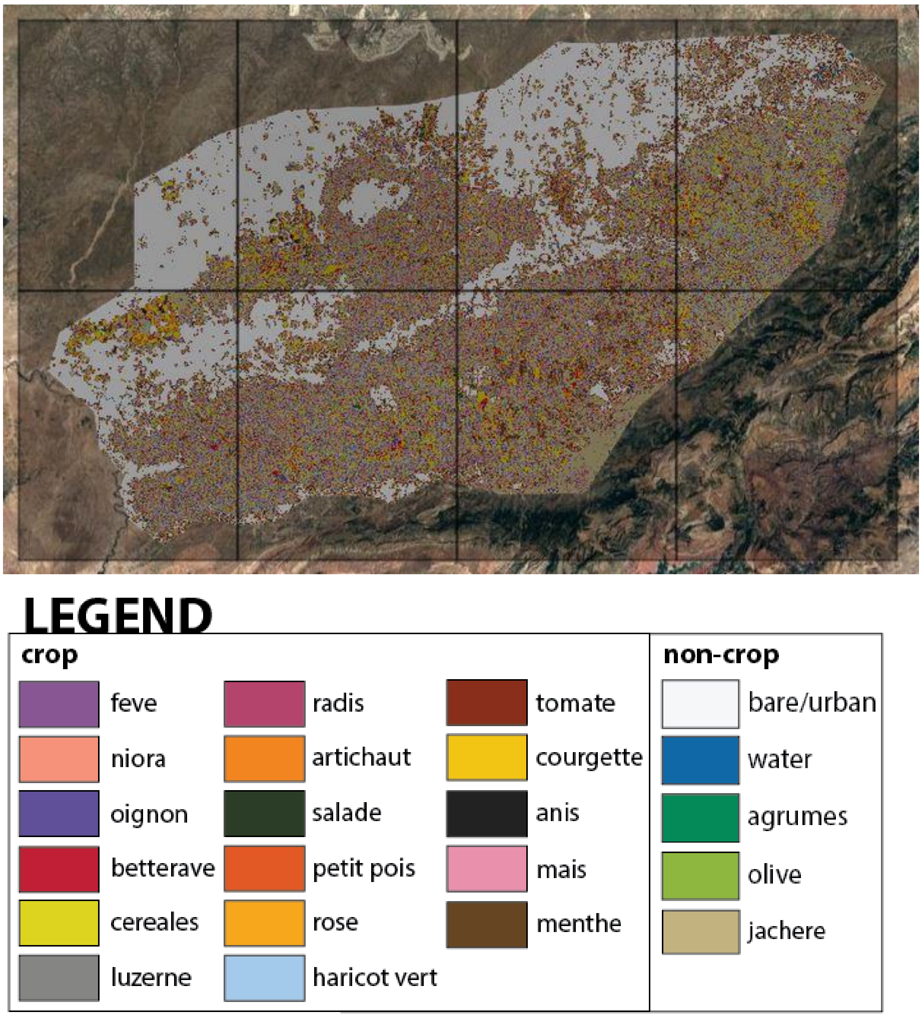
Crop class ground truth polygons	Area [ha]	Area [% of total]	Training points per ha	Small frequency crops: 1 - 50 fields each												Large frequency crops: 100 - 400 fields each, divided into SetA (red) and SetB (blue)						Non-crops: fruit trees and paved area		
Crop class classified				C15	C02	C17	C14	C16	C07	C18	C04	C01	C10	C08	C19	C06	C11	C12	C03	C05	C09	C13	C00	C20
Total area classified [ha]				45	60	27	2	8	10	22	22	61	39	82	47	119	73	47	164	382	273	42	95	11
[% of total area]				3	4	2	0	1	1	1	1	4	2	5	3	7	4	3	10	23	17	3	6	1
Area overestimated [% of total area]				3	4	2	0	0	0	1	1	3	2	3	2	5	1	1	3	4	3	2	3	0
C15 – Radis	0.2	0.0	158	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				86	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	4	0
C02 – Artichaut	0.4	0.0	135	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0
C17 – Salade	0.6	0.0	122	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				3	0	76	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	19	0
C14 – PetitPois	0.8	0.0	36	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
C16 – Rose	1.2	0.1	103	0	0	0	0	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	0	99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
C07 – HaricotVert	2.1	0.1	58	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				0	0	0	0	0	97	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0
C18 – Tomate	1.7	0.1	82	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				6	0	1	0	0	0	59	2	0	3	1	3	0	0	3	0	1	4	1	12	0
C04 – Courgette	6.3	0.4	27	0	0	0	0	0	0	1	13	0	2	0	0	0	1	1	0	0	0	0	0	0
				2	0	1	0	0	0	5	46	0	14	2	3	0	7	5	0	4	4	1	6	0
C01 – Anis	16.4	1.0	12	1	0	1	1	1	2	0	1	18	1	0	2	0	0	2	0	0	0	1	0	0
				2	0	1	0	1	1	1	1	68	2	1	5	2	0	6	2	2	2	2	2	0
C10 – Mais	16.7	1.0	11	0	0	0	0	0	2	9	4	0	21	1	0	0	0	5	0	0	0	1	1	0
				0	0	1	0	0	1	12	5	1	49	3	1	1	1	14	1	1	3	3	4	0
C08 – Jachere	39.2	2.4	5	0	0	0	0	4	9	0	1	1	0	36	0	0	3	1	0	0	0	4	1	11
				0	0	0	0	1	2	0	0	2	0	76	0	1	5	1	0	1	1	4	3	3
C19 – Menthe	41.5	2.5	5	11	1	10	2	7	3	8	8	4	0	1	23	0	2	5	0	0	2	5	2	0
				12	2	7	0	1	1	4	4	6	0	1	26	1	3	5	1	1	13	5	6	0
Feve				1	2	0	0	1	2	0	0	4	1	2	0	25	1	0	1	2	1	1	1	0
C06A	26.7	2.9	0	1	3	0	0	0	1	0	0	6	0	4	0	64	1	0	2	14	4	1	0	0
C06B	20.5		9	1	3	0	0	0	0	0	0	5	2	1	0	64	1	0	2	12	5	1	2	0
Niora				3	1	26	13	12	11	13	11	0	9	9	2	3	69	8	0	1	1	3	4	0
C11A	45.0	5.9	0	1	0	8	0	2	1	4	3	0	4	9	1	3	48	7	1	1	2	1	3	0
C11B	50.4		4	2	1	7	0	0	1	2	2	0	3	7	1	4	56	1	0	3	3	2	4	0
Oignon				0	1	5	33	29	48	32	46	6	44	6	1	2	4	60	1	0	0	3	3	0
C12A	49.0	5.8	0	0	1	2	1	3	5	11	11	2	15	6	0	5	2	28	2	2	1	1	1	0
C12B	45.1		3	0	0	1	1	2	5	4	10	5	21	4	1	2	4	34	1	0	1	2	4	0
BetteraveASucre				4	53	9	3	0	1	4	6	37	5	1	2	19	1	1	70	8	5	8	1	0
C03A	136.3	15.4	0	0	16	1	0	0	0	0	0	9	0	1	0	9	0	0	44	12	4	1	0	0
C03B	114.2		1	1	9	1	0	0	0	0	1	8	1	0	0	9	0	0	48	11	7	2	1	0
Cereales				8	29	7	0	1	1	4	2	10	2	7	4	35	11	1	8	84	5	13	3	0
C05A	263.7	27.2	0	0	4	0	0	0	0	0	0	1	0	1	0	10	1	0	2	77	2	1	0	0
C05B	180.2		1	2	4	1	0	0	0	0	0	1	0	2	1	9	3	0	5	64	5	2	1	0
Luzerne				65	12	37	34	30	1	20	9	18	14	13	58	13	9	6	19	6	84	28	28	1
C09A	252.7	27.9	0	6	2	3	0	0	0	1	0	2	1	3	6	3	1	1	5	4	52	2	7	0
C09B	202.1		1	7	2	1	0	1	0	1	0	3	1	2	6	4	2	1	9	5	49	3	5	0
C13 – Olive	31.7	1.9	6	2	0	0	0	0	0	2	0	1	1	6	2	1	1	2	1	1	1	29	5	0
				2	0	0	0	0	0	2	0	2	1	16	3	2	2	3	3	6	5	38	14	0
C00 – Agrumes	63.6	3.9	3	4	0	0	0	0	0	2	1	0	0	3	5	0	0	8	0	0	1	4	51	0
				3	0	0	0	0	0	1	0	0	0	4	3	0	0	6	0	0	2	3	76	0
C20 – Paved	22.1	1.4	8	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	0	88
				0	0	0	0	0	0	0	0	0	0	57	0	0	0	0	0	0	0	0	0	42

upper value: accuracy per classified class (white-blue), lower values: correctness per polygons of class (white-green)

Appendix III Tadla basin classified map

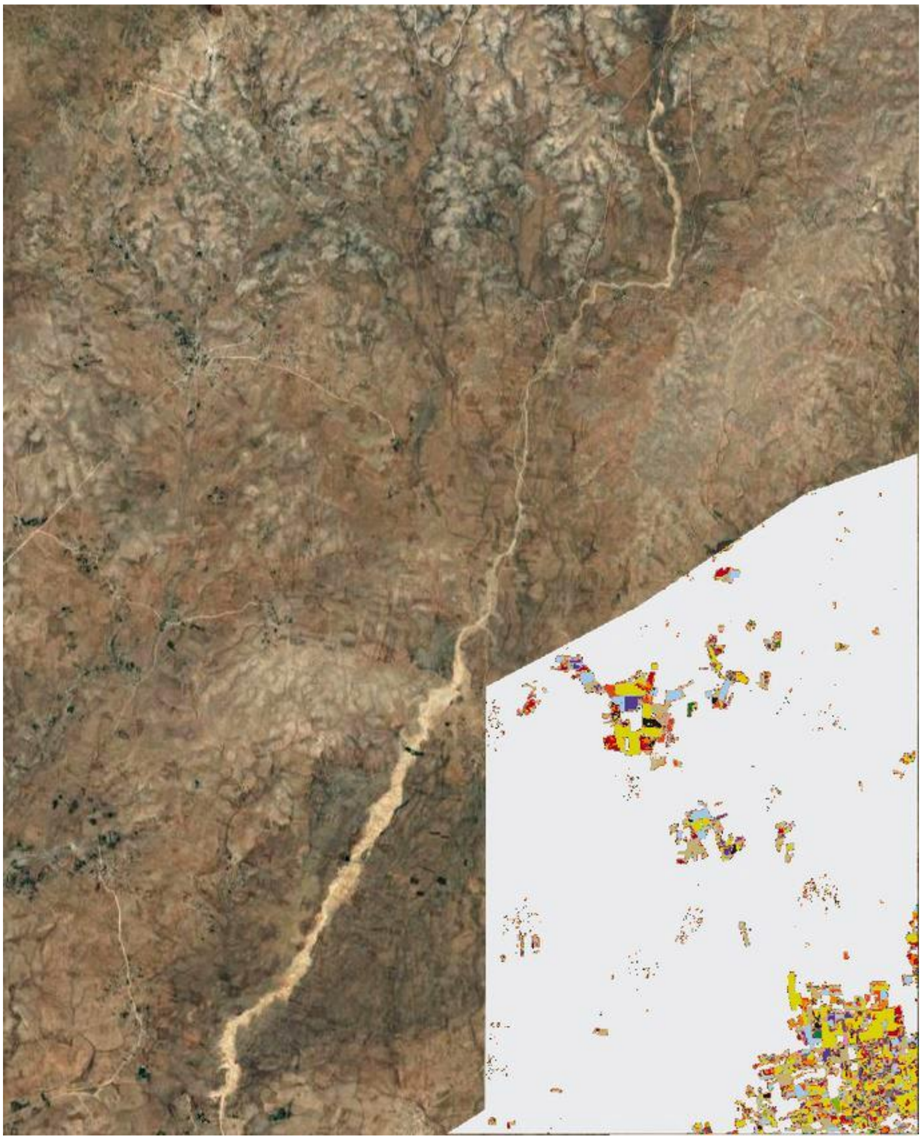
In figure 8 a map of the classification result S2L8L7-B was given. To visualize the result in more detail, the classified basin is divided into 8 parts, numbered from left to right, from top to bottom:

1, 2, 3, 4,
5, 6, 7, 8

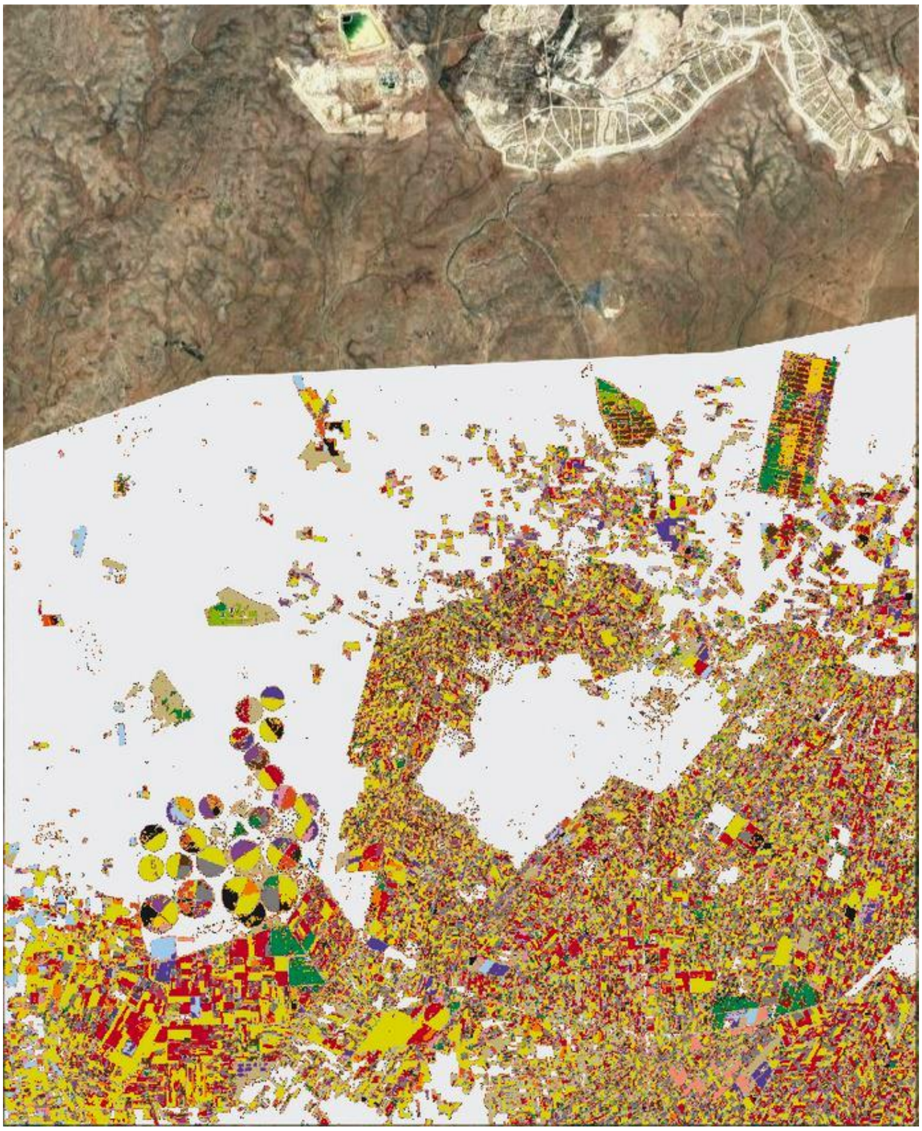


The same legend applies as is used in earlier visualizations and is repeated above.

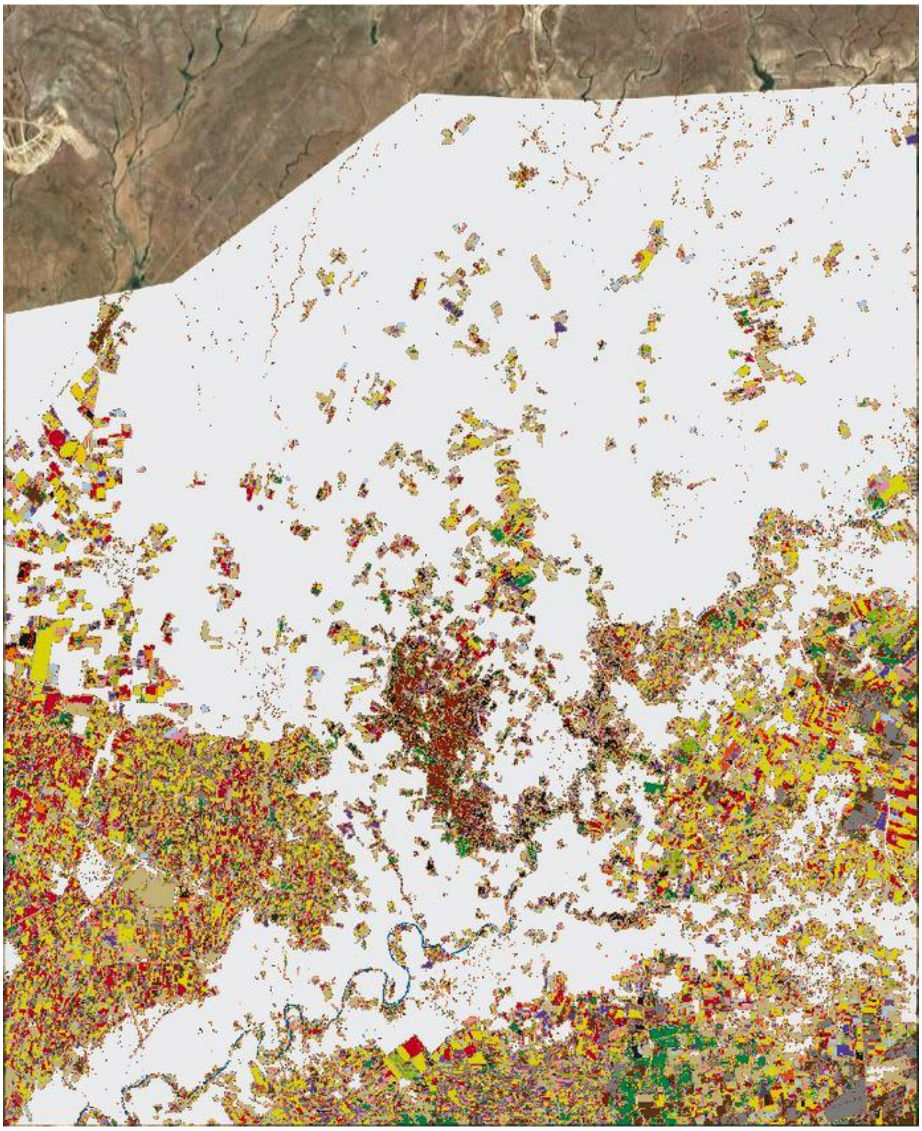
Detail map 1



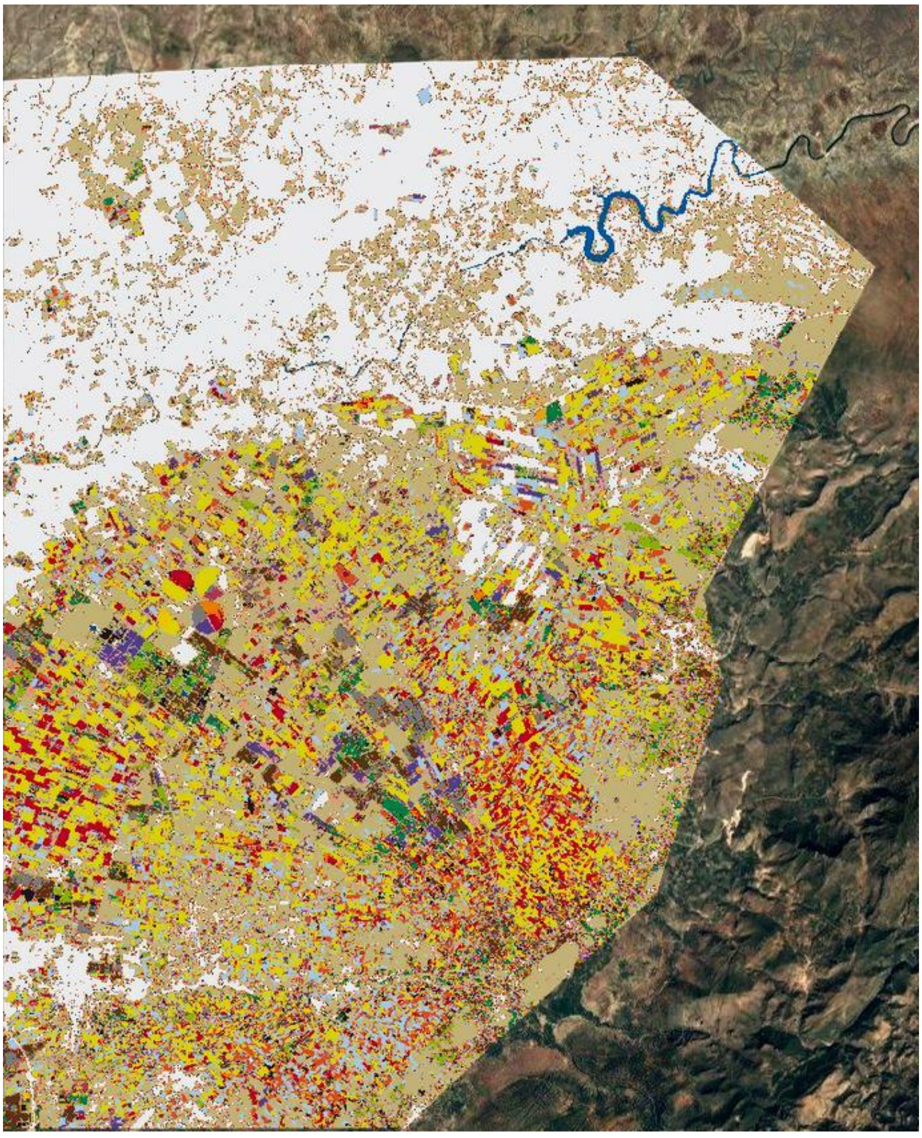
Detail map 2



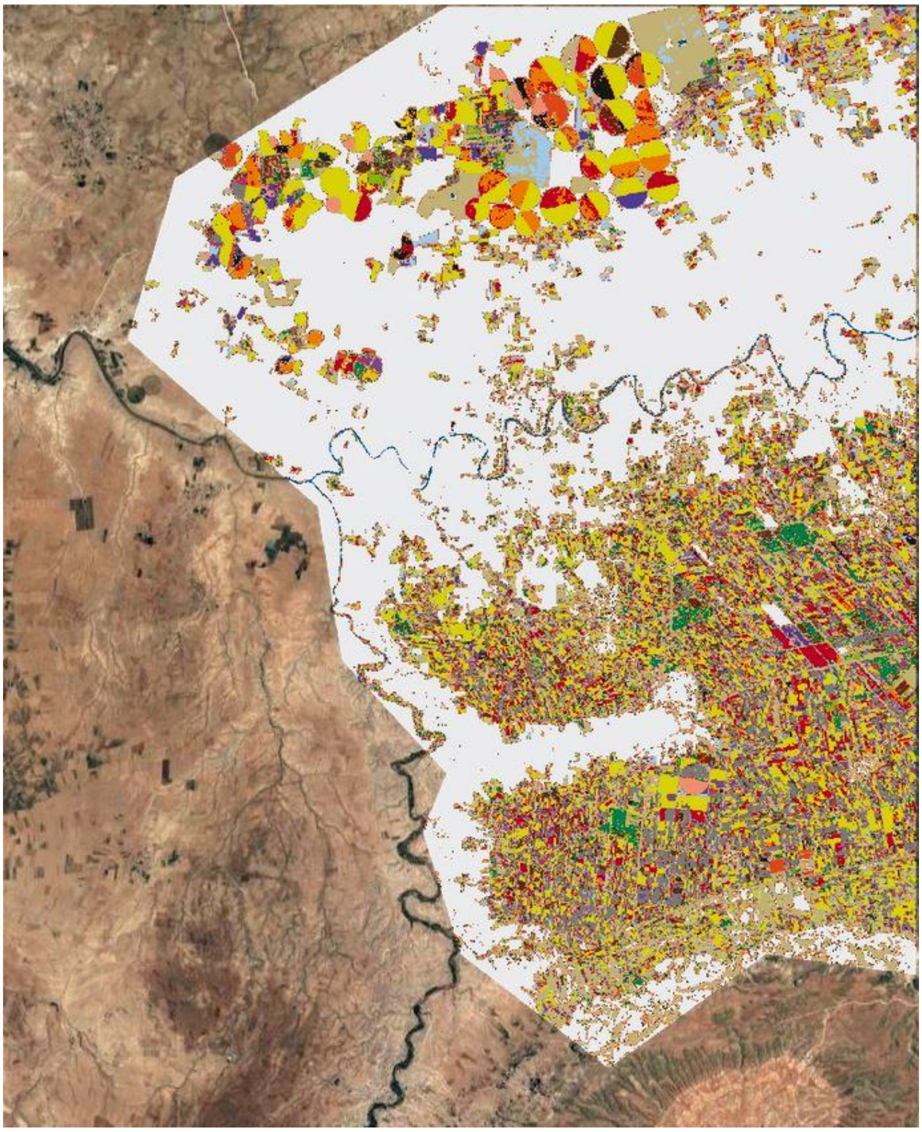
Detail map 3



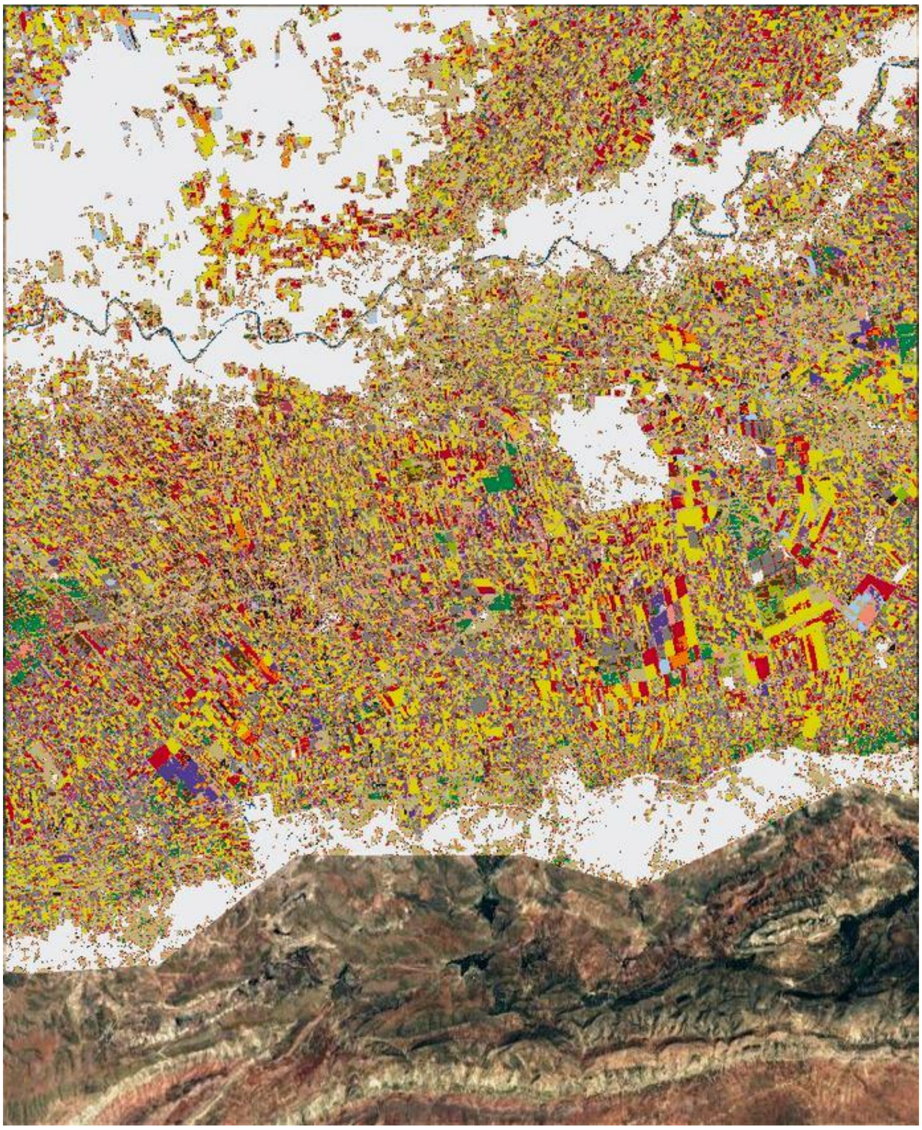
Detail map 4



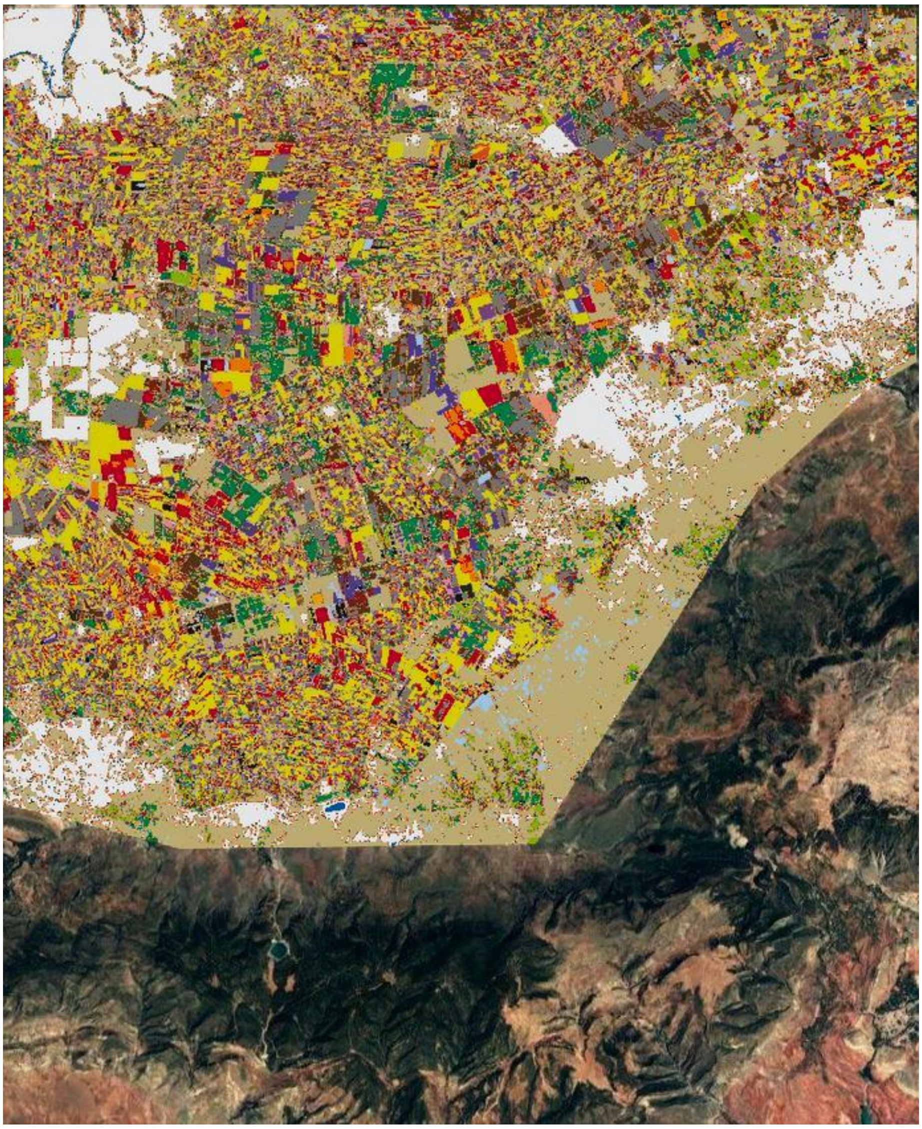
Detail map 5



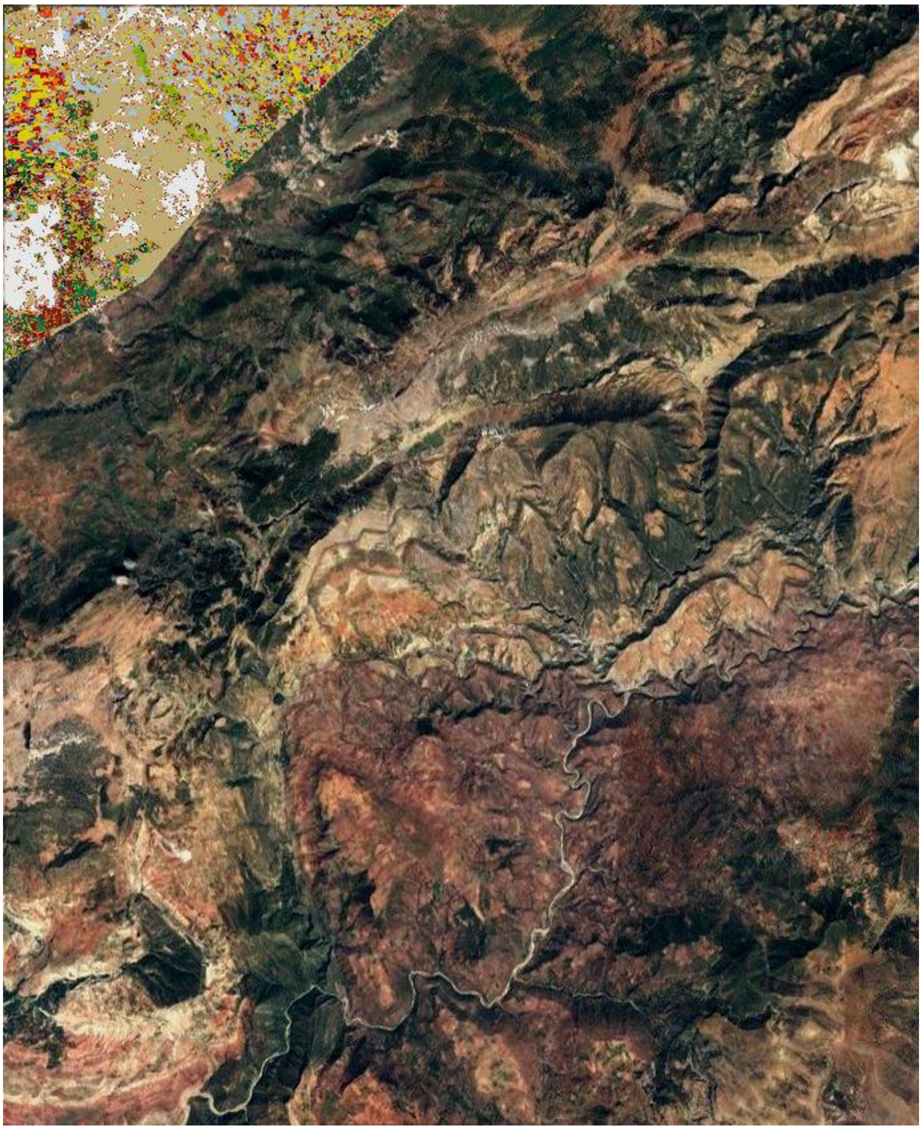
Detail map 6



Detail map 7



Detail map 8



F

Method for land use classification in Google Earth Engine using crop cycle

Lower Limpopo Basin Mozambique Maize fields Classification

For April 2016 – January 2017

Charlotte van der Leer
July 6th 2017

Abstract

A land use classification of the smallholder or family sector area in the Lower Limpopo Basin near Xai-Xai is conducted in Google Earth Engine, for the area where the ThirdEye project by FutureWater is carried out. A total area of 1211 ha is classified. The target is to obtain a collection of agricultural plots where maize is cultivated, to be used for SEBAL analysis with Landsat 8 imagery. This is obtained first by deduction of pixels with high likelihood of maize cultivation in a season in the recent past. Secondly, the obtained collection is filtered for polygons with cloud coverage on Landsat 8 days. This has resulted in a the total collection, 75 polygons are above 0.05 ha, representing a total area of 8,5 ha.

Introduction

Selection of a typical field in the area of study is required. From this field SEBAL results will be retrieved. These results are used in the calibration of SWAP/WOFOST against SEBAL.

The family sector smallholder farmers is divided in irrigation/drainage blocks. Blocks are observed where the ThirdEye project is active. The major crop in the area is corn and two growing seasons can be recognized. In January usually heavy rainfall occurs and the month February is known as "inundation month". After drainage of excess water farmers remove reed which is the natural vegetation and plant maize in April/May to harvest this in August. Maize is planted again in August/September to harvest this in December/January just before the wet season. All year round the soil is moisturized with water flowing from the surrounding sand dunes. Drainage is crucial in this system. The drainage system consists of primary, secondary and tertiary canals, valves and a pumping station to pump water out of the system into the river. The local water board (RBL) is responsible for the land and water management in this area. RBL controls the valves, the pumping station and is responsible for cleaning and maintenance of the primary and secondary canals. The farmers pay a yearly fee to RBL and are responsible for the tertiary canals near their field. The years 2014 until early 2016 have been extremely dry caused by El Nino/ In the second half of 2016 farmers planted maize. However, in November 2016 the pumping station broke down at the beginning of the wet season. In December/January excessive rainfall occurred. Because of malfunctioning of the drainage system, the majority of the harvest failed. In March/April again unusual rainfall fell. During the visit in May 2017 still a large part of the area was water logged and covered with reed. Only a small fraction of the land was used where farmers were working cleaning away reed and some of them even started to plant new maize.

Season selection

It is difficult to choose the right season to simulate since it is hard to find a "normal" season among the floods and droughts. The two most recent seasons in September 2016 are chosen since from these seasons more information is available through farmers interviews compared to previous seasons. Sowing and harvest dates are assumed based on information from farmers interviews:

A. Sowing 1-15 April 2016, harvest August/September (reduction from draught reported)
B. Sowing 1-15 September 2016, harvest December/January (reduction from wetness reported)

Classification using NDVI

In the maize growing cycle 4 stages can be observed having the following durations (source: http://cropchatter.com/tag/hail-damage/) assuming a length of crop cycle of 100 days:

1. Initial growth, tiltering, day 0-30
2. Rapid growth, stem extension, day 31-50
3. Mid-season , heading, day 50-75
4. Late season, ripening, day 75-100

Calibrated WOFOST input file for maize (Van Heemst, 1988) reports an temperature sum from sowing to emergence of 70.0 degree days (TSUMEM) and a lower threshold temperature for emergence of 10.0 degrees. FAO (source) mentions a length of cropping cycle of 110-145 days for season A and 90- 120 days for season B. For the first season (A) a crop cycle of 130 days is assumed, for the second season (B) a length of 120 days. Length of growth stages are assumed relative to the durations indicated by (see source above).

Observing the daily average temperatures retrieved from GLDAS, the indicated sowing days result at emergence in the following periods:

A. Sowing 1-15 April 2016, emergence after 5-6 days: 7-20 April 2016
B. Sowing 1-15 September 2016, emergence after 6-7 days: 8-21 September 2016

Assuming this range of possible sowing days, for each of the growing stages also a time range can be assigned. Before emergence the land needs to be cleared from reed. The time span in which the land is clear at some moment is 'stage 0'.

	start date A	**end date A**	**start date B**	**end date B**
stage 0	2016-03-01	2016-04-20	2016-08-01	2016-09-21
stage 1	2016-04-07	2016-05-29	2016-09-08	2016-10-27
stage 2	2016-05-16	2016-06-24	2016-10-14	2016-11-20
stage 3	2016-06-11	2016-07-26	2016-11-07	2016-12-20
stage 4	2016-07-13	2016-08-28	2016-12-07	2017-01-19

The localization of maize fields is conducted with NDVI imagery. In prior research (http://www.fagro.edu.uy/agrociencia/index.php/directorio/article/view/1126) the following NDVI values were found for corn along the four stages of its development:

1. NDVI 0.18-0.53
2. NDVI 0.54-0.80
3. NDVI 0.20-0.74
4. NDVI 0.28-0.41

High values of NDVI can be found throughout the year on non-maize fields and outside the growing season because of reed vegetation. NDVI can be observed from Landsat and Sentinel data. Because the parcels are very small (0.2 ha) and the temporal resolution is larger than for Landsat, Sentinel-2 was selected.

Criteria were formulated for NDVI to analyze land use and coverage. Collections of NDVI images over a time span are analyzed for its minimum, maximum or mean value. Then for this reduced NDVI value a range is of minimum and maximum value is determined. In this way each pixel is analyzed.

A pixel is flooded when during the possible crop cycle from sowing to maturity an NDVI value below 0.0 (season A) or 0.10 (season B) is observed. Reed is assumed when from field preparation (stage 0) to initial growth (stage 1) a mean NDVI above 0.40 is observed. A pixel is bare or poorly cropped when during the rapid growth (stage 2) and mid-season (stage 3) the maximum NDVI is below 0.40. This order is also the hierarchy that is used in in assigning these classes to the pixels.

	start date	end date	operator	NDVI min	NDVI max	hierarchy
flood A	2016-04-01	2016-08-28	min	- ∞	0.0	1
flood B	2016-09-01	2017-01-19	min	- ∞	0.1	1
reed A	2016-03-01	2016-05-29	mean	0.4	∞	2
reed B	2016-08-01	2016-10-27	mean	0.4	∞	2
bare A	2016-05-16	2016-07-26	max	0.0	0.4	3
bare B	2016-10-14	2016-12-20	max	0.0	0.4	3

For the remaining area, ranges of NDVI are used to determine the likelihood of maize cultivation for both season based on various criteria. These are determined separately for the two seasons based on visual inspection of the individual criteria and available NDVI images within the crop stages.

For season A the NDVI ranges indicated by (source above) are used. Farmers have cleared the reed coverage from their field before sowing. It is therefore assumed that from stage 0 until crop emergence there must be a mean NDVI value below 0.30. When the mean values of all available NDVI values within the crop stages are within the corresponding range of NDVI value for this stage, then the criteria is met. All five criteria are given the same weight in season A. For the criteria of stage 0, additional to Sentinel-2 also Landsat-7 and Landsat-8 images are used because of cloud coverage during this stage.

	start date A	end date A	operator	NDVI min	NDVI max	weight
stage 0	2016-03-01	2016-04-20	mean	0.00	0.30	1
stage 1	2016-04-07	2016-05-29	mean	0.18	0.53	1
stage 2	2016-05-16	2016-06-24	mean	0.54	0.80	1
stage 3	2016-06-11	2016-07-26	mean	0.20	0.74	1
stage 4	2016-07-13	2016-08-28	mean	0.28	0.41	1

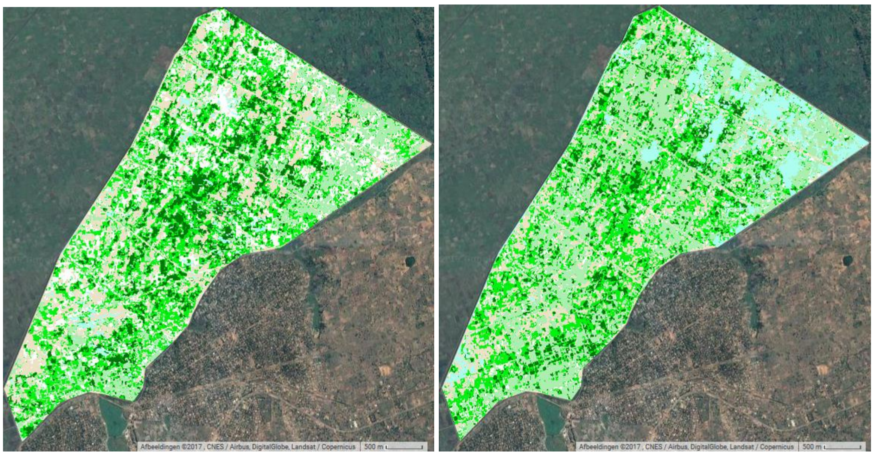
For season B a slightly different method is applied because of cloud coverage. Also the late growing season (stage 4) is not considered because various farmers reported that their crops were destroyed because of heavy rainfall during this stage. Stage 2 and 3 are combined because stage 2 is relatively short and cloud coverage during this stage limits the available amount of images. Farmers have cleared the reed coverage from their field before sowing. It is therefore assumed that from august until crop emergence there must be an NDVI value below 0.30. An actual clear field would result in an even lower NDVI value but since this might not have coincided with a cloud free Sentinel overpass, the threshold is set at 0.30. Also during initial growth (stage 1) the mean NDVI value should be between 0.18 and 0.53 according to (source above). During rapid growth until mid-season (stages 2-3) higher NDVI values are expected. The corresponding criteria is a maximum NDVI value between 0.55 and 0.80. These three criteria for corn likelihood are given weights where the first and third criteria are more weighted based on visual inspection of the result of these criteria, which is also influenced by the amount of available cloud free images during its period.

	start date	end date	operator	NDVI min	NDVI max	weight
stage 0	2016-08-01	2016-09-21	min	0.00	0.30	2
stage 1	2016-09-08	2016-10-27	mean	0.18	0.53	1
stage 2-3	2016-10-14	2016-11-20	max	0.55	0.80	2

For both seasons, every pixel that is not classified as flooded, reed covered or bare, is evaluated according to the corn specific criteria as listed above and multiplied with the corresponding weight, resulting in a value of 0-5 of maize likelihood.

A class of high likelihood for corn consists of pixels with likelihood of 4-5 for both seasons. The class with low corn likelihood consists of pixels with score 3 for season A and 2-3 for season B. The remaining pixels are considered 'unknown'.

Thus, a total area of 1211 ha is classified. The result is shown below for both seasons (left A, right B).

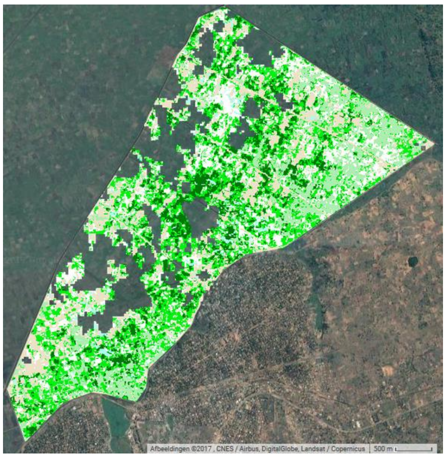


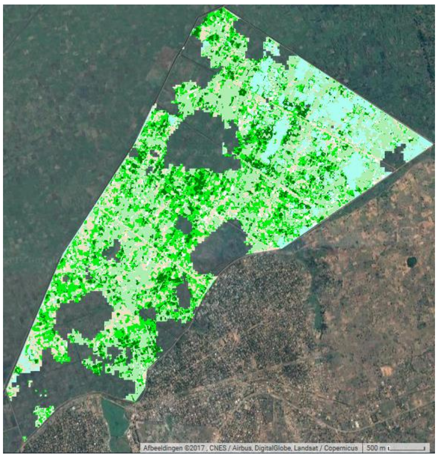
	Season A [%]	Season B [%]
Flooded	3	11
Reed	14	34
Bare	20	13
Maize unlikely	32	29
Maize likely	13	10
Unknown	19	4

Cloud coverage of Landsat8

SEBAL analysis will be conducted for high likelihood maize pixels as classified with sentinel 2 data, using Landsat 8 imagery. Landsat 16 overpass has a temporal resolution of 16 days.

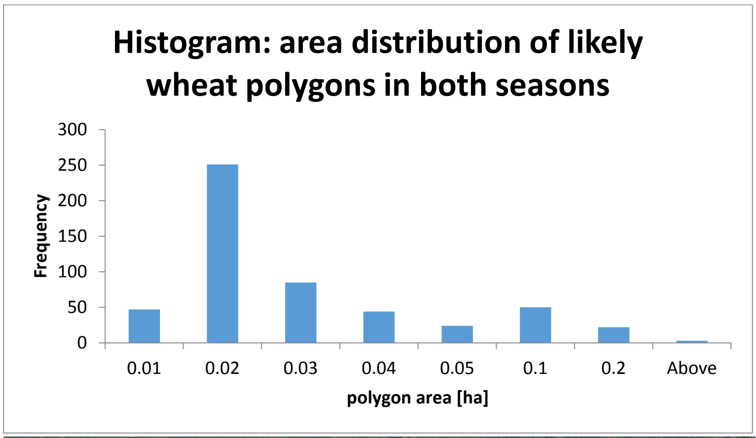
This has resulted in resulting in 13 images for season A and 15 images for season B. These images were analyzed for cloud occurrence in the classified area and given a score of 0 to 5 where 0 is totally covered with clouds and 5 no cloud coverage. For season A along the crop stages, a total of 9 Landsat-8 images are found useful for SEBAL analysis. Within season B, a collection of 5 Landsat 8 images are for SEBAL analysis. Pixels are used that are cloud free for all images in the collection. This has resulted in some gaps in the previous constructed maps. The selection of Landsat-8 images for both collections is a trade-off between the least amount of "pixel loss" because of clouds and as much Landsat-8 images in order to analyze the crop characteristics.

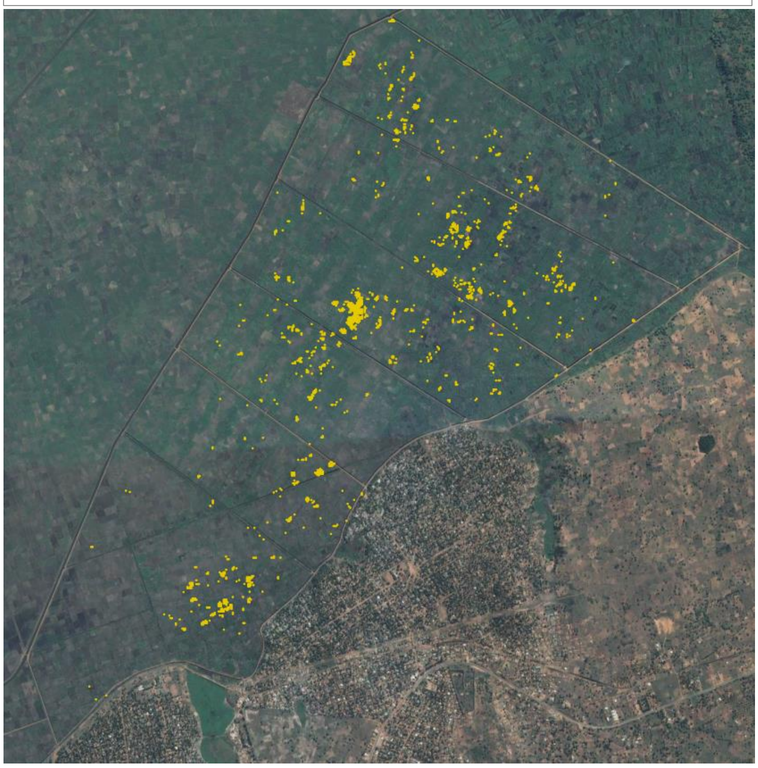




Ultimately, pixels are selected from both seasons that are classified as "corn high likelihood" from the Sentinel-2 NDVI analysis and that are not limited by cloud coverage in the Landat-8 images.

Hence, a collection of 526 polygons is obtained with high likelihood that in these pixels corn was cultivated in both seasons of 2016. The polygons range in area between 0.01 and 1.85 ha. Most polygons have an area of 0.02 ha. Farmers have small fields, a general field has an area of 0.20 ha (45 by 45 m). Thus the majority of the polygons represents fractions of fields. Landsat8 has a pixel size of 0.09 ha (30m x 30m pixels). Of the total collection, 75 polygons are above 0.05 ha, representing a total area of 8,5 ha.


Histogram: area distribution of likely wheat polygons in both seasons
Frequency
300
250
200
150
100
50
0
0.01
0.02
0.03
0.04
0.05
0.1
0.2
Above
polygon area [ha]



G

Used datasets theoretical background

The field altitude is obtained from Digital Elevation Map (DEM) data from Hydrological data and maps based on Hydrological SHuttle Elevation Derivatives at multiple Scales (HydroSHEDS). HydroSHEDS is a mapping product that provides hydrographic information for regional and global-scale applications in a consistent format. It offers a suite of geo-referenced data sets at various scales, including river networks, watershed boundaries, drainage directions, and flow accumulations. HydroSHEDS is based on high-resolution elevation data obtained during a space shuttle flight for the National Aeronautics and Space Administration (NASA)'s **SRTM!** (**SRTM!**) and has been developed by the Conservation Science Program of the World Wildlife Fund (WWF) (U.S. Department of the Interior & U.S. Geological Survey, 2010).

The model HiHydroSoil (de Boer, 2016) generates the Van Genuchten parameters. The model derives these soil hydraulic properties from the global soil map 'SoilGrids1km' with high resolution and accuracy (Hengl et al., 2014), utilizing the Harmonized World Soil Database (HWSD) (Droogers, 2011) to fill in missing data. The generated maps with soil hydraulic properties have a resolution up to 100m. The model assumes a top layer of 30 cm and a second underlying layer. HiHydroSoil generates the following parameters required in the Soil-Water-Atmosphere-Plant model (SWAP): θ_{res} $[cm^3\ cm^{-3}]$, θ_{sat} $[cm^3\ cm^{-3}]$, α $[-]$, n and K_{sat} $[cm\ d^{-1}]$.

Optical satellite images from Landsat 7 imagery (L7) and Landsat 8 imagery (L8) (U.S. Geological Survey, 2017) and Sentinel 2 imagery (S2) (European Space Agency, 2017) are utilized. The S2 has a precision of 10 m and is generated every five days. the L8 and L7 have a precision of 30 m and are produced both every 16 days, 8 days apart.

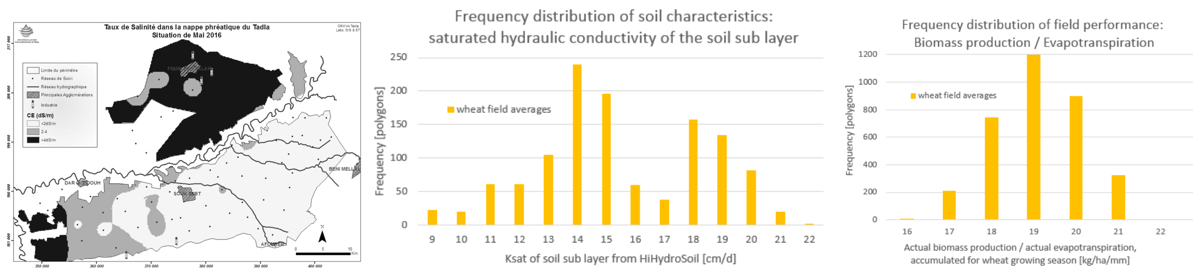
H

Identification of representative winter wheat field in Tadla Basin 2015/2016

Tadla Basin in Morocco is a sub basin with an area of 3440 km^2 within the larger Oum Er Rhiba Basin. The conducted land use classification for the period September 2015 to August 2016 revealed winter wheat to be the most common crop type. Validation indicated an accuracy of 83% for the identification of winter wheat fields. The total area of cultivated winter wheat is 345 km^2 represented by 21,920 polygons, polygon area varying from 0.1 to 184 ha. The field selected from this collection is a general performing field with characteristics representative for the majority of fields in the area. Three steps are used to diminish this collection of polygons.

The collection of fields is first diminished based on performance. Performance for this purpose is defined as seasonal actual biomass production B_{act} divided over seasonal actual evapotranspiration ET_{act}. Both biomass production and evapotranspiration is derived from the Surface Energy Balance Algorithm for Land model (SEBAL), an estimation of seasonal quantities is generated through linear interpolation between the SEBAL dates. An initially observed time span for the winter wheat growing season is estimated from October 20^{th} 2015 to June 20^{th} 2016, based on literature. The Food and Agriculture Organization (FAO) publishes crop calendars, indicates for winter wheat in Morocco sowing dates between October 20th and December 15th and harvest between June 1^{st} and July 10^{th}, with a length of cropping cycle between 180 and 200 days (Food and Agriculture Organization of the United Nations, 2010). Other research reports dates of crop emergence for durum and soft wheat in Morocco between November 24^{th} and January 29^{th} and crop maturity between April 19^{th} and June 17^{th}, and a crop cycle length of 129 to 183 days (Pagani et al., 2013). The observed time span includes 9 SEBAL days. In Fig. H.1(c) the distribution of field performance is visualized. The values are field averages for the ratio of actual biomass per actual evapotranspiration, interpolated between SEBAL dates and accumulated for the initially estimated wheat growing season. A normal distribution is observed. To select a general performing field, the collection of wheat polygons is restricted to a performance rate of 18-19 $kg\ ha^{-1}\ mm^{-1}$.

Field characteristics of salinity and soil type are analyzed. Salinity is obtained from yearly local analysis (Ormva-Tadla, 2017) providing a map of electrical conductivity (EC) for the area. An estimation of soil variation within the area is obtained from data on the saturated hydraulic conductivity from HiHydroSoil (de Boer, 2016). Polygon averages are obtained for field performance and soil characteristic from which the frequency distribution is studied. In Fig. H.1(a) the soil salinity is indicated, revealing a division of the area in EC below 2 $dS\ m^{-1}$, between 2 and 4 $dS\ m^{-1}$ and above 4 $dS\ m^{-1}$. The largest area has a relatively low EC and is found in the the Eastern part of the left bank of the Oum Er Rhiba river, known as Beni Moussa Est. To select a general performing field, the collection of wheat polygons is restricted to this area. Field averages are obtained from the HiHydroSoil data of saturated hydraulic conductivity K_{sat} for the soil sub layer. In Fig. H.1(b) the distribution of these field averages for the collection of winter wheat fields is observed. Two peaks can be observed in the frequency of occurrence. The highest peak is selected, the collection of wheat polygons is restricted to saturated hydraulic conductivity values for the sub soil layer of 13-15 $cm\ d^{-1}$.



(a) (b) (c)

Fig. H.1: Spatially distributed characteristics in Tadla Basin used to select a typical and representative wheat field. Left: Salinity, selected largest area East-South is characterize by EC below 2 dS/m (Ormva-Tadla, 2017). Center: Saturated hydraulic conductivity K_{sat} sub layer from HiHydroSoil (de Boer, 2016), field averages distribution indicating two peaks. Selected largest peak is characterized by K_{sat} values from 13 to 15 $cm\ d^{-1}$. Right: Estimation of field performance rate (accumulated B_{act}/ET_{act}) obtained from SEBAL results. Field averages distribution indicates normal distribution, selected normal range is characterized by a rate of 18-19 $kg\ ha^{-1}\ mm^{-1}$.

This selection procedure diminished the collection of polygons to a set of 217 polygons representing a total area of 592 ha.

I

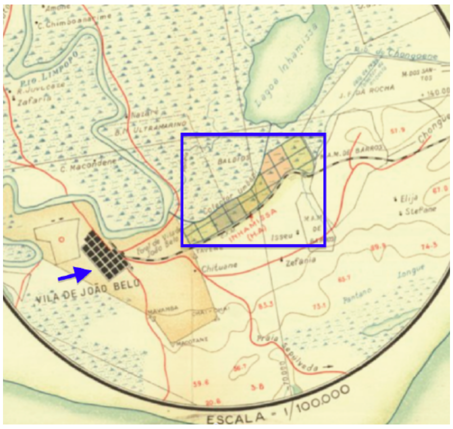
Smallholder maize field near Xai-Xai Mozambique in the Lower Limpopo basin additional information

A smallholder maize field is selected in the Fidel Castro irrigation/drainage block near Xai-Xai Mozambique in the Lower Limpopo basin. The area is oberved for the season 2016 with Surface Energy Balance Algorithm for Land model (SEBAL) results. Additional information is collected from local interviews, a few field measurements and literature study. A total of 22 personal interviews were conducted in May 2017 with farmers in the observed area and key actors in Mozambican governmental organizations at local and national level.

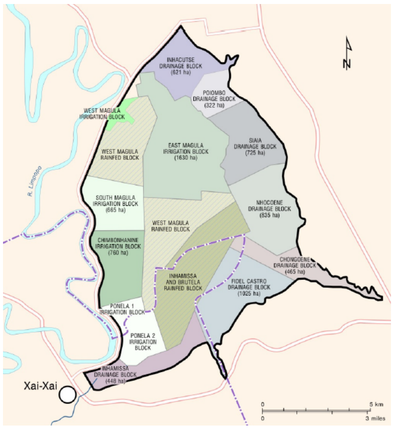
Geographical location The area is known to be poor performing and crop cultivation often fails (Mugabe, 2015*a*). From the SEBAL results for July 2016 in the middle of the growing season, field averages were observed for the Leaf Area Index (LAI). Polygons are removed from the collection where the field average LAI is below 2.0. This results in a collection of 18 fields representing a total area of 7.6 ha. A single field having an area of 0.22 ha is selected which is representative for this well performing collection. In Fig. 3.7 in the center map the position of this field within the collection of maize polygons is indicated, the right map shows the position of this field.

In 1951, drainage works were implemented in the marshy, rich soils between Xai-Xai (formerly Vila João Belo) and the Inhamissa Lagoon. The map in Fig. I.1(a) indicating this first block, originates from 1952. Demarcation of land was gradually extended to the north. By 1967, about 11,300 ha had been reclaimed and most was under cultivation (Torres, 1967). The drainage works enabled intensive food production. Between 1991 and 2003, most production in the Regadio do Baixo Limpopo (Water Board in the Lower Limpopo Basin) (RBL) area effectively came to a halt, as infrastructure damaged by floods remained unrepaired and many people left the area to seek work in South Africa or in urban areas. In 2003 the Massingir Dam and Smallholder Agricultural Rehabilitation project (MDSAR) was approved to undertake repair of infrastructure and reorganization of agricultural production, supported by a loan from the African Development Bank. Because of cost escalation during the delay of the project implementation, funds were insufficient to complete the works planned in 1993 (Massingir Dam and Smallholder Agricultural Rehabilitation Project, 2008). Currently, RBL's 11,787 ha are organized in 12 blocks. The two distinct areas are the irrigation/drainage blocks where the family sector (small-scale producers) is located, and the large irrigated blocks, intended for commercial agriculture. The 12 blocks are visualized in Fig. I.1(b) The observed field is located in the Fidel Castro block. The system of primary and secondary canals is indicated in more detail in a map from the MDSAR project provided in Fig. I.1(c).

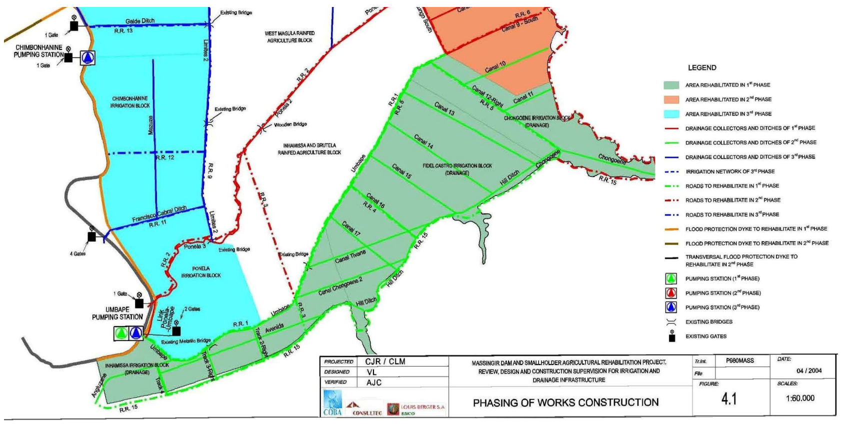
Meteorology and area characteristics In Mozambique the mean annual rainfall decreases from 800-1000 mm near the coast to less than 400 mm in the interior, mainly concentrated during the rainy period between October and April (Reddy, 1986). Mozambique's tropical to sub-tropical climate is moderated by its mountainous topography and influenced by the movement of the Intertropical Convergence Zone (ITCZ), El Niño



(a)



(b)



(c)

Fig. I.1: Maps of the research area in Lower Limpopo Basin Mozambique, near Xai-Xai city. (a) Location of Inhamissa drainage area, first drainage block of the Regadio do Baixo Limpopo (RBL) established in 1951. Image adapted from Monteiro and Fonseca (1952) by (Ganho, 2013). (b) Lower Limpopo Irrigation scheme, Regadio do Baixo Limpopo (RBL). Image from Cartographic Unit, The University of Manchester, adapted from maps provided by RBL-EP and Xai-Xai Municipal Council, by (Ganho, 2013). Selected field is located in Fidel Castro block (blue). (c) Map of construction works for Massingir Dam and Smallholder Agricultural Rehabilitation project (MDSAR), image provided by FutureWater. Indicates primary and secondary canals in the observed area.

and surface temperatures in the Indian Ocean. Variability between years is high due to variations in patterns of atmospheric and oceanic circulation.
According to the Oceanic Niño Index (INO) which is the standard used by the National Oceanic and Atmospheric Administration (NOAA) to identify the effects of the El Niño Southern Oscillation (ENSO) effects in the tropical Pacific, the years 2015-2016 are categorized as a very strong ENSO period (NOAA, 2017). The rainy season is a function of the southern migration of the ITCZ, corresponding to the warmest months of the year. Inter-annual variability in wet-season rainfall in Mozambique is very high, particularly in the central and southern regions including the Lower Limpopo basin. Severe droughts in the past were related to strong El Niño events. The catastrophic flooding that occurred during 2000 and 2001 was strongly linked to La Niña conditions, coupled with destructive cyclones occurring during the same period. Floods and droughts are common occurrences in the central and southern regions, often occurring during the same year. Mozambique's long coastline facing the Indian Ocean places the country in the path of increasingly more intense cyclones (Dyoulgerov et al., 2011).

Because of the pattern of rainfall distribution the coastal zones are the most heavily populated and consequently having a high land use intensity, despite the low fertility of these soils and consequent very low yields (Snijders, 1985). The observed area near to Xai-Xai city is prone to extreme events such as drought and flooding. Facing these adverse conditions, the traditional family sector smallholder farmers in the RBL area turned to the fertile regions indicated as 'swamp area', 'wetlands', 'spring zone' or in the local designation: 'zonas verdes' or 'machongos'. This is a palustrine wetland ecosystem, occurring in a form of seepage or springs. The present peat soils are now of enormous importance for small-scale agriculture in semi-arid climatic conditions, associated to water availability all year round. Gomes et al. (1997) states this system plays a very important role for food security and household income of thousands of families. In the machongos, organic (peat) soils are present, generally very fertile and continuously wet. The soil receives fresh water all year round as seepage from the surrounding dune areas with high infiltration and high recharge rates. The area also present a very good soil structure for plant growth, characterized by high water holding capacity, high soil aeration, and easy workability. When subjected to drainage, machongos are intensively used for crop production though excessive drainage can contribute to mineralization of the peat, resulting in soil acidification (Gomes et al., 1997). In Fig. 3.8 a map by Hassing (2017) is shown. The green colored area indicates the present machongos, located in between the higher sand dunes and toward the river the clayey lowland. The seepage originates from precipitation infiltrated in the adjacent sand dunes locally known as 'encostas', this water moves through the subsurface towards the lower plains with clayed soils. This flow is generally year round and often referred to as irrigation (Van Der Zaag et al., 2010).

Most peat soils in Mozambique occur under poorly drained and swampy conditions in the vicinity of the coast and in some delta areas. Many are very young soils characterized by little or no soil formation. Thick layers of black to very dark grey-brown, raw to well decomposed peat, peat clay and clayey peat, alternating with one or more mineral horizon(s) are most typical. Within one soil profile it is often possible to find individual peat layers in various stages of decomposition. These soils are moderately to high permeable and the run-off is absent. Water table is found between the surface and 0.5 m depth (Gomes et al., 1997).

In field measurements, only in the plots at the feet of the sand dunes pure peat soil was found. Towards the lowland the peat occurrence gradually declines. In most of the area clayey peat is found and at about 100 cm depth a solid heavy grey clay layer. In the selected field clayey peat soil is observed with a heavy clay layer starting from 100 cm depth. This is contrary to research by Marques et al. (2006*b*) indicating hydromorphic organic soils with a thickness up to 30 cm and over 200 cm to be present, see Fig. I.2.

The computed saturated hydraulic conductivity K_{sat} of the top soil layer obtained from the double ring infiltrometer test is 19 $cm\ d^{-1}$. Measurements with CTD-diver in canal water and ground water in different bore holes revealed an average solute concentration of 615.665 $mg\ cm^{-3}$ in the field. The solute concentration in the canal water is lower. The data obtained from the infiltrometer test and CTD-diver logging is visualized in Fig. I.3

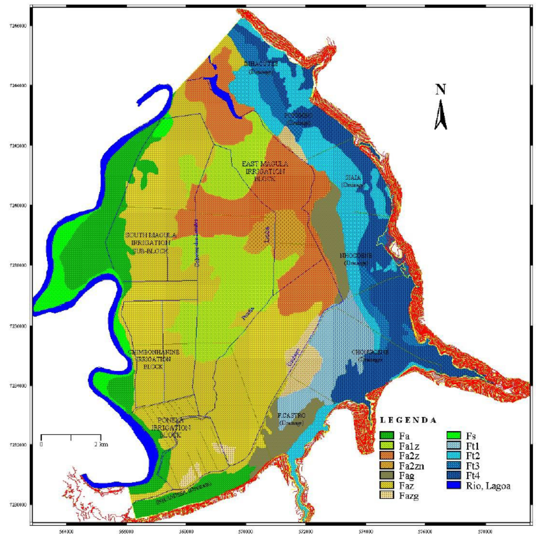
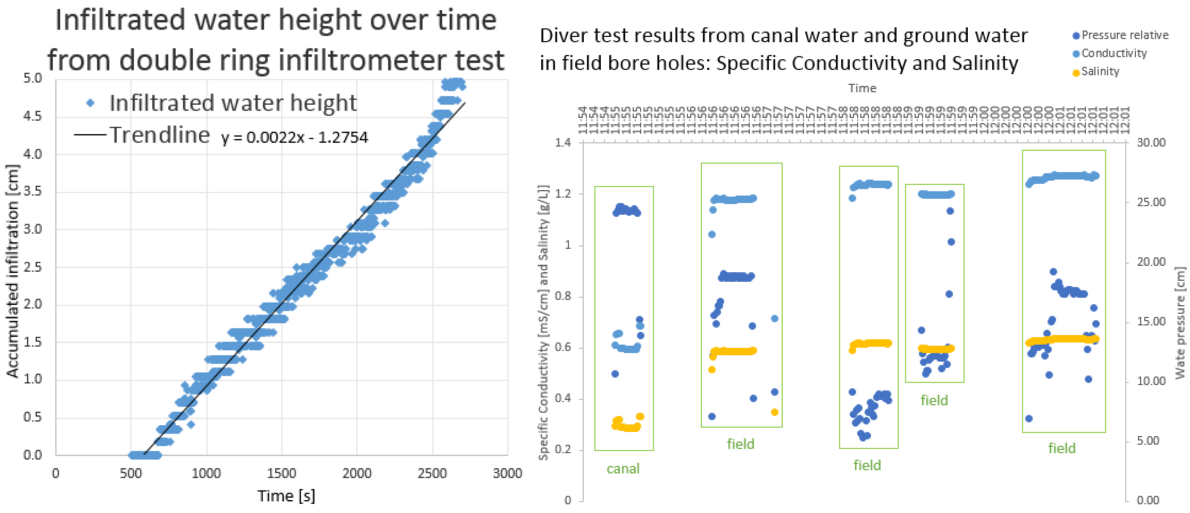


Fig. I.2: Map of Regadio do Baixo Limpopo by Marques et al. (2006*b*) indicating soil types.

DNGRH: The Direcção Nacional de Águas (DNA) was split in 2015 into the Direcção Nacional de Abastecimento de Água e Saneamento (DNAAS) for water supply and sanitaion and the Direcção Nacional de Gestão de Recursos Hídricos (DNGRH) for water resources management. Two employees of DNGRH are interviewed and a meeting and presentations concerning monitoring of efficient water use was attended. DNGRH is responsible for monitoring of water in the country and carries out projects. In Limpopo basin flooding is regarded a greater problem than drought. DNGRH has three objectives, the third objective concerns water for development, including agriculture, where water is seen as crucial. The vision of DNGRH is to build more dams to create hydropower and to decrease their dependency on upstream countries for fresh water. Water shortage has increased in the past few years. This has resulted in national campaigns on the radio, encour-



(a) (b)

Fig. I.3: Data obtained from field measurements in selected field in Fidel Castro drainage system near Xai-Xai city, Mozambique. (a) Double ring infiltrometer test infiltration rate. (b) CTD-diver data in canal water and different bore holes in field.

aging people to reduce car washing and tap use. Concerning agricultural water use DNGRH has no plans or strategy, this is seen as the responsibility of the Instituto Nacional de Irrigação (INIR). DNGRH within DNA reports to the Ministério das Obras Públicas, Habitação e Recursos Hidricos (MOPH). The five Administração Regional de Águas (ARAs) report to DNGRH. The projects carried out by DNGRH depend on possibilities for funding and presently interested parties. A meeting was attended where DNGRH managers were informed that the African Development Bank (ADB) approved a trust fund project within Mozambique for which the collaboration with DNGRH was needed. Although such projects offer benefits for the country, foreign invested projects are largely defined by the foreign investors and there is little room for DNGRH to follow their own vision regarding national water management.

INIR: Instituto Nacional de Irrigação (INIR) is the irrigation institute which is part of the Ministério da Agricultura e Segurança Alimentar (MASA). An INIR employee and local expert were interviewed. An amount of water is allocated to INIR who determines what individual users receive. However, quantifiction is a problem, both water fluxes and data on land productivity is wanted but not quantified yet. Water productivity is seen as important and interpreted as the amount of production and financial gain produced with a certain amount of water applied at the field. INIR regards the machongo area in the Lower Limpopo basin to be an important area for food production, it is seen as an example of irrigation by controlled water table. Efficient use of water in this area is explained to be optimal management of the water table to preserve the present organic matter. This definition of efficient water use is labeled in this report as $EWU_{organic}$, water management resulting in optimal preserving of the organic content of the soil.

$$EWU_{organic} = 1 - (O_{pot} - O_{act}) \tag{I.1}$$

In this equation, O_{pot} is the potential organic content of the soil and O_{act} is the actual organic content. Both can be expressed as a fraction of the total soil content.

To increase efficient water use in the machongos, INIR thinks training of farmers, monitoring and communication of monitoring results is seen as most important. INIR is interested in data on the production from this subsurface irrigated area. Literature reports that there are no national strategies to support the use of wetlands for agricultural purposes in Mozambique as these ecosystems are viewed as sensitive zones that should not be disturbed, although the wetlands in Mozambique do not have a conservation status (Frenken & Mharapara, 2001). The Instituto Nacional de Gestão de Calamidades (INGC) is the National Institute for Disaster Management. In a synthesis report on responding to climate change in Mozambique, adjustment of sowing and planting dates is suggested as the first adaptation measure (Van Logchem & Queface, 2012). This strategy is also mentioned by companies and research institutes in the Netherlands and presented in paragraph **??**. In the publication by (Van Logchem & Queface, 2012) is stated that water management remains key and water-use efficiency must be improved to cope with increasing water scarcity. Improving water-use efficiency is illustrated as 'more crop per drop'.

ARA-Sul: The Administração Regional de Água do Sul (ARA-Sul) is the Regional Water Authority for Southern Mozambique. All ARAs have to report to the Direcção Nacional de Águas (DNA). Three ARA-Sul employees and local experts were interviewed. ARA-Sul includes all water uses, both on the surface and underground. Water users are clients, how water is used has never been of interest for ARA-Sul. However, water has become more limited because of drought in the last years. Because of drought local people have become more aware. People in ARA-Sul now question whether users use the amount of allocated water or more. There is no monitoring system and thus no information on how much water is used in the irrigation scheme. Generally, gravity irrigation is applied. Change to sprinkler irrigation is desired but too expensive. Interviewed ARA-Sul employees interpret efficient water use initially as efficiency applicable on the management of the dam. Efficient water use at the field is seen as something that can be improved with technique of crop production. Proposed strategies are moment of irrigation, where irrigation during the night can decrease loss from evapotranspiration. Also suggested are sensors in the ground to measure humidity decide irrigation timing from this information. Selection of crop type, irrigation system and soil protection are also mentioned. Water productivity is something the interviewees do not know about. Intuitively they describe it as the result per used water.

RBL: The Regadio do Baixo Limpopo (RBL) was established under Portuguese rule, starting in the 1950s (Ganho, 2013). It is the local water board responsible for management of water, land and infrastructure for an area of 11,787 ha including the Fidel Castro block where the observed field is located. RBL has to report to the Instituto Nacional de Irrigação (INIR). Five RBL employees, multiple farmers and several other local experts were interviewed. Most interviewees have not heard of the term 'water productivity'. Interviewees report that RBL does not use water productivity in their monitoring and evaluation of projects within the RBL region. Efficient water use in the machongos is stated to be maintaining soil moisture and proper management of the ground water level. This definition of efficient water use is labeled in this report as EWU_θ, water management resulting in optimal water content of the soil.

$$EWU_\theta = 1 - abs(\theta_{opt} - \theta_{act}) \tag{I.2}$$

In this equation,θ_{opt} is the optimal soil moisture content and θ_{act} is the actual soil moisture content during a growing season. Soil moisture content can be expressed in cm^3cm^{-3}.

In the 1950s Dutch research and construction realized the drainage of the area. The area is described in paragraph 3.2.2. Under Portuguese rule in the years 1956 - 1975 RBL employees including extension officers and engineers lived close to the area to control the system for which specified people are needed. The extension officers used to be permanently in the field. His task was to monitor water levels and agricultural performance, to inform the engineers and to tell the farmers when to clean the canals ('collectores') and when to plant or harvest. The engineer used to decide when to open or close valves in the system. With the Massingir Dam and Smallholder Agricultural Rehabilitation project (MDSAR) in 2003 a pumping station was build downstream along the Limpopo River, from which the whole RBL area is regulated. Water drainage is required for the machongos and this fresh water can be used to irrigate rice cultivation in the lowlands. The pumping station has two sets of pumps, one set pumps water into a tank from which it flows by gravity to the rice blocks. The other set can be used to pump excess fresh water from the system to the Limpopo river. Without the pumps this drainage happens by gravity. The four drainage pumps each have a capacity of 1.96 m3/s. Data on pump use or discharges is not kept. The pumps are operated by four technicals (Mugabe, 2015*c*).

RBL communicates with the farmers through the farmer organizations: Casas Agrarias (CA). The CA has a president and each agricultural block and subblock is managed by a chief. The president and chiefs are instructed by RBL. Farmers pay a fee to RBL of 500 mt/y/ha, this is a tax for land, water and operation and maintenance of the system. However, most farmers do not pay and RBL has no information on the individual users.

Results from interviews reflect conflicts between RBL and the farmers on several issues. The first issue concerns the responsibility and need for cleaning and maintenance of the canals, especially the secondary canals. The water level in the system is measured daily at the pumping station. A certain height at the pumping station represents the critical height at the field, at this moment the pumps are turned on. However, this method requires proper drainage between the fields and this measurement point. Often drains are blocked resulting in flooding in the field before the critical height is determined at the pumping station. Blockage of the drains is often observed. RBL states that it succeeds in its yearly plans concerning cleaning of primary and secondary ditches (Mugabe, 2015*a*). Literature reports the secondary and tertiary canals in the family sector to be the the users' responsibility and states that this should be the responsibility of the users downstream which are the commercial rice producers that benefit from the drainage system in the irrigation of their fields (Ganho, 2013). The second issue is the operation of the system valves. This is the responsibility of extension officers of RBL, adjustment of the valves can be requested by the farmers through the CA. In practice farmers report to adjusts the valves themselves. Some of the valves are currently broken. A third issue concerns the crop production. The organic soils are suitable for cultivation of vegetables and RBL wants crop rotation to be applied. In practice the majority of farmers cultivates maize without crop rotation.

In each of these issues is brought up that there are only very few RBL empoloyees in the field and multiple local expert express that the system is lacking proper coordination from RBL. Local experts and farmers suggest that soil moisture and water height is measured in the field and not only at the pumping station. Literature reports that current extension officers assist each up to 1,000 individual farmers (Mugabe, 2015*b*). Present technical agricultural support is provided by extension officers from the Services of District Economic Activities (SDAE), which is understaffed for this task (Ganho, 2013). Local interviewees report that RBL expects much of the CA but does not pay the commissioned president or chiefs. To make a living these managers need to work on their own plot and the CA does not function well. Interviewees also complain that engineers live far away in the cities, because of this pumps are often activated too late.

RBL employees report that RBL has plans for the area. This includes cleaning the canals every three months, assisting farmers and providing technology, construction of new pumping station and maintenance of the roads. RBL is aware that production in the machongos is relatively cheap (Mugabe, 2015*b*). Nevertheless, expectations for food production and foreign investments are focused on rice production in the low lands (Mugabe, 2015*a*). An RBL interviewee reports that there has never been any research by RBL in the machongos. There are no measurements of the seepage or spring water flow that originates from the surrounding hills. Literature indicates that the World Bank has shifted its emphasis from smallholder farming in Africa (recognized in the 1993 loan from ADB for the MDSAR project) towards an explicit role for large-scale farming (Ganho, 2013). (Ganho, 2013) also makes the assumption that the smallholder model proposed in the initial MDSAR plan was merely donor-led and not owned by Mozambican elites.

RBL's largest challenge in the machongos to prevent flooding of the agricultural fields and thus maintain the proper ground water level (Mugabe, 2015*a*,*b*). The pumping station is essential for drainage of the area (Mugabe, 2015*a*) and could allow agricultural production in the machongos all year round. Heavy rainfall after planting can destroy the crop, in three days water should be removed to prevent crop failure. In the December of the 2014/2015 season the production was lost due to lack of energy at the pumping station (Mugabe, 2015*b*). In the 2016/2017 season the pump engines broke down in November and the majority of the production was lost after heavy rainfall occurrence. All interviewees see the yearly inundation of the fields as a thread and totally agree on the statement that if water is gone quicker after the wet season that farmers could start planting earlier.

To increase efficient water use, the cleaning of the canals is seen as crucial. Also widening of the canals and an increase of canal frequency is suggested by local experts. Another RBL interviewee states that the canal beds need to be provided covered to prevent percolation and that the currently open canals need to be closed to prevent evaporation. Beside a functioning pumping station for drainage of excess water, an RBL interviewee also states that more storage needs to be realized in the system to store water for the dry season and that this needs to be provided together with good regulation and instruction of farmers. The upstream canal along the hills can be seen as a reservoir functioning when all valves are closed. The construction of more storage is seen as most problematic since funds are currently not available. Storage is seen as efficient water use since this will prevent that in the wet season fresh water needs to be pumped to the ocean.

Farmers Farmers all state that the yearly flooding is a problem, the area is not accessible during and after the wet season. Canals and adjustments of the valves allow water to be maintained or drained from the system. For proper functioning the system needs to be clean. Farmers report that each farmer is held responsible by the Casas Agrarias (CA) to clean the canals around his or her field. However, there is no clear ownership of the plots, when plots are not used the adjacent canals will be blocked. The plots closer to the hills are preferred, these fields are closer to the water springs from the hills and are observed to have a higher organic content which allows vegetable production. Fields further away from the hills and thus more downstream are reported to be dryer during the dry season. When downstream fields are not used the downstream part of the system gets blocked causing drainage problems upstream. Literature reports that farmers continue to rely on off-farm jobs to supplement subsistence agriculture, when production is possible. Many in the family sector in the region are elderly, after massive migration of youths to towns and to South Africa (Ganho, 2013). April to October is the dry season, according to interviewed farmers and local experts this is the best time to plant and harvest crops. November-March is the wet season, machongos are not suitable for agricultural production during these months. February is known as 'inundation month', during these weeks the area becomes a swamp and is unaccessible. During this time reed grows. This is manually removed by the farmers when the water table has lowered. Because of this heavy work, farmers can only cultivate small plots.

An interviewed farmer close to the hills where soil with a high organic content is found, cultivates some vegetables and has access to fertilizers and pesticides. Most farmers think that the plots closer to the hills are better for cultivation. Farmers further away from the hills where the soil is more clayey state that the soil is most suitable for maize production. The farmers report that maize is cultivated each year, planted in April after the wet season, harvested in August or September after which maize is planted again to be harvested in December just before the heavy rains. Sometimes maize is inter cropped, most commonly with sweet potato and beans. The majority of the farmers says that the soil quality is good, some even state that fertilizers are not needed. An interviewee states that insects is a problem.

Farmers mention that if drainage would function properly then crops would less often be destroyed and the start of the dry season could start earlier. Proper management of the system and cleaning of the canals is mentioned. Farmers think that increasing the number of canals could result in improvement but only if these are properly cleaned and maintained. Crop rotation is not applied, after the wet season reed which is the natural vegetation is removed manually before sowing. In between harvest and sowing for the next season, the soil is loosened. Seed quality is said to be poor and some farmers report that insects are a thread. Only some of the farmers have access to fertilizers and pesticides. All farmers cultivate maize since this is seen as successful and suitable for home consumption. Sometimes inter cropping with sweet potato and beans is done. Farmers report that vegetables are difficult since these cannot be saved. Local experts state that the farmers lack market thinking and that lack of wealth prevents them from investing in fertilizers, pesticides and good seed. Often a part of the maize production is used for planting in the next season without any preparation. Other interviewees state that land ownership is an issue. Farmers have no security on how long they can use the land, because it is not theirs they are not investing in the land. Farmers state that they do not pay the RBL fee. The majority reports that this is because there are still problems with water in the system. Also farmers are not personally contacted about the fee and mention that they do not know about it.
An interviewee is afraid that there is no interest from the local governmental organizations for the machongos and the smallholder farmers from the family sector. However, the interviewer believes that with proper management it will be very cheap to cultivate in this area. He reports that farmers barely irrigate their field. He also reports that RBL does not actually control the system, there is no plan. Only little of the area is operational. Another interviewee states that the problem in the machongos is caused by the current social structure. The farmers association is forced by the government and not properly functioning. The system should be well coordinated, the problems cannot be solved by individual farmers. Drainage and fertility is the problem. Efficient water use is seen as important. Efficient water use in his case means proper drainage. Water productivity can also be used but is less important than efficient water use. Efficient water use applies to system scale of pumps and pipes. Strategy: land preparation and more technical assistance. Farmers plots are small because weeding is a lot of work. Small agronomic improvements like land preparation and better seed quality can increase yield.

J

Input files for simulations in SWAP/WOFOST

On the following pages, calibrated input files for the Soil-Water-Atmosphere-Plant model (SWAP) with the WOrld FOod STudies simulation model (WOFOST) are included, for two different fields.

The first simulated field is an average performing winter wheat field in Tadla Basin Morocco having an area of 5.5 ha. The growing season is observed from November 2015 to May 2016, length of the season is 190 days. It is located on the left bank of the Oum Er Rhiba river and is part of the large Beni Moussa irrigation system. A deep ground water table is observed and field irrigation is applied from a field inlet. In the observed season, 180 mm precipitation is received. In the field baseline scenario, 570 mm irrigation is applied and the produced yield is 6.6 t/ha.
The second simulated field is a relatively good performing smallholder maize field in Lower Limpopo Basin Mozambique having an area of 0.22 ha. The growing season is observed from April to September 2016, length of season is 150 days. The field is located in the Fidel Castro irrigation/drainage system near Xai-Xai in the 'Machongos'. In this area a year round spring flow and shallow water table is observed. Management of the water table in the system is crucial for preserving the organic soils and enabling agricultural practices. Sub-surface irrigation is applied by management of the ground water. In the observed season, 125 mm precipitation is received. In the field baseline scenario, 506 mm irrigation is applied and the produced yield is 4.7 t/ha.

The following files are included for both fields:

- .swp general input file
- .crp detailed crop file
- .yyy yearly meteorological input files
- .dra drainage file (for maize field only)

```
******************************************************************************************************************
* Filename: Tadla_general.swp
* Contents: General input data for SWAP simulation
*   Calibrated for Tadla Morocco 2015/2016
*   Author: Charlotte van der Leer, part of MSc master thesis Water Management at Delft University, September 2017
*
******************************************************************************************************************
*
*   The general input file .swp contains the following settings:
*            1  General
*            2  Soil profile
*                   2.1 Soil layers
*                   2.2 Richards' equation
*                   2.3 Salinity
*            3  Top boundary
*                   3.1 Meteo
*                   3.2 Crop
*            4  Bottom boundary
*
*   Comment line starting with      *
*   Comment in line starting with   !
*
*   Parameters are provided with    [ range , unit , data type ]    {source}
*   Switches are provided with      {source}
*
*                       range       Range allowed by SWAP model
*                       unit        Unit assumed by SWAP model
*                       data type   Data types used by SWAP model:
*                                       I = Integer
*                                       R = Real
*                                       Ax = character string of x positions
*                                       dd = daynumber, mm = monthnumber, yy = yearnumber
*                       source      Source for used parameter or switch:
*                                       C  = Calibrated or decided upon in this research
*                                       R# = Used from Representative calibration          1 = SWAP Hupsel (NL) example
*                                       L  = Used from Literature
*                                       E  = Used from Expert knowledge, SEBAL analyis or fieldwork
*
******************************************************************************************************************
*
*
********     swp.1      ********        GENERAL SETTINGS    **********************************************************
*
 PROJECT   = 'Tadla'!                   Project description                                        [A80]
 PATHWORK  = '.\'!                      Path to work folder                                        [A80]
 PATHATM   = '.\data\weather\'!         Path to folder with weather files                          [A80]
 PATHCROP  = '.\data\crops\'!           Path to folder with crop files                             [A80]
 PATHDRAIN = '.\data\drainage\'!        Path to folder with drainage files                         [A80]
 METFIL    = 'Tadla'!                   File name of meteorological data without extension .YYY    [A200]
*                                       Extension is equal to last 3 digits of year, e.g. 003 denotes year 2003
*
 SWSCRE   = 0!                          Switch, 0 = No display of display progression of simulation run to screen
 SWERROR  = 1!                          Switch, 1 = Printing errors to screen
*
 TSTART    = 01-aug-2015!               Start date of simulation run                               [dd-mmm-yyyy]      {C}
 TEND      = 31-oct-2016!               End date of simulation run                                 [dd-mmm-yyyy]      {C}
*
* Number of output times during a day
 NPRINTDAY = 1!                         Number of output times during a day                        [1..1000, I]       {C}
 PERIOD = 1!                            Length of fixed output interval in days                    [0..366, I]        {C}
 SWMONTH = 0!                           Switch, 0 = No output each month
 SWRES = 0!                             Switch, 0 = Do not reset output interval counter each year
 SWODAT = 0!                            Switch, 0 = No extra output dates are given in table
*
* Output times for overall water and solute balances in *.BAL and *.BLC file:
 SWYRVAR = 0!                           Switch, 0 = Each year output of balances at the same date
 DATEFIX = 31 12!                       Day and month for output of yearly balances                [dd mm]
*
 OUTFIL = 'Tadla'!                      Generic file name of output files                          [A16]
 SWHEADER = 0!                          Switch, 0 = Print no header at the start of each balance period               {C}
*
* Optional output files
 SWVAP = 1!                             Switch, 1 = Generate output profiles of moisture, solute and temperature
 SWBLC = 0!                             Switch, 0 = Generate no output file with detailed yearly water balance
 SWATE = 0!                             Switch, 0 = Generate no output file with soil temperature profiles
 SWBMA = 0!                             Switch, 0 = Generate no output file with water fluxes, only for macropore flow
 SWDRF = 0!                             Switch, 0 = Generate no output of drainage fluxes, only for extended drainage
 SWSWB = 0!                             Switch, 0 = Generate no output surface water reservoir, only for extended drainage
*
* Optional output file with formatted and unformatted hydrological data
* for water quality models (PEARL, ANIMO) or other specific use (SWAFO to DZNEW)
 SWAFO = 0!                             Switch, 0 = Generate no formatted output
 SWAUN = 0!                             Switch, 0 = Generate no unformatted output
*
```

```
* Critical deviation of water balance:
 CRITDEVMASBAL = 0.00001!             Critical Deviation in water balance during PERIOD                          [0.0..1.0 cm, R]            {R1}
*
*
*
********     swp.2      ********        SOIL PROFILE    ***************************************************************************************************************
*
* Switch, type of initial soil moisture condition:
 SWINCO = 2!                          Switch, 2 = Pressure head of each compartment                                                          {C}
*                                     is in hydrostatic equilibrium with initial groundwater level
 GWLI = -1500.0!                      Initial groundwater level                                                  [-10000..100 cm, R]         {C, E(WimBastiaanssen)}
*
* Maximum rooting depth:
 RDS = 80.0!                          Maximum rooting depth allowed by the soil profile                          [1..5000 cm, R]             {E(WimBastiaanssen)}
*
* Processes not included in simulation:
 SWHYST = 0!                          Switch, 0 = No simulation of hysteresis                                                                {C}
 SWSCAL = 0!                          Switch, 0 = No simulation of similar media scaling                                                     {C}
 SWMACRO = 0!                         Switch, 0 = No simulation of macropore flow                                                            {C}
 SWDRA = 0!                           Switch, 0 = No simulation of lateral drainage                                                          {C}
 SWHEA = 0!                           Switch, 0 = No simulation of  heat transport                                                           {C}
*
*
***     swp.2.1         ********        SOIL LAYERS     ***
*
* List thickness of each compartment:
 DZNEW = 1.0 5.0 10.0 50.0!           Thickness of compartments, total thickness                                 [1.0d-6...5.0d2, cm, R]     {C}
*                                     should correspond to soil profile layering
*
* Specify soil profile layering:
*                                     ISOILLAY = Number of soil layer, start with 1 at soil surface              [1..MAHO, I]
*                                     ISUBLAY  = Number of sub layer, start with 1 at soil surface               [1..MACP, I]
*                                     HSUBLAY  = Height of sub layer                                             [0.0..1000.0 cm, R]         {C}
*                                     HCOMP    = Height of compartments in this layer                            [0.0..1000.0 cm, R]         {C}
*                                     NCOMP    = Number of compartments in this layer = HSUBLAY/HCOMP            [1..MACP, I]                {C}
*
 ISOILLAY ISUBLAY  HSUBLAY    HCOMP    NCOMP
    1       1        5.0       1.0       5
    1       2       25.0       5.0       5
    2       3       70.0      10.0       7
    2       4      200.0      50.0       4
* end of table, maximum MACP lines
*
* Switch for Mualem - van Genuchten parameters or detailed tabels:
  SWSOPHY = 0!                        Switch, 0 = use Mualem - van Genuchten parameters
*
* Specifiy for each layer:
*                                     ISOILLAY1   = number of soil layer                                     [1..MAHO, I]
*                                     ORES        = Residual water content                                   [0..0.4 cm3/cm3, R]         {L(HiHydroSoil)}
*                                     OSAT        = Saturated water content                                  [0..0.95 cm3/cm3, R]        {L(HiHydroSoil)}
*                                     ALFA        = Shape parameter alfa of main drying curve                [0.0001..1 /cm, R]          {C}
*                                     NPAR        = Shape parameter n                                        [1..4 -, R]                 {C}
*                                     KSAT        = Saturated vertical hydraulic conductivity                [1.d-5..1000 cm/d, R]       {C}
*                                     LEXP        = Exponent in hydraulic conductivity function              [-25..25 -, R]              {E(Wim Bastiaanssen)}
*                                     ALFAW       = Alfa parameter of main wetting curve in case of hysteresis    [0.0001..1 /cm, R]     {C}
*                                     H ENPR      = Air entry pressure head                                  [-40.0..0.0 cm, R]          {C}
*
  ISOILLAY1  ORES    OSAT      ALFA    NPAR     KSAT      LEXP    ALFAW H_ENPR  KSATEXM
1 0.041 0.42 0.0200 1.5000 50.0000 1.5 0.025 -40.00 50.0
2 0.041 0.39 0.0700 1.0300 15.0000 1.5 0.040 -14.29 15.0
*
*
***     swp.2.2         ********        RICHARDS EQUATION   ***
*
* Settings for Numerical solution of Richards' equation:
 DTMIN = 0.000001!                    Minimum timestep                                                           [1.d-7..0.01 d, R]          {R1}
 DTMAX = 0.01!                        Maximum timestep                                                           [ 0.01..0.5 d, R]           {R1}
 GWLCONV = 100.0!                     Maximum dif. groundwater level between iterations                          [1.d-5..1000 cm, R]         {R1}
 CritDevh1Cp = 0.01!                  Maximum relative difference in pressure heads per compartment              [1.0d-10..0.1 -, R]         {R1}
 CritDevh2Cp = 0.1!                   Maximum difference in pressure heads per compartment                       [1.0d-10..1.0 cm, R]        {R1}
 CritDevPondDt = 0.0001!              Maximum water balance error of ponding layer                               [1.0d-6..0.1 cm, R]         {R1}
 MaxIt = 30!                          Maximum number of iteration cycles                                         [5..100 -, I]               {R1}
 MaxBackTr = 3!                       Maximum number of back track cycles within an iteration cycle              [1..10 -,I]                 {R1}
*
* Mean of hydraulic conductivity:
 SWkmean = 4!                         Switch, 4 = Weighted geometric mean                                                                    {E(Wim Bastiaanssen)}
*
* Explicit/implicit solution Richards equation with hydraulic conductivity:
 SWkImpl = 0!                         Switch, 0 = Explicit solution                                                                          {E(Wim Bastiaanssen)}
```

```
***     swp.2.3         ********        SALINITY    ***
*
* Switch for simulation of solute transport:
 SWSOLU = 1!                            Switch, 1 = Simulate solute transport, initial concentration over depth:
*                                           CML   = Initial solute concentration                          [1..1000 mg/cm3, R]         {L}
*                                           ZC    = Soil depth                                            [-10000..0 cm, R]
     ZC       CML
   -10.0      0.64
   -95.0      0.64
* End of table, max. MACP records
*
* Miscellaneous parameters as function of soil depth:
*                                       ISOILLAY6 = Number of soil layer, as defined in soil water section         [1..MAHO, I]                {R1}
*                                       LDIS      = Dispersion length                                     [0..100 cm, R]              {R1}
*                                       KF        = Freundlich adsorption coefficient                     [0..100 cm3/mg, R]          {R1}
*                                       BDENS     = Dry soil bulk density                                 [500..3000 mg/cm3, R]       {R1}
*                                       DECPOT    = Potential decomposition rate                          [0..10 /d, R]               {R1}
*
 ISOILLAY6     LDIS          KF     BDENS  DECPOT
     1         5.00   0.0001389   1315.00     0.0
     2         5.00   0.0001378   1318.00     0.0
* end of Table, maximum MAHO
*
* Diffusion constant:
 DDIF = 0.0!                            Molecular diffusion coefficient                                   [0..10 cm2/day, R]          {R1}
*
* Root uptake of solutes:
 TSCF = 0.0!                            Relative uptake of solutes by roots                               [0..10 -, R]                {R1}
*
* Solute adsorption:
 SWSP = 1!                              Switch, 1 = Consider solute adsorption
 FREXP = 0.9!                           Freundlich exponent                                               [0..10 -, R]                {R1}
 CREF = 1.0!                            Reference solute concentration for adsorption                     [0..1000 mg/cm3, R]         {R1}
*
* Solute decomposition:
 SWDC = 1!                              Switch, 1 = Consider solute decomposition
 GAMPAR = 0.0!                          Factor reduction decomposition due to temperature                 [0..0.5 /uuC, R]            {R1}
 RTHETA = 0.3!                          Minimum water content for potential decomposition                 [0..0.4 cm3/cm3, R]         {R1}
 BEXP = 0.7!                            Exponent in reduction decomposition due to dryness                [0..2 -, R]                 {R1}
*
* List the reduction of potential decomposition:
*                               ISOILLAY7 = Number of soil layer, as defined in soil water section        [1..MAHO, I]                {R1}
*                               FDEPTH    = Reduction of potential decomposition                          [0..1 -, R]                 {R1}
  ISOILLAY7  FDEPTH
       1       1.00
       2       0.65
* End of table, maximum MAHO records
*
* Mixed reservoir:
 SWBR = 1!                              Switch, 1 = Consider mixed reservoir for saturated zone                                       {R1}
 CDRAIN = 0.51!                         Solute concentration in groundwater                               [0..100 mg/cm3, R]          {R1}
 DAQUIF = 110.0!                        Thickness saturated part of aquifer                               [0..10000 cm, R]            {R1}
 POROS = 0.4!                           Porosity of aquifer                                               [0..0.6 -, R]               {R1}
 KFSAT = 0.2!                           Linear adsorption coefficient in aquifer                          [0..100 cm3/mg, R]          {R1}
 DECSAT = 1.0!                          Decomposition rate in aquifer                                     [0..10 /d, R]               {R1}
```

```
 CDRAINI = 0.2!                    Initial solute concentration in groundwater                       [0..100 mg/cm3, R]        {R1}
*
*
*
*******     swp.3      ********       TOP BOUNDARY    *********************************************************************************************
*
* Switch, in case of snow and frost, calculate snow accumulation and melt and reduction of soil water flow:
 SWSNOW = 0!                       Switch, 0 = No snow                                                                         {E}
 SWFROST = 0!                      Switch, 0 = No frost                                                                        {E}
*
* In case of ponding:
 PONDMX = 20.0!                    Minimum thickness for runoff                                      [0..1000 cm, R]           {E(Wim Bastiaanssen)}
 RSRO = 0.5!                       Drainage resistance for surface runoff                            [0.001..1.0 d, R]         {R1}
 RSROEXP = 1.0!                    Exponent in drainage equation of surface runoff                   [0.1..10.0 -, R]          {R1}
*
* Specify whether runon data are provided in extra input file :
 SWRUNON = 0!                      Switch, 0 = No input of runon data                                                          {C}
*
* Switch for use of soil factor CFBS to calculate Epot from ETref
 SWCFBS = 0!                       Switch, 0 = CFBS is not used                                                                {C}
*
* Switch, method for reduction of potential soil evaporation:
 SWREDU = 2!                       Switch, 2 = reduction to maximum Darcy flux and to maximum Bo/Str. (1986)                   {E(Wim Bastiaanssen)}
 COFRED = 0.63!                    Soil evaporation coefficient of Boesten/Stroosnijder              [0..1 cm1/2, R]           {R1}
 RSIGNI =  0.5!                    Minimum rainfall to reset method                                  [0..1 cm/d, R]            {R1}
*
* Define top boundary of soil temperature:
 SwTopbHea = 1!                    Switch, 1 = use air temperature of meteo input file as top boundary
*
*
***     swp.3.1        ********       METEO SETTINGS  ***
*
* Use of reference evapotranspiration data
 SWETR =  0!                       Switch, 0 = compute reference ET from basic meteorological data                             {C}
*
* If SWETR = 0, specify:
 LAT = 32.2934174865!              Latitude of meteo station                                         [-60..60 degrees N=+, R]  {E}
 ALT = 426.0!                      Altitude of meteo station                                         [-400..3000 m, R]         {E(DEM)}
 ALTW =  2.0!                      Altitude of wind speed measurement (10 m is default)              [0..99 m, R]              {E(SEBAL)}
*
* Use of detailed meteorological records for both ET and rainfall (< 1 day) in stead of daily values
 SWMETDETAIL = 0!                  Switch, 0 = Do not use detailed meteorological records of ET and rainfall                   {C}
 SWETSINE = 0!                     Switch, 0 = Do not distribute daily Tp and Ep according to sinus wave                       {C}
 SWRAIN = 0!                       Switch, 0 = Use daily rainfall amounts                                                      {C}
*
* Salinity of precipitation water:
 CPRE = 0.0!                       Solute concentration in precipitation                             [1..100 mg/cm3, R]        {E(Wim Bastiaanssen)}
*
*
***     swp.3.2        ********       CROP SETTINGS   ***
*
* Specify information for each crop (maximum MACROP):
*                                  CROPSTART  = Date of crop emergence                               [dd-mmm-yyyy]             {E(SEBAL)}
*                                  CROPEND    = Date of crop harvest                                 [dd-mmm-yyyy]             {E(SEBAL)}
*                                  CROPNAME   = Crop name                                            [A40]
*                                  CROPFIL    = Name of file with crop input parameters, without .CRP [A40]
*                                  CROPTYPE   = Type of crop model:
*                                                  simple = 1, detailed general = 2, detailed grass = 3
*
  CROPSTART      CROPEND       CROPNAME   CROPFIL     CROPTYPE
 28-nov-2015    22-may-2016   'Wheat'    'Wwheat_Tadla'      2
* End of table
*
* Switch for fixed irrigation applications
 SWIRFIX = 1!                      Switch, 1 = Irrigation applications are prescribed
 SWIRGFIL = 0!                     Switch, 0 = Data are specified in the .swp file
*                                      IRDATE   =  Date of irrigation                                [dd-mmm-yyyy]             {C in R1}
*                                      IRDEPTH  =  Amount of water                                   [0.0..100.0 cm, R]        {C in R1}
*                                      IRCONC   =  Concentration of irrigation water                 [0.0..1000.0 mg/cm3, R]   {E(Wim Bastiaanssen)}
*                                      IRTYPE   =  Type of irrigation: sprinkling = 0, surface = 1                             {E(Wim Bastiaanssen)}
*
      IRDATE   IRDEPTH     IRCONC   IRTYPE
 23-nov-2015       60.0     0.0        1
 01-feb-2016      110.0     0.0        1
 07-mar-2016      100.0     0.0        1
 04-apr-2016      100.0     0.0        1
 18-apr-2016      100.0     0.0        1
 02-may-2016      100.0     0.0        1
 16-may-2016       60.0     0.0        1
* end of table, max. MAIRG
*
*
*
*******     swp.4      ********       BOTTOM BOUNDARY    ******************************************************************************************
*
* Switch for file with bottom boundary conditions:
 SWBBCFILE = 0!                    Switch, 0 = Data are specified in the .swp file                                             {C}
 SWBOTB = 7 !                      Switch, 7 = Free drainage of soil profile                                                   {C}
*
* Define bottom boundary soil temperature condition:
 SwBotbHea = 1!                    Switch, 1 = No heat flux;                                                                   {C}
*
* End of the main input file .SWP!
*******************************************************************************************************************************************
```

```
******************************************************************************************
* Filename: Tadla.015
* Contents: SWAP - Meteorological data derived through GLDAS and CHIRPS
******************************************************************************************
* Comment area:
* 01-aug to 31-dec
******************************************************************************************
Station DD MM YYYY RAD Tmin Tmax HUM WIND RAIN ETref WET
*       nr nr   nr kJ/m2 C C kPa m/s mm mm d
******************************************************************************************
'Tadla' 01 08 2015 24639.0134765625 21.133691406250023 40.00368652343752 1.553866534842827 1.4810012578964233 0.000 -99.9 0.0000
'Tadla' 02 08 2015 23784.732421875 22.656854248046898 37.92705688476565 1.7986951581247446 1.9684853553771973 0.000 -99.9 0.0000
'Tadla' 03 08 2015 22589.2810546875 21.799737548828148 37.60405883789065 1.8658813113215964 2.2575345039367676 0.000 -99.9 0.0000
'Tadla' 04 08 2015 23630.50810546875 21.930780029296898 42.08541259765627 1.8283166727029252 1.406026840209961 0.000 -99.9 0.0000
'Tadla' 05 08 2015 21499.560791015625 25.333032226562523 44.20205078125002 1.3758244703395182 1.7193541526794434 1.400 -99.9 0.0000
'Tadla' 06 08 2015 21830.147314453126 25.798883056640648 44.34072265625002 0.9287697613038681 1.9568381309509277 0.000 -99.9 0.0000
'Tadla' 07 08 2015 19034.24326171875 25.576562500000023 42.83175048828127 1.317781136468513 1.6944574117660522 0.000 -99.9 0.0000
'Tadla' 08 08 2015 20735.028369140626 24.472375488281273 43.25921020507815 1.4154374480768026 1.3076300621032715 0.000 -99.9 0.0000
'Tadla' 09 08 2015 21998.412158203126 24.784570312500023 43.2575622558594 1.454362403273379 1.6679203510284424 2.030 -99.9 0.0000
'Tadla' 10 08 2015 22598.135156250002 26.206842041015648 40.86354980468752 1.537268219261745 1.9436252117156982 0.000 -99.9 0.0000
'Tadla' 11 08 2015 20082.491894531253 25.189599609375023 42.12276611328127 1.385582496261012 1.5429176092147827 1.000 -99.9 0.0000
'Tadla' 12 08 2015 24777.03515625 25.827172851562523 44.7000671386719 1.331834335333876 1.5179780721664429 1.000 -99.9 0.0000
'Tadla' 13 08 2015 12745.836474609376 26.830468750000023 38.0255065917969 1.7353186524092312 1.5679242610931396 0.000 -99.9 0.0000
'Tadla' 14 08 2015 24492.456738281253 23.936639404296898 35.71502075195315 1.6166404016667364 1.556931734085083 0.000 -99.9 0.0000
'Tadla' 15 08 2015 24513.19189453125 21.037927246093773 33.56655273437502 1.2492583254482503 1.843084812164306 0.000 -99.9 0.0000
'Tadla' 16 08 2015 25593.19189453125 19.222741699218773 34.75008544921877 1.3225047989063599 1.617309808731079 0.000 -99.9 0.0000
'Tadla' 17 08 2015 24527.77294921875 20.061578369140648 35.1929870605469 1.5970697603521136 1.394501328468322 0.000 -99.9 0.0000
'Tadla' 18 08 2015 22579.667578125 20.604577636718773 31.47170410156252 1.800810310046162 1.771730899810791 0.000 -99.9 0.0000
'Tadla' 19 08 2015 26207.92705078125 17.290734863281273 36.80825195312502 1.3758393407389797 1.182346224784851 0.000 -99.9 0.0000
'Tadla' 20 08 2015 19923.0837890625 21.039971923828148 36.8901306152344 1.6574442351991536 1.9177801609039307 0.000 -99.9 0.0000
'Tadla' 21 08 2015 20826.612158203126 22.638604736328148 37.6390319824219 1.8247478822016245 1.9932228326797485 0.000 -99.9 0.0000
'Tadla' 22 08 2015 24644.08916015625 21.904565429687523 35.45781860351565 1.7293882866486725 2.1430962085723877 0.000 -99.9 0.0000
'Tadla' 23 08 2015 25850.12431640625 18.734368896484398 34.84267578125002 1.3504983420400618 1.455693006515503 0.000 -99.9 0.0000
'Tadla' 24 08 2015 25661.448632812502 18.493951416015648 34.29763183593752 1.318698395842509 1.5332484245300293 0.000 -99.9 0.0000
'Tadla' 25 08 2015 26012.232421875 17.278466796875023 35.48977050781252 1.2889882628455862 1.295765995979309 0.000 -99.9 0.0000
'Tadla' 26 08 2015 25901.7486328125 20.438531494140648 34.68551025390627 1.540598926573768 1.6552536487579346 0.000 -99.9 0.0000
'Tadla' 27 08 2015 25205.04052734375 18.541284179687523 38.52678833007815 1.3640867557608445 1.4546620845794678 0.000 -99.9 0.0000
'Tadla' 28 08 2015 20637.828369140625 20.930841064453148 42.36678466796877 1.444564257756833 2.0318522453308105 3.280 -99.9 0.0000
'Tadla' 29 08 2015 16416.6486328125 24.822351074218773 42.12526855468752 1.2155942648010887 2.0685765743255615 1.640 -99.9 0.0000
'Tadla' 30 08 2015 23979.132421875 24.919366455078148 39.91030273437502 1.348878776111289 2.093374252319336 0.000 -99.9 0.0000
'Tadla' 31 08 2015 22423.716210937502 24.352746582031273 37.5782409667969 1.7865399075395487 2.0060954093933105 0.000 -99.9 0.0000
'Tadla' 01 09 2015 18010.620263671877 22.780969238281273 35.40923461914065 1.620597677850136 1.8292789459228516 0.000 -99.9 0.0000
'Tadla' 02 09 2015 23373.251367187502 21.485742187500023 32.3569274902344 1.5409573468676503 1.8820676803588867 0.000 -99.9 0.0000
'Tadla' 03 09 2015 23631.69462890625 18.481103515625023 30.72469482421877 3 1.5946208786396963 1.54213416576385 5 0.000 -99.9 0.0000
'Tadla' 04 09 2015 24750.57568359375 16.991479492187523 32.41347656250002 1.3402182421466782 1.3572824001312256 0.000 -99.9 0.0000
'Tadla' 05 09 2015 24671.73515625 16.301293945312523 33.86599121093752 1.3359737800739502 1.3816263675689697 0.000 -99.9 0.0000
'Tadla' 06 09 2015 24222.456738281253 18.312188720703148 33.8735290527344 1.2945566142655807 1.491470456123352 0.000 -99.9 0.0000
'Tadla' 07 09 2015 21396.312158203127 18.579888916015648 34.4267517089844 1.2392169916617797 1.5917577743530273 0.000 -99.9 0.0000
'Tadla' 08 09 2015 23576.724316406253 19.662469482421898 32.74141845703127 1.4927930189973357 1.4591034650802612 0.000 -99.9 0.0000
'Tadla' 09 09 2015 24043.5 18.523797607421898 35.16448364257815 1.453930096996831 1.442313313484192 0.000 -99.9 0.0000
'Tadla' 10 09 2015 23657.50810546875 19.177423095703148 37.10637817382815 1.4142247249305728 1.2439231872558594 0.000 -99.9 0.0000
'Tadla' 11 09 2015 15717.131103515627 20.642022705078148 38.59404907226565 1.3631927648632782 1.4814330339431763 0.000 -99.9 0.0000
'Tadla' 12 09 2015 19609.128369140628 19.972802734375023 33.34258422851565 1.5253508009258598 1.644370198249817 0.000 -99.9 0.0000
'Tadla' 13 09 2015 22862.518945312502 18.402124023437523 34.81475219726565 1.3478762888937765 1.5312172174453735 0.000 -99.9 0.0000
'Tadla' 14 09 2015 23154.983789062502 18.135980224609398 33.8030944824219 1.4063896271974037 1.4200159311294556 0.000 -99.9 0.0000
'Tadla' 15 09 2015 22872.88916015625 18.426141357421898 31.737023925781273 1.4567065762582039 1.4179010391235352 0.000 -99.9 0.0000
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'Tadla' 16 09 2015 22989.527050781253 17.680688476562523 31.089685058593773 1.5277987080992952 1.6302295923233032 0.000 -99.9 0.0000
'Tadla' 17 09 2015 22924.72705078125 16.987786865234398 32.14006958007815 1.4094467595759996 1.2540289163589478 0.000 -99.9 0.0000
'Tadla' 18 09 2015 22830.335156250003 16.622644042968773 33.77376708984377 1.5525828390729948 1.0304731130599976 0.000 -99.9 0.0000
'Tadla' 19 09 2015 22442.50810546875 16.833581542968773 34.9531188964844 1.2607368209472216 1.178649663925171 0.000 -99.9 0.0000
'Tadla' 20 09 2015 9542.447973632814 20.191796875000023 30.525476074218773 1.2418142129931746 1.71613609790802 6.920 -99.9 0.0000
'Tadla' 21 09 2015 22248.108105468753 18.824395751953148 35.62310180664065 1.123278632110268 1.1810401678085327 0.000 -99.9 0.0000
'Tadla' 22 09 2015 19794.455419921876 20.143609619140648 36.59465942382815 0.940511310726255 1.681850552558899 0.000 -99.9 0.0000
'Tadla' 23 09 2015 9063.359472656251 21.532434082031273 34.51702270507815 1.0105460914123308 1.3048444986343384 7.160 -99.9 0.0000
'Tadla' 24 09 2015 15222.27568359375 18.800347900390648 32.26442871093752 1.335420712716815 1.147631287574768 0.000 -99.9 0.0000
'Tadla' 25 09 2015 18391.212158203125 17.350610351562523 31.598352050781273 1.268618802405107 1.107925295829773 0.000 -99.9 0.0000
'Tadla' 26 09 2015 21197.59189453125 16.553308105468773 30.687615966796898 1.156470907718638 1.3303520679473877 0.000 -99.9 0.0000
'Tadla' 27 09 2015 11178.108105468751 16.328485107421898 32.37920532226565 1.2884197480340067 1.431060552597046 0.000 -99.9 0.0000
'Tadla' 28 09 2015 9542.447973632814 20.288964843750023 29.542687988281273 1.4015421468749878 1.944928765296936 0.000 -99.9 0.0000
'Tadla' 29 09 2015 11311.379736328126 16.532250976562523 28.337701416015648 1.476113674483051 1.4051402807235718 0.000 -99.9 0.0000
'Tadla' 30 09 2015 20795.185107421876 17.467187500000023 30.849969482421898 1.1883619362989244 1.3185219764709473 0.000 -99.9 0.0000
'Tadla' 01 10 2015 19064.7 15.701623535156273 31.634667968750023 1.1243992343044535 0.8323072791099548 0.000 -99.9 0.0000
'Tadla' 02 10 2015 13187.447314453126 17.006219482421898 32.54506835937502 0.8447424519702055 1.0054768323898315 0.000 -99.9 0.0000
'Tadla' 03 10 2015 18151.991894531253 17.792291259765648 33.67342529296877 0.9195122579410867 1.4459984302520752 0.000 -99.9 0.0000
'Tadla' 04 10 2015 18612.287841796875 21.183068847656273 37.24117431640627 1.0645764203928645 1.2948288917541504 0.000 -99.9 0.0000
'Tadla' 05 10 2015 16331.004052734375 20.182122802734398 37.7933288574219 1.212320440036181 1.8828431367874146 0.000 -99.9 0.0000
'Tadla' 06 10 2015 19324.00810546875 20.643212890625023 33.51128540039065 1.2591591804645865 1.3198530673980713 0.000 -99.9 0.0000
'Tadla' 07 10 2015 18542.412158203126 19.205072021484398 31.671563720703148 1.7118066916139154 1.5692782402038574 0.000 -99.9 0.0000
'Tadla' 08 10 2015 12717.2162109375 18.064691162109398 24.753991699218773 1.4427733868838126 1.2704217433929443 0.000 -99.9 0.0000
'Tadla' 09 10 2015 19344.420263671876 12.386254882812523 27.279656982421898 1.1161778691899793 1.1185224056243896 0.000 -99.9 0.0000
'Tadla' 10 10 2015 18254.916210937503 12.280694580078148 28.933312988281273 1.0069224277670863 1.1793417930603027 0.000 -99.9 0.0000
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* 01-jan to 31-oct
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* Filename: Wwheat_Tadla.CRP
* Contents: Data for detailed crop model (WOFOST)
*   Winter wheat ( Tritium aestivum L.)
*   Calibrated for Tadla Morocco 2015/2016
*   author: Charlotte van der Leer, part of MSc master thesis Water Management at Delft University, September 2017
*
*********************************************************************************************************************************************************************
*
*   The crop input file .crp contains the following settings:
*            0  Irrigation and salinity
*       Corresponding steps of calibration:
*            1  Phenology
*            2  Characteristics for potential transpiration and leaf area index
*            3  Characteristics for actual transpiration and soil moisture content
*            4  Characteristics for actual biomass production and yield
*
*
*   Comment line starting with      *
*   Comment in line starting with   !
*
*   Parameters are provided with    [ range , unit , data type ]    {source}
*   Switches are provided with      {source}
*
*                       range       Range allowed by SWAP model
*                       unit        Unit assumed by SWAP model
*                       data type   Data types used by SWAP model:
*                                       I = Integer
*                                       R = Real
*                                       Ax = character string of x positions
*                                       dd = daynumber, mm = monthnumber, yy = yearnumber
*                       source      Source for used parameter or switch:
*                                       C  = Calibrated or decided upon in this research
*                                       R# = Used from Representative calibration          1 = Pagani 2013 WOFOST parameters for durum wheat in Morocco
*                                                                                          2 = WOFOST input file 'Winter wheat 107, S-Spain, S-Greece'
*                                                                                          3 = SWAP simple crop file WheatD
*                                                                                          4 = SWAP detail crop file WheatS
*                                       L  = Used from Literature
*                                       E  = Used from Expert knowledge, SEBAL analyis or fieldwork
*
*                                   When used values deviate from other used datasets (above or below) this is indicated.
*
*********************************************************************************************************************************************************************
*
*
*******     crp.0      ********        IRRIGATION SCHEDULING   *********************************************************************************************************
*
***  For initial optimal scenario define irrigation by stress criterion Trel = 1.00               ***
***  Irrigation settings can be adjusted for strategy scenario simulation                         ***
***  Salt stress is used from calibration of SWAP with simple crop module, not changed for WOFOST  ***
*
* Irrigation scheduling
 SCHEDULE = 0             !           Switch,     0 = No irrigation scheduling applied,                                              {C}
*                                                 1 = Application of irrigation scheduling
 STARTIRR = 28 11         !           Day and month after which irrigation scheduling is allowed            [dd mm]                  {C}
```

```
 ENDIRR   = 22 05          !          Day and month after which irrigation scheduling is NOT allowed        [dd mm]                 {C}
 CIRRS    = 0.0            !          Solute concentration of scheduled irrig. water,                       [0..100 mg/cm3, R]      {E(Wim Bastiaanssen)}
 ISUAS    = 1              !          Switch,     0 = sprinkling irrigation, 1 = surface irrigation                                 {C}
*
* Irrigation timing criteria
 TCS      = 1              !          Switch,     0 = Daily Stress,                                                             {C}
*                                                 2 = Depletion of Readily Available Water
*                                                 5 = Pressure head or moisture content
*
*                                     DVS_tc1   = Development stage                                     [0..2, R]               {C}
*                                     DVS_tc2   = Development stage                                     [0..2, R]               {C}
*                                     DVS_tc5   = Development stage                                     [0..2, R]               {C}
*                                     Trel      = Mimimum of ratio actual/potential transpiration       [0..1, R]               {C}
*                                     RAW       = Minimal fraction of readily available water           [0..1, R]               {C}
*                                     Value_tc5 = Critical pressure head                                [-1.d6..-100 cm, R]     {C}
*                                                 or critical moisture content                          [0..1.0 cm3/cm3, R]     {C}
* Daily stress criterion (TCS = 1)
  DVS_tc1  Trel
      0.0  1.00
      2.0  1.00
* End of table, maximum 7 records
*
* Depletion of Readily Available Water criterion (TCS = 2)
  DVS_tc2   RAW
      0.0  0.95
      2.0  0.95
* End of table, maximum 7 records
 phFieldCapacity = -100.0  !          Soil hydraulic pressure head                                          [-1000.0 .. 0.0,cm, R]  {C}
*
* Pressure head or Moisture content criterion (TCS = 5)
  DVS_tc5  Value_tc5
      0.0    -1000.0
      2.0    -1000.0
* End of table
 PHORMC = 0                !          Switch, 0 = Use pressure head, 1 = Use soil moisture content
 DCRIT = -30.0             !          Depth of the sensor                                                   [-100..0 cm, R]         {E}
*
*
* Relation between ECsat, crop reduction and concentration
 ECMAX    =     6.0        !          ECsat level at which salt stress starts                               [0..20 dS/m, R]         {R3}
 ECSLOP   =     7.1        !          Decline of rootwater uptake above ECMAX                               [0..40 %/dS/m, R]       {R3}
 C2ECa    =     4.21       !          coefficient a to convert concentration to EC                          [0.0..1000.0 -, R]      {R3}
 C2ECb    =     0.763      !          exponent b to convert concentration to EC                             [0.0..10.0 -, R]        {R3}
 SWC2ECF  =     1          !          Switch, 1 = Use one factor f for whole model profile                                          {C}
 C2ECf    =     1.7        !          Factor f to convert concentration to EC                               [0.0..10.0 -, R]        {R3}
*
*
********     crp.1     ********       CROP PHENOLOGY  **************************************************************************************************************
*
*
 IDSL    =     2           !          Switch,     2 = Crop development before anthesis depends              {R1}
*                                                 on both temperature and daylength
 DLO     =    13.50        !          Optimum daylength for crop development                                [0..24 h, R]            {R1}
 DLC     =     8.00        !          Minimum daylength                                                     [0..24 h, R]            {R1}
```

```
 TSUMEA =   630.00        !          Temperature sum from emergence to anthesis                    [0..10000 C, R]          {C, below R1,2,3}
 TSUMAM =  1115.00        !          Temperature sum from anthesis to maturity                     [0..10000 C, R]          {C, above R1,2,3}
 DVSEND =     2.00        !          development stage at harvest                                  [-]                      {R1,2}
*
* List increase in temperature sum:
*                                    TAV     = Daily average temperature                           [0..100 C, R]
*                                    DTSM    = Temperature sum increase temperature                [0..60 C, R]             {R1, below R2,3}
*          TAV    DTSM
  DTSMTB =
          0.00   0.00      !
          30.0   24.5      !
          42.0   0.00      !
* End of Table, maximum 15 records
*
* For initial optimal scenario set life span of leaves at maximum to neglect death from aging:
 SPAN   =  28.00           !         Life span under leaves under optimum conditions               [0..366 d, R]            {C, below R1,2,3}
*
*
********     crp.2     ********      CHARACTERISTICS FOR POTENTIAL TRANSPIRATION AND LEAF AREA INDEX     *************************************************************
*
* Use of crop factor or crop height:
  SWCF = 2                 !         Switch,     2 = Crop height                                                            {C}
*                                    DVS = Development stage                                       [0..2 -,R]
*                                    CF  = Crop factor for development stage (not used)            [0.5..1.5, R]
*                                    CH  = Crop height CH  for development stage                   [0..1000 cm, R]          {L,C}
    DVS      CH      CF
    0.01      0.00    1.0
    0.39     20.00    1.0
    0.70     70.00    1.0
    1.01    110.00    1.0
    1.90    110.00    1.0
    2.00      1.00    1.0
* End of Table, maximum 36 records
*
* Coefficients for use of Penman-Monteith:
 ALBEDO =    0.181        !          Crop reflection coefficient                                   [0..1.0 -, R]            {E(SEBAL)}
 RSC    =   40.0          !          Minimum canopy resistance                                     [0..10^6 s/m, R]         {C}
 RSW    =    0.00         !          Canopy resistance of intercepted water                        [0..10^6 s/m, R]         {R3}
*
* Initial values:
 TDWI   =  60.00          !          Initial total crop dry weight                                 [0..10000 kg/ha]         {E(Allard de Wit)}
 LAIEM  =  0.150          !          Leaf area index at emergence                                  [0..10 m2/m2, R]         {C, below R1,2,3}
 RGRLAI =  0.006          !          Maximum relative increase in LAI                              [0..1 m2/m2/d, R]        {C, between R1 and R2,3}
*
* Green surface area:                DVS = Development stage                                       [0..2 -,R]
*                                    SLA = Specific leaf area for development stage                [0..1 ha/kg, R]          {C, above R1,2,3}
*         DVS   SLA
  SLATB =
         0.00 0.0047
         1.00 0.0009
* End of Table, maximum 15 records
*
 SPA    =  0.0000         !          Specific pod area                                             [0..1 ha/kg, R]          {R2,3}
 SSA    =  0.0000         !          Specific stem area                                            [0..1 ha/kg, R]          {R1,2,3}
```

```
 TBASE  =  0.0000          !          Lower threshold temperature for ageing of leaves                    [-10..30 C, R]            {R1,2,3}
*
 COFAB  =  0.5             !          Interception coefficient Von Hoyningen-Hune and Braden              [0..1 cm, R]              {E(Wim Bastiaanssen), above R3
*
* Light use:
 KDIF   =    0.72          !          Extinction coefficient for diffuse visible light                    [0..2 -, R]               {C, above R1,2,3}
 KDIR   =    0.80          !          Extinction coefficient for direct visible light                     [0..2 -, R]               {C, above R3}
 EFF    =    0.45          !          Light use efficiency for real leaf                                  [0..10 kg/ha/hr/(Jm2s)]   {R2,3}
*
* CO2 assimiliation:                  DVS  = Development stage                                            [0..2 -,R]
*                                     TAVD = Average day temperature                                      [-10..50 C, R]
*                                     TMNR = Minimum day temperature                                      [-10..50 C, R]
*                                     AMAX = Maximum CO2 assimilation rate for development stage          [0..100 kg/ha/hr, R]      {C, below R1,2,3}
*                                     TMPF = Reduction factor of AMAX for average day temperature         [-, R]                    {R2,3}
*                                     TMNF = Reduction factor of AMAX for minimum day temperature         [-, R]                    {R2,3}
*          DVS    AMAX
  AMAXTB =
           0.39  13.000
           0.50  21.000
* End of table, maximum 15 records
*
*          TAVD   TMPF
  TMPFTB =
           0.00  0.000
          10.00  0.600
          15.00  1.000
          29.00  1.000
          34.00  1.000
* End of table, maximum 15 records
*
*          TMNR    TMNF
  TMNFTB =
           0.00  0.000
           3.00  1.000
* End of table, maximum 15 records
*
*
********     crp.3      ********      CHARACTERISTICS FOR ACTUAL TRANSPIRATION AND SOIL MOISTURE  **********************************************************************
*
* Death rates:
 PERDL =   0.030            !         Maximum rel. death rate of leaves due to water stress               [0..3 /d, R]              {R2,3 above R1}
*                                             DVS  = Development stage                                    [0..2 -,R]
*                                             RDRR = Relative death rates of roots for development stage  [kg/kg/d]                 {R2,3}
*                                             RDRS = relative death rates of stems for development stage  [kg/kg/d]                 {R2,3}
*          DVS    RDRR
  RDRRTB =
          0.0000 0.0000
          1.5000 0.0000
          1.5001 0.0200
          2.0000 0.0200
* End of table, maximum 15 records
*
*          DVS     RDRS
  RDRSTB =
```

```
          0.0000 0.0000
          1.5000 0.0000
          1.5001 0.0200
          2.0000 0.0200
* End of table, maximum 15 records
*
* Efficiencies of conversion of assimilates into biomass:
 CVL    =  0.6950          !          Efficiency of conversion into leaves                          [0..1 kg/kg, R]           {C above R1,2,3}
 CVO    =  0.7090          !          Efficiency of conversion into storage organs                  [0..1 kg/kg, R]           {R2,3 below R1}
 CVR    =  0.6940          !          Efficiency of conversion into roots                           [0..1 kg/kg, R]           {R1,2,3}
 CVS    =  0.7620          !          Efficiency of conversion into stems                           [0..1 kg/kg, R]           {C, above R1,2,3}
*
* Root water extraction
 swroottyp =      1        !          Switch,     1 = Method of De Jong van Lier et al. 2006                                  {R4}
*                                                 for type of root water extraction computation
 HLIM1     =      0.0      !          No water extraction at higher pressure heads                  [-100..100 cm, R]         {R4}
 HLIM2U    =    -30.0      !          h below which optimum water extr. starts for top layer        [-1000..100 cm, R]        {R4}
 HLIM2L    =    -30.0      !          h below which optimum water extr. starts for sub layer        [-1000..100 cm, R]        {R4}
 HLIM3H    =   -400.0      !          h below which water uptake red. starts at high Tpot           [-10000..100 cm, R]       {R4}
 HLIM3L    =   -900.0      !          h below which water uptake red. starts at low Tpot            [-10000..100 cm, R]       {R4}
 HLIM4     = -16000.0      !          No water extraction at lower pressure heads                   [-16000..100 cm, R]       {R4}
 ADCRH     =      0.7      !          Level of high atmospheric demand                              [0..5 cm/d, R]            {R4}
 ADCRL     =      0.1      !          Level of low atmospheric demand                               [0..5 cm/d, R]            {R4}
*
* Root density distribution and root growth
*                                     RD  = Relative rooting depth                                  [0..1 -, R]               {R3}
*                                     RDC = Relative root density                                   [0..1 -, R]               {R3}
*          RD     RDC
  RDCTB =
           0.00   1.00
           1.00   1.00
* End of table, maximum 11 records
*
 RDI    =   10.00          !          Initial rooting depth                                         [0..1000 cm, R]           {R2,3}
 RRI    =    1.20          !          Maximum daily increase in rooting depth                       [0..100 cm/d, R]          {R1,2,3}
 RDC    =   80.00          !          Maximum rooting depth crop/cultivar                           [0..1000 cm, R]           {E(Wim Bastiaanssen)}
*
*
********     crp.4     ********       CHARACTERISTICS FOR ACTUAL BIOMASS PRODUCTION AND YIELD ***************************************************************************
*
* Maintenance respiration
 Q10    =  2.0000          !          Rel. increase in respiration rate with temperature            [0..5 /10 C, R]           {R2,3 below R1}
 RML    =  0.0300          !          Rel. maintenance respiration rate of leaves                   [0..1 kgCH2O/kg/d, R]     {R2,3 below R1}
 RMO    =  0.0100          !          Rel. maintenance respiration rate of storage organs           [0..1 kgCH2O/kg/d, R]     {R1,2,3}
 RMR    =  0.0150          !          Rel. maintenance respiration rate of roots                    [0..1 kgCH2O/kg/d, R]     {R1,2,3}
 RMS    =  0.0150          !          Rel. maintenance respiration rate of stems                    [0..1 kgCH2O/kg/d, R]     {R2,3 above R1}
*
* Reduction of senescence:            DVS  = Development stage                                      [0..2 -,R]
*                                     RFSE = Reduction factor of senescence                         [-, R]                    {C, below R2,3}
*          DVS    RFSE
  RFSETB =
           0.00   1.00
           0.95   1.00
           1.05   0.80
```

```
          2.00   0.50
* End of table, maximum 15 records
*
* Partitioning of biomass:
*                                        DVS = Development stage                                            [0..2 -,R]
*                                        FR  = Fraction of total dry matter increase partitioned to the roots    [kg/kg, R]                  {R1,2,3}
*                                        Fraction of total above ground dry matter increase partitioned to ...
*                                            FL  = ... the leaves                                           [kg/kg, R]                  {C, above R1,2,3}
*                                            FS  = ... the stems                                            [kg/kg, R]                  {C, below R1,2,3}
*                                            FO  = ... the storage organs                                   [kg/kg, R]                  {C, below R1,2,3}
*         DVS     FR
  FRTB =
          0.00   0.50
          0.10   0.50
          0.20   0.40
          0.35   0.22
          0.40   0.17
          0.50   0.13
          0.70   0.07
          0.90   0.03
          1.20   0.00
          2.00   0.00
* End of table, maximum 15 records
*
*         DVS     FL
  FLTB =
          0.00   0.65
          0.10   0.65
          0.25   0.70
          0.50   0.50
          0.70   0.25
          0.95   0.25
          1.05   0.25
          1.95   0.25
          2.00   0.25
* End of table, maximum 15 records
*
*         DVS    FS
  FSTB =
          0.00   0.35
          0.10   0.35
          0.25   0.30
          0.50   0.50
          0.70   0.75
          0.95   0.75
          1.05   0.20
          1.95   0.00
          2.00   0.00
* End of table, maximum 15 records
*
*         DVS    FO
  FOTB =
          0.00   0.00
          0.95   0.00
          1.05   0.55
          1.95   0.75
          2.00   0.75
* End of table, maximum 15 records
*
* End of the crop input file .CRP!
**********************************************************************************************************************************************************
```

```
**********************************************************************************************************************************************************************
* Filename: Limpo_general.swp
* Contents: General input data for SWAP simulation
*   Calibrated for Lower Limpopo Basin Mozambique 2016
*   Author: Charlotte van der Leer, part of MSc master thesis Water Management at Delft University, September 2017
*
**********************************************************************************************************************************************************************
*
*   The general input file .swp contains the following settings:
*            1  General
*            2  Soil profile
*                 2.1 Soil layers
*                 2.2 Richards' equation
*            3  Top boundary
*                 3.1 Meteo
*                 3.2 Crop
*            4  Bottom boundary
*
*   Comment line starting with      *
*   Comment in line starting with   !
*
*   Parameters are provided with    [ range , unit , data type ]    {source}
*   Switches are provided with      {source}
*
*                       range       Range allowed by SWAP model
*                       unit        Unit assumed by SWAP model
*                       data type   Data types used by SWAP model:
*                                       I = Integer
*                                       R = Real
*                                       Ax = character string of x positions
*                                       dd = daynumber, mm = monthnumber, yy = yearnumber
*                       source      Source for used parameter or switch:
*                                       C  = Calibrated or decided upon in this research
*                                       R# = Used from Representative calibration          1 = SWAP Hupsel (NL) example
*                                       L  = Used from Literature
*                                       E  = Used from Expert knowledge, SEBAL analyis or fieldwork
*
**********************************************************************************************************************************************************************
*
*
*******     swp.1      ********       GENERAL SETTINGS    ********************************************************************************************************
*
 PROJECT   = 'Limpo'!                   Project description                                                    [A80]
 PATHWORK  = '.\'!                      Path to work folder                                                    [A80]
 PATHATM   = '.\data\weather\'!         Path to folder with weather files                                      [A80]
 PATHCROP  = '.\data\crops\'!           Path to folder with crop files                                         [A80]
 PATHDRAIN = '.\data\drainage\'!        Path to folder with drainage files                                     [A80]
 METFIL    = 'XaiXai'!                  File name of meteorological data without extension .YYY                [A200]
*                                       Extension is equal to last 3 digits of year, e.g. 003 denotes year 2003
*
 SWSCRE   = 0!                          Switch, 0 = No display of display progression of simulation run to screen
 SWERROR  = 1!                          Switch, 1 = Printing errors to screen
*
 TSTART    = 01-jan-2016!               Start date of simulation run                                           [dd-mmm-yyyy]            {C}
 TEND      = 31-may-2017!               End date of simulation run                                             [dd-mmm-yyyy]            {C}



*
* Number of output times during a day
 NPRINTDAY = 1!                         Number of output times during a day                                    [1..1000, I]             {C}
 PERIOD = 1!                            Length of fixed output interval in days                                [0..366, I]              {C}
 SWMONTH = 0!                           Switch, 0 = No output each month
 SWRES = 0!                             Switch, 0 = Do not reset output interval counter each year
 SWODAT = 0!                            Switch, 0 = No extra output dates are given in table
*
* Output times for overall water and solute balances in *.BAL and *.BLC file:
 SWYRVAR = 0!                           Switch, 0 = Each year output of balances at the same date
 DATEFIX = 31 12!                       Day and month for output of yearly balances                            [dd mm]
*
 OUTFIL = 'Limpo'!                      Generic file name of output files                                      [A16]
 SWHEADER = 0!                          Switch, 0 = Print no header at the start of each balance period                                 {C}
*
* Optional output files
 SWVAP = 1!                             Switch, 1 = Generate output profiles of moisture, solute and temperature
 SWBLC = 0!                             Switch, 0 = Generate no output file with detailed yearly water balance
 SWATE = 0!                             Switch, 0 = Generate no output file with soil temperature profiles
 SWBMA = 0!                             Switch, 0 = Generate no output file with water fluxes, only for macropore flow
 SWDRF = 0!                             Switch, 0 = Generate no output of drainage fluxes, only for extended drainage
 SWSWB = 0!                             Switch, 0 = Generate no output surface water reservoir, only for extended drainage
*
* Optional output file with formatted and unformatted hydrological data
* for water quality models (PEARL, ANIMO) or other specific use (SWAFO to DZNEW)
 SWAFO = 0!                             Switch, 0 = Generate no formatted output
```

```
 SWAUN = 0!                         Switch, 0 = Generate no unformatted output
*
* Critical deviation of water balance:
 CRITDEVMASBAL = 0.00001!           Critical Deviation in water balance during PERIOD                 [0.0..1.0 cm, R]          {R1}
*
*
*
*******    swp.2     ********       SOIL PROFILE    ***************************************************************************************
*
* Switch, type of initial soil moisture condition:
 SWINCO = 2!                        Switch, 2 = Pressure head of each compartment                                               {C}
*                                   is in hydrostatic equilibrium with initial groundwater level
 GWLI = -500.0!                     Initial groundwater level                                         [-10000..100 cm, R]       {C}
*
* Maximum rooting depth:
 RDS = 80.0!                        Maximum rooting depth allowed by the soil profile                 [1..5000 cm, R]           {E(fieldwork)}
*
* Processes not included in simulation:
 SWHYST = 0!                        Switch, 0 = No simulation of hysteresis                                                     {C}
 SWSCAL = 0!                        Switch, 0 = No simulation of similar media scaling                                          {C}
 SWMACRO = 0!                       Switch, 0 = No simulation of macropore flow                                                 {C}
 SWHEA = 0!                         Switch, 0 = No simulation of  heat transport                                                {C}
 SWSOLU = 0!                        Switch, 0 = No Simulation of solute transport                                               {C}
*
* Lateral drainage:
 SWDRA = 1 !                        Switch,  1 = Simulation of lateral drainage with basic drainage routine                     {E}
 DRFIL = 'XaiXai'!                  File name with drainage input data without extension .DRA         [A16]
*



*
***    swp.2.1       ********       SOIL LAYERS    ***
*
* List thickness of each compartment:
 DZNEW = 1.0 5.0 10.0 50.0!         Thickness of compartments, total thickness                        [1.0d-6...5.0d2, cm, R]   {C}
*                                   should correspond to soil profile layering
*
* Specify soil profile layering:
*                                   ISOILLAY = Number of soil layer, start with 1 at soil surface     [1..MAHO, I]
*                                   ISUBLAY  = Number of sub layer, start with 1 at soil surface      [1..MACP, I]
*                                   HSUBLAY  = Height of sub layer                                    [0.0..1000.0 cm, R]       {C}
*                                   HCOMP    = Height of compartments in this layer                   [0.0..1000.0 cm, R]       {C}
*                                   NCOMP    = Number of compartments in this layer = HSUBLAY/HCOMP   [1..MACP, I]              {C}
*
 ISOILLAY ISUBLAY HSUBLAY  HCOMP  NCOMP
 1  1  5.0 1.0  5
 1  2  25.0 5.0  5
 1  4  70.0 10.0 7
 2  5 200.0 50.0 4
* end of table, maximum MACP lines
*
* Switch for Mualem - van Genuchten parameters or detailed tabels:
  SWSOPHY = 0!                      Switch, 0 = use Mualem - van Genuchten parameters
*
* Specifiy for each layer:
*                                   ISOILLAY1   = number of soil layer                                [1..MAHO, I]
*                                   ORES        = Residual water content                              [0..0.4 cm3/cm3, R]       {L(SWAP)}
*                                   OSAT        = Saturated water content                             [0..0.95 cm3/cm3, R]      {E(Fieldwork)}
*                                   ALFA        = Shape parameter alfa of main drying curve           [0.0001..1 /cm, R]        {L(SWAP)}
*                                   NPAR        = Shape parameter n                                   [1..4 -, R]               {L(SWAP)}
*                                   KSAT        = Saturated vertical hydraulic conductivity           [1.d-5..1000 cm/d, R]     {E(Fieldwork)}
*                                   LEXP        = Exponent in hydraulic conductivity function         [-25..25 -, R]            {L(SWAP)}
*                                   ALFAW       = Alfa parameter of main wetting curve in case of hysteresis [0.0001..1 /cm, R] {L(SWAP)}
*                                   H ENPR      = Air entry pressure head                             [-40.0..0.0 cm, R]        {L(SWAP)}
*
  ISOILLAY1  ORES    OSAT     ALFA    NPAR     KSAT      LEXP    ALFAW H_ENPR  KSATEXM
1 0.010 0.6176 0.0136 1.3155 19.01 -2.13 0.0136 -40.00 19.01
2 0.000 0.5700 0.0194 1.0890  4.37 -5.96 0.0194 -40.00  4.37
*
*
***    swp.2.2       ********       RICHARDS EQUATION   ***
*
* Settings for Numerical solution of Richards' equation:
 DTMIN = 0.000001!                  Minimum timestep                                                  [1.d-7..0.01 d, R]        {R1}
 DTMAX = 0.01!                      Maximum timestep                                                  [ 0.01..0.5 d, R]         {R1}
 GWLCONV = 100.0!                   Maximum dif. groundwater level between iterations                 [1.d-5..1000 cm, R]       {R1}
 CritDevh1Cp = 0.01!                Maximum relative difference in pressure heads per compartment     [1.0d-10..0.1 -, R]       {R1}
 CritDevh2Cp = 0.1!                 Maximum difference in pressure heads per compartment              [1.0d-10..1.0 cm, R]      {R1}
 CritDevPondDt = 0.0001!            Maximum water balance error of ponding layer                      [1.0d-6..0.1 cm, R]       {R1}
 MaxIt = 30!                        Maximum number of iteration cycles                                [5..100 -, I]             {R1}
 MaxBackTr = 3!                     Maximum number of back track cycles within an iteration cycle     [1..10 -,I]               {R1}
*
* Mean of hydraulic conductivity:
 SWkmean = 4!                       Switch, 4 = Weighted geometric mean                                                         {E(Wim Bastiaanssen)}
```

```
*
* Explicit/implicit solution Richards equation with hydraulic conductivity:
 SWkImpl = 0!                          Switch, 0 = Explicit solution                                                                                      {E(Wim Bastiaanssen)}
*
*
*
*******     swp.3      ********        TOP BOUNDARY    *******************************************************************************************************
*
* Switch, in case of snow and frost, calculate snow accumulation and melt and reduction of soil water flow:
 SWSNOW = 0!                           Switch, 0 = No snow                                                                                                {E}
 SWFROST = 0!                          Switch, 0 = No frost                                                                                               {E}
*
* In case of ponding:
 PONDMX = 20.0!                        Minimum thickness for runoff                                        [0..1000 cm, R]            {E(Wim Bastiaanssen)}
 RSRO = 0.5!                           Drainage resistance for surface runoff                              [0.001..1.0 d, R]          {R1}
 RSROEXP = 1.0!                        Exponent in drainage equation of surface runoff                     [0.1..10.0 -, R]           {R1}
*
* Specify whether runon data are provided in extra input file :
 SWRUNON = 0!                          Switch, 0 = No input of runon data                                                             {C}
*
* Switch for use of soil factor CFBS to calculate Epot from ETref
 SWCFBS = 0!                           Switch, 0 = CFBS is not used                                                                   {C}
*
* Switch, method for reduction of potential soil evaporation:
 SWREDU = 2!                           Switch, 2 = reduction to maximum Darcy flux and to maximum Bo/Str. (1986)                      {E(Wim Bastiaanssen)}
 COFRED = 0.63!                        Soil evaporation coefficient of Boesten/Stroosnijder                [0..1 cm1/2, R]            {R1}
 RSIGNI =  0.5!                        Minimum rainfall to reset method                                    [0..1 cm/d, R]             {R1}
*
* Define top boundary of soil temperature:
 SwTopbHea = 1!                        Switch, 1 = use air temperature of meteo input file as top boundary
*
*
***     swp.3.1         ********       METEO SETTINGS  ***
*
* Use of reference evapotranspiration data
 SWETR =  0!                           Switch, 0 = compute reference ET from basic meteorological data                                {C}
*
* If SWETR = 0, specify:
 LAT = -25.0014423708!                 Latitude of meteo station                                           [-60..60 degrees N=+, R]   {E}
 ALT =   3.0!                          Altitude of meteo station                                           [-400..3000 m, R]          {E(DEM)}
 ALTW =  2.0!                          Altitude of wind speed measurement (10 m is default)                [0..99 m, R]               {E(SEBAL)}
*
* Use of detailed meteorological records for both ET and rainfall (< 1 day) in stead of daily values
 SWMETDETAIL = 0!                      Switch, 0 = Do not use detailed meteorological records of ET and rainfall                      {C}
 SWETSINE = 0!                         Switch, 0 = Do not distribute daily Tp and Ep according to sinus wave                          {C}
 SWRAIN = 0!                           Switch, 0 = Use daily rainfall amounts                                                         {C}
*
* Salinity of precipitation water:
 CPRE = 0.0!                           Solute concentration in precipitation                               [1..100 mg/cm3, R]         {E(Wim Bastiaanssen)}
*
*
***     swp.3.2         ********       CROP SETTINGS   ***
*
* Specify information for each crop (maximum MACROP):


*                                      CROPSTART  = Date of crop emergence                                [dd-mmm-yyyy]              {E(SEBAL)}
*                                      CROPEND    = Date of crop harvest                                  [dd-mmm-yyyy]              {E(SEBAL)}
*                                      CROPNAME   = Crop name                                             [A40]
*                                      CROPFIL    = Name of file with crop input parameters, without .CRP [A40]
*                                      CROPTYPE   = Type of crop model:
*                                                    simple = 1, detailed general = 2, detailed grass = 3
*
  CROPSTART      CROPEND       CROPNAME   CROPFIL      CROPTYPE
18-apr-2016    15-sep-2016    'Maize'    'Maize_Limpo'     2
25-sep-2016    16-jan-2017    'Maize'    'Maize_Limpo'     2
* End of table
*
* Switch for fixed irrigation applications
 SWIRFIX = 0!                          Switch, 0 = No irrigation applications are prescribed                                          {E(fieldwork)}
*
*
*
*******     swp.4      ********        BOTTOM BOUNDARY     ***************************************************************************************************
*
* Switch for file with bottom boundary conditions:
 SWBBCFILE = 0!                        Switch, 0 = Data are specified in the .swp file                                                {C}
 SWBOTB = 2 !                          Switch, 2 = Bottom flux is prescribed                                                          {C}
 SW2 =  2!                             Switch, 2 = Table is used to prescribe bottom flux:
*                                          DATE2 = Date                                                    [dd-mmm-yyyy]              {C}
*                                          QBOT2 = Bottom flux                                             [-100..100 cm/d + = up, R] {C}
```

```
 DATE2 QBOT2
 01-jan-2016 -0.6
 01-mar-2016 -0.3
 01-may-2016 0.0
 01-jun-2016 0.4
 10-jun-2016 0.7
 01-jul-2016 0.7
 12-jul-2016 0.5
 01-aug-2016 0.3
 01-sep-2016 0.2
 01-nov-2016 0.0
 01-jan-2017 0.0
 01-mar-2017 0.0
 01-may-2017 0.0
* End of table, maximum MABBC records
*
* Define bottom boundary soil temperature condition:
 SwBotbHea = 1!                        Switch, 1 = No heat flux                                                     {C}
*
* End of the main input file .SWP!
*****************************************************************************************************************************************************

**********************************************************************************************************************
* Filename: Tadla.016
* Contents: SWAP - Meteorological data derived through GLDAS and CHIRPS
**********************************************************************************************************************
* Comment area:
*
**********************************************************************************************************************
Station DD MM YYYY RAD Tmin Tmax HUM WIND RAIN ETref WET
*        nr nr nr   kJ/m2    C C    kPa m/s mm mm d
**********************************************************************************************************************
'XaiXai' 1 1 2016 31607.97883495516 21.793265573356184 31.080339028902475 2.2368674845310714 3.749206675981834 0.0 -99.9 0.
'XaiXai' 2 1 2016 25311.831679179377 22.02139609197304 30.542094040308932 2.3717197061259987 3.279897125817085 0.0 -99.9 0.
'XaiXai' 3 1 2016 31584.62957645851 22.609079752543796 29.298235282689788 2.2826569244343395 4.169771590552271 0.0 -99.9 0.
'XaiXai' 4 1 2016 31010.22633457196 20.795217655926162 30.37978924871872 2.371659928181054 3.5287998806130587 0.0 -99.9 0.
'XaiXai' 5 1 2016 31126.815183098886 20.932713791020603 30.835335420644252 2.4265082640928717 3.5463131781704402 0.0 -99.9 0.
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'XaiXai' 26 12 2016 19103.039464254507 23.079448327063673 28.496029830622003 2.3857174733471216 3.0257706470008725 2.0 -99.9 0.
'XaiXai' 27 12 2016 19468.243016930293 23.40533693166783 29.08708445550764 2.8129141914102656 3.23245553922673 0.0 -99.9 0.
'XaiXai' 28 12 2016 29276.32010854993 23.652106258056868 33.736513519119256 2.836232293574719 3.0427392461627165 0.0 -99.9 0.
'XaiXai' 29 12 2016 13362.409078458864 24.652928777744375 26.205015421663898 2.7747141773687733 6.65787797118398 55.0 -99.9 0.
'XaiXai' 30 12 2016 13682.664293315569 24.02901789436049 26.761503790954965 2.665079525623226 5.535268044810762 0.0 -99.9 0.
'XaiXai' 31 12 2016 13426.747706223972 23.56456254319912 28.15179736043715 2.672327131399247 2.7372057630562643 5.0 -99.9 0.
```

```
**********************************************************************************************************************************************************
* Filename: Maize_Limpo.CRP
* Contents: Data for detailed crop model (WOFOST)
*   Grain maize (Zea mays L.)
*   Calibrated for Lower Limpopo Basin Mozambique 2016
*   author: Charlotte van der Leer, part of MSc master thesis Water Management at Delft University, September 2017
*
**********************************************************************************************************************************************************
*
*   The crop input file .crp contains the following settings:
*            0  Irrigation
*       Corresponding steps of calibration:
*            1  Phenology
*            2  Characteristics for potential transpiration and leaf area index
*            3  Characteristics for actual transpiration and soil moisture content
*            4  Characteristics for actual biomass production and yield
*
*
*   Comment line starting with      *
*   Comment in line starting with   !
*
*   Parameters are provided with    [ range , unit , data type ]    {source}
*   Switches are provided with      {source}
*
*                       range       Range allowed by SWAP model
*                       unit        Unit assumed by SWAP model
*                       data type   Data types used by SWAP model:
*                                       I = Integer
*                                       R = Real
*                                       Ax = character string of x positions
*                                       dd = daynumber, mm = monthnumber, yy = yearnumber
*                       source      Source for used parameter or switch:
*                                       C  = Calibrated or decided upon in this research
*                                       R# = Used from Representative calibration          1 = Boogaard 2014
*                                                                                          2 = WOFOST input file 'Maize,(Van Heemst, 1988)'
*                                                                                          3 = SWAP detail crop file MaizeD
*                                                                                          4 = SWAP simple crop file MaizeS
*                                       L  = Used from Literature
*                                       E  = Used from Expert knowledge, SEBAL analyis or fieldwork
*
*                                   When used values deviate from other used datasets (above or below) this is indicated.
*
**********************************************************************************************************************************************************
*
*
********     crp.0      ********        IRRIGATION SCHEDULING   **************************************************************************************
*
***  For initial optimal scenario define irrigation by stress criterion Trel = 1.00                ***
***  Irrigation settings can be adjusted for strategy scenario simulation                          ***
***  Salt stress is used from calibration of SWAP with simple crop module, not changed for WOFOST  ***
*
* Irrigation scheduling
 SCHEDULE = 0            !            Switch,     0 = No irrigation scheduling applied,                                                  {C}
*                                                 1 = Application of irrigation scheduling
 STARTIRR = 01 01        !            Day and month after which irrigation scheduling is allowed             [dd mm]                 {C}


 ENDIRR   = 31 12        !            Day and month after which irrigation scheduling is NOT allowed         [dd mm]                 {C}
 CIRRS    = 0.0          !            Solute concentration of scheduled irrig. water,                        [0..100 mg/cm3, R]      {E(Wim Bastiaanssen)}
 ISUAS    = 1            !            Switch,     0 = sprinkling irrigation, 1 = surface irrigation                                  {C}
*
* Irrigation timing criteria
 TCS      = 1            !            Switch,     0 = Daily Stress,                                                                  {C}
*                                                 2 = Depletion of Readily Available Water
*                                                 5 = Pressure head or moisture content
*
*                                     DVS_tc1   = Development stage                                  [0..2, R]               {C}
*                                     DVS_tc2   = Development stage                                  [0..2, R]               {C}
*                                     DVS_tc5   = Development stage                                  [0..2, R]               {C}
*                                     Trel      = Mimimum of ratio actual/potential transpiration    [0..1, R]               {C}
*                                     RAW       = Minimal fraction of readily available water        [0..1, R]               {C}
*                                     Value_tc5 = Critical pressure head                             [-1.d6..-100 cm, R]     {C}
*                                                 or critical moisture content                       [0..1.0 cm3/cm3, R]     {C}
* Daily stress criterion (TCS = 1)
  DVS_tc1  Trel
      0.0  1.00
      2.0  1.00
* End of table, maximum 7 records
*
* Depletion of Readily Available Water criterion (TCS = 2)
  DVS_tc2   RAW
      0.0  0.95
      2.0  0.95
* End of table, maximum 7 records
```

```
 phFieldCapacity = -100.0  !           Soil hydraulic pressure head                                  [-1000.0 .. 0.0,cm, R]      {C}
*
* Pressure head or Moisture content criterion (TCS = 5)
  DVS_tc5  Value_tc5
     0.0    -1000.0
     2.0    -1000.0
* End of table
 PHORMC = 0                !           Switch, 0 = Use pressure head, 1 = Use soil moisture content
 DCRIT = -30.0             !           Depth of the sensor                                           [-100..0 cm, R]             {E}
*
*
*******     crp.1      ********       CROP PHENOLOGY  ************************************************************************************************************
*
*
 IDSL   =     0            !           Switch,     2 = Crop development before anthesis                                              {R1,2,3}
*                                                  depends on temperature only
 TSUMEA  =  1110.0         !           Temperature sum from emergence to anthesis                    [0..10000 C, R]             {C, above R1,2,3,4}
 TSUMAM  =  1020.0         !           Temperature sum from anthesis to maturity                     [0..10000 C, R]             {C, below R1, above2,3,4}
 DVSEND =     2.00         !           development stage at harvest                                  [-]                         {R1,2}
*
* List increase in temperature sum:
*                                      TAV     = Daily average temperature                           [0..100 C, R]
*                                      DTSM    = Temperature sum increase temperature                [0..60 C, R]                {R2, above R1, below R3}
*         TAV    DTSM
  DTSMTB =
          0.00   0.00
          8.00   0.00

         30.00  22.00
         35.00  22.00
* End of Table, maximum 15 records
*
* For initial optimal scenario set life span of leaves at maximum to neglect death from aging:
 SPAN   =  39.00            !          Life span under leaves under optimum conditions               [0..366 d, R]               {C, above R1,2, below2}
*
*
*******     crp.2      ********       CHARACTERISTICS FOR POTENTIAL TRANSPIRATION AND LEAF AREA INDEX     ***************************************************************
*
* Use of crop factor or crop height:
  SWCF = 2                  !          Switch,     2 = Crop height                                                               {C}
*                                      DVS = Development stage                                       [0..2 -,R]
*                                      CF  = Crop factor for development stage (not used)            [0.5..1.5, R]
*                                      CH  = Crop height CH  for development stage                   [0..1000 cm, R]             {L,C, below R4}
    DVS       CH      CF
    0.00     1.0     1.0
    0.08     4.0     1.0
    0.32    25.0     1.0
    0.54    25.0     1.0
    0.74    65.0     1.0
    0.92   112.0     1.0
    1.10   140.0     1.0
    1.97   140.0     1.0
* End of Table, maximum 36 records
*
* Coefficients for use of Penman-Monteith:
 ALBEDO =    0.15          !           Crop reflection coefficient                                   [0..1.0 -, R]               {E(SEBAL)}
 RSC    =   63.80          !           Minimum canopy resistance                                     [0..10^6 s/m, R]            {E(SEBAL)}
 RSW    =    0.00          !           Canopy resistance of intercepted water                        [0..10^6 s/m, R]            {R3}
*
* Initial values:
 TDWI   =  15.00           !           Initial total crop dry weight                                 [0..10000 kg/ha]            {C below R1,2,3}
 LAIEM  =  0.300           !           Leaf area index at emergence                                  [0..10 m2/m2, R]            {C, above R1,2,3}
 RGRLAI =  0.050           !           Maximum relative increase in LAI                              [0..1 m2/m2/d, R]           {R2, above R1,3}
*
* Green surface area:                  DVS = Development stage                                       [0..2 -,R]
*                                      SLA = Specific leaf area for development stage                [0..1 ha/kg, R]             {C, above R1, belowR2,3}
*          DVS   SLA
  SLATB =
         0.00  0.00240
         0.10  0.00140
         1.00  0.00140
* End of Table, maximum 15 records
*
 SPA    =  0.0000          !           Specific pod area                                             [0..1 ha/kg, R]             {R1,2,3}
 SSA    =  0.0000          !           Specific stem area                                            [0..1 ha/kg, R]             {R1,2,3}
 TBASE  =  8.0000          !           Lower threshold temperature for ageing of leaves              [-10..30 C, R]              {R1,2,3}
*
 COFAB  =  0.5             !           Interception coefficient Von Hoyningen-Hune and Braden        [0..1 cm, R]                {E(Wim Bastiaanssen), above R3}
*
* Light use:
 KDIF   =    0.05          !           Extinction coefficient for diffuse visible light              [0..2 -, R]                 {C, below R1,2,3}
 KDIR   =    1.00          !           Extinction coefficient for direct visible light               [0..2 -, R]                 {C, above R3}
```

```
 EFF    =    0.60          !           Light use efficiency for real leaf                              [0..10 kg/ha/hr/(Jm2s)]     {C, above R1,2,3}
*
* CO2 assimiliation:                   DVS  = Development stage                                        [0..2 -,R]
*                                      TAVD = Average day temperature                                  [-10..50 C, R]
*                                      TMNR = Minimum day temperature                                  [-10..50 C, R]
*                                      AMAX = Maximum CO2 assimilation rate for development stage      [0..100 kg/ha/hr, R]        {C, below R1,2,3}
*                                      TMPF = Reduction factor of AMAX for average day temperature     [-, R]                      {R2,3}
*                                      TMNF = Reduction factor of AMAX for minimum day temperature     [-, R]                      {R2,3}
*          DVS    AMAX
  AMAXTB =
           0.00 76.000
           1.00 35.000
           1.75 10.000
           2.00 10.000
* End of table, maximum 15 records
*
*          TAVD   TMPF
  TMPFTB =
           0.00  0.000
           6.00  0.000
          30.00  1.000
          42.00  1.000
          50.00  0.000
* End of table, maximum 15 records
*
*          TMNR    TMNF
  TMNFTB =
           5.00  0.000
          12.00  1.000
* End of table, maximum 15 records
*
*
*******     crp.3      ********        CHARACTERISTICS FOR ACTUAL TRANSPIRATION AND SOIL MOISTURE  **********************************************************************
*
* Death rates:
 PERDL =    0.030           !          Maximum rel. death rate of leaves due to water stress           [0..3 /d, R]                {R2,3 above R1}
*                                              DVS  = Development stage                                [0..2 -,R]
*                                              RDRR = Relative death rates of roots for development stage      [kg/kg/d]           {R1,2,3}
*                                              RDRS = relative death rates of stems for development stage      [kg/kg/d]           {R1,2,3}
*          DVS    RDRR
  RDRRTB =
          0.0000 0.0000
          1.5000 0.0000
          1.5001 0.0200
          2.0000 0.0200
* End of table, maximum 15 records
*
*          DVS     RDRS
  RDRSTB =
          0.0000 0.0000
          1.5000 0.0000
          1.5001 0.0200
          2.0000 0.0200
* End of table, maximum 15 records


*
* Efficiencies of conversion of assimilates into biomass:
 CVL    =  0.810           !           Efficiency of conversion into leaves                            [0..1 kg/kg, R]             {C, above R1,2,3}
 CVO    =  0.600           !           Efficiency of conversion into storage organs                    [0..1 kg/kg, R]             {C, below R1,2,3}
 CVR    =  0.920           !           Efficiency of conversion into roots                             [0..1 kg/kg, R]             {C, above R1,2,3}
 CVS    =  0.790           !           Efficiency of conversion into stems                             [0..1 kg/kg, R]             {C, above R1,2,3}
*
* Root water extraction
 swroottyp =      1         !          Switch,     1 = Method of De Jong van Lier et al. 2006                                          {R3}
*                                                  for type of root water extraction computation
 HLIM1     =    -10.0       !          No water extraction at higher pressure heads                    [-100..100 cm, R]           {R3}
 HLIM2U    =    -25.0       !          h below which optimum water extr. starts for top layer          [-1000..100 cm, R]          {R3}
 HLIM2L    =    -25.0       !          h below which optimum water extr. starts for sub layer          [-1000..100 cm, R]          {R3}
 HLIM3H    =   -500.0       !          h below which water uptake red. starts at high Tpot             [-10000..100 cm, R]         {R4}
 HLIM3L    =   -600.0       !          h below which water uptake red. starts at low Tpot              [-10000..100 cm, R]         {R3}
 HLIM4     = -10000.0       !          No water extraction at lower pressure heads                     [-16000..100 cm, R]         {L}
 ADCRH     =       0.5      !          Level of high atmospheric demand                                [0..5 cm/d, R]              {R3}
 ADCRL     =       0.1      !          Level of low atmospheric demand                                 [0..5 cm/d, R]              {R3}
*
* Root density distribution and root growth
*                                      RD  = Relative rooting depth                                    [0..1 -, R]                 {R1,2,3}
*                                      RDC = Relative root density                                     [0..1 -, R]                 {R1,2,3}
*          RD     RDC
  RDCTB =
           0.00   1.00
           1.00   1.00
* End of table, maximum 11 records
```

```
*
 RDI    =   10.00          !         Initial rooting depth                                         [0..1000 cm, R]           {R1,2,3}
 RRI    =    1.50          !         Maximum daily increase in rooting depth                       [0..100 cm/d, R]          {C, below R1, above R2,3}
 RDC    =  100.00          !         Maximum rooting depth crop/cultivar                           [0..1000 cm, R]           {R1, above R2, below R3}
*
*
*******     crp.4     ********       CHARACTERISTICS FOR ACTUAL BIOMASS PRODUCTION AND YIELD ****************************************************************************
*
* Maintenance respiration
 Q10    =  2.0000          !         Rel. increase in respiration rate with temperature            [0..5 /10 C, R]           {R1,2,3}
 RML    =  0.0300          !         Rel. maintenance respiration rate of leaves                   [0..1 kgCH2O/kg/d, R]     {R1,2,3}
 RMO    =  0.0100          !         Rel. maintenance respiration rate of storage organs           [0..1 kgCH2O/kg/d, R]     {R1,2,3}
 RMR    =  0.0100          !         Rel. maintenance respiration rate of roots                    [0..1 kgCH2O/kg/d, R]     {R1,2,3}
 RMS    =  0.0150          !         Rel. maintenance respiration rate of stems                    [0..1 kgCH2O/kg/d, R]     {R1,2,3}
*
* Reduction of senescence:           DVS  = Development stage                                      [0..2 -,R]
*                                    RFSE = Reduction factor of senescence                         [-, R]                    {C, below R1,2,3}
*         DVS    RFSE
  RFSETB =
          0.00   0.05
          1.00   0.10
          2.00   0.40
* End of table, maximum 15 records
*
* Partitioning of biomass:
*                                    DVS = Development stage                                       [0..2 -,R]
*                                    FR  = Fraction of total dry matter increase partitioned to the roots   [kg/kg, R]       {R1,2,3}



*                                    Fraction of total above ground dry matter increase partitioned to ...
*                                        FL  = ... the leaves                                      [kg/kg, R]                {C, above R1,2,3}
*                                        FS  = ... the stems                                       [kg/kg, R]                {C, above R1,2,3}
*                                        FO  = ... the storage organs                              [kg/kg, R]                {C, below R1,2,3}
*         DVS     FR
  FRTB =
          0.00   0.40
          0.10   0.37
          0.20   0.34
          0.30   0.31
          0.40   0.27
          0.50   0.23
          0.60   0.19
          0.70   0.15
          0.80   0.10
          0.90   0.06
          1.00   0.00
          2.00   0.00
* End of table, maximum 15 records
*
*         DVS     FL
  FLTB =
          0.00   0.70
          0.33   0.70
          0.88   0.15
          0.95   0.10
          1.05   0.10
          2.00   0.10
* End of table, maximum 15 records
*
*         DVS    FS
  FSTB =
          0.00   0.30
          0.33   0.30
          0.88   0.85
          0.95   0.90
          1.05   0.45
          2.00   0.35
* End of table, maximum 15 records
*
*         DVS    FO
  FOTB =
          0.00   0.00
          0.95   0.00
          1.05   0.45
          2.00   0.55
* End of table, maximum 15 records
*
* End of the crop input file .CRP!
**********************************************************************************************************************************************************************
```

```
************************************************************************************
* Filename: XaiXai.DRA
* Contents: SWAP 3.2 - Input data for basic and extended drainage
************************************************************************************
* Comment area:
* Adjusted from Hupsel example for Maize field near Xai-Xai Mozambique, 2016
*
************************************************************************************
*
*
*** BASIC DRAINAGE SECTION ***
*
************************************************************************************
* Part 0: General
*
  DRAMET = 3!           Switch, method of lateral drainage calculation:                                    _
!                           METHOD 1 = Use table of drainage flux - groundwater level relation       _
!                           METHOD 2 = Use drainage formula of Hooghoudt or Ernst                    _
!                           METHOD 3 = Use drainage/infiltration resistance, multi-level if needed   _
*
  SWDIVD = 0!           Calculate vertical distribution of drainage flux in groundwater [Y=1, N=0]          _
*
* If SWDIVD = 1, specify anisotropy factor COFANI (horizontal/vertical saturated hydraulic
* conductivity) for each soil layer (maximum MAHO), [0..1000 -, R] :
  COFANI =    1.0    1.0
*
* Switch to adjust upper boundary of model discharge layer
  SWDISLAY = 0!         switch to adjust discharge layer  [0,1,2, -, I]                 _
*
* If SWDISLAY = 1, specify for the drainage systems 1 - NRLEVS or NRSRF:
*  - swtopdislay(madr)  ! Switch, for each drainage level, to distribute drainage
*                          flux vertically with a given position of the top of the
*                          model discharge layers: [0,1 - , I]   0 = no; 1 = yes
*  - ztopdislay(madr)   ! Array with depth of top of model discharge layer for
*                          each drain level, see also swtopdislay (L);
* If SWDISLAY = 2, then specify ftopdislay instead of ztopdislay:
*  - ftopdislay(madr)   ! Array with factor of top of model discharge layer for
*                          each drain level, see also swtopdislay ();

*  (level is a dummy array, just as either ztopdislay or ftopdislay)
 level  swtopdislay  ztopdislay  ftopdislay
   1        1           -200.0      0.5
   2        0           -0.01       0.0
* end of SWDISLAY-tabel
************************************************************************************
*
*
************************************************************************************
* METHOD 1 - Part 1: Table of drainage flux - groundwater level relation (DRAMET = 1)
*
* If SWDIVD = 1, specify the drain spacing:
  LM1 = 30!             Drain spacing, [1..1000 m, R]               _
*
* Specify drainage flux Qdrain [-100..1000 cm/d, R] as function of groundwater level
* GWL [-1000.0..10.0 cm, R, negative below soil surface]; maximum of 25 records
* start with highest groundwater level:

     GWL     Qdrain
   -20.0        0.5
   -100.        0.1
* End of table
************************************************************************************
*
*
************************************************************************************
* METHOD 2 - Part 2: Drainage formula of Hooghoudt or Ernst (DRAMET = 2)
*
* Drain characteristics:
  LM2 = 11.0!               Drain spacing, [1..1000 m, R]                                                     _
  SHAPE = 0.8!              Shape factor to account for actual location between drain and water divide [0.0..1.0 -, R]     _
  WETPER =  30.0!           Wet perimeter of the drain,  [0..1000 cm, R]                                      _
  ZBOTDR = -80.0!           Level of drain bottom, [-1000..0 cm, R, neg. below soil surface]                  _
  ENTRES =  20.0!           Drain entry resistance, [0..1000 d, R]                                            _
*
* Soil profile characteristics:
*
  IPOS = 2!                 Switch for position of drain:                                                     _
!       1 = On top of an impervious layer in a homogeneous profile                   _
!       2 = Above an impervious layer in a homogeneous profile                       _
!       3 = At the interface of a fine upper and a coarse lower soil layer          _
!       4 = In the lower, more coarse soil layer                                     _
!       5 = In the upper, more fine soil layer                                       _
*
* For all positions specify:
```

```
  BASEGW = -200.!           Level of impervious layer, [-1d4..0 cm, R]
  KHTOP = 25.!              Horizontal hydraulic conductivity top layer, [0..1000 cm/d, R]
*
* In addition, in case IPOS = 3,4,5
  KHBOT = 10.0!             horizontal hydraulic conductivity bottom layer, [0..1000 cm/d, R]
  ZINTF = -150.!            Level of interface of fine and coarse soil layer, [-1d4..0 cm, R]
*
* In addition, in case IPOS = 4,5
  KVTOP = 5.0!              Vertical hydraulic conductivity top layer, [0..1000 cm/d, R]
  KVBOT = 10.0!             Vertical hydraulic conductivity bottom layer, [0..1000 cm/d, R]
*
* In addition, in case IPOS = 5
  GEOFAC = 4.8!             Geometry factor of Ernst,  [0..100 -, R]
**********************************************************************************
*
*
**********************************************************************************
* METHOD 3 - Part 3: Drainage and infiltration resistance (DRAMET = 3)
*
  NRLEVS = 2!               Number of drainage levels, [1..5, I]
*
* Option for interflow in highest drainage level (shallow system with short residence time)
  SWINTFL = 1!              Switch for interflow [0,1, I]
*
* If SWINTFL = 1, specify:
  COFINTFLB = 0.5!          Coefficient for interflow relation  [0.01..10.0 d, R]
  EXPINTFLB = 1.0!          Exponent for interflow relation  [0.1..1.0 -, R]
*

* Switch to adjust the bottom of the model discharge layer; only
* in case of lateral (swdivdra=1) interflow or rapid drainage (Swnrsrf=1 or Swnrsrf=2).
* When the switch is on (SwTopnrsrf=1) then the bottom of the highest order drainage
* system (Zbotdr(NumDrain)) represents the max depth of the interflow.
 SwTopnrsrf = 0!            Switch to enable adjustment of model discharge layer [0,1, I]
**********************************************************************************
*
*
**********************************************************************************
* Part 3a: Drainage to level 1
*
  DRARES1 = 1.!                 Drainage resistance, [10..1d5 d, R]             original: 100
  INFRES1 = 1.!                 Infiltration resistance, [0..1d5 d, R]
  SWALLO1 =   1!                Switch, for allowance drainage/infiltration:
!            1 = Drainage and infiltration are both allowed
!            2 = Drainage is not allowed
!            3 = Infiltration is not allowed

* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L1   = 100.43!                    Drain spacing, [1..1000 m, R]
*
  ZBOTDR1 = -30.0!              Level of drainage medium bottom, [-1000..0 cm, R]
  SWDTYP1 = 2!                  Type of drainage medium: 1 = drain tube, 2 = open channel
*
* In case of open channel (SWDTYP1 = 2), specify date DATOWL1 [dd-mmm-yyyy] and channel
* water level LEVEL1 [cm, negative if below soil surface], maximum MAOWL records:
*
  DATOWL1   LEVEL1
  01-jan-2016    -20.00
  01-mar-2016    -20.00
  01-may-2016    -30.00
  01-jul-2016    -30.00
  01-sep-2016    -30.00
  01-nov-2016    -30.00
  01-jan-2017    -30.00
  01-mar-2017    -30.00
  01-may-2017    -30.00
* End of table
**********************************************************************************
*
*
**********************************************************************************
* Part 3b: Drainage to level 2
*
  DRARES2 = 1.!                 Drainage resistance, [10..1E5 d, R]
  INFRES2 = 1.!                 Infiltration resistance, [0..1E5 d, R]
  SWALLO2 =   1!                Switch, for allowance drainage/infiltration:
!            1 = Drainage and infiltration are both allowed
!            2 = Drainage is not allowed
!            3 = Infiltration is not allowed
*
* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L2 = 109.72!                      Drain spacing, [1..1000 m, R]
*
```

```
  ZBOTDR2 = -50.0!              Level of drainage medium bottom, [-1000..0 cm, R]
  SWDTYP2 = 2!                  Type of drainage medium: 1 = drain tube, 2 = open channel
*
* In case of open channel (SWDTYP2 = 2), specify date DATOWL2 [dd-mmm-yyyy] and channel
* water level LEVEL2 [cm, negative if below soil surface], maximum MAOWL records:
*
  DATOWL2   LEVEL2
  01-jan-2016    -20.00
  01-mar-2016    -20.00
  01-may-2016    -50.00
  01-jul-2016    -50.00
  01-sep-2016    -50.00
  01-nov-2016    -50.00
  01-jan-2017    -50.00
  01-mar-2017    -50.00
  01-may-2017    -50.00
* End of table
**********************************************************************************
*
*
**********************************************************************************
* Part 3c: Drainage to level 3
*
  DRARES3 = 100.!               Drainage resistance, [10..1E5 d, R]
  INFRES3 = 100.!                   Infiltration resistance, [0..1E5 d, R]
  SWALLO3 =   1!                Switch, for allowance drainage/infiltration:
!            1 = Drainage and infiltration are both allowed
!            2 = Drainage is not allowed
!            3 = Infiltration is not allowed
*
* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L3 = 20.!                     Drain spacing, [1..1000 m, R]
*
  ZBOTDR3 = -90.0!              Level of drainage medium bottom, [-1000..0 cm, R]
  SWDTYP3 = 2!                  Type of drainage medium: 1 = drain tube, 2 = open channel
*
* In case of open channel (SWDTYP3 = 2), specify date DATOWL3 [dd-mmm-yyyy] and channel
* water level LEVEL3 [cm, negative if below soil surface], maximum MAOWL records:
*
  DATOWL3   LEVEL3
  14-dec-2015    -90.0
  12-jan-2016    -90.0
* End of table
**********************************************************************************
*
*
**********************************************************************************
* Part 3d: Drainage to level 4
*
  DRARES4 = 100.!               Drainage resistance, [10..1E5 d, R]
  INFRES4 = 100.!                   Infiltration resistance, [0..1E5 d, R]
  SWALLO4 =   1!                Switch, for allowance drainage/infiltration:
!            1 = Drainage and infiltration are both allowed
!            2 = Drainage is not allowed

!            3 = Infiltration is not allowed
*
* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L4 = 20.!                     Drain spacing, [1..1000 m, R]
*
  ZBOTDR4 = -90.0!              Level of drainage medium bottom, [-1000..0 cm, R]
  SWDTYP4 = 2!                  Type of drainage medium: 1 = drain tube, 2 = open channel
*
* In case of open channel (SWDTYP4 = 2), specify date DATOWL4 [dd-mmm-yyyy] and channel
* water level LEVEL4 [cm, negative if below soil surface], maximum MAOWL records:
*
  DATOWL4   LEVEL4
  14-dec-2015    -90.0
  12-jan-2016    -90.0
* End of table
**********************************************************************************
*
*
**********************************************************************************
* Part 3e: Drainage to level 5
*
  DRARES5 = 100.!                   Drainage resistance, [10..1E5 d, R]
  INFRES5 = 100.!                   Infiltration resistance, [0..1E5 d, R]
  SWALLO5 =   1!                Switch, for allowance drainage/infiltration:
!            1 = Drainage and infiltration are both allowed
!            2 = Drainage is not allowed
!            3 = Infiltration is not allowed
```

```
* If SWDIVD = 1 (drainage flux vertically distributed), specify the drain spacing:
  L5 = 20.!                    Drain spacing, [1..1000 m, R]                              _
*
  ZBOTDR5 = -90.0!             Level of drainage medium bottom, [-1000..0 cm, R]          _
  SWDTYP5 = 2!                 Type of drainage medium: 1 = drain tube, 2 = open channel  _
*
* In case of open channel (SWDTYP5 = 2), specify date DATOWL5 [dd-mmm-yyyy] and channel
* water level LEVEL5 [cm, negative if below soil surface], maximum MAOWL records:
*
  DATOWL5   LEVEL5
  14-dec-2015    -90.0
  12-jan-2016    -90.0
* End of table
**********************************************************************************
*
*
*** EXTENDED DRAINAGE SECTION ***
*
*
*******************************************************************************
* Part 0: Reference level
*
 ALTCU = 0.0!                  ALTitude of the Control Unit relative to reference level   _
*               AltCu = 0.0 means reference level coincides with
*               surface level [-300000..300000 cm, R]
*


*******************************************************************************
* Part 1a: drainage characteristics
*
 NRSRF  = 2!                   number of subsurface drainage levels [1..5, I]             _
*
*** Table with physical characteristics of each subsurface drainage level:
*
* LEVEL                        ! drainage level number [1..NRSRF, I]
* SWDTYP                       ! type of drainage medium [open=0, closed=1]
* L                            ! spacing between channels/drains [1..1000 m, R]
* ZBOTDRE                      ! altitude of bottom of channel or drain [ALTCU-1000..ALTCU-0.01 cm,R]
* GWLINF                       ! groundw. level for max. infiltr. [-1000..0 cm rel. to soil surf., R]
* RDRAIN                       ! drainage resistance [1..100000 d, R]
* RINFI                        ! infiltration resistance  [1..100000 d, R]

* Variables RENTRY, REXIT, WIDTHR and TALUDR must have realistic values when the
*          type of drainage medium is open (second column of this table:SWDTYP=0)
*          For closed pipe drains (SWDTYP=1) dummy values may be entered
* RENTRY                       ! entry resistance  [1..100 d, R]
* REXIT                        ! exit resistance   [1..100 d, R]
* WIDTHR                       ! bottom width of channel [0..100 cm, R]
* TALUDR                       ! side-slope (dh/dw) of channel [0.01..5, R]
*
 LEV SWDTYP    L   ZBOTDRE GWLINF RDRAIN RINFI RENTRY REXIT  WIDTHR TALUDR
  1   0      250.0  1093.0 -350.0 150.0  4000.0  0.8    0.8  100.0  0.66
  2   0      200.0  1150.0 -300.0 150.0  1500.0  0.8    0.8  100.0  0.66
* End_of_table
*******************************************************************************
*
*******************************************************************************
* Part 1b: Separate criteria for highest (shallow) drainage system
*
 SWNRSRF = 0     ! Switch to introduce rapid subsurface drainage [0..2, I]
*           0 = no rapid drainage
*           1 = rapid drainage in the highest drainage system (=NRSRF)
*               (implies adjustment of RDRAIN of highest drainage system)
*           2 = rapid drainage as interflow according to a power relation
*               (implies adjustment of RDRAIN of highest drainage system)
* When SWRNSRF = 1, then enter realistic values for rapid drainage
 RSURFDEEP    = 30.0!                  maximum resistance of rapid subsurface Drainage [0.001..1000.0 d, R]    _
 RSURFSHALLOW = 10.0!                  minimum resistance of Rapid subsurface Drainage [0.001..1000.0 d, R]    _
*
* When SWRNSRF = 2, then enter coefficients of power function
 COFINTFL = 0.1!                       coefficient of interflow relation [0.01..10.0 d-1, R]                   _
 EXPINTFL = 0.5!                       exponent of interflow relation [0.1...1.0 -, R]                         _
*
*
*******************************************************************************
* Part 2a: Specification and control of surface water system

 SWSRF = 2!                            option for interaction with surface water system [1..3, I]             _
*        1 = no interaction with surface water system
*        2 = surf. water system is simulated with no separate primary system
*        3 = surf. water system is simulated with separate primary system
```

```
**********************************************************************************
*
**********************************************************************************
* Part 2b: Surface water level of primary system
*
* Only if SWSRF = 3 then the following table must be entered
* Table with Water Levels in the Primary system [max. = 52]:
* no levels above soil surface for primary system
*
* Water level in primary water course WLP [ALTCU-1000..ALTCU-0.01 cm, R] as function of
* DATE1 [dd-mmm-yyyy]
*
      DATE1      WLP
 02-jan-2016    -100.
 14-jun-2016     -80.
 24-oct-2016    -120.
*End_of_table
**********************************************************************************
*
**********************************************************************************
* Part 2c: Surface water level of secondary system
*
* If SWSRF =  2 or 3  then the variable SWSEC must be entered
*
 SWSEC = 2!                    Option for surface water level of secondary system [1..2, I]
*        1 = surface water level is input
*        2 = surface water level is simulated
**********************************************************************************
*
**********************************************************************************
* Part 3: surface water level in secondary water course is input
*
* Table with Water Levels in the Secondary system [max. = 52]:
*
* Water level in secondary water course WLS [ALTCU-1000..ALTCU-0.01 cm, R] as function of
* DATE2 [dd-mmm-yyyy]
*
      DATE2      WLS
 02-jan-2016    -100.
 14-jun-2016     -80.
 24-oct-2016    -120.
*End_of_table
**********************************************************************************
*
**********************************************************************************
* Part 4: surface water level is simulated
*
**********************************************************************************
* Part 4a: Miscellaneous parameters
*
 WLACT  = 1123.0!                  initial surface water level [ALTCU-1000..ALTCU cm,R]
 OSSWLM =   2.5!                   criterium for warning about oscillation [0..10 cm, R]
**********************************************************************************
*

**********************************************************************************
* Part 4b: management of surface water levels
*
 NMPER  =  4!                      number of management periods [1..10, I]
*
* For each management period specify:
* IMPER  index of management period [1..NMPER, I]
* IMPEND date that period ends [dd-mmm-yyyy]
* SWMAN  type of water management [1..2, I]
*        1 = fixed weir crest
*        2 = automatic weir
* WSCAP  surface water supply capacity [0..100 cm/d, R]
* WLDIP  allowed dip of surf. water level, before starting supply [0..100 cm, R]
* INTWL  length of water-level adjustment period (SWMAN=2 only) [1..31 d, R]
*
 IMPER_4b          IMPEND    SWMAN   WSCAP   WLDIP   INTWL
        1     01-nov-2015       1    0.00     0.0       1
        2     31-dec-2015       2    0.00     5.0       1
        3     31-jan-2016       2    0.00     5.0       1
        4     01-apr-2016       1    0.00     0.0       1
*End_of_table
*
 SWQHR  = 1!                       option for type of discharge relationship [1..2, I]
*         1 = exponential relationship
*         2 = table
**********************************************************************************
*
**********************************************************************************
* Part 4c: exponential discharge relation (weir characteristics)
*
* If SWQHR=1 and for ALL periods specify:
*
 SOFCU = 100.0!                    Size of the control unit [0.1..100000.0 ha, R]
*
* IMPER  index of management period [1..NMPER, I]
* HBWEIR weir crest; levels above soil surface are allowed, but simulated
*        surface water levels should remain below 100 cm above soil surface;
*        the crest must be higher than the deepest channel bottom of the
*        secondary system (ZBOTDR(1 or 2),  [ALTCU-ZBOTDR..ALTCU+100 cm,R].
*        If SWMAN = 2: HBWEIR represents the lowest possible weir position.
* ALPHAW alpha-coefficient of discharge formula [0.1..50.0, R]
* BETAW  beta-coefficient of discharge formula [0.5..3.0, R]
```

```
 IMPER_4c  HBWEIR  ALPHAW   BETAW
     1     1114.0    3.0    1.4765
     2     1110.0    3.0    1.4765
     3     1110.0    3.0    1.4765
     4     1114.0    3.0    1.4765
*End_of_table
*******************************************************************************
*
*******************************************************************************
* Part 4d: table discharge relation
*

* If SWQHR=2 and for ALL periods specify:
*
* IMPER  index of management period [1..NMPER, I]
* ITAB   index per management period [1..10, I]
* HTAB   surface water level [ALTCU-1000..ALTCU+100 cm, R]
*        (first value for each period = ALTCU + 100 cm)
* QTAB   discharge [0..500 cm/d, R]
*        (should go down to a value of zero at a level that is higher than
*        the deepest channel bottom of secondary surface water system)
*
 IMPER_4d IMPTAB  HTAB    QTAB
    1       1      100.0   2.0
    1       2        0.0   1.0
    1       3     -100.0   0.5
    1       4     -185.0   0.0
*End_of_table
*******************************************************************************
*
*******************************************************************************
* Part 4e: automatic weir control
*
* For the periods when SWMAN=2 specify next two tables:
*
*** Table #1
*
*
* IMPER  index of management period [1..NMPER, I]
* DROPR  maximum drop rate of surface water level [0..100 cm/d, positive, R]
*        if the value is set to zero, the parameter does not play
*        any role at all
* HDEPTH depth in soil profile for comparing with HCRIT
*        [-100..0 cm below soil surface, R]
*
 IMPER_4E1 DROPR   HDEPTH
      2    0.0     -15.0
      3    0.0     -15.0
*End_of_table
*
*** Table #2
*
* IMPER   index of management period [1..NMPER, I]
* IPHASE  index per management period [1..10, I]
* WLSMAN  surface water level of phase IPHASE [ALTCU-500.0..ALTCU cm,R]
* GWLCRIT groundwater level of phase IPHASE,  max. value
*         [-500..0 cm  below soil surface, R]
* HCRIT   critical pressure head, max. value, (at HDEPTH, see above)
*         for allowing surface water level [-1000..0 cm, neg., R]
* VCRIT   critical unsaturated volume (min. value) for all
*         surface water level [0..20 cm, R]
*         surface water level [0..20 cm, R]
*
*   Notes: 1) The zero's for the criteria on the first record are in fact
*             dummy's, because under all circumstances the scheme will set
*             the surface water level at least to wlsman(imper,1)

*          2) The lowest level of the scheme must still be above the
*             deepest channel bottom of the secondary surface water system
*
 IMPER_4E2 IMPPHASE WLSMAN GWLCRIT    HCRIT   VCRIT
        2     1    1114.0     0.0      0.0     0.0
        2     2    1124.0   -80.0      0.0     0.0
        2     3    1124.0   -90.0      0.0     0.0
        2     4    1154.0  -100.0      0.0     0.0
        3     1    1114.0     0.0      0.0     0.0
        3     2    1124.0   -80.0      0.0     0.0
        3     3    1124.0   -90.0      0.0     0.0
        3     4    1154.0  -100.0      0.0     0.0
*End_of_table
*******************************************************************************
*
* End of .dra file!
*
```

```
**********************************************************************************************************************************************************
* Filename: Tadla_general.swp
* Contents: General input data for SWAP simulation
*   Calibrated for Tadla Morocco 2015/2016
*   Author: Charlotte van der Leer, part of MSc master thesis Water Management at Delft University, September 2017
*
**********************************************************************************************************************************************************
*
*   The general input file .swp contains the following settings:
*            1  General
*            2  Soil profile
*                  2.1 Soil layers
*                  2.2 Richards' equation
*                  2.3 Salinity
*            3  Top boundary
*                  3.1 Meteo
*                  3.2 Crop
*            4  Bottom boundary
*
*   Comment line starting with      *
*   Comment in line starting with   !
*
*   Parameters are provided with    [ range , unit , data type ]    {source}
*   Switches are provided with      {source}
*
*                     range       Range allowed by SWAP model
*                     unit        Unit assumed by SWAP model
*                     data type   Data types used by SWAP model:
*                                     I = Integer
*                                     R = Real
*                                     Ax = character string of x positions
*                                     dd = daynumber, mm = monthnumber, yy = yearnumber
*                     source      Source for used parameter or switch:
*                                     C  = Calibrated or decided upon in this research
*                                     R# = Used from Representative calibration           1 = SWAP Hupsel (NL) example
*                                     L  = Used from Literature
*                                     E  = Used from Expert knowledge, SEBAL analyis or fieldwork
*
**********************************************************************************************************************************************************
*
*
********     swp.1      ********        GENERAL SETTINGS    ******************************************************************************************
*
 PROJECT   = 'Tadla'!                  Project description                                                       [A80]
 PATHWORK  = '.\'!                     Path to work folder                                                       [A80]
 PATHATM   = '.\data\weather\'!        Path to folder with weather files                                         [A80]
 PATHCROP  = '.\data\crops\'!          Path to folder with crop files                                            [A80]
 PATHDRAIN = '.\data\drainage\'!       Path to folder with drainage files                                        [A80]
 METFIL    = 'Tadla'!                  File name of meteorological data without extension .YYY                   [A200]
*                                      Extension is equal to last 3 digits of year, e.g. 003 denotes year 2003
*
 SWSCRE   = 0!                         Switch, 0 = No display of display progression of simulation run to screen
 SWERROR  = 1!                         Switch, 1 = Printing errors to screen
*
 TSTART    = 01-aug-2015!              Start date of simulation run                                              [dd-mmm-yyyy]           {C}
 TEND      = 31-oct-2016!              End date of simulation run                                                [dd-mmm-yyyy]           {C}
*
* Number of output times during a day
 NPRINTDAY = 1!                        Number of output times during a day                                       [1..1000, I]            {C}
 PERIOD = 1!                           Length of fixed output interval in days                                   [0..366, I]             {C}
 SWMONTH = 0!                          Switch, 0 = No output each month
 SWRES = 0!                            Switch, 0 = Do not reset output interval counter each year
 SWODAT = 0!                           Switch, 0 = No extra output dates are given in table
*
* Output times for overall water and solute balances in *.BAL and *.BLC file:
 SWYRVAR = 0!                          Switch, 0 = Each year output of balances at the same date
 DATEFIX = 31 12!                      Day and month for output of yearly balances                               [dd mm]
*
 OUTFIL = 'Tadla'!                     Generic file name of output files                                         [A16]
 SWHEADER = 0!                         Switch, 0 = Print no header at the start of each balance period                                   {C}
*
* Optional output files
 SWVAP = 1!                            Switch, 1 = Generate output profiles of moisture, solute and temperature
 SWBLC = 0!                            Switch, 0 = Generate no output file with detailed yearly water balance
 SWATE = 0!                            Switch, 0 = Generate no output file with soil temperature profiles
 SWBMA = 0!                            Switch, 0 = Generate no output file with water fluxes, only for macropore flow
 SWDRF = 0!                            Switch, 0 = Generate no output of drainage fluxes, only for extended drainage
 SWSWB = 0!                            Switch, 0 = Generate no output surface water reservoir, only for extended drainage
*
* Optional output file with formatted and unformatted hydrological data
* for water quality models (PEARL, ANIMO) or other specific use (SWAFO to DZNEW)
 SWAFO = 0!                            Switch, 0 = Generate no formatted output
 SWAUN = 0!                            Switch, 0 = Generate no unformatted output
*
```

```
* Critical deviation of water balance:
 CRITDEVMASBAL = 0.00001!             Critical Deviation in water balance during PERIOD                        [0.0..1.0 cm, R]          {R1}
*
*
*
********     swp.2      ********        SOIL PROFILE    ***********************************************************************************************************************
*
* Switch, type of initial soil moisture condition:
 SWINCO = 2!                          Switch, 2 = Pressure head of each compartment                                                      {C}
*                                     is in hydrostatic equilibrium with initial groundwater level
 GWLI = -1500.0!                      Initial groundwater level                                                [-10000..100 cm, R]       {C, E(WimBastiaanssen)}
*
* Maximum rooting depth:
 RDS = 80.0!                          Maximum rooting depth allowed by the soil profile                        [1..5000 cm, R]           {E(WimBastiaanssen)}
*
* Processes not included in simulation:
 SWHYST = 0!                          Switch, 0 = No simulation of hysteresis                                                            {C}
 SWSCAL = 0!                          Switch, 0 = No simulation of similar media scaling                                                 {C}
 SWMACRO = 0!                         Switch, 0 = No simulation of macropore flow                                                        {C}
 SWDRA = 0!                           Switch, 0 = No simulation of lateral drainage                                                      {C}
 SWHEA = 0!                           Switch, 0 = No simulation of  heat transport                                                       {C}
*
*
***     swp.2.1         ********        SOIL LAYERS     ***
*
* List thickness of each compartment:
 DZNEW = 1.0 5.0 10.0 50.0!           Thickness of compartments, total thickness                               [1.0d-6...5.0d2, cm, R]   {C}
*                                     should correspond to soil profile layering
*
* Specify soil profile layering:
*                                     ISOILLAY = Number of soil layer, start with 1 at soil surface            [1..MAHO, I]
*                                     ISUBLAY  = Number of sub layer, start with 1 at soil surface             [1..MACP, I]
*                                     HSUBLAY  = Height of sub layer                                           [0.0..1000.0 cm, R]       {C}
*                                     HCOMP    = Height of compartments in this layer                          [0.0..1000.0 cm, R]       {C}
*                                     NCOMP    = Number of compartments in this layer = HSUBLAY/HCOMP          [1..MACP, I]              {C}
*
 ISOILLAY ISUBLAY  HSUBLAY    HCOMP    NCOMP
    1       1       5.0      1.0       5
    1       2       25.0     5.0       5
    2       3       70.0     10.0      7
    2       4      200.0     50.0      4
* end of table, maximum MACP lines
*
* Switch for Mualem - van Genuchten parameters or detailed tabels:
  SWSOPHY = 0!                        Switch, 0 = use Mualem - van Genuchten parameters
*
* Specifiy for each layer:
*                                     ISOILLAY1   = number of soil layer                                   [1..MAHO, I]
*                                     ORES        = Residual water content                                 [0..0.4 cm3/cm3, R]       {L(HiHydroSoil)}
*                                     OSAT        = Saturated water content                                [0..0.95 cm3/cm3, R]      {L(HiHydroSoil)}
*                                     ALFA        = Shape parameter alfa of main drying curve              [0.0001..1 /cm, R]        {C}
*                                     NPAR        = Shape parameter n                                      [1..4 -, R]               {C}
*                                     KSAT        = Saturated vertical hydraulic conductivity              [1.d-5..1000 cm/d, R]     {C}
*                                     LEXP        = Exponent in hydraulic conductivity function            [-25..25 -, R]            {E(Wim Bastiaanssen)}
*                                     ALFAW       = Alfa parameter of main wetting curve in case of hysteresis   [0.0001..1 /cm, R]  {C}
*                                     H ENPR      = Air entry pressure head                                [-40.0..0.0 cm, R]        {C}
*
  ISOILLAY1  ORES    OSAT      ALFA    NPAR     KSAT      LEXP    ALFAW H_ENPR  KSATEXM
1 0.041 0.42 0.0200 1.5000 50.0000 1.5 0.025 -40.00 50.0
2 0.041 0.39 0.0700 1.0300 15.0000 1.5 0.040 -14.29 15.0
*
*
***     swp.2.2         ********        RICHARDS EQUATION   ***
*
* Settings for Numerical solution of Richards' equation:
 DTMIN = 0.000001!                    Minimum timestep                                                         [1.d-7..0.01 d, R]        {R1}
 DTMAX = 0.01!                        Maximum timestep                                                         [ 0.01..0.5 d, R]         {R1}
 GWLCONV = 100.0!                     Maximum dif. groundwater level between iterations                        [1.d-5..1000 cm, R]       {R1}
 CritDevh1Cp = 0.01!                  Maximum relative difference in pressure heads per compartment            [1.0d-10..0.1 -, R]       {R1}
 CritDevh2Cp = 0.1!                   Maximum difference in pressure heads per compartment                     [1.0d-10..1.0 cm, R]      {R1}
 CritDevPondDt = 0.0001!              Maximum water balance error of ponding layer                             [1.0d-6..0.1 cm, R]       {R1}
 MaxIt = 30!                          Maximum number of iteration cycles                                       [5..100 -, I]             {R1}
 MaxBackTr = 3!                       Maximum number of back track cycles within an iteration cycle            [1..10 -,I]               {R1}
*
* Mean of hydraulic conductivity:
 SWkmean = 4!                         Switch, 4 = Weighted geometric mean                                                                {E(Wim Bastiaanssen)}
*
* Explicit/implicit solution Richards equation with hydraulic conductivity:
 SWkImpl = 0!                         Switch, 0 = Explicit solution                                                                      {E(Wim Bastiaanssen)}
```

```
***     swp.2.3        ********        SALINITY    ***
*
* Switch for simulation of solute transport:
 SWSOLU = 1!                           Switch, 1 = Simulate solute transport, initial concentration over depth:
*                                          CML   = Initial solute concentration                        [1..1000 mg/cm3, R]         {L}
*                                          ZC    = Soil depth                                          [-10000..0 cm, R]
     ZC       CML
   -10.0      0.64
   -95.0      0.64
* End of table, max. MACP records
*
* Miscellaneous parameters as function of soil depth:
*                                      ISOILLAY6 = Number of soil layer, as defined in soil water section          [1..MAHO, I]          {R1}
*                                      LDIS      = Dispersion length                                   [0..100 cm, R]              {R1}
*                                      KF        = Freundlich adsorption coefficient                   [0..100 cm3/mg, R]          {R1}
*                                      BDENS     = Dry soil bulk density                               [500..3000 mg/cm3, R]       {R1}
*                                      DECPOT    = Potential decomposition rate                        [0..10 /d, R]               {R1}
*
 ISOILLAY6     LDIS         KF     BDENS  DECPOT
    1          5.00   0.0001389   1315.00     0.0
    2          5.00   0.0001378   1318.00     0.0
* end of Table, maximum MAHO
*
* Diffusion constant:
 DDIF = 0.0!                           Molecular diffusion coefficient                                 [0..10 cm2/day, R]          {R1}
*
* Root uptake of solutes:
 TSCF = 0.0!                           Relative uptake of solutes by roots                             [0..10 -, R]                {R1}
*
* Solute adsorption:
 SWSP = 1!                             Switch, 1 = Consider solute adsorption
 FREXP = 0.9!                          Freundlich exponent                                             [0..10 -, R]                {R1}
 CREF = 1.0!                           Reference solute concentration for adsorption                   [0..1000 mg/cm3, R]         {R1}
*
* Solute decomposition:
 SWDC = 1!                             Switch, 1 = Consider solute decomposition
 GAMPAR = 0.0!                         Factor reduction decomposition due to temperature               [0..0.5 /ᴹᴹC, R]            {R1}
 RTHETA = 0.3!                         Minimum water content for potential decomposition               [0..0.4 cm3/cm3, R]         {R1}
 BEXP = 0.7!                           Exponent in reduction decomposition due to dryness              [0..2 -, R]                 {R1}
*
* List the reduction of potential decomposition:
*                               ISOILLAY7 = Number of soil layer, as defined in soil water section     [1..MAHO, I]                {R1}
*                               FDEPTH    = Reduction of potential decomposition                       [0..1 -, R]                 {R1}
  ISOILLAY7  FDEPTH
      1       1.00
      2       0.65
* End of table, maximum MAHO records
*
* Mixed reservoir:
 SWBR = 1!                             Switch, 1 = Consider mixed reservoir for saturated zone                                     {R1}
 CDRAIN = 0.51!                        Solute concentration in groundwater                             [0..100 mg/cm3, R]          {R1}
 DAQUIF = 110.0!                       Thickness saturated part of aquifer                             [0..10000 cm, R]            {R1}
 POROS = 0.4!                          Porosity of aquifer                                             [0..0.6 -, R]               {R1}
 KFSAT = 0.2!                          Linear adsorption coefficient in aquifer                        [0..100 cm3/mg, R]          {R1}
 DECSAT = 1.0!                         Decomposition rate in aquifer                                   [0..10 /d, R]               {R1}
```

```
 CDRAINI = 0.2!                      Initial solute concentration in groundwater                         [0..100 mg/cm3, R]         {R1}
*
*
*
********     swp.3      ********       TOP BOUNDARY   *****************************************************************************************************
*
* Switch, in case of snow and frost, calculate snow accumulation and melt and reduction of soil water flow:
 SWSNOW = 0!                         Switch, 0 = No snow                                                                            {E}
 SWFROST = 0!                        Switch, 0 = No frost                                                                           {E}
*
* In case of ponding:
 PONDMX = 20.0!                      Minimum thickness for runoff                                        [0..1000 cm, R]            {E(Wim Bastiaanssen)}
 RSRO = 0.5!                         Drainage resistance for surface runoff                              [0.001..1.0 d, R]          {R1}
 RSROEXP = 1.0!                      Exponent in drainage equation of surface runoff                     [0.1..10.0 -, R]           {R1}
*
* Specify whether runon data are provided in extra input file :
 SWRUNON = 0!                        Switch, 0 = No input of runon data                                                             {C}
*
* Switch for use of soil factor CFBS to calculate Epot from ETref
 SWCFBS = 0!                         Switch, 0 = CFBS is not used                                                                   {C}
*
* Switch, method for reduction of potential soil evaporation:
 SWREDU = 2!                         Switch, 2 = reduction to maximum Darcy flux and to maximum Bo/Str. (1986)                      {E(Wim Bastiaanssen)}
 COFRED = 0.63!                      Soil evaporation coefficient of Boesten/Stroosnijder                [0..1 cm1/2, R]            {R1}
 RSIGNI =  0.5!                      Minimum rainfall to reset method                                    [0..1 cm/d, R]             {R1}
*
* Define top boundary of soil temperature:
 SwTopbHea = 1!                      Switch, 1 = use air temperature of meteo input file as top boundary
*
*
***     swp.3.1         ********       METEO SETTINGS  ***
*
* Use of reference evapotranspiration data
 SWETR =  0!                         Switch, 0 = compute reference ET from basic meteorological data                                {C}
*
* If SWETR = 0, specify:
 LAT = 32.2934174865!                Latitude of meteo station                                           [-60..60 degrees N=+, R]   {E}
 ALT = 426.0!                        Altitude of meteo station                                           [-400..3000 m, R]          {E(DEM)}
 ALTW =  2.0!                        Altitude of wind speed measurement (10 m is default)                [0..99 m, R]               {E(SEBAL)}
*
* Use of detailed meteorological records for both ET and rainfall (< 1 day) in stead of daily values
 SWMETDETAIL = 0!                    Switch, 0 = Do not use detailed meteorological records of ET and rainfall                      {C}
 SWETSINE = 0!                       Switch, 0 = Do not distribute daily Tp and Ep according to sinus wave                          {C}
 SWRAIN = 0!                         Switch, 0 = Use daily rainfall amounts                                                         {C}
*
* Salinity of precipitation water:
 CPRE = 0.0!                         Solute concentration in precipitation                               [1..100 mg/cm3, R]         {E(Wim Bastiaanssen)}
*
*
***     swp.3.2         ********       CROP SETTINGS   ***
*
* Specify information for each crop (maximum MACROP):
*                                    CROPSTART  = Date of crop emergence                                 [dd-mmm-yyyy]              {E(SEBAL)}
*                                    CROPEND    = Date of crop harvest                                   [dd-mmm-yyyy]              {E(SEBAL)}
*                                    CROPNAME   = Crop name                                              [A40]
*                                    CROPFIL    = Name of file with crop input parameters, without .CRP  [A40]
*                                    CROPTYPE   = Type of crop model:
*                                                  simple = 1, detailed general = 2, detailed grass = 3
*
  CROPSTART      CROPEND       CROPNAME   CROPFIL     CROPTYPE
 28-nov-2015    22-may-2016   'Wheat'    'Wwheat_Tadla'      2
* End of table
*
* Switch for fixed irrigation applications
 SWIRFIX = 1!                        Switch, 1 = Irrigation applications are prescribed
 SWIRGFIL = 0!                       Switch, 0 = Data are specified in the .swp file
*                                        IRDATE   =  Date of irrigation                                  [dd-mmm-yyyy]              {C in R1}
*                                        IRDEPTH  =  Amount of water                                     [0.0..100.0 cm, R]         {C in R1}
*                                        IRCONC   =  Concentration of irrigation water                   [0.0..1000.0 mg/cm3, R]    {E(Wim Bastiaanssen)}
*                                        IRTYPE   =  Type of irrigation: sprinkling = 0, surface = 1                                {E(Wim Bastiaanssen)}
*
      IRDATE   IRDEPTH     IRCONC   IRTYPE
 23-nov-2015       60.0     0.0        1
 01-feb-2016      110.0     0.0        1
 07-mar-2016      100.0     0.0        1
 04-apr-2016      100.0     0.0        1
 18-apr-2016      100.0     0.0        1
 02-may-2016      100.0     0.0        1
 16-may-2016       60.0     0.0        1
* end of table, max. MAIRG
*
*
*
********     swp.4      ********       BOTTOM BOUNDARY    **************************************************************************************************
*
* Switch for file with bottom boundary conditions:
 SWBBCFILE = 0!                      Switch, 0 = Data are specified in the .swp file                                                {C}
 SWBOTB = 7 !                        Switch, 7 = Free drainage of soil profile                                                      {C}
*
* Define bottom boundary soil temperature condition:
 SwBotbHea = 1!                      Switch, 1 = No heat flux;                                                                      {C}
*
* End of the main input file .SWP!
*******************************************************************************************************************************************************
```

```
******************************************************************************************************
* Filename: Tadla.015
* Contents: SWAP - Meteorological data derived through GLDAS and CHIRPS
******************************************************************************************************
* Comment area:
* 01-aug to 31-dec
******************************************************************************************************
Station DD MM YYYY RAD Tmin Tmax HUM WIND RAIN ETref WET
*       nr nr   nr kJ/m2 C C kPa m/s mm mm d
******************************************************************************************************
'Tadla' 01 08 2015 24639.0134765625 21.133691406250023 40.00368652343752 1.553866534842827 1.4810012578964233 0.000 -99.9 0.0000
'Tadla' 02 08 2015 23784.732421875 22.656854248046898 37.92705688476565 1.7986951581247446 1.9684853553771973 0.000 -99.9 0.0000
'Tadla' 03 08 2015 22589.2810546875 21.799737548828148 37.60405883789065 1.8658813113215964 2.2575345039367676 0.000 -99.9 0.0000
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'Tadla' 10 08 2015 22598.135156250002 26.206842041015648 40.86354980468752 1.537268219261745 1.9436252117156982 0.000 -99.9 0.0000
'Tadla' 11 08 2015 20082.491894531253 25.189599609375023 42.12276611328127 1.385582496261012 1.5429176092147827 1.000 -99.9 0.0000
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'Tadla' 14 08 2015 24492.456738281253 23.936639404296898 35.71502075195315 1.616640401666736 4 1.556931734085083 0.000 -99.9 0.0000
'Tadla' 15 08 2015 24513.1918945312 5 21.037927246093773 33.56655273437502 1.2492583254482503 1.843084812164306 6 0.000 -99.9 0.0000
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'Tadla' 17 08 2015 24527.7729492187 5 20.061578369140648 35.1929870605469 1.5970697603521136 1.3945013284683228 0.000 -99.9 0.0000
'Tadla' 18 08 2015 22579.667578125 20.604577636718773 31.47170410156252 3 1.8008103100461625 1.771730899810791 0.000 -99.9 0.0000
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'Tadla' 22 08 2015 24644.0891601562 5 21.904565429687523 35.45781860351565 1.7293882866486725 2.1430962085723877 0.000 -99.9 0.0000
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'Tadla' 25 08 2015 26012.232421875 17.278466796875023 35.48977050781252 1.2889882628455862 1.295765995979309 0.000 -99.9 0.0000
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'Tadla' 28 08 2015 20637.828369140625 20.930841064453148 42.36678466796877 1.444564257756833 2.0318522453308105 3.280 -99.9 0.0000
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'Tadla' 28 10 2015 14204.15947265625 13.389489746093773 25.451440429687523 1.3129033661174985 0.9314755201339722 0.000 -99.9 0.0000
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* 01-jan to 31-oct
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**********************************************************************************************************************************************************************
* Filename: Wwheat_Tadla.CRP
* Contents: Data for detailed crop model (WOFOST)
*   Winter wheat ( Tritium aestivum L.)
*   Calibrated for Tadla Morocco 2015/2016
*   author: Charlotte van der Leer, part of MSc master thesis Water Management at Delft University, September 2017
*
**********************************************************************************************************************************************************************
*
*   The crop input file .crp contains the following settings:
*            0  Irrigation and salinity
*       Corresponding steps of calibration:
*            1  Phenology
*            2  Characteristics for potential transpiration and leaf area index
*            3  Characteristics for actual transpiration and soil moisture content
*            4  Characteristics for actual biomass production and yield
*
*
*   Comment line starting with      *
*   Comment in line starting with   !
*
*   Parameters are provided with    [ range , unit , data type ]    {source}
*   Switches are provided with      {source}
*
*                       range       Range allowed by SWAP model
*                       unit        Unit assumed by SWAP model
*                       data type   Data types used by SWAP model:
*                                       I = Integer
*                                       R = Real
*                                       Ax = character string of x positions
*                                       dd = daynumber, mm = monthnumber, yy = yearnumber
*                       source      Source for used parameter or switch:
*                                       C  = Calibrated or decided upon in this research
*                                       R# = Used from Representative calibration          1 = Pagani 2013 WOFOST parameters for durum wheat in Morocco
*                                                                                          2 = WOFOST input file 'Winter wheat 107, S-Spain, S-Greece'
*                                                                                          3 = SWAP simple crop file WheatD
*                                                                                          4 = SWAP detail crop file WheatS
*                                       L  = Used from Literature
*                                       E  = Used from Expert knowledge, SEBAL analyis or fieldwork
*
*                                   When used values deviate from other used datasets (above or below) this is indicated.
*
**********************************************************************************************************************************************************************
*
*
********     crp.0      ********        IRRIGATION SCHEDULING   **********************************************************************************************************
*
***  For initial optimal scenario define irrigation by stress criterion Trel = 1.00                ***
***  Irrigation settings can be adjusted for strategy scenario simulation                          ***
***  Salt stress is used from calibration of SWAP with simple crop module, not changed for WOFOST  ***
*
* Irrigation scheduling
 SCHEDULE = 0             !           Switch,     0 = No irrigation scheduling applied,                                                    {C}
*                                                 1 = Application of irrigation scheduling
 STARTIRR = 28 11         !           Day and month after which irrigation scheduling is allowed             [dd mm]                   {C}
```

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 ENDIRR   = 22 05          !           Day and month after which irrigation scheduling is NOT allowed         [dd mm]                  {C}
 CIRRS    = 0.0            !           Solute concentration of scheduled irrig. water,                        [0..100 mg/cm3, R]       {E(Wim Bastiaanssen)}
 ISUAS    = 1              !           Switch,     0 = sprinkling irrigation, 1 = surface irrigation                                   {C}
*
* Irrigation timing criteria
 TCS      = 1              !           Switch,     0 = Daily Stress,                                                                   {C}
*                                                  2 = Depletion of Readily Available Water
*                                                  5 = Pressure head or moisture content
*
*                                      DVS_tc1   = Development stage                                          [0..2, R]                {C}
*                                      DVS_tc2   = Development stage                                          [0..2, R]                {C}
*                                      DVS_tc5   = Development stage                                          [0..2, R]                {C}
*                                      Trel      = Mimimum of ratio actual/potential transpiration            [0..1, R]                {C}
*                                      RAW       = Minimal fraction of readily available water                [0..1, R]                {C}
*                                      Value_tc5 = Critical pressure head                                     [-1.d6..-100 cm, R]      {C}
*                                                  or critical moisture content                               [0..1.0 cm3/cm3, R]      {C}
* Daily stress criterion (TCS = 1)
  DVS_tc1  Trel
      0.0  1.00
      2.0  1.00
* End of table, maximum 7 records
*
* Depletion of Readily Available Water criterion (TCS = 2)
  DVS_tc2   RAW
      0.0  0.95
      2.0  0.95
* End of table, maximum 7 records
 phFieldCapacity = -100.0  !           Soil hydraulic pressure head                                           [-1000.0 .. 0.0,cm, R]   {C}
*
* Pressure head or Moisture content criterion (TCS = 5)
  DVS_tc5  Value_tc5
      0.0    -1000.0
      2.0    -1000.0
* End of table
 PHORMC = 0                !           Switch, 0 = Use pressure head, 1 = Use soil moisture content
 DCRIT = -30.0             !           Depth of the sensor                                                    [-100..0 cm, R]          {E}
*
*
* Relation between ECsat, crop reduction and concentration
 ECMAX    =     6.0        !           ECsat level at which salt stress starts                                [0..20 dS/m, R]          {R3}
 ECSLOP   =     7.1        !           Decline of rootwater uptake above ECMAX                                [0..40 %/dS/m, R]        {R3}
 C2ECa    =     4.21       !           coefficient a to convert concentration to EC                           [0.0..1000.0 -, R]       {R3}
 C2ECb    =     0.763      !           exponent b to convert concentration to EC                              [0.0..10.0 -, R]         {R3}
 SWC2ECF =      1          !           Switch, 1 = Use one factor f for whole model profile                                            {C}
 C2ECf    =     1.7        !           Factor f to convert concentration to EC                                [0.0..10.0 -, R]         {R3}
*
*
********     crp.1     ********        CROP PHENOLOGY  ****************************************************************************************
*
*
 IDSL   =     2            !           Switch,     2 = Crop development before anthesis depends               {R1}
*                                                  on both temperature and daylength
 DLO    =   13.50          !           Optimum daylength for crop development                                 [0..24 h, R]             {R1}
 DLC    =    8.00          !           Minimum daylength                                                      [0..24 h, R]             {R1}
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 TSUMEA =   630.00        !          Temperature sum from emergence to anthesis                          [0..10000 C, R]          {C, below R1,2,3}
 TSUMAM =  1115.00        !          Temperature sum from anthesis to maturity                           [0..10000 C, R]          {C, above R1,2,3}
 DVSEND =     2.00        !          development stage at harvest                                        [-]                      {R1,2}
*
* List increase in temperature sum:
*                                    TAV     = Daily average temperature                                 [0..100 C, R]
*                                    DTSM    = Temperature sum increase temperature                      [0..60 C, R]             {R1, below R2,3}
*         TAV    DTSM
  DTSMTB =
          0.00   0.00      !
          30.0   24.5      !
          42.0   0.00      !
* End of Table, maximum 15 records
*
* For initial optimal scenario set life span of leaves at maximum to neglect death from aging:
 SPAN   =  28.00           !         Life span under leaves under optimum conditions                     [0..366 d, R]            {C, below R1,2,3}
*
*
********     crp.2     ********       CHARACTERISTICS FOR POTENTIAL TRANSPIRATION AND LEAF AREA INDEX     ***************************************************************
*
* Use of crop factor or crop height:
  SWCF = 2                 !         Switch,     2 = Crop height                                                                  {C}
*                                    DVS = Development stage                                             [0..2 -,R]
*                                    CF  = Crop factor for development stage (not used)                  [0.5..1.5, R]
*                                    CH  = Crop height CH  for development stage                         [0..1000 cm, R]          {L,C}
    DVS       CH      CF
    0.01      0.00    1.0
    0.39     20.00    1.0
    0.70     70.00    1.0
    1.01    110.00    1.0
    1.90    110.00    1.0
    2.00      1.00    1.0
* End of Table, maximum 36 records
*
* Coefficients for use of Penman-Monteith:
 ALBEDO =    0.181        !          Crop reflection coefficient                                         [0..1.0 -, R]            {E(SEBAL)}
 RSC    =   40.0          !          Minimum canopy resistance                                           [0..10^6 s/m, R]         {C}
 RSW    =    0.00         !          Canopy resistance of intercepted water                              [0..10^6 s/m, R]         {R3}
*
* Initial values:
 TDWI   =  60.00          !          Initial total crop dry weight                                       [0..10000 kg/ha]         {E(Allard de Wit)}
 LAIEM  =  0.150          !          Leaf area index at emergence                                        [0..10 m2/m2, R]         {C, below R1,2,3}
 RGRLAI =  0.006          !          Maximum relative increase in LAI                                    [0..1 m2/m2/d, R]        {C, between R1 and R2,3}
*
* Green surface area:                DVS = Development stage                                             [0..2 -,R]
*                                    SLA = Specific leaf area for development stage                      [0..1 ha/kg, R]          {C, above R1,2,3}
*        DVS   SLA
  SLATB =
         0.00 0.0047
         1.00 0.0009
* End of Table, maximum 15 records
*
 SPA    =  0.0000         !          Specific pod area                                                   [0..1 ha/kg, R]          {R2,3}
 SSA    =  0.0000         !          Specific stem area                                                  [0..1 ha/kg, R]          {R1,2,3}
```

```
 TBASE  =  0.0000          !           Lower threshold temperature for ageing of leaves                     [-10..30 C, R]             {R1,2,3}
*
 COFAB  =  0.5             !           Interception coefficient Von Hoyningen-Hune and Braden               [0..1 cm, R]               {E(Wim Bastiaanssen), above R3
*
* Light use:
 KDIF   =    0.72          !           Extinction coefficient for diffuse visible light                     [0..2 -, R]                {C, above R1,2,3}
 KDIR   =    0.80          !           Extinction coefficient for direct visible light                      [0..2 -, R]                {C, above R3}
 EFF    =    0.45          !           Light use efficiency for real leaf                                   [0..10 kg/ha/hr/(Jm2s)]    {R2,3}
*
* CO2 assimiliation:                   DVS  = Development stage                                             [0..2 -,R]
*                                      TAVD = Average day temperature                                       [-10..50 C, R]
*                                      TMNR = Minimum day temperature                                       [-10..50 C, R]
*                                      AMAX = Maximum CO2 assimilation rate for development stage           [0..100 kg/ha/hr, R]       {C, below R1,2,3}
*                                      TMPF = Reduction factor of AMAX for average day temperature          [-, R]                     {R2,3}
*                                      TMNF = Reduction factor of AMAX for minimum day temperature          [-, R]                     {R2,3}
*          DVS    AMAX
  AMAXTB =
           0.39  13.000
           0.50  21.000
* End of table, maximum 15 records
*
*          TAVD   TMPF
  TMPFTB =
           0.00  0.000
          10.00  0.600
          15.00  1.000
          29.00  1.000
          34.00  1.000
* End of table, maximum 15 records
*
*          TMNR    TMNF
  TMNFTB =
           0.00  0.000
           3.00  1.000
* End of table, maximum 15 records
*
*
********     crp.3      ********       CHARACTERISTICS FOR ACTUAL TRANSPIRATION AND SOIL MOISTURE  **********************************************************************
*
* Death rates:
 PERDL =   0.030            !          Maximum rel. death rate of leaves due to water stress                [0..3 /d, R]               {R2,3 above R1}
*                                              DVS  = Development stage                                     [0..2 -,R]
*                                              RDRR = Relative death rates of roots for development stage   [kg/kg/d]                  {R2,3}
*                                              RDRS = relative death rates of stems for development stage   [kg/kg/d]                  {R2,3}
*          DVS    RDRR
  RDRRTB =
          0.0000 0.0000
          1.5000 0.0000
          1.5001 0.0200
          2.0000 0.0200
* End of table, maximum 15 records
*
*          DVS     RDRS
  RDRSTB =
```

```
          0.0000 0.0000
          1.5000 0.0000
          1.5001 0.0200
          2.0000 0.0200
* End of table, maximum 15 records
*
* Efficiencies of conversion of assimilates into biomass:
 CVL    =  0.6950          !          Efficiency of conversion into leaves                        [0..1 kg/kg, R]          {C above R1,2,3}
 CVO    =  0.7090          !          Efficiency of conversion into storage organs                [0..1 kg/kg, R]          {R2,3 below R1}
 CVR    =  0.6940          !          Efficiency of conversion into roots                         [0..1 kg/kg, R]          {R1,2,3}
 CVS    =  0.7620          !          Efficiency of conversion into stems                         [0..1 kg/kg, R]          {C, above R1,2,3}
*
* Root water extraction
 swroottyp =      1        !          Switch,     1 = Method of De Jong van Lier et al. 2006                               {R4}
*                                                 for type of root water extraction computation
 HLIM1     =      0.0      !          No water extraction at higher pressure heads                [-100..100 cm, R]        {R4}
 HLIM2U    =    -30.0      !          h below which optimum water extr. starts for top layer      [-1000..100 cm, R]       {R4}
 HLIM2L    =    -30.0      !          h below which optimum water extr. starts for sub layer      [-1000..100 cm, R]       {R4}
 HLIM3H    =   -400.0      !          h below which water uptake red. starts at high Tpot         [-10000..100 cm, R]      {R4}
 HLIM3L    =   -900.0      !          h below which water uptake red. starts at low Tpot          [-10000..100 cm, R]      {R4}
 HLIM4     = -16000.0      !          No water extraction at lower pressure heads                 [-16000..100 cm, R]      {R4}
 ADCRH     =      0.7      !          Level of high atmospheric demand                            [0..5 cm/d, R]           {R4}
 ADCRL     =      0.1      !          Level of low atmospheric demand                             [0..5 cm/d, R]           {R4}
*
* Root density distribution and root growth
*                                     RD  = Relative rooting depth                                [0..1 -, R]              {R3}
*                                     RDC = Relative root density                                 [0..1 -, R]              {R3}
*          RD      RDC
  RDCTB =
           0.00    1.00
           1.00    1.00
* End of table, maximum 11 records
*
 RDI    =   10.00          !          Initial rooting depth                                       [0..1000 cm, R]          {R2,3}
 RRI    =    1.20          !          Maximum daily increase in rooting depth                     [0..100 cm/d, R]         {R1,2,3}
 RDC    =   80.00          !          Maximum rooting depth crop/cultivar                         [0..1000 cm, R]          {E(Wim Bastiaanssen)}
*
*
********     crp.4     ********       CHARACTERISTICS FOR ACTUAL BIOMASS PRODUCTION AND YIELD ****************************************************************************
*
* Maintenance respiration
 Q10    =  2.0000          !          Rel. increase in respiration rate with temperature          [0..5 /10 C, R]          {R2,3 below R1}
 RML    =  0.0300          !          Rel. maintenance respiration rate of leaves                 [0..1 kgCH2O/kg/d, R]    {R2,3 below R1}
 RMO    =  0.0100          !          Rel. maintenance respiration rate of storage organs         [0..1 kgCH2O/kg/d, R]    {R1,2,3}
 RMR    =  0.0150          !          Rel. maintenance respiration rate of roots                  [0..1 kgCH2O/kg/d, R]    {R1,2,3}
 RMS    =  0.0150          !          Rel. maintenance respiration rate of stems                  [0..1 kgCH2O/kg/d, R]    {R2,3 above R1}
*
* Reduction of senescence:            DVS  = Development stage                                    [0..2 -,R]
*                                     RFSE = Reduction factor of senescence                       [-, R]                   {C, below R2,3}
*          DVS     RFSE
  RFSETB =
           0.00    1.00
           0.95    1.00
           1.05    0.80
```

```
        2.00   0.50
* End of table, maximum 15 records
*
* Partitioning of biomass:
*                                   DVS = Development stage                                       [0..2 -,R]
*                                   FR  = Fraction of total dry matter increase partitioned to the roots    [kg/kg, R]          {R1,2,3}
*                                   Fraction of total above ground dry matter increase partitioned to ...
*                                       FL  = ... the leaves                                      [kg/kg, R]          {C, above R1,2,3}
*                                       FS  = ... the stems                                       [kg/kg, R]          {C, below R1,2,3}
*                                       FO  = ... the storage organs                              [kg/kg, R]          {C, below R1,2,3}
*         DVS     FR
  FRTB =
        0.00   0.50
        0.10   0.50
        0.20   0.40
        0.35   0.22
        0.40   0.17
        0.50   0.13
        0.70   0.07
        0.90   0.03
        1.20   0.00
        2.00   0.00
* End of table, maximum 15 records
*
*         DVS     FL
  FLTB =
        0.00   0.65
        0.10   0.65
        0.25   0.70
        0.50   0.50
        0.70   0.25
        0.95   0.25
        1.05   0.25
        1.95   0.25
        2.00   0.25
* End of table, maximum 15 records
*
*         DVS    FS
  FSTB =
        0.00   0.35
        0.10   0.35
        0.25   0.30
        0.50   0.50
        0.70   0.75
        0.95   0.75
        1.05   0.20
        1.95   0.00
        2.00   0.00
* End of table, maximum 15 records
*
*         DVS    FO
  FOTB =
        0.00   0.00
        0.95   0.00
        1.05   0.55
        1.95   0.75
        2.00   0.75
* End of table, maximum 15 records
*
* End of the crop input file .CRP!
**********************************************************************************************************************************************************
```

K

Survey design: Evaluation of observed strategies and indicators by key actors in efficient water use at the agricultural field

In the following pages, the developed web survey is included.

Efficient Water Use at the Agricultural Field

Welcome to the online survey on efficient water use in agriculture!

Thank you for participating in this survey, contributing to a MSc thesis project at Delft University of Technology, the Netherlands.

This survey requires about 20 minutes of your time. Please complete the survey before Monday October 15th.

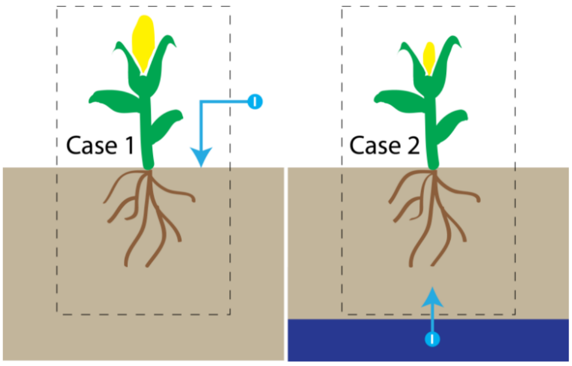
Irrigated agriculture around the world uses more than 70% of the available fresh water. Since food demand rises against water availability, food security is endangered. Water use at the agricultural field needs to become more efficient.

What is efficient water use? How can it be improved?

These two questions are asked for two different fields. Both fields receive about the same amount of rainfall and apply the same amount of irrigation. The crops are healthy and not threatened by salt. Both fields are part of a system, when water is not applied at the field it is available for other users.

Case 1 is located in a mountainous region with a deep ground water table. The field is irrigated by gravity from a field inlet. Harvested yield is normal.

Case 2 is located in a coastal region with a shallow ground water table. The field is irrigated sub-surface by management of the ground water level. Harvested yield is low.



The survey includes 10 questions. Please click 'Next page' to start!

OK

Next page

Personal

Please provide your details. Your name and company will only be used in a list of participants. They will not be linked to your responses on the following pages.

OK

* 1. Initials and last name: *(example: M.E. Smith)*

* 2. Function, company: *(example: Researcher, TU Delft)*

* 3. Country of residence: (example: the Netherlands)

* 4. At what level are you involved in agricultural water use and/or in the discussion on efficient water use in agriculture? (select best fit)

- Practice
- Research
- Policy
- I am not involved

Previous page | Next page

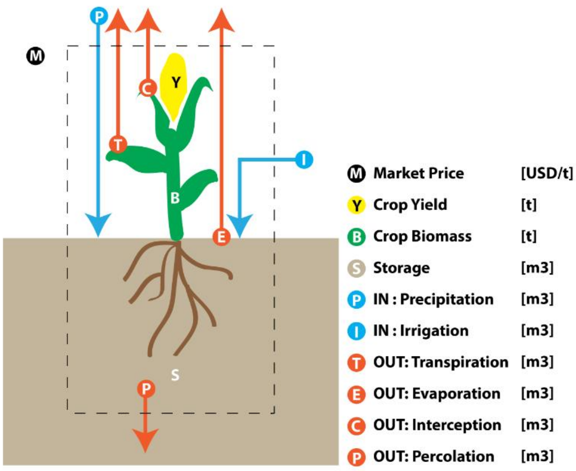
Efficient water use in Case 1

Case 1 has a deep ground water table and is irrigated from a field inlet.

The field is observed for a single growing season, from sowing to harvest. This single field for a single growing season can be seen as a system. This is visualized in a side view, its boundaries indicated with a dotted line.

In this system, biomass (B) and yield (Y) are produced. The yield is sold for a market price (M). In the soil, water is stored (S). Water inflows and outflows are observed. Into the system: precipitation/rainfall (P) and irrigation (I). Out from the system: crop transpiration (T), soil evaporation (E), crop interception (C) and percolation to the ground water (P). Horizontal flows like runon or drainage are not observed. The flows visualized with arrows are the total water volumes that have entered or left the field within the growing season.

The field is part of an irrigation scheme. Water that is not applied in irrigation (I) is available for other users.



The following two question correspond to this case.

OK

* 5. *What is efficient water use?*

This is defined by an indicator. When the indicator increases, improvement takes place.

Illustrated by an example in sports: *distance traveled per time* can be an indicator for sport performance. This indicator increases when the athlete runs a larger distance in the same time, or the same distance in less time.

Unlike in sports, concerning efficient water use in agriculture there is not a single clear-cut indicator. Multiple definitions are used by people involved in the issue.

What do you consider relevant indicators?

The field receives water from both irrigation and rainfall. Some indicators concern the effect of the irrigation water only. In this case, the field is also observed for the rain-fed situation. Elements used from this situation have the subscript 'rf'. For example, Y_rf is the yield that would have been produced if the field was not irrigated. To define the yield produced by the irrigation water specifically, Y_rf is subtracted from Y.

Please let us know what you think about the potential relevance of the 13 indicators below.

	Most Relevant	Relevant	Not Relevant	Misleading	Unclear
Indicator 1: Gross Added Value (YxM) per applied water (I) [USD/m3] $\frac{Y \times M}{I}$	○	○	○	○	○
Indicator 2: Yield from applied water (Y - Yrf) per consumed applied water (ET - ETrf) $\frac{Y - Y_{rf}}{E + T - (E_{rf} + T_{rf})}$	●	○	○	○	○
Indicator 3: Crop consumption of applied water (T - Trf) per applied water (I) $\frac{T - T_{rf}}{I}$	○	○	○	○	○
Indicator 4: Crop water requirement to avoid water stress (ETp - (P - Erf - Prf)) per applied water (I) $\frac{E_{pot} + T_{pot} - (P - E_{rf} - P_{rf})}{I}$	○	○	○	○	○

Indicator 5: Biomass production (B) per transpiration (T) $\frac{B}{T}$	○	○	○	○	○
Indicator 6: Biomass production (B) per applied water (I) $\frac{B}{I}$	○	○	○	○	○
Indicator 7: Beneficially used applied water (T - Trf) per non-stored applied water (I - (S - Srf)) $\frac{T - T_{rf}}{I - (S - S_{rf})}$	○	○	○	○	○
Indicator 8: Yield (Y) per applied water (I) $\frac{Y}{I}$	○	○	○	○	○
Indicator 9: Yield (Y) per water input (P + I) $\frac{Y}{P + I}$	○	○	○	○	○
Indicator 10: Yield (Y) per depleted water (E + T + P) $\frac{Y}{E + T + P}$	○	○	○	○	○
Indicator 11: Yield (Y) per water depleted for the intended process (T) $\frac{Y}{T}$	○	○	○	○	○
Indicator 12: Applied water saved (-I) $-I$	○	○	○	○	○
Indicator 13: Yield produced (Y) Y	○	○	○	○	○

OK

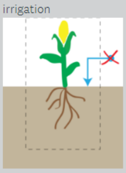
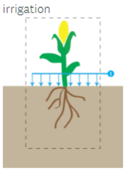
* 6. *How can efficient water use be improved?*

Improvement is obtained by a strategy.

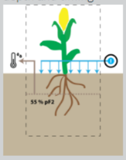
Illustrated by the example in sports: *optimal shoe quality* is a strategy for better sport performance. Without the strategy, performance of the 'baseline scenario' with the old shoes is observed. With the strategy, performance of the 'strategy scenario' with the old shoes is observed.

In this question, the baseline scenario is the field from Case 1. The field is irrigated from a field inlet. The ground water table is deep and the harvested yield is normal. Multiple strategies can be applied. Efficient water use improves when the indicator (see previous question) for the strategy scenario is larger than for the baseline scenario.
What do you consider effective strategies to obtain this improvement?

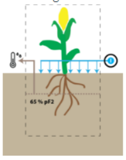
Please let us know what you think about the potential effectiveness of the 10 strategies below.

	Most Effective	Effective	Not Effective	Counter-effective	Unclear
Strategy 1: Eliminate irrigation 					
strategy 2: Sprinkler irrigation 					

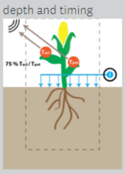
strategy 3: Using sensor data, regulate moderate soil water deficit by irrigation depth and timing



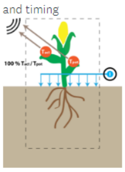
strategy 4: Using sensor data, regulate mild soil water deficit by irrigation depth and timing



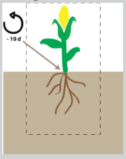
strategy 5: Using sensor data, regulate transpiration deficit by irrigation depth and timing



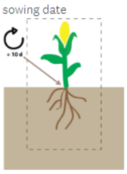
strategy 6: Using sensor data, regulate transpiration optimum by irrigation depth and timing



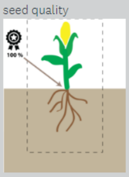
strategy 7: Advance sowing date



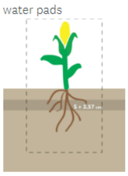
strategy 8: Postpone sowing date



strategy 9: Optimum seed quality



strategy 10: Increase soil water retention capacity in root zone, e.g. by using polymere water pads



Previous page Next page

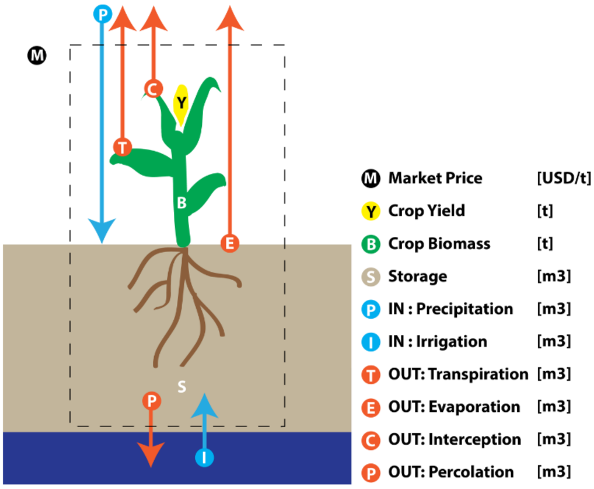
Efficient water use in Case 2

Case 2 has a shallow ground water table and is irrigated sub-surface by management of the ground water level

The field is observed for a single growing season, from sowing to harvest. This single field for a single growing season can be seen as a system. This is visualized below in a side view, its boundaries indicated with a dotted line.

Similar to Case 1, in this system biomass (B) and yield (Y) are produced. The yield is sold for a market price (M). In the soil, water is stored (S). Water inflows and outflows are observed. Into the system: precipitation/rainfall (P) and irrigation (I). Out from the system: crop transpiration (T), soil evaporation (E), crop interception (C) and percolation to the ground water (P). Horizontal flows like runon or drainage are not observed. The flows visualized with arrows are the total water volumes that have entered or left the field within the growing season.

The field is part of an irrigation/drainage scheme. Water that is not applied in irrigation (I) is available for other users.



The following two questions concern Case 2. The questions are identical to those corresponding to Case 1.

OK

* 7. *What is efficient water use?*

This is defined by an indicator. When the indicator increases, improvement takes place.

Illustrated by an example in sports: *distance traveled per time* can be an indicator for sport performance. This indicator increases when the athlete runs a larger distance in the same time, or the same distance in less time.

Unlike in sports, concerning efficient water use in agriculture there is not a single clear-cut indicator. Multiple definitions are used by people involved in the issue.

What do you consider relevant indicators?

The field receives water from both irrigation and rainfall. Some indicators concern the effect of the irrigation water only. In this case, the field is also observed for the rain-fed situation. Elements used from this situation have the subscript 'rf'. For example, Y_rf is the yield that would have been produced if the field was not irrigated. To define the yield produced by the irrigation water specifically, Y_rf is subtracted from Y.

Please let us know what you think about the potential relevance of the 13 indicators below. All indicators used for Case 1 are available.

	Most Relevant	Relevant	Not Relevant	Misleading	Unclear
Indicator 1: Gross Added Value (YxM) per applied water (I) [USD/m3] $\frac{Y \times M}{I}$	○	○	○	○	○
Indicator 2: Yield from applied water (Y - Yrf) per consumed applied water (ET - ETrf) $\frac{Y - Y_{rf}}{E + T - (E_{rf} + T_{rf})}$	○	○	○	○	○
Indicator 3: Crop consumption of applied water (T - Trf) per applied water (I) $\frac{T - T_{rf}}{I}$	○	○	○	○	○

Indicator 4: Crop water requirement to avoid water stress (ETp - (P - Erf - Prf)) per applied water (I)

$$\frac{E_{pot} + T_{pot} - (P - E_{rf} - P_{rf})}{I}$$

Indicator 5: Biomass production (B) per transpiration (T)

$$\frac{B}{T}$$

Indicator 6: Biomass production (B) per applied water (I)

$$\frac{B}{I}$$

Indicator 7: Beneficially used applied water (T - Trf) per non-stored applied water (I - (S - Srf))

$$\frac{T - T_{rf}}{I - (S - S_{rf})}$$

Indicator 8: Yield (Y) per applied water (I)

$$\frac{Y}{I}$$

Indicator 9: Yield (Y) per water input (P + I)

$$\frac{Y}{P + I}$$

Indicator 10: Yield (Y) per depleted water (E + T + P)

$$\frac{Y}{E + T + P}$$

Indicator 11: Yield (Y) per water depleted for the intended process (T) $\frac{Y}{T}$					
Indicator 12: Applied water saved (-I) $-I$					
Indicator 13: Yield produced (Y) Y					

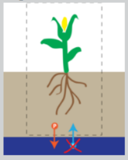
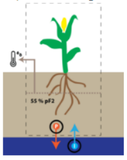
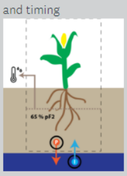
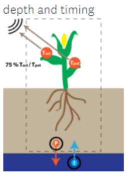
* 8. *How can efficient water use be improved?*

Improvement is obtained by a strategy.

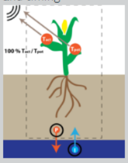
Illustrated by the example in sports: *optimal shoe quality* is a strategy for better sport performance. Without the strategy, performance of the 'baseline scenario' with the old shoes is observed. With the strategy, performance of the 'strategy scenario' with the old shoes is observed.

In this question, the baseline scenario is the field from Case 2. The is field irrigated by management of the ground water table and the harvested yield is low. Multiple strategies can be applied. Efficient water use improves when the indicator (see previous question) for the strategy scenario is larger than for the baseline scenario.
What do you consider effective strategies to obtain this improvement?

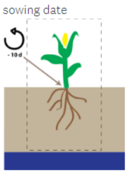
Please let us know what you think about the potential effectiveness of the 9 strategies below. Apart from sprinkler irrigation which does not apply, all strategies used for Case 1 are available.

	Most Effective	Effective	Not Effective	Counter-effective	Unclear
Strategy 1: Eliminate irrigation 					
strategy 3: Using sensor data, regulate moderate soil water deficit by irrigation depth and timing 					
strategy 4: Using sensor data, regulate mild soil water deficit by irrigation depth and timing 					
strategy 5: Using sensor data, regulate transpiration deficit by irrigation depth and timing 					

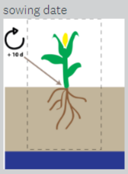
strategy 6: Using sensor data, regulate transpiration optimum by irrigation depth and timing



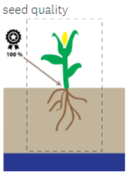
strategy 7: Advance sowing date



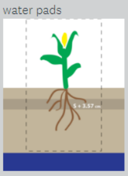
strategy 8: Postpone sowing date



strategy 9: Optimum seed quality



strategy 10: Increase soil water retention capacity in root zone, e.g. by using polymere water pads



Previous page

Next page

Efficient water use in General

Thank you for evaluating the different indicators and strategy for the two cases!

In many areas and agricultural fields, improvement of efficient water use is desired.

The **final two questions** concern not a specific case but these agricultural fields in general.

OK

* 9. What do you consider the single **most relevant indicator** for efficient water use at the agricultural field?

Indicator 1: Gross Added Value (YxM) per applied water (I) [USD/m3]
Indicator 2: Yield from applied water (Y - Yrf) per consumed applied water (ET - ETrf)
Indicator 3: Crop consumption of applied water (T - Trf) per applied water (I)
Indicator 4: Crop water requirement to avoid water stress (ETp - (P - Erf - Prf)) per applied water (I)
Indicator 5: Biomass production (B) per transpiration (T)
Indicator 6: Biomass production (B) per applied water (I)
Indicator 7: Beneficially used applied water (T - Trf) per non-stored applied water (I - (S - Srf))
Indicator 8: Yield (Y) per applied water (I)
Indicator 9: Yield (Y) per water input (P + I)
Indicator 10: Yield (Y) per depleted water (E + T + P)
Indicator 11: Yield (Y) per water depleted for the intended process (T)
Indicator 12: Applied water saved (-I)
Indicator 13: Yield produced (Y)

* 10. What do you consider the single **most effective strategy** for improvement of efficient water use at the agricultural field?

strategy 1: Eliminate irrigation
strategy 2: Sprinkler irrigation
strategy 3: Using sensor data, regulate moderate soil water deficit by irrigation depth and timing
strategy 4: Using sensor data, regulate mild soil water deficit by irrigation depth and timing
strategy 5: Using sensor data, regulate transpiration deficit by irrigation depth and timing
strategy 6: Using sensor data, regulate transpiration optimum by irrigation depth and timing
strategy 7: Advance sowing date
strategy 8: Postpone sowing date
strategy 9: Optimum seed quality
strategy 10: Increase soil water retention capacity in root zone, e.g. by using polymere water pads

Previous page Next page

Thank you so much for completing this survey!

Your participation is an important contribution to a MSc thesis project on efficient water use in agriculture, at Delft University of Technology, the Netherlands.

If you want to be informed on the results of this project, please send an e-mail to the following address:

c.t.groen@student.tudelft.nl

OK

Previous page Gereed

L

Survey participants: Evaluation of observed strategies and indicators by key actors in efficient water use at the agricultural field

List of participants personal information from online survey. A total of 25 persons participated between October 6^{th} and November 2^{nd} 2017. Responses where no questions were answered have been removed and are not included in the list below. Completion rate is 80%, typical time spent is 27 mins.

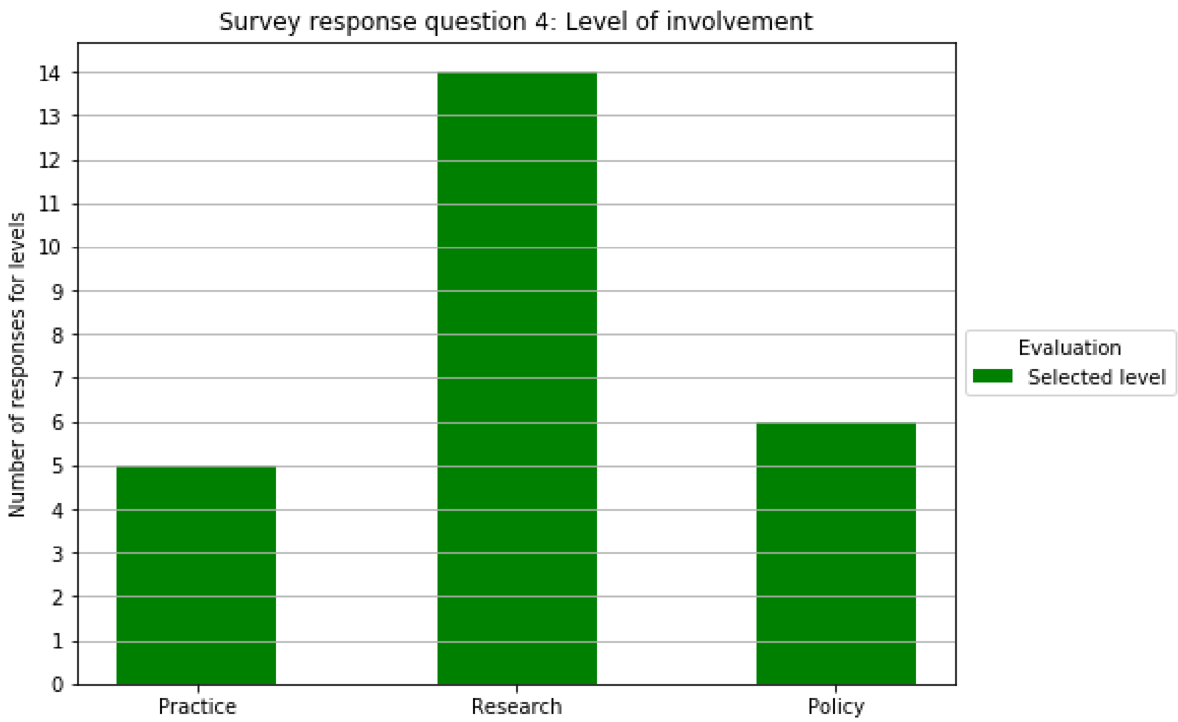
Table L.1: List of participants in online survey

Name	**Function, Company**	**Country**	**Level**
G. Simons	Hydrologist, FutureWater	the Netherlands	Research
C. Eladio	Extension officer	Mozambique	Practice
N.I. den Besten	Field manager/ hydrologist	Mozambique	Research
W.G.M. Bastiaanssen	UNESCO - IHE	the Netherlands	Research
A. Zoric	n.a.	the Netherlands	Research
P.A.G. Hassing	Consultant	the Netherlands	Policy
C.J. Tsimpho	Irrigation and drainage Dpto, RBL, Gaza-Mozambique	Mozambique	Practice
P. Raatjes	director, RMA	the Netherlands	Practice
I. Supit	Researcher WUR	the Netherlands	Research
G.E. Espinoza Davalos	Researcher, IHE Delft	the Netherlands	Research
T. Hessels	Researcher	the Netherlands	Research
K. W. van Krieken	Consultant, Embassy of the Kingdom of the Netherlands	Mozambique	Policy
S. Chevalking	Programme manager	the Netherlands	Practice
X. Cai	Researcher, IHE	the Netherlands	Research
C. Graveland	Researcher UN-SEEA - Environmental Accounts	the Netherlands	Research
J.C. van Dam	Researcher, Wageningen UR	the Netherlands	Research
A.J. Keizer	Consultant	the Netherlands	Practice
J.R. Goldberg	Consultant, retiree, World Bank	U.S.A.	Policy
T. vd Horst	Researcher, unemployed	the Netherlands	Research
J. Merks	Researcher TU Delft	the Netherlands	Research
F.P. Vaille	Intern, IHE-DELFT	the Netherlands	Research
J.D. van Opstal	Researcher, IHE	the Netherlands	Research
J. Hoogeveen	FAO	Italy	Policy
C.J. Perry	Researcher	UK	Research
L.Peiser	Technical officer, FAO	Italy	Policy

M

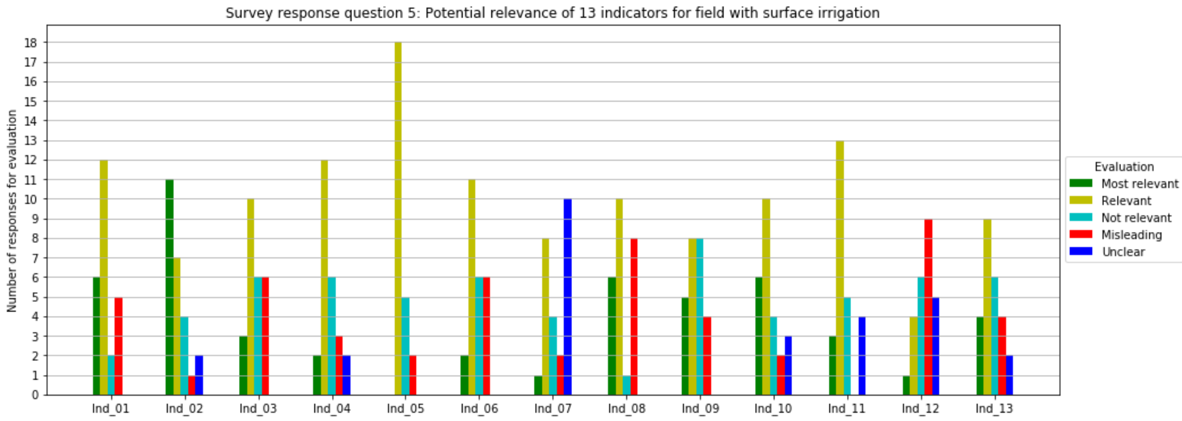
Survey results: Evaluation of observed strategies and indicators by key actors in efficient water use at the agricultural field

An on-line survey is designed to observe the evaluation of the observed strategies and indicators by key actors involved at different levels in (the discussion on) efficient water use in agriculture. The following graphs visualize the responses to questions 4-10. Questions 1-3 concern personalities of the survey participants. A total of 25 participants responded to the survey.

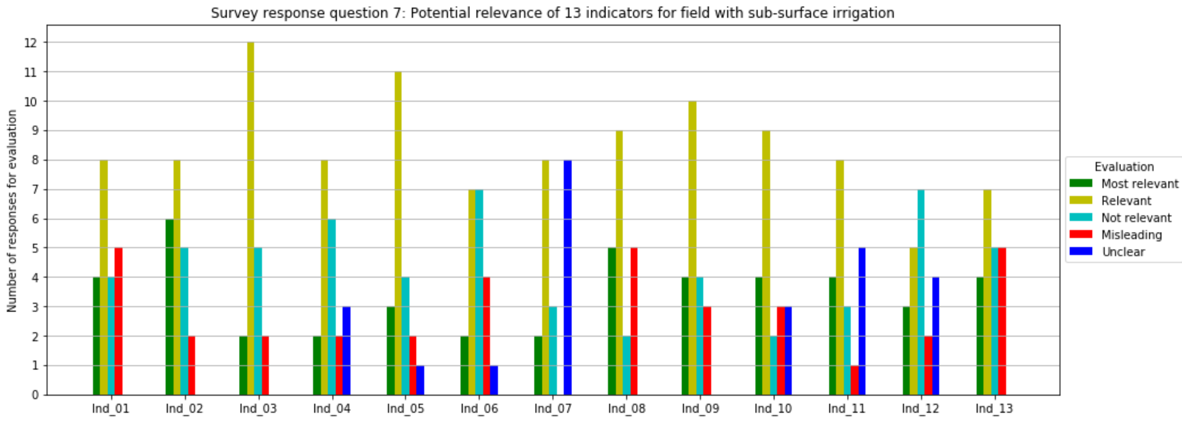


(a)

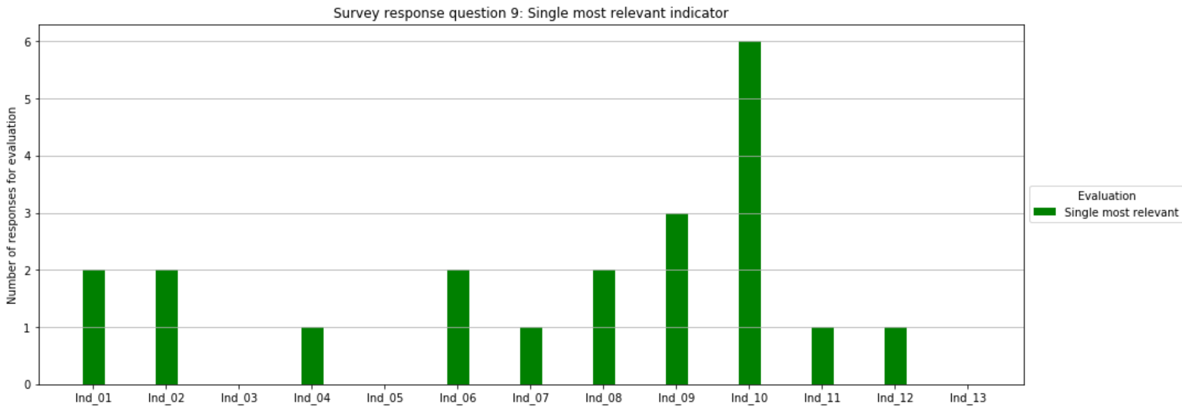
Fig. M.1: Responses to on-line survey question 4. Level of involvement in (the discussion on) efficient water use in agriculture.



(a)

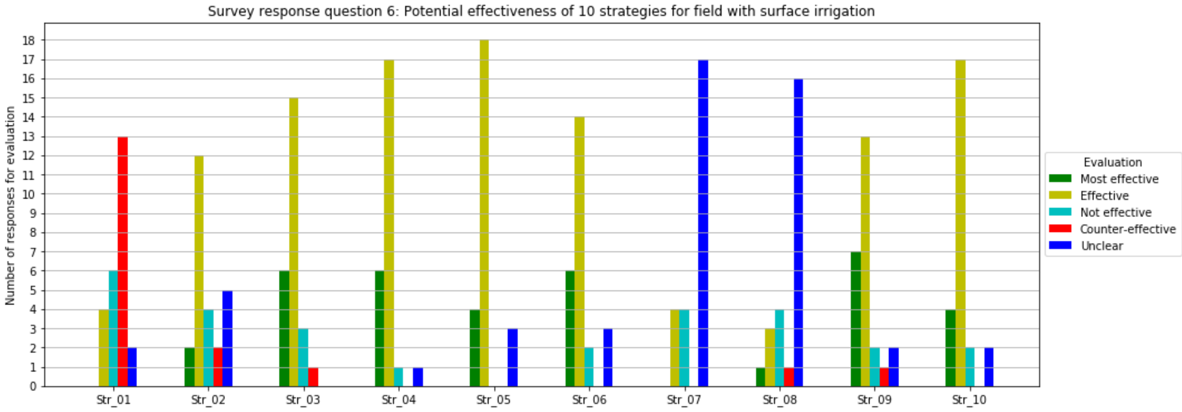


(b)

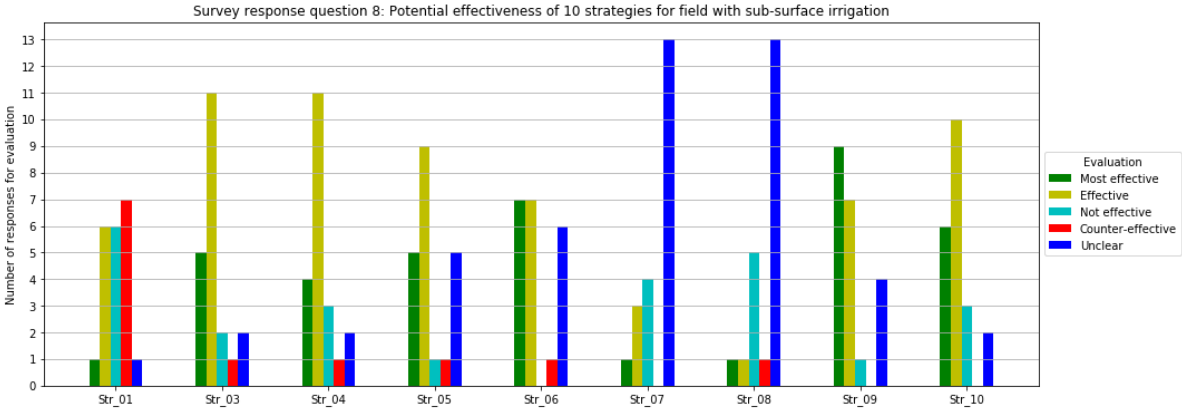


(c)

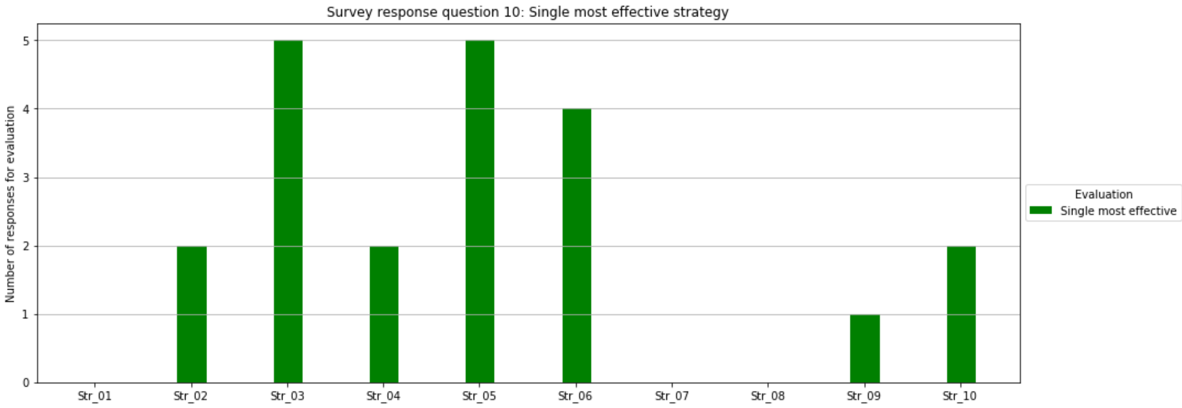
Fig. M.2: Responses to on-line survey questions 5,7 and 9 concerning indicators to quantify efficient water use. (a) Evaluation of relevance of 13 indicators for Case 1 with surface irrigation. (b) Evaluation of relevance of 13 indicators for Case 2 with sub surface irrigation. (c) Choice of single most relevant indicator in general.



(a)



(b)



(c)

Fig. M.3: Responses to on-line survey questions 6, 8 and 10 concerning strategies to improve efficient water use. (a) Evaluation of effectiveness of 10 strategies for Case 1 with surface irrigation. (b) Evaluation of effectiveness of 10 strategies for Case 2 with sub surface irrigation. (c) Choice of single most effective strategy in general.