Possibilities To Detect Supplementary Irrigation In Polder Areas With Remote Sensing

Geomatics MSc Thesis

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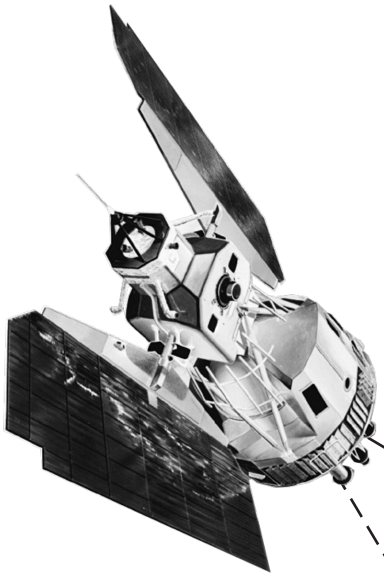

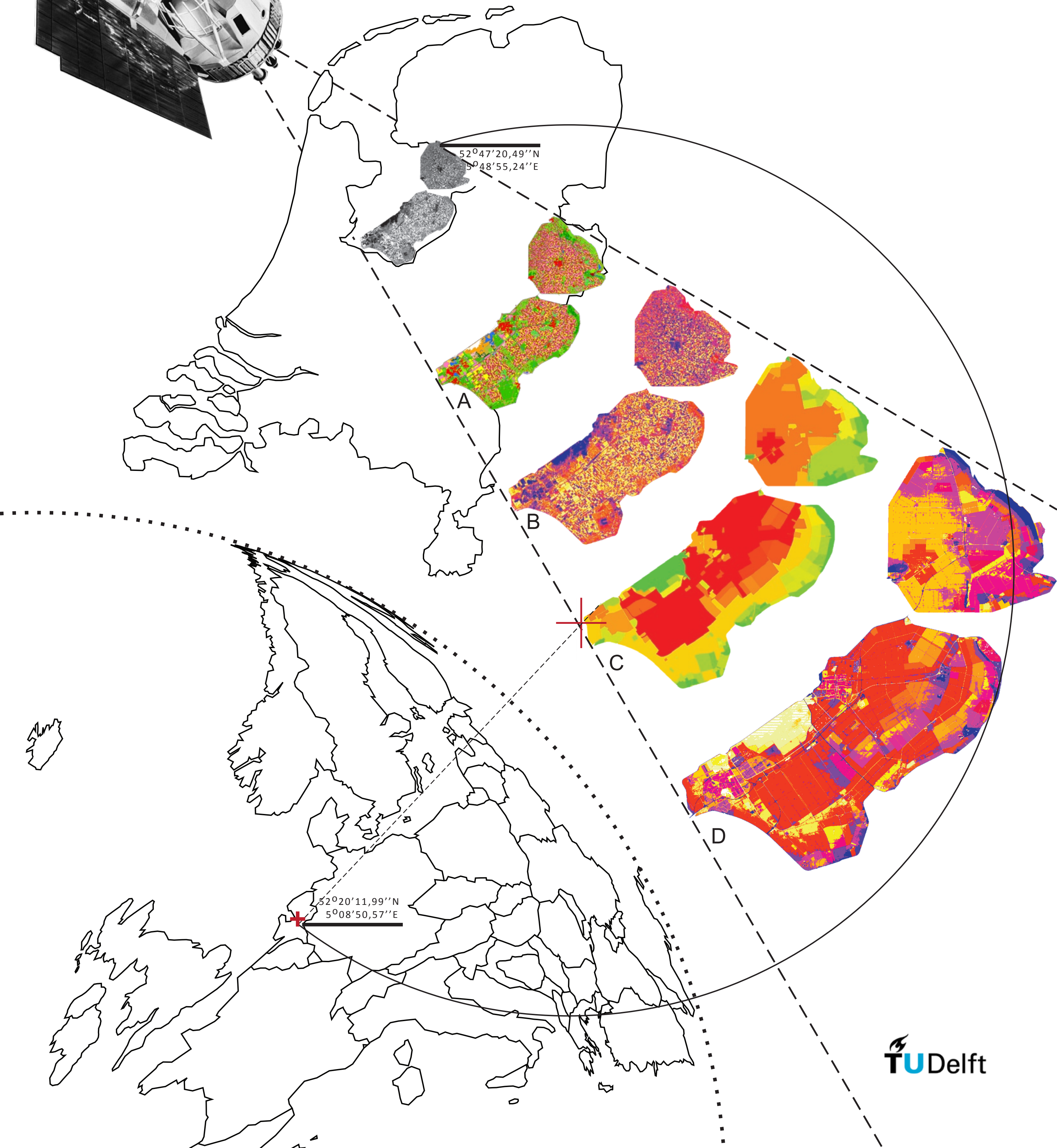

TU Delft

Possibilities to Detect Supplementary Irrigation in Polder Areas With Remote Sensing

A Flevoland Polders case study

Geomatics MSc Thesis

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Delft, June 2008

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Preface

This is my MSc thesis report. The MSc thesis is credited for 45 ECTS points and forms the final part of the master Geomatics. The duration of the MSc Geomatics is two academic years (120 ECTS). My graduation project was accomplished on the Water Resources department, of the faculty of Civil Engineering which hosted me for the past eight months while I was doing my research. At this point I would like to thank every involved individual from Water Resources who supported me during my thesis.

I started my thesis in early November 2007, with the idea of applying my Geomatics background to a topic relevant to water resources management. Professors Nick van de Giesen and Wim Bastiaanssen with their valuable support and willingness helped me to transform this idea into an interesting and challenging topic.

From the beginning my ambition was to undertake an application of remote sensing. On the same time water resources sounded an excellent field where remote sensing could be applied and potentially reveal new possibilities. The initial idea for Flevoland was triggered by Olivier Hoes, whom I truly thank for his support, when he mentioned to me the problem in the area. Polder areas are special environments with water being the dominant feature. On the same time water and irrigation managers of the area do not have any specific information of when, where or how many farmers actually do irrigate. They realize that this situation has to be changed; by getting more insight on irrigation they could manage water resources more effectively.

Data availability was from the beginning an important issue since I needed a great number of relevant datasets. At this point I would like to express my gratitude to Professor Wim Bastiaanssen and his company WaterWatch who provided me with all the necessary means (data) for the research. They also introduced me to Flevoland region and its particular conditions which I was ignorant before. In addition Olivier Hoes also provided me with some data.

Furthermore I thank my graduation committee. Each member was very helpful and cooperative throughout the completion of my thesis. At almost any given moment I could come by their office to discuss a matter I was interesting.

I wish you a pleasant reading.

Nick Madentzoglou

Delft, June 2008

Abstract

Whenever a piece of land is reclaimed for some reasons it becomes a polder. Polder areas by definition lie below the mean sea level and constitute special environments with respect to the prevailed wet conditions. In Netherlands, where the biggest part of the country is below the mean sea level, polders are common features of topography. Three typical polders are Southern & Eastern Flevoland and the Northern polder. They have been established for more than five decades now and they are well-known for their agricultural character.

Whenever we refer to agriculture or crops cultivation we always imply irrigation activities. Nevertheless, this implication is not fully true for polders, where many crops like sugar beets, maize, wheat etc. are never irrigated. On the other hand plants like flower bulbs and potatoes sometimes they are irrigated and sometimes not. It remains therefore a mystery, for water authorities which farmers actually irrigate and which not given that water consumption from irrigation is a crucial parameter for the management of water resources in the area. Therefore the main objective of the study is to locate farmers who irrigate (for a certain period) and to estimate this amount of water.

Remote sensing is a powerful tool which has the potential to provide reliable and accurate water related information at a wide range of spatial (0.5-5000 m) and temporal resolutions (0.5-24 days). This information is essential for policy makers, consultants, water and irrigation managers as for public authorities. It becomes therefore challenging to investigate the potentiality of detecting irrigation with remote sensing. The growth of GIS has greatly enhanced the opportunity to integrate conventional and remote sensing data and the current research attempts to fully exploit it. In order to accomplish that, various data were selected ranging from remotely sensed e.g. ET_{act}, ET_{pot}, biomass production, land use to other water related data like seepage, precipitation, elevation and the water level maintained in polders' canals.

The research took place on 1995 which was a relatively dry year. From the land use map of the area potatoes, flower bulbs, orchards and other arable crops were selected for irrigation's investigation. These crop types are evidently irrigated and also for June 1995 presented particularly different soil wetness levels. For the assessment of soil's moisture state, ET_{def} was used as an indicator. The proposed method consists of two steps. First step involved the identification of wet and dry plots based only on satellite data (ET_{def}). Certain ET_{def} thresholds were drawn in order to facilitate that distinction. Following dry plots were discarded and the analysis was carried with wet ones.

Second step involved the identification of soil's wetness sources. The potential sources which allow a plot to appear wet are: precipitation, seepage, soil moisture (depending on soil type), the water level maintained in canals and finally irrigation. The impact of each source was assessed for every individual (wet) plot and in cases where this was

negligible wetness was attributed to irrigation, otherwise not. This process resulted in a final irrigation map, consisting of 9 distinct classes ranging from potentially irrigated to non-irrigated plots. Moreover the volume of water which was used for irrigation was calculated for each plot separately. Findings revealed that on the 25th of June 37.2% of potatoes, 51.3% of flower bulbs, 44% of orchards and 37.1% of other arable crops were irrigated by farmers. The total amount of water used for irrigation was approximately 184229 m^3 day^{-1} ha^{-1}.

Unfortunately validation of the results was possible only qualitatively since no relevant field data were available for comparison. Interviews with local water managers revealed that final irrigation maps depict reality accurately and describe the situation very close to actual conditions. Overall the objectives of the study were accomplished and from now on polders' irrigation is no longer a mystery.

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List of acronyms

AHN	Actual Height Netherlands
ASTER	Advanced Spaceborne Thermal Emission & Reflection Radiometer
APAR	Absorbed Photosynthetic Active Radiation
GIS	Geographical Information Systems
KNMI	Royal Dutch Meteorological Institute
LGN	Land Use (map) Netherlands
LIDAR	Light Detection And Ranging
MODIS	Moderate Resolution Imagining Spectro-Radiometer
NAP	Mean Sea Level (in the North Sea)
NDVI	Normalized Difference Vegetation Index
NOAA-AVHRR	National Oceanic & Atmospheric Administration – Advanced Very High Resolution Radiometer
PAR	Photosynthetic Active Radiation
SEBAL	Surface Energy Balance Algorithm for Land
USGS	United States Geological Survey

1.1 Introduction

Increasing pressure on water resources requires a sound knowledge of where, when and how much water is used. Increasing food production with limited water resources is the main challenge for the irrigated agriculture sector in the 21st century and, therefore, monitoring the irrigation supply and performance is meaningful.

Irrigation is the largest user of fresh water – around 70% of withdrawals are for irrigation. Irrigation produces 30 to 40 % of the world's food crops on 17% of all arable land. In order to meet future demands for food with an increasingly scarce water supply, we must manage our water resources better and more effectively. When water supplies are abundant and environmental pollution and degradation is no issue, water managers can afford to be lax in its management. But, with growing population and subsequent need for water for food, health and environment, there will be few places in the next centaury where we have this luxury. Management and planning requires accurate information and reliable information on water resources use is also at present a scarce resource. (W. Bastiaanssen, D. Molden, W. Makin, 2000)

Scarcity of water is evident in many areas throughout the world, with water becoming a primary constraint to agricultural production and environmental sustainability. Information on the size, extent and nature of the scarcity can improve water management. On the other hand in areas where water availability is not an issue this information can prove a powerful tool for the effective and beneficial management of water resources. In the past there was a strong focus on the productivity of land (yield per hectare) but with water becoming increasingly scarce this focus will shift to the productivity of water (yield per m^3).

The task of providing reliable and accurate information from scales of farmer fields to entire river basins, encompassing millions of hectares of irrigated land, is far from trivial. Space-borne remote sensing measurements can, however, provide regular information on agricultural and hydrological conditions of the land surface for vast areas. This information contributes substantially to knowledge we lack by delivering unbiased datasets, universally accessible to all interested parties. The capability of remote sensing to identify and monitor crop growth and other related biophysical parameters has undergone major improvements during the last 20 years, albeit several issues remain unresolved.

Presently, remote sensing is essentially a research tool and is rarely applied in the management of irrigated agricultural systems either at a local scale or nationally. Two main reasons for this gap may be identified: first, it is 'supply driven' by the research community which basically implies that researchers have influence on the sensor design and flight characteristics (e.g. revisit period, spatial resolution). These decisions not necessarily respond to the needs of practitioners in the field of water resources. Second, discussions with water managers and policy makers have revealed that this community is quite often unaware of the new technical possibilities, partly because the discussion about remote sensing remains within the remote sensing community. (W. Bastiaanssen, D. Molden, W. Makin, 2000)

1.2 Possible applications of remote sensing

What kind of information can remote sensing provide? Remote sensing has the possibility of offering important water resource-related information to policy makers, managers, consultants, researchers and to the general public. This information is potentially useful in legislation, planning, water allocation, performance assessment, impact assessment, research and environment-related fields.

Environmental physics based on electromagnetic radiation and micro-hydrology has evolved in the development of quantitative algorithms to convert remotely sensed spectral radiances into useful information such as, crop evapotranspiration, root zone soil moisture, crop yield, crop water requirements, salinity and biomass production. This information when presented in the context of management can be extremely valuable for planning and evaluation purposes (Table 1).

Table 1.1 – Remote sensing products for water management (W. Bastiaanssen, D. Molden, W. Makin, 2000)

Remote sensing deliverables	Water use / productivity	Performance diagnosis	Strategic planning	Water rights	Operations	Impact assessment
Land use	•		•			
Irrigated area	•	•	•	•	•	•
Crop type	•	•		•	•	•
Crop yield	•	•	•			•
Daily ET		•				
Seasonal ET	•	•		•		•
Crop stress		•			•	
Salinity		•				•
Historical data		•	•	•		•

For instance evapotranspiration maps have the potential to inform us about the actual ET for each unit of land on a daily, monthly, annually or even seasonally basis. They can also inform us about the potential ET, which would be achieved under pristine conditions with no water stress. Therefore it becomes possible to locate and monitor which areas have adequate water supplies and on the other hand which areas encounter water stress. All this information can be beneficially used to show differences between the intensity of favored and non-favored water use, to monitor droughts, to identify areas for possible water savings and the potential volume of such savings. Furthermore, it can be used to measure the incremental ET as a result of irrigation and to estimate water requirements for a range of agricultural systems. When actually combined with land use information beneficial and non-beneficial ET can be illustrated. We can realize the water use by each different crop type and also identify areas where water consumption can or cannot be controlled.

The growing conditions for agro-ecosystems are not always ideal. There can be either stress from a water shortage or there can be water logging that reduces growth and evapotranspiration relative to the upper envelope of good and healthy production. The conditions in the unsaturated zone can be manipulated by man through irrigation and drainage systems. Understanding the temporal and spatial distribution of evapotranspiration is essential for managing river basins and water supply systems. Southern and eastern Flevoland as also the northern polder host mostly irrigated agriculture, rain-fed agriculture and areas of natural interest, all of which transmit water into the atmosphere through evapotranspiration. Digital maps of land use and actual evaporative depletion of water resources enables policy- makers to address the issue of consumptive water use including beneficial and non-beneficial depletions (W.G.M. Bastiaanssen et al., 2005).

In general terms remote sensing has several advantages over field (*in situ*) measurements. First, measurements derived from remote sensing are objective; they are not based on opinions. Second, the information is collected in a systematic way which allows time series and comparison between schemes. Third, remote sensing covers a wide area such as entire river basins and agro-ecosystems. Ground studies are often confined to a small pilot area because of the expense and logistical constraints. Fourth, information can be aggregated to give a bulk representation, or disaggregated to very fine scales to provide more detailed and explanatory information related to spatial uniformity. Fifth, information can be spatially represented through geographic information systems, revealing information that is often not apparent when information is provided in tabular form. (W. Bastiaanssen, D. Molden, W. Makin, 2000)

1.3 Problem statement

Netherlands is probably one of the few countries – if not the only one – where the frequency of irrigation activities is slightly different, from the rest of the European countries in the mid and southern Europe. A considerable part of the country lies below the mean sea level, and the precipitation rate on average is high during the year. These two parameters by themselves are sufficient enough to explain the supplementary role of irrigation when compared to other irrigated agricultural countries like e.g. Spain, Italy, and Greece. By saying different we imply the duration of the irrigation season, the intensity of irrigation and above all the total amount of water used for that purpose. For instance a considerable part of the total agricultural production e.g. cereals, wheat, sugar beets etc is never irrigated since annual precipitation and ground moisture appear adequate for their growth and vital development. On the other hand, however, crops like flower bulbs are systematically irrigated in order to ensure high yields and minimize the losses throughout the annual production.

Climate changes are occurring constantly over the last decade and we witness frequently prolonged drought periods and higher temperatures. In Netherlands for example spring and summer of 1995, 1996, 2003 and 2007 were extremely dry. Consequently, arable land and vegetation are obviously exposed to the danger of possible water stress and devastation. In occasions like this, farmers whose prosperity depends on productive yields, in order to protect their crops will logically irrigate. Sometimes irrigation can be very intense and permanent e.g. on a daily basis and other times short termed. How exactly the situation is, remains a mystery. Unknown is also the total amount of water used for irrigation under these circumstances. It becomes therefore challenging to investigate whether remote sensing can potentially answer these kinds of questions as traditional (agricultural) surveying methods are time consuming, expensive and often subjective.

Therefore, it is a mystery for certain agricultural areas like the Flevoland or North Holland whether they are irrigated on a regular basis or not. Sometimes soil appears wet and potentially satisfies plants' water requirements. But this wetness does not necessarily originate from irrigation. Instead it might becomes from precipitation, seepage or even the targeted water level maintained in the drains as it is the case in polder areas. Undoubtedly all these parameters create a complex environment which needs special consideration before we extract any conclusion.

A number of certain reasons have triggered and motivated the current research study. Each one of them emphasizes on different aspects of irrigation but simultaneously addresses the same problem. Firstly, the absence of concrete data or related records with respect to crops irrigation over time. This absence when combined with the fact that farmers usually do not reveal whether they irrigate or not, obstacles water managers and local water boards to manage effectively water resources in the area. Farmers' obscurity comes directly from their denial to pay for the water they use for irrigation. Another reason is that within the area various types of crops are cultivated. This inevitably means that some crops are more valuable and economically important than others e.g. flower bulbs 8 to 10 times more valuable than sugar beets. So we assume that different irrigation practices should be applied and hopefully could be detected by remote sensing. Moreover, remote sensing lately is excessively used in environmental and agricultural studies because of its feasibility to provide cheap, accurate and almost real time information. Data can be supplied at various spatial and temporal resolutions allowing us to make over time aggregations and comparisons.

Above all, local water authorities (water boards) expect in the coming years that farmers will intensify their landuse. The characterization of irrigation as supplementary will possibly become obsolete and change to a more regular activity. This can be implemented by using more expensive high-tech crops. Therefore the majority of the farmers are expected to irrigate by utilizing their existed installations in order to protect their crops and deter potential losses. There are two main reasons for these authorities' expectations. First, on the framework of general climate changes, drier years are observed frequently over the last decade and secondly there is a shift in agricultural competition by means of cheaper labor in Easter Europe. Presently, the amount of water used for irrigation is absolutely unknown and its future (upcoming) evolution is unpredictable as well.

1.4 Research question

If we attempt to summarize all previous speculations in one broad research question, this could be the following: *'is it possible to detect which farmers have been irrigating their plots and which not, for a certain period, based mainly on remotely sensed data?'*

Whenever it is attempted to detect irrigation activities by objective means, like satellite measurements, and not based on farmers testimonies, it should considered that a certain degree of uncertainty is always present. Even in areas where precipitation is frequent, cannot be claimed with certainty whether farmers utilize their irrigation installations or not. Consequently irrigation is not just an issue of yes or no but goes beyond that.

In order to answer the principal research question we must simultaneously address additional sub questions which enlighten and unravel the main issue. These kinds of sub-questions could be:

- *Which crop types are favorable for the imminent investigation?*
- *Which period is preferable to detect different irrigation practice?*
- *How is it possible to distinguish irrigation from the other sources which contribute to soil's wetness*?
- *In what way should soil's wetness sources be manipulated in order to disclose their impact on wetness profile?*

And finally '*is it feasible to quantify the amount of water which was used for irrigation?'* All these challenging questions constitute a kind of driving wheel which steers the following study and will attempt to decipher another potential application of remote sensing.

2. Description of the study area

2.1 Introduction

The area of study is located at Flevoland. Flevoland is a province of Netherlands, which is located in the centre of the country, at the area of the former Zuiderzee. The province was established on January 1, 1986 and is the twelfth province of the country, with Lelystad as its capital. The province has approximately 374,300 inhabitants who live on an area extending over 1450 km^2 (2007) and consists of 6 municipalities. These are namely: Almere, Dronten, Lelystad, Noordoostpolder, Urk and Zeewolde as presented respectively on Figure 2.1.

Figure 2.1 – Geographical location of the study area and its administrative division

2.2 Historical development

The place where Flevoland polders lie now, used to be the Zuider Zee. The name Flevoland was originally conceived by the Romans. In the beginning of our era, an increasing number of lakes came together, thus creating one large lake in the Zuider Zee region. This lake was called 'Flevo' by the Romans. In the 17th century, hydraulic engineers started to look at the Zuider Zee with longing eyes. But it wasn't until the 19th century that Cornelis Lely was the first to present a technically feasible plan for impoldering the Zuider Zee. Public attention for the plan grew when the disastrous flood of 1916 caused a tremendous calamity. On June 14, 1918, the Zuider Zee law was a fact. This law meant the closure and drainage of the Zuider Zee.

In 1920 a start was made on the impoldering, and the Wieringermeer polder was the first to be dry in 1930. Two years later the workers closed the last hole in the Afsluitdijk (the IJsselmeer dam) the showpiece of Dutch road construction and hydraulic engineering. The Zuider Zee had become the IJsselmeer. In September 1949 the Noordoostpolder was dry. Later, the first residential areas started to appear. This new land included the former islands of Urk and Schokland.

After the Noordoostpolder, the workers started with the construction of Eastern Flevoland which comprised the Southeastern (1957) and the Southwestern (1968) parts. This polder had to accommodate the population of the overcrowded urban conurbation (Randstad) of western Holland. After the successful construction of the eastern polder (1957), the southern polder soon followed (1968).

Where there is land, there is life. And where there is life, people live. Fertile ground for municipalities. The same applies to the two polders. Slowly but surely, an administrative region came about. On January 1st 1986, the newest and twelfth province of the Netherlands came into existence: the province of Flevoland. (Province of Flevoland, 2008)

2.3 Polders

A polder is a low-lying tract of land enclosed by embankments known as dikes, which forms an artificial hydrological entity, meaning it has no connection with outside water other than through man operated devices. There are three types of polders:

- Land reclaimed from a body of water, such as a lake or the sea bed
- Flood plains separated from the sea or river by a dike
- Marshes separated from the surrounding water by a dike and consequently drained

The ground level in drained marshes subsides over time and thus all polders will eventually be below the surrounding water level some or all of the time. Water enters the low-lying polder through: seepage (ground swell due to the water pressure on ground water), rainfall and transportation of water by rivers and canals. This usually means that polders have an excess of water that needs to be pumped out or drained by opening sluices at low tide. However care must be taken in not setting the internal water level too low.

Polders are at risk from flooding at all times and caution must be paid to protect the dikes surrounding a polder. Dikes are mostly built using locally available materials and each has its own risk factor: sand is prone to collapse due to over saturation by water; dry peat is lighter than water, making the barrier potentially unstable in very dry conditions.

Netherlands is frequently associated with polders. The Dutch have a long history of reclamation of marshes resulting in some 3000 polders nationwide. About half of all polder surfaces within northwest Europe are located within the Netherlands. Due to flooding disasters water boards were set up to maintain the integrity of the water defenses around polders, maintain the waterways inside a polder and control the various water levels inside and outside the polder. (Wikipedia[1], 2008)

The study area literally consists of three polders the eastern and southern Flevoland and the northern polder (Noordoostpolder). It is common though eastern and southern Flevoland polders to be considered as one. Eastern (Oostelijk or Oost-Flevoland) and Southern Flevoland (Zuidelijk or Zuid-Flevoland), unlike the Noordoostpolder, have peripheral lakes between them and the mainland: the Veluwemeer and Gooimeer respectively, making them, together, the world's largest artificial island (Figure 2.2).

Figure 2.2 – On the left the Southern & Eastern Flevoland (Flevopolder) and on the right the Northern polder (Noordoostpolder) (Wikipedia[1], 2008)

In fact, Southern and Eastern Flevoland polders have a joint hydrological infrastructure, with a dividing dike in the middle, the *Knardijk*, which will keep one polder safe should the other be flooded. The two main drainage canals that traverse the dike can be closed by weirs in such an event. The pumping stations are the *Wortman* (diesel powered) at Lelystad-Haven, the *Lovink* near Harderwijk on the mainland and the *Colijn* (both electrically powered) along the northern dike beside the Ketelmeer.

Southern Flevoland has only one pumping station; the diesel powered *De Blocq van Kuffeler*. The centre of the polder most closely resembles the pre-war polders in that it is almost exclusively agricultural. In contrast, the southeastern part is dominated by extensive forests and natural preserved areas. (Wikipedia[1], 2008)

2.4 Land use

One of the main reasons for selecting Flevoland's polders as the study area is their strongly agricultural character. Both polders are cultivated intensively for the most of their extent throughout the year and authorities expect that farmers will intensify the land use in the coming years. The main crop types one meet in the area are potatoes, flower bulbs, sugar beets, apples, cereals (wheat), maize, onions and cabbages. It is also evident that many farmers in the area are changing successively their cultivations every year in order to ensure high levels in the annual production. Besides the referred crops it is important to mention that there is also a remarkable natural reserved area in the southern and eastern Flevoland which alternates the landscape of the area. A detailed description of the land use of the area with all its encompassing characteristics is following given on Chapter 3.

3 Data sources

3.1 Introduction

As discussed earlier irrigation activities in polder areas have a supplementary character, at least for the moment. This is mainly due to the prevailing climatic conditions and the abundance of water which characterizes areas like polders. Therefore for the isolation and detection of irrigated areas we need to assess the impact of all the other sources which potential contribute to soil's wetness. Consequently a considerable amount of various datasets, which would facilitate such an analysis, is necessary. It is very likely though the initial data sources not to reveal immediately the desired information and only after certain analysis we would be able to obtain meaningful results.

Before the description of each separate dataset it is essential to refer to the way which data will be manipulated. Since the primary objective is to distinguish plots which have been irrigated or not, it is rather logical individual plots to be the target upon which analysis will be focused. Specifically the analysis will initiate from different crop types and will end up in monitoring each plot separately. Therefore special emphasis will be given on the attributes each plot should hold. The optimal solution for each plot would be to bear multiple information (in the form of different attributes) which describe the prevailing conditions in the corresponding location e.g. elevation, soil type, seepage, evapotranspiration, biomass production etc. In that way it would be possible to assess the condition of every plot with respect to irrigation (independent of the crop type).

Moreover, as it is realized every plot might consist of one, two or numerous of pixels, depending on its size. Having multiple values for each attribute (of each plot) wouldn't be functional. For that reason it was decided to take an average (mean) value for each plot's attribute in order to describe its condition. That consideration is also in line with the notion that if a farmer decides to irrigate his land then he will do it for the whole of it and not merely for a part. Consequently mean values per attribute can illustrate plots' situation in a safe and effective mode.

3.2 Satellite images

The scale of satellite measurements is a measure of its quality and which is associated with two parameters, namely *spatial resolution* and *temporal resolution*. The spatial resolution measures the ability of a sensor to distinguish among closely spaced objects in the terrain. One pixel is the smallest area of the terrain that can be recorded as a unique element by the sensor. Ground objects smaller than the pixel size can be detected but not be resolved. In a satellite image, a ground object of whatever shape has to be identified approximately by a cluster of square shaped pixels I.e. a raster based image. The temporal resolution of a remote sensing system determines the frequency of revisits to capture images of the same area. In practice, the frequency of image capture can be hampered by cloud cover, which makes the measurements useless.

For the current study a number of satellites and their associated characteristics were considered carefully before selecting the suitable one. On Appendix A, are presented the sensors or satellites that provide images suitable for agricultural management. Images from satellites such as Landsat 5 TM, Landsat 7 ETM or ASTER produce a more accurate shape of the ground object because of their smaller pixel size (e.g. 30 m x 30 m) compared to those of the MODIS or the NOAA-AVHRR satellites which have pixels of 1000 m x 1000 m and 1100 m x 1100 m respectively (Eurimage, 2008). Additionally the spatial resolution of their thermal band which was an essential element to take into consideration was much better than those of NOAA-AVHRR and MODIS. Unfortunately both Landsat and ASTER satellites have a 16 day temporal resolution, meaning even if there would be no cloud cover, they could provide only 2 measurements of a particular area per month in contrast with MODIS and NOAA-AVHRR satellites which provide daily measurements (K.M.P.S Bandara, 2006).

The processing of the original images of 1995 for Flevoland was not necessary to be repeated since their products such as evapotranspiration and biomass production maps were sufficient enough for the scope of the analysis. These maps were kindly provided by WaterWatch in order to be used as primary inputs. The specifications and characteristics of each image though were considered thoroughly before the final decision for their suitability.

Therefore the available Landsat 5 TM images were considered appropriate material for the summer of 1995. The 120 m spatial resolution of the thermal detector seemed adequate to support the desired level of the analysis, which was confined to numerous plots at Flevoland polders. The main characteristics of the satellites which considered for the current study are presented below in Table 3.1.

Table 3.1 – Trade-off table of the main characteristics of the satellites considered for the study.

Characteristics	Unit	**Landsat 5 TM**	**Landsat 7 ETM+**	**ASTER**	**NOAA-AVHRR**	**MODIS**
Platform/Sensor	-	Landsat Thematic Mapper	Landsat Enhanced Thematic Mapper	Advanced Space borne Thermal Emission & Reflection Radiometer	National Oceanic & Atmospheric Administration – Advanced Very High Resolution Radiometer	Moderate Resolution Imagining Spectro-Radiometer
Type	-	High resolution	High resolution	High resolution	Low resolution	Low resolution
Orbital Altitude	km	705	705	705	833	705
Swath	km	185	185	60	2399	2330
Temporal Resolution	days	18	16	16	½	1
Visible Detectors						
Band Numbers	-	1, 2,3	1,2,3	1-2	1	1,3,4 & 8-14
Spectral Range	µm	0.45-0.69	0.45-0.69	0.52-0.69	0.58-0.68	0.545-0.670
Spatial Resolution	m	30	30	15	1100	250 (band1), 500 (band 3&4), 1000 (band 8-14)
Infrared Detectors						
Band Numbers	-	4,5&7	4,5&7	3-9	2-3	2, 5-7 & 15-30
Spectral Range	µm	0.76-2.35	0.76-2.35	0.76-2.43	0.725-3.93	0.62-9.88
Spatial Resolution	m	30	30	15 (band 3) 30 (band 4-9)	1100	250 (band 2) 500 (band 5-7) 1000 (band 15-30)
Thermal Detectors						
Band Numbers	-	6	6	10-14	4-5	31-36
Spectral Range	µm	10.4-12.5	10.4-12.5	8.125-11.65	10.3-12.5	10.78-14.385
Spatial Resolution	m	120	60	90	1100	1000

3.3 Land use map

The land use map of the Flevoland area is one of the element keys in the following analysis. Knowledge of *land use* and *land cover* is important for many planning and management activities and is considered an essential element for modeling and understanding the earth as a system. The term *land cover* relates to the type of feature present on the surface of the earth. Corn fields, lakes, maple trees and concrete highways are all examples of land cover types. The term *land use* relates to the human activity or economic function associated with a specific piece of land. As an example, a tract of land on the fringe of an urban area may be used for single-family housing. Depending on the level of mapping detail, its land use could be described as urban use, residential use, or single-family residential use (T. Lillesand, R. Kiefer, J. Chipman, 2004).

Land use maps provide us vital information about the location and extend of different land use classes such as agricultural, forest, water, cities etc. They also tell us about the area and extent of various crops, the cropping intensity (i.e. number of crops per year) and the extent and location of irrigated areas. For the Netherlands the LGN (Landelijk Grondgebruik Nederland) is the national land use map. Until now there are four LGNs for the country namely LGN1, LGN2. LGN3 (LGN3 plus), LGN4 and LGN5 each one corresponding to a different period of compilation. For the imminent study the LGN3 file was used in accordance with the temporal framework of the study. The LGN3 file is based on satellite images from 1995 and 1997, the TOP10-vector file and the agricultural statistics from the Central Bureau for Statistics (CBS). LGN3 is not significantly different from LGN2. The information is stored in a raster format with pixels of 25 by 25 meters (Alterra 2008).

From the following map is easily deducted, that in the Noordoostpolder potatoes and flower bulbs are the two dominant agricultural cultivations. This is also supported by the relatively humid conditions which accommodate cost-effective agricultural productions. Atlanta, the international centre for potatoes cultivation and trade is also located in that polder. In 1995 according to the LGN3, the Noordoostpolder was occupied by forest areas (4.4%), grass fields (14.1%), potatoes (23.1%), cultivated areas (3.7%) and the remaining by a class defined as other arable land.

The class forest encompasses subclasses such as forest of needle-pine trees, forest of maple trees, forest in wetland, forest with dense buildings etc. The class 'other arable land 'as specified by the LGN legend includes all crops that do not fall within the other classes and which also are not included in the class of flower bulbs. Instead it includes cabbages, onions, carrots, chicories etc. On the other hand, in Southern and Eastern Flevoland polder the 67.5% of the land is shared between 5 classes: forest (14.5%), grass (13.7%), potatoes (12.4%), build-urban areas (12.9%) and other arable land (14%). The classes of cereals (11.6%) and sugar beets (8.8%) occupy smaller percentage following by the classes of water (4%) and maize (2%) (Water Watch[2], 2006).

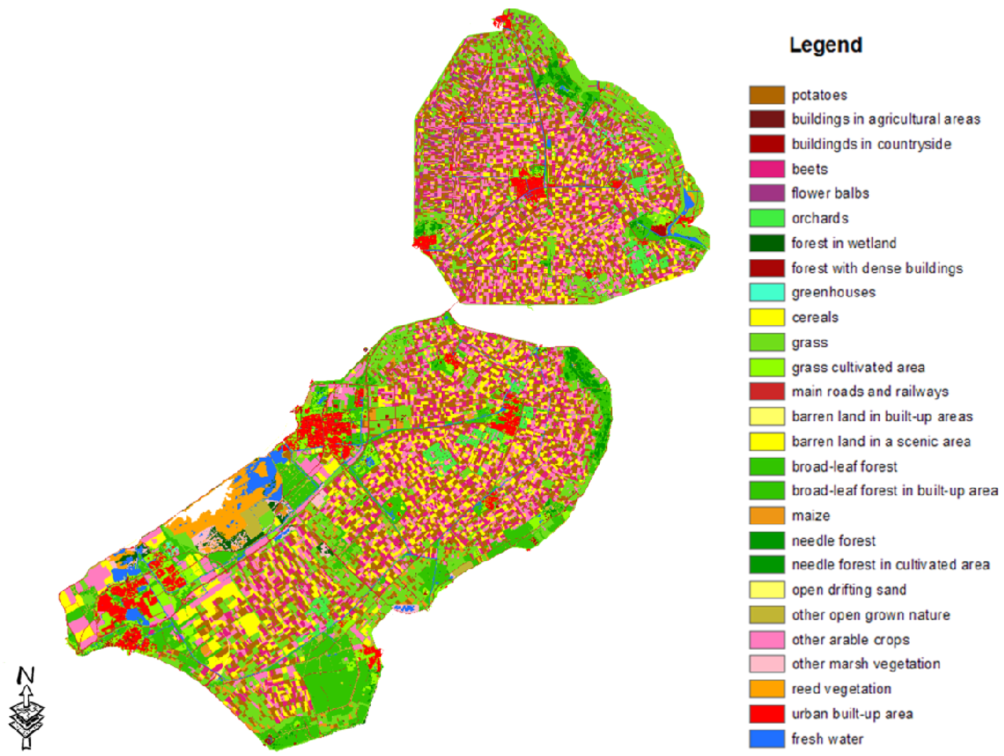


Figure 3.1 – Land use map (LGN3) of Flevoland in 1995 (source Water Watch)

Table 3.2 - Land use distribution in Southern & Eastern Flevoland based on LGN3 (Water Watch[2], 2006)

	Southern & Eastern Flevoland (ha)	Southern & Eastern Flevoland (%)
Forest	14.296	14.5
Nature area	5.863	5.9
Water	3.904	4
Build area	12.718	12.9
Grass	13.446	13.7
Maize	2.001	2
Potatoes	12.236	12.4
Beets (sugar)	8.696	8.8
Wheat	11.419	11.6
Other agricultural	13.812	14
TOTAL	**98.391**	**99.8**

3.4 Evapotranspiration

The process known as evapotranspiration (ET) is of great importance in many disciplines, including irrigation system design, irrigation scheduling and hydrologic and drainage studies. In a broad definition, the evapotranspiration is a combined process of both evaporation from soil and plant surfaces and transpiration through plant canopies. In the evapotranspiration process, the water is transferred from the soil and plant surfaces into the atmosphere in the form of water vapor. In practice, the estimation of the evapotranspiration rate for a specific crop requires first calculating potential or reference evapotranspiration and then applying the proper crop coefficients (K_c) to estimate actual crop evapotranspiration (ET_{act}). The determination of evapotranspiration is extremely difficult and not straightforward due to the natural heterogeneity and complexity of hydrological processes (S. Irmak, D. Haman, 2003).

3.4.1 Traditional methods to estimate ET

A common procedure to estimate evapotranspiration under non-ideal conditions is the three-stage modeling procedure. In stage one, the reference ET is computed for a standard crop, such as grass. The second step is to make a correction between the standard crop and the crop to be investigated through crop coefficients K_c. Most consumptive use studies are following this two-step approach, assuming that moisture and nutrients are at ideal levels and that management is perfect or precipitation occurs at the right time and at the right place. However, for application to actual conditions, step three must include a realistic soil moisture reduction term. This three stage concept is in line with the Food and Agricultural Organization of the United Nations (FAO) dual crop coefficient approach and with most hydrological simulation models that reduce ET_{pot} into ET_{act} using soil water potential or another availability indicator.

Instead of being modeled, evapotranspiration can be measured *in situ*. Most field measurements, however, are indirect and based on equations and assumptions. Classical water balance studies that measure the vertical distribution of soil moisture must approximate the percolation flux and any error in the percolation or capillary rise will be propagated into the ET measurement. Bowen ratio surface energy balance systems depend mainly on sensor accuracy to measure small differences in air humidity. Eddy-covariance systems are frequently beset by under measurement of heat and vapor fluxes, thereby causing energy balance closure error. Moreover, the performance of lysimeter ET depends on the precision of installation and that vegetation is not hanging over the edge of the lysimeter. The accuracy of the lysimeter measurements also depends critically on how representative of the surrounding vegetation and soil moisture regime the lysimeter is. Thus, none of these *in situ* methods are completely trustworthy and all require substantial resources for their attention (W.G.M. Bastiaanssen, et al., 2005).

3.4.2 Estimation of ET with remote sensing

The close dependence of surface temperature on actual evapotranspiration makes thermal remote sensing suitable for crop consumptive use studies. Thus remote sensing serves as an indirect evapotranspiration measurement technique which involves the using of a set of equations in a strict sequence in order to convert the spectral radiances measured by satellites into estimates of actual ET. Spatial coverage is available at a great variety of scales ranging from small agricultural plots to river basins and vast natural areas. In addition, temporal coverage is vastly superior at minimal cost to provide similar detail when compared to the field measurement of data (W.G.M. Bastiaanssen, et al., 2005).

SEBAL (Surface Energy Balance Algorithm for Land) was applied to estimate the actual evapotranspiration and biomass production for May 24th, June 25th, July 11th and August 12th of 1995 over the Flevoland area. SEBAL uses cloud free, satellite imagery from sensors measuring the visible, near-infrared and thermal radiation plus ordinary meteorological data to solve the energy balance at the earth's surface at the moment of satellite's overpass. It can be applied for diverse agro-ecosystems and does not require ancillary information on land use or crop types. Its primary outputs are water consumption or evapotranspiration (actual) and biomass production of agricultural crops and native vegetation, pixel by pixel.

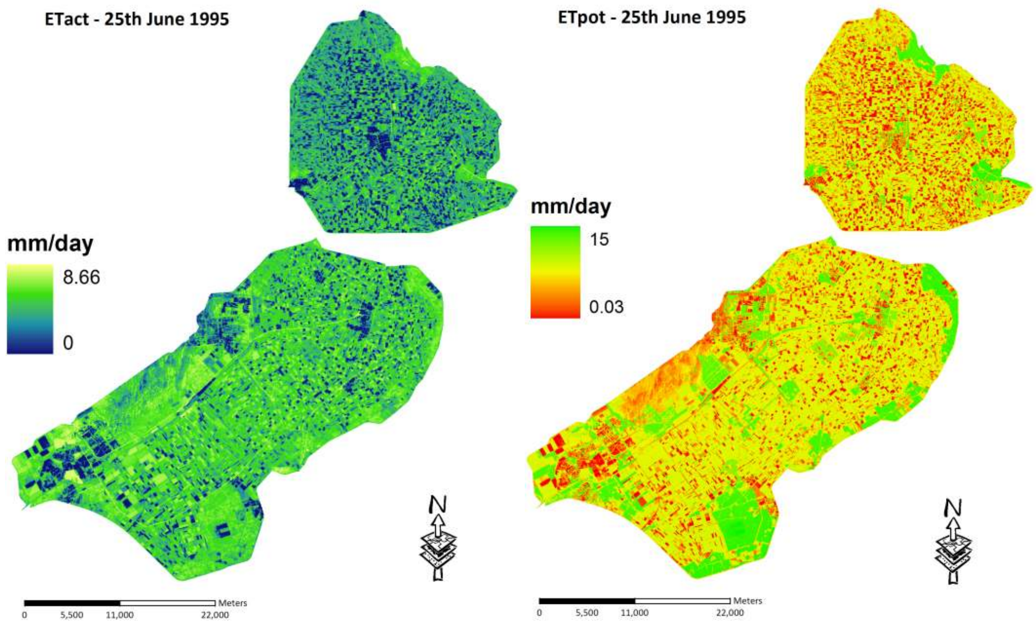


Figure 3.2 – Actual (left) and Potential (right) ET maps - 25th June 1995 (source Water Watch)

Instantaneous and daily ET and biomass production outputs are computed directly by SEBAL, and can be extrapolated to longer time periods of weeks or months using ratios of ET from SEBAL to reference ET computed from ground-based weather stations. Integration over time provides accurate seasonal and annual estimates of ET and biomass production with the same spatial resolution of the source image. ET_{act} is calculated as a residual of the energy balance expressed by the latent heat flux, based on the fact that evaporation consumes energy. The latent heat flux (LE) was computed on a pixel by pixel basis as a residual of the energy balance:

$$LE = R_n - G - H \ (W/m^2) \tag{3.1}$$

Where R_n is the net radiation (W/m^2), G the soil heat flux (W/m^2) and H is the sensible heat flux (W/m^2). The net radiation (R_n) is the actual radiation that is available at the earth surface, which is equal to the sum of the net shortwave and longwave radiation. The former was computed as a function of the surface albedo, while the latter was computed from the difference between incoming and outgoing longwave radiation. Incoming longwave radiation was calculated using a modified Stefan-Boltzmann equation that uses an apparent emissivity, which is coupled to an atmospheric transmissivity and a measured air temperature. The outgoing longwave radiation was calculated using the Stefan-Boltzmann equation with a calculated surface emissivity and a surface temperature measured by the satellite sensor.

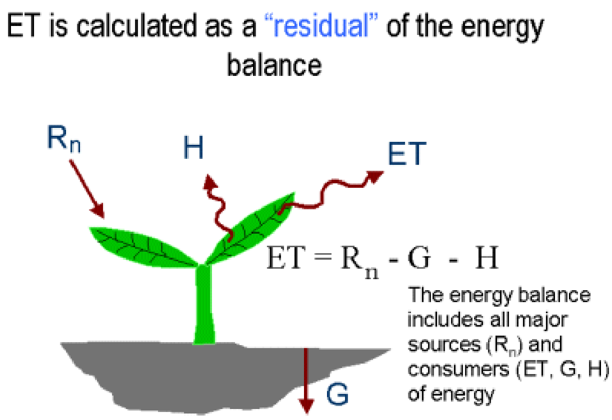


Figure 3.3 – Schematic representation of the surface energy balance

The soil heat flux (G) was estimated as a fraction from R_n, surface temperature and NDVI. The sensible heat flux (H) was estimated from surface temperature, surface roughness and measured wind speed. An essential step in the application of SEBAL is the solution of extreme values for H, prior to the pixel by pixel computations. In desert surroundings H is considered equal to $R_n - G$, while for water surfaces H is equal to 0 (W.W. Immerzeel, A. Gauur, S.J. Zwart, 2007)

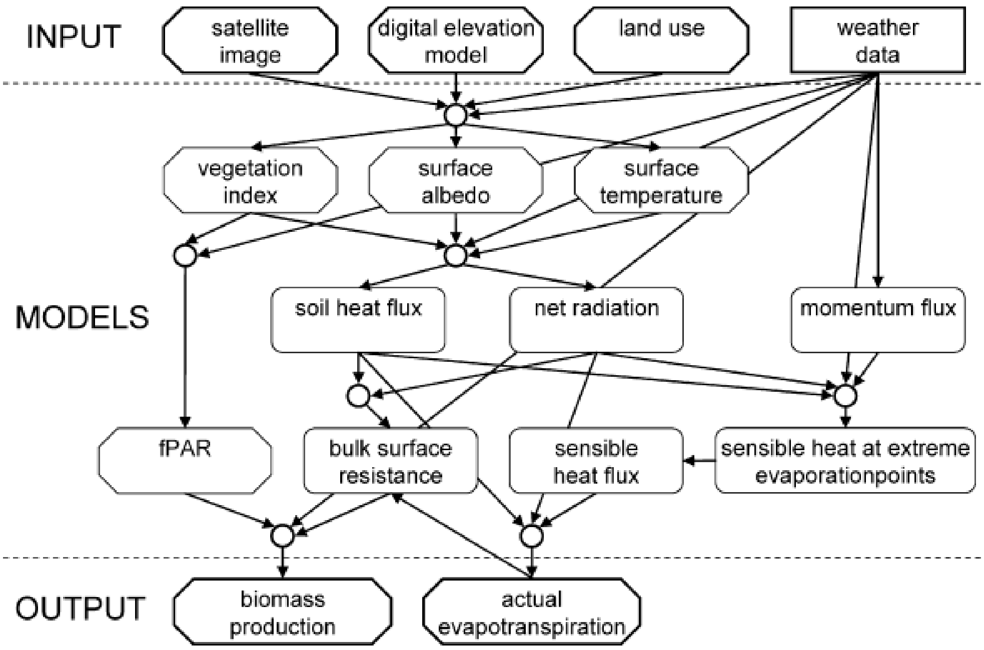


Figure 3.4 – Schematic overview of the SEBAL model (S.J. Zwart, W. Bastiaanssen, 2007)

The final maps of ET_{act} have a spatial resolution which is limited by the resolution of the thermal band used in the algorithm. The original resolution of the thermal band on Landsat 5 is 120 meters. The other bands have a resolution of 30 meters. For the ET calculation the thermal band (120 m) was the driving factor while for the biomass production was the NDVI. In order to run the models the inputs needed to have the same pixel size. Therefore, the thermal band was re-sampled to 30 meters using bilinear interpolation. This is why ET images appear somehow smoother whereas the biomass production maps look very sharp. Landsat products can be ordered from USGS at 25, 28.5 and 30 meters resolution. For the Flevoland region the original images had pixel size of 25 meters and all the final maps correspond to this spatial resolution.

3.4.3 Accuracy of ET estimates based on SEBAL

The accuracy of ET estimates derived from satellite images has two distinct components. One is the absolute accuracy of the estimate at any point and the other is the relative accuracy between points.

Absolute accuracy

SEBAL estimates of evapotranspiration differ from traditional methods such as computed Penman-Monteith ET values, lysimeter ET measurements, soil water balance measurements, eddy correlation measurements and scintillometer measurements.

Since none of the above methods are easy and/or error free, it remains difficult to validate spatial distributed SEBAL evapotranspiration with the above mentioned point ET. Validation efforts until now have shown that the error at a 1 ha scale varies between 10 and 20% and that the uncertainty diminishes with increasing scale. Additionally over time intervals of a month or more, the difference between ET estimates from SEBAL and other carefully implemented techniques will typically be less than 5%, whereas the deviation of SEBAL ET values for shorter periods (instantaneous and up to 10 days) based on a single satellite image will approximately be 15 to 20% when compared to ground based measurements. For an area of 1000 ha, the error is reduced to 5% and for regions of 1 million ha of farmland, the error becomes negligibly small (W.G.M. Bastiaanssen et al., 2005).

Relative accuracy

Once an image has been processed to derive ET, the relative accuracy between points is high- thus it can be stated with confidence that the ET of a particular area of interest is higher or lower, expressed as a percentage, than another area within the same image. In the current study where mean values of ET are considered per plot, relative accuracy is much higher than the absolute one allowing us to feel more confident when processing $ET_{act/pot}$ maps.

3.5 Biomass production

Biomass production maps can provide us vital information about the productivity of land at various scales. Having a time series of biomass production maps we can deduce whether crops are being developed according to the management planning and if not, to locate the source of the problem. Moreover we can infer the incremental production from irrigation and more further on farmers income. The combination of land use, evapotranspiration and biomass maps is possible to give us insight on the value of water in agriculture and the potential to save water with same production levels.

Growth of biomass occurs through the mechanisms of photosynthesis and carbon assimilation, which needs light in the visible part of the spectrum, besides carbon dioxide and water as the major inputs. Chlorophyll absorbs light from 0.4 to 0.7 μm and this photosynthetic active radiation (PAR) can be approximated from the total solar radiation. The Absorbed PAR (APAR) varies with the vegetation density, as well as with PAR. The ratio of APAR/PAR can be computed on a pixel by pixel basis using NDVI from remote sensing data. Satellite measurements of clouds (for PAR) being combined with NDVI (for APAR/PAR) can thus give us estimates of APAR (W. Bastiaanssen, D. Molden, W. Makin, 2000).

As stated before, the Surface Energy Balance Algorithm for Land (SEBAL) is a robust remote sensing model that can be applied to estimate the different components of the energy balance of the earth surface and thus also actual evapotranspiration (ET). This model can be extended to produce estimates of crop biomass production. Above ground biomass production on a single image acquisition day (bio_{day}) is calculated by the SEBAL model as:

$$bio_{day} = 0.48 \cdot K_{EXO}^{\downarrow} \cdot \tau_{sw} \cdot f \cdot \varepsilon_{\max} \cdot \Phi_h \cdot \frac{s_a + \phi \cdot (1 + r_{s,\min} / r_{av})}{s_a + \phi \cdot (1 + r_s / r_{av})} \cdot 0.864 (kg / ha / day) \tag{3.2}$$

Where $K_{EXO}^{\uparrow}$ is the incoming shortwave radiation at the top of the atmosphere (W m^{-2}), τ_{sw} the atmospheric transmissivity, ε_{max} the maximum light use efficiency (g MJ^{-1}), Φ_h the stomatal response to ambient temperature, s_a the slope of the saturated vapor pressure curve (mbar K^{-1}), ϕ the psychometric constant (mbar K^{-1}), r_s the bulk surface resistance (s m^{-1}), $r_{s,min}$ the minimum bulk surface resistance (s m^{-1}) and r_{av} is the aerodynamic resistance to water vapor transport (s m^{-1}). The resistances r_s, $r_{s,min}$ and r_{av} are routinely solved in the latent heat flux. The fraction of photosynthetically active radiation (f) can directly be estimated from the NDVI (S.J. Zwart, W. Bastiaanssen, 2007).

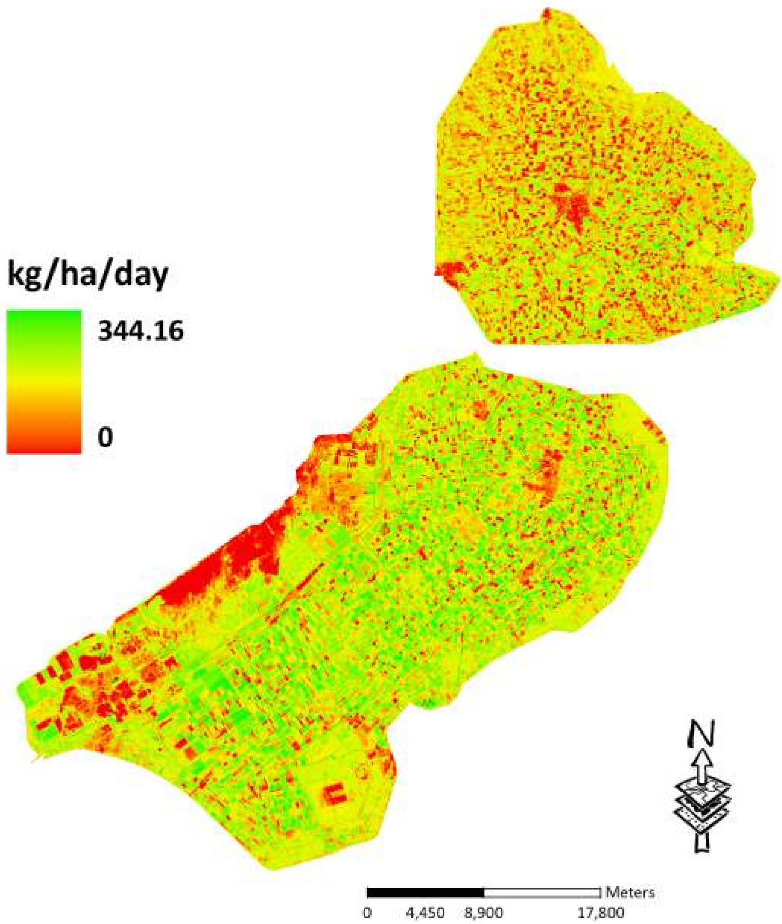


Figure 3.5 – Biomass production map - 25th June 1995 (source Water Watch)

3.6 Digital elevation model

The AHN (Actueel Hoogtebestand Nederland) is a detailed elevation model of the whole country using airborne laser altimetry (LIDAR). It covers the topography of the entire Nederlands, including Flevoland polders. Rijkswaterstaat is owner of this dataset. The basic AHN file consists of a selection of the original height points as measured using laser altimetry. The selection includes the points measured on the surface level, which means that errors and measurements on objects and vegetation are more or less removed. Data from rural and agricultural areas like Flevoland have been filtered during preprocessing, so the data represents only the topography. The 'Adviesdienst Geo-Informatie and ICT' organizations checked the data on precision and completeness. The point density in the basic file of the AHN is at least one point per 16 m^2 (Van Heerd, 2000). Exceptions to this are forested areas, with a minimum of one point per 36 m^2. For the Flevoland area, the point density is 3 to 5 points per 16 m^2 (AHN, 2008). The accuracy of the AHN data is in the centimeter level and is described by precision and reliability. Precision corresponds to the geometric quality of the data in the basic file, and is described by the systematic and the stochastic error. The stochastic error, also called point noise, is the error in the measurements and can be estimated using the standard deviation. For the laser altimetry the standard deviation is given 15 cm (AHN, 2008). The systematic errors are errors in the coordinate determination with GPS and INS.

From figure 3.6 it is easily deducted that the eastern side of the Southern polder lies within ± -3.30 m NAP, much higher than the western side which is ± -4.50 m NAP height. The Hoge Vaart is the separation between the higher parts of land in the east and the lower parts in the west side of the polder. The deepest point is located near the Flevocentrale and lies in a height less than -4.70 m NAP. In this area one can meet a number of muted barge channels. These channels as others in the vicinity can be as well observed in the elevation image. The average height in Southern and Eastern Flevoland is at -3.65 m NAP. In addition the average height in the Northern polder (Noordoostpolder) lies at -3.44m NAP, not significantly different from the average height in Southern and Eastern polders. Moreover, the eastern and southern parts of the Noordoostpolder are much higher (-3.00± m NAP) than the western parts. The deepest point is located at -5.60m NAP.

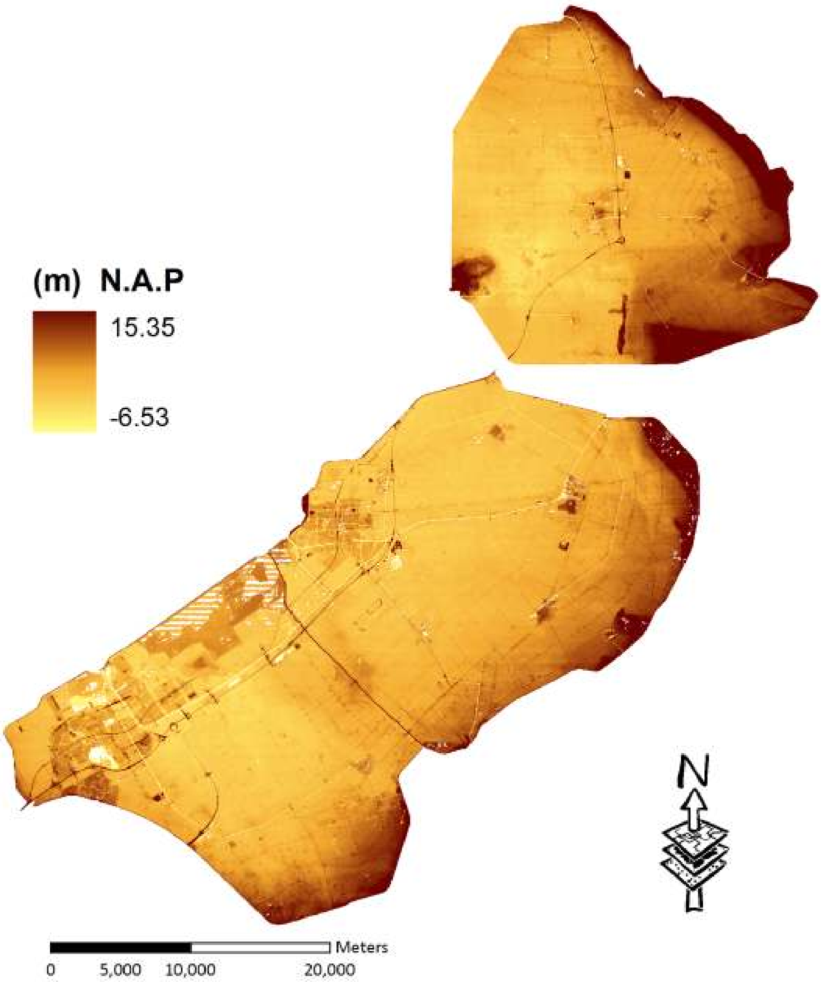


Figure 3.6 – Digital elevation model of the study area (source Water Watch)

3.7 Water level

Netherlands consists of 34,000 km^2 on the frontier between land and water, cultivated by man and made fit for habitation, development, agriculture, industry and recreation. We take all these activities for granted and rarely consider that 25% of the Netherlands lies under average sea level. More than half of the Netherlands would be flooded if there were no dunes and water barriers, structures which provide good protection against storm floods from the sea and high water in the rivers. The many dikes, sluices, pumping stations, dams, canals and drainage ditches keep the Netherlands habitable. Without this infrastructure more than half of the Netherlands, where more than nine million people live and work, would simply not exist.

Dutch Water Boards (*waterschappen* or *hoogheemraadschappen*) are a form of decentralization in the country's government. Water boards are among the oldest governmental institutions, some were founded in the 13th century, in the Netherlands – with 25% of the country below mean sea level and three main rivers going through a small area, it has always been in the common interest to keep the water out (wikipedia[2], 2008). Typically, a water board’s territory is made up of one or more polders or watersheds. In 2006, there were 27 water boards in the Netherlands. In its territory, the water board is responsible for:

- Management and maintenance of water barriers: dunes, dikes, quays and levees
- Management and maintenance of waterways
- Maintenance of a proper water level in polders and waterways
- Maintenance of surface water quality through water treatment

At Flevoland’s polders a certain target water level is always maintained within the drains by water boards, affecting soil’s moisture content. Although a clear distinction is established between winter and summer water levels, in practice the difference is minimal. Establishing water levels in the area is a rather careful and lengthy process since various interests should be balanced.

The following map was created based on maps which were provided by the local water boards. It illustrates the maintained water level during the summers. The coarse scale differences observed in the map arise due to different water level practices applied in the two polders by water boards, while the small scale differences stem from the progress of gradual differences in the absolute water level, resulting from geological deposits and sedimentary processes. On dry periods, like in the summer or the late spring, it is used to maintain polder's water level on rather higher levels than on wetter periods like in the autumn or in the winter. For instance, during the summer if the water level becomes too shallow then plant's capillary attraction would be limited and rather ineffective – if we assume that polder's water level corresponds to ground water.

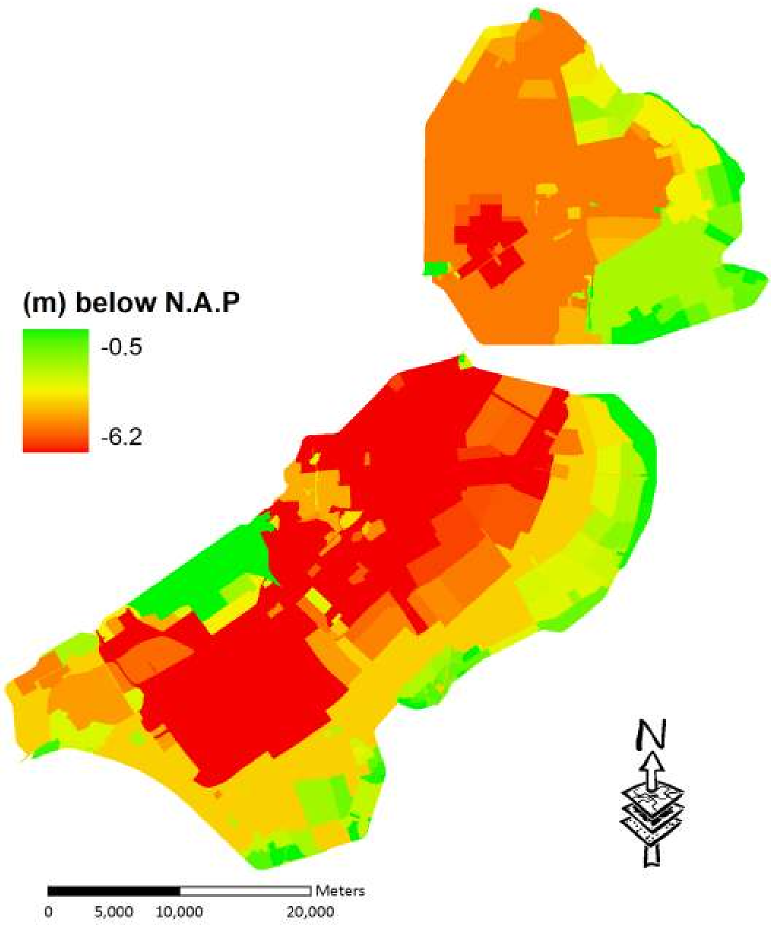


Figure 3.7 – Summer target water level as maintained by water boards (source WaterWatch)

3.8 Seepage

Seepage is referred to the amount of water which reaches the surface by ground water flows. In Netherlands, seepage by dikes along polders is a normal and frequently observed phenomenon. Seepage is the flow of a fluid through soil pores and constitutes an important component of the soil zone, contributing positive or negative to its moisture. Despite its importance, it is also one of the most difficult soil factors to be determined. Direct measurement of seepage is not possible so therefore, it is usually determined by hydrological ground water modeling encompassing all the relevant uncertainties modeling could have.

The concept of seepage relates two common types in the area namely *dike-seepage* (dijkskwel) and *regional-seepage* (regionale kwel). The dike-seepage is created by the potential difference between the open water level of the Ijsselmeer lake and the ground water level of the polder. It is usually of good quality and directed upwards to the inside of the dike. In contrast, the regional-seepage is more complex and is created in the regions of Veluwe, the Drents Plateau and the Ijsselmeer. The regional-seepage in the hill-sides is usually of good quality and rich in nutrients (Water Watch[1], 2006).

The current map was provided by WaterWatch, acknowledging in advance that due to its computational complexities, it is not highly accurate. On the other hand seepage is amongst the most important contributors to soil's wetness in the area. Therefore under the circumstances it proved the most suitable and accessible source of information for seepage values. On map's legend (figure 3.8) one can notice positive and negative values of seepage. The positive values stand for the upward direction of water which translates to seepage, while the negative ones stand for downward direction of water or percolation. Usually during the summer period seepage is larger than in the winter time. This comes directly from the different water levels maintained within the polders during different epochs. A seepage map in millimeters/day, for the study area, is presented below.

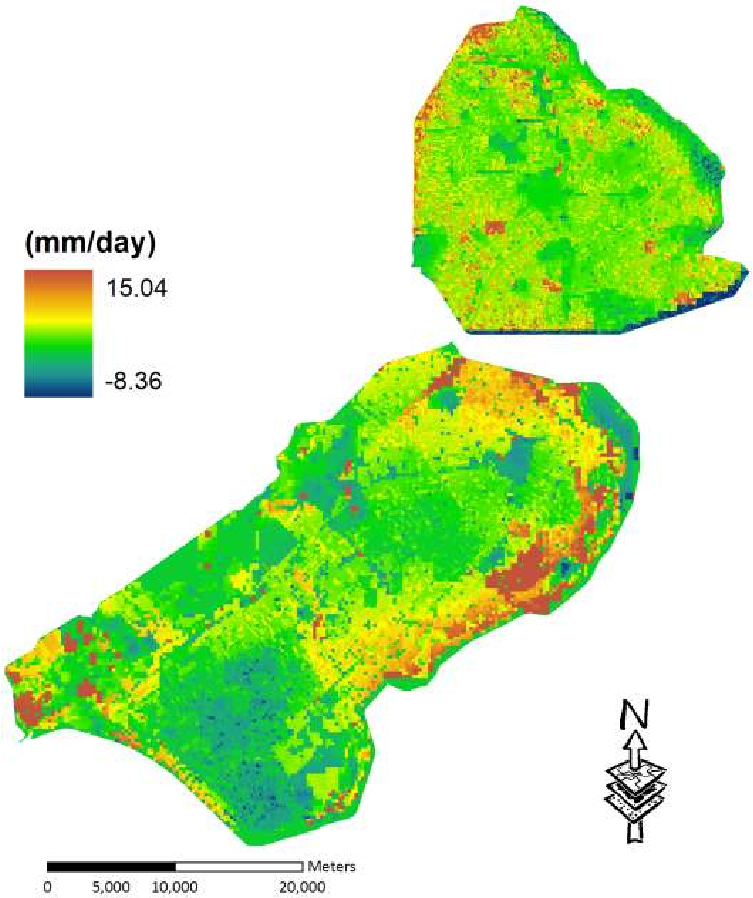


Figure 3.8 – Seepage map of the polders (source Water Watch)

3.9 Soil

Another significant parameter which influences soil's wetness is the soil type. It is evident that some soils facilitate faster and more effectively the drainage of water than others. For that reason they tend to support usually drier conditions than wet. As such, the influence of various soil types to wetness' profile cannot be omitted. The soil map used for the current study derived from a base map of 1:50.000, which was set up by the foundation Bodemkartering (Stibokal).

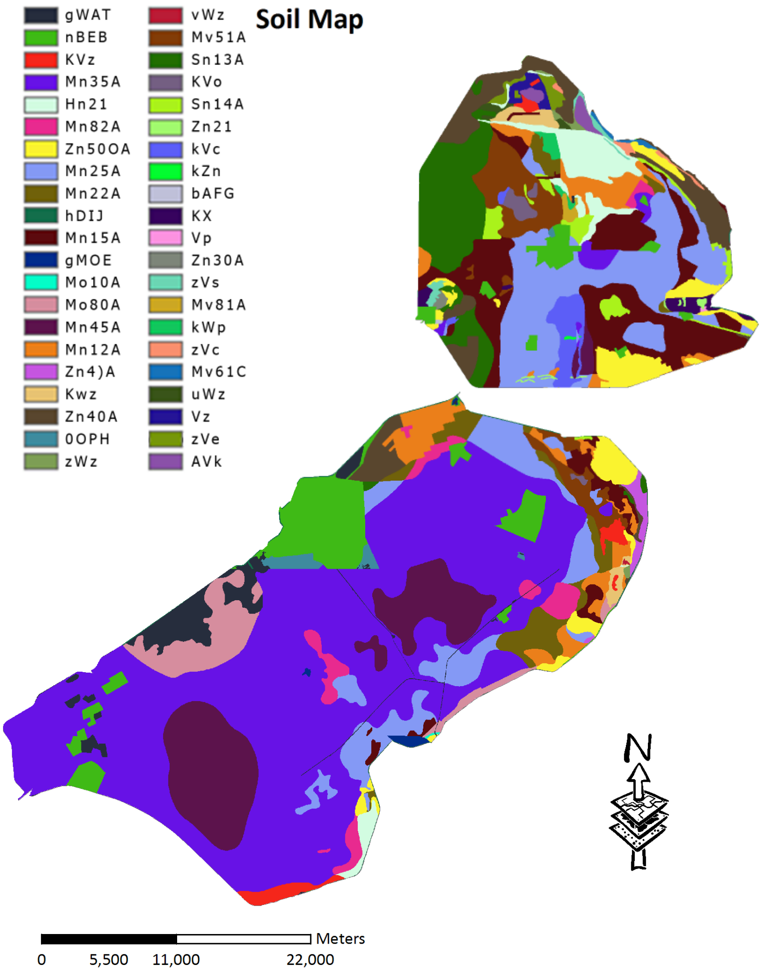


Figure 3.9 – Main soil types of the study area (source Water Resources, TU Delft)

The soil map of Southern and Eastern Flevoland reveals remarkable homogeneity mainly due to the presence of young soils in the area. The largest part of the land is occupied by light clay with lutum concentration between 25 to 35% (code Mn35A, Appendix B). The land is becoming heavier in the southern Flevoland with lutum percentages more than 35%, which is identified with heavy clay. This heavy clay is also frequently met in the vicinity of Lelystad. Such soils usually exhibit lower hydraulic permeability and can potentially cause trouble in the drainage, resulting in permanent wet conditions. Heavy loam soils with lutum content 17 to 25% (Mn25A) are present in the northern and eastern side of the polder. Furthermore it is noticeable that in the area between Dronten and Elburg there are significant successions in the soil types from light loam to sandy soils (Water Watch[2], 2006)

The relatively homogeneous soils of Southern and Eastern Flevoland are not evident, in the case of the Northern polder which consists of 37 different soil types. The upper parts of the polder (-1 m and above NAP) are mainly sandy while loamish soils are observed at the lower parts of the polder. Even the above classification is highly accurate and depicts the variety of soil types in the polders; it would be preferable if it was more compact. By saying that, it is meant to create more general classes of soil types, which share common characteristics. So the initial soil map was reclassified to 15 classes (figure 3.10). In that way it will be easier to distinguish soils which support dry, wet or intermediate conditions.

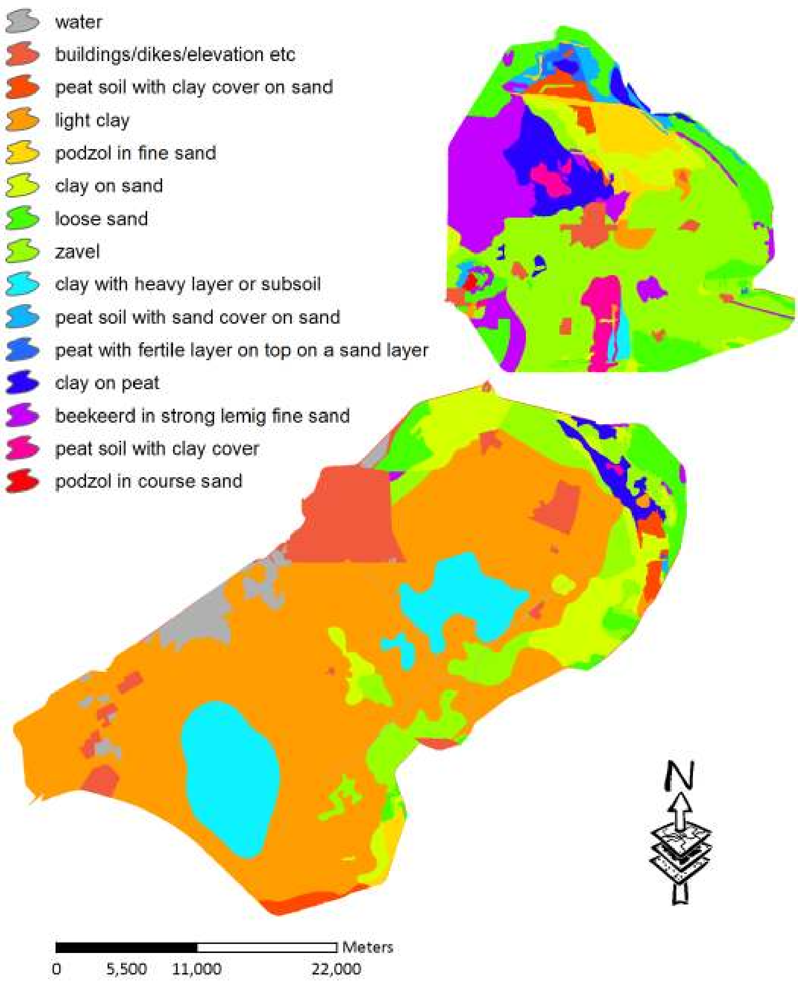


Figure 3.10 – Soil map of Flevoland (source Water Resources, TU Delft)

3.10 Precipitation

As stated before soil's moisture is a dynamically complex issue with various factors to contribute in the final observed result. The most obvious of them is undoubtedly precipitation. Precipitation can be responsible for the wetness of extensive areas depending on its intensity, frequency and duration. Its impact cannot be isolated neither over weighted to the rest of the sources but balanced as an additional parameter. In order to estimate precipitation's contribution to soil's wetness, we need to acknowledge beforehand two things. The first one is the amount of precipitation at the day of images acquisition and the second one is rain's profile for a predetermined period before images' dates. To avoid ambiguities we set this period to two weeks, a reasonable interval in order to detect protracted or not precipitation.

The geographical locations of the meteorological stations are shown in figure 3.11. It would be more beneficial to have daily measurements from more stations, for the assessment of precipitation but no further data were available. Additionally the radar of the national weather agency (KNMI) in 1995 was not functional for technical reasons.

Figure 3.11 – Spatial distribution of the meteo stations considered for the study

As it will be explained later June was decided as the most appropriate month for irrigation's investigation. On the 25th of June of 1995 when the image was taken there was no precipitation at all. In that case we can exclude with certainty the effect of rainfall that specific date. Indeed, that was expected since the satellite image must have been captured during a cloud free day when rain was absent. On the contrary two weeks before the 25th of June there were many rainy days. The amount of precipitation which was recorded by the meteo stations is presented on Appendix C. After the interpolation of rainfall's values, a precipitation map for the two weeks period in advance has been created. In that way we could estimate the impact of precipitation to the wetness of the various plots.

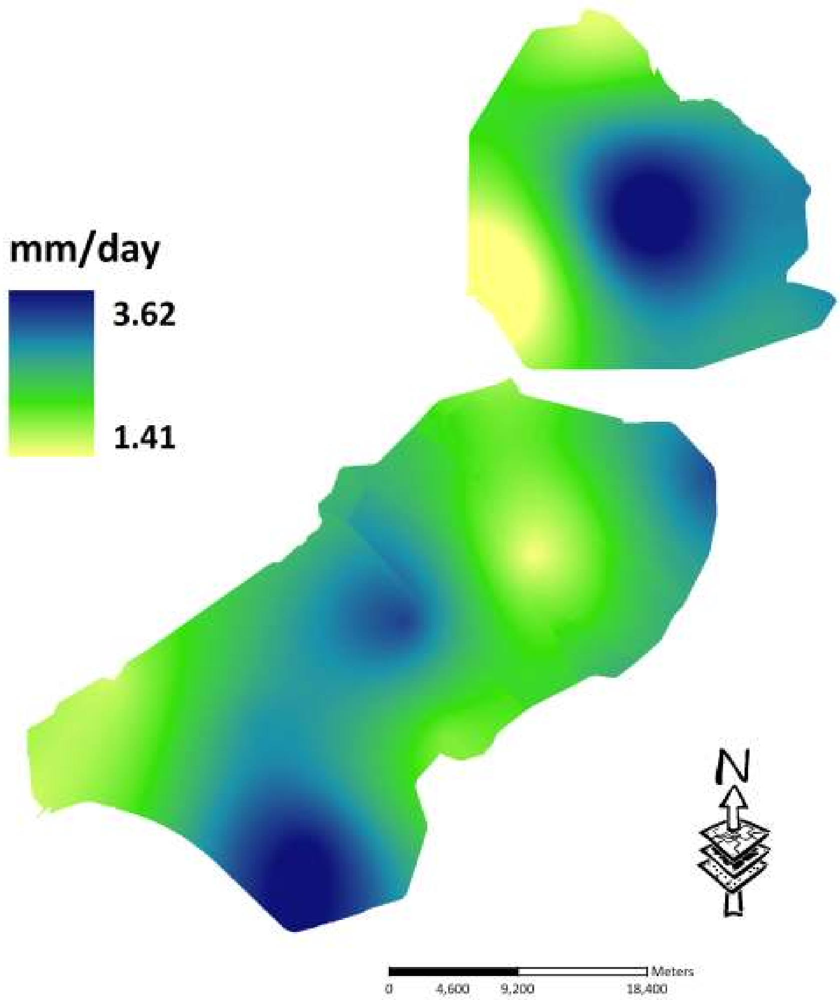


Figure 3.12 - Precipitation map for the period 11-24 June, 1995

4. Methodology and results

4.1 Introduction

One of the numerous possibilities a GIS platform can offer is the capability to extract information from various data sources which prior to GIS analysis were not visible. For example you may start from a certain point with a number of data and after the analysis you come up with information which was not apparent in the initial data sources. This situation is more or less the context of the following data analysis. Specifically, it will be attempted to develop a decision making model which will be based on certain data sources. These various data sources after analysis are expected to reveal further information which deciphers whether certain plots are irrigated or not. As it is shown in the figure below data will be handled as different layers in a GIS environment with ultimate goal the revelation of irrigated land.

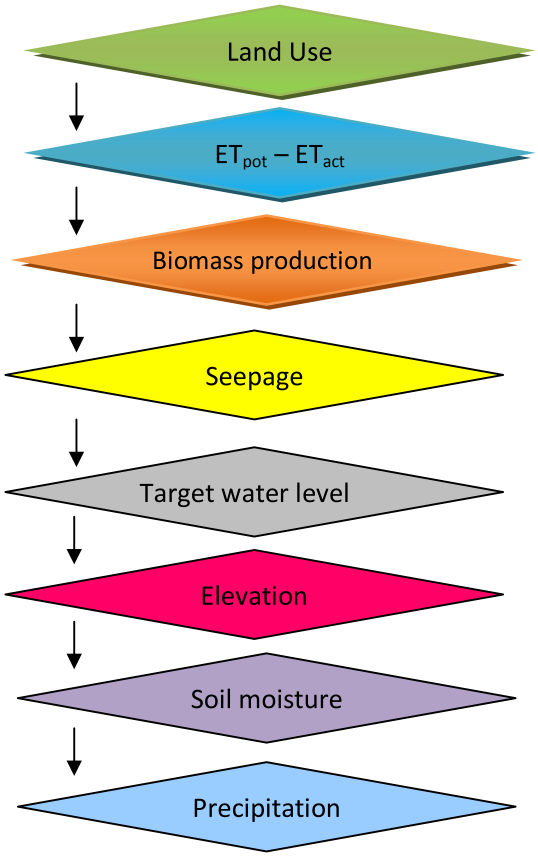


Figure 4.1 – Schematic representation of data manipulation

4.2 Crop water deficit

One of the first parameters calculated during the analysis was the deficit evapotranspiration (ET_{def}) or crop water deficit. ET_{def} is amongst the most commonly used indicators for irrigation performance besides irrigation efficiency, relative evapotranspiration, relative water supply, water productivity etc. Knowledge of soil's condition with respect to moisture for every plot in the area, independently of the cultivated crop type, considered essential for the beginning. In that way, it would be possible to distinguish between wet and dry plots or in other words, areas where crops have sufficient water to cover their needs, rather than being water stressed. Therefore an ET_{def} map would illustrate pixels which are wet, dry or in an intermediate situation.

For the more analytical description of wet and dry pixels, figure 4.2 is presented which characteristically illustrates the behavior of each component of the land surface energy balance, under different conditions. Every distinct quantity is denoted with different color and the size of each arrow declares the correspondence between unlike conditions. The only constant parameter is the incoming solar radiation, while the rest are changing in each occasion. Dry pixels show characteristically smaller evapotranspiration rate than wet ones. Additionally the sensible heat is greater in dry than in wet pixels.

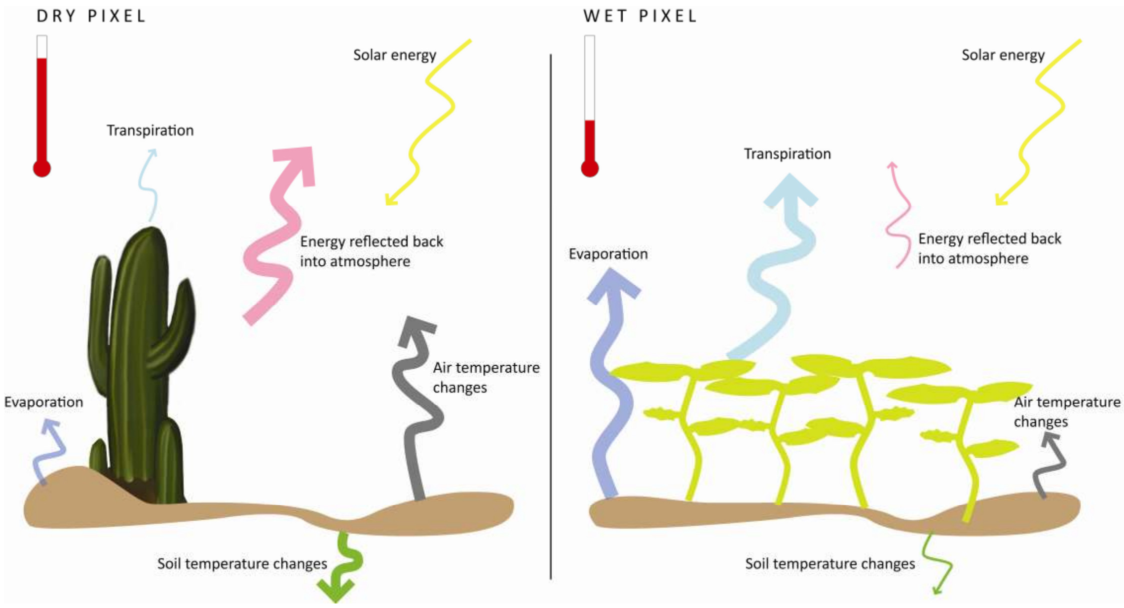


Figure 4.2 – Schematic representation of the land surface energy budget for wet and dry pixels

ET_{def} is a reliable and straightforward indicator of soil's moisture. It can be easily calculated from the actual and potential evapotranspiration as follows:

$$ET_{def} = ET_{pot} - ET_{act} \tag{4.1}$$

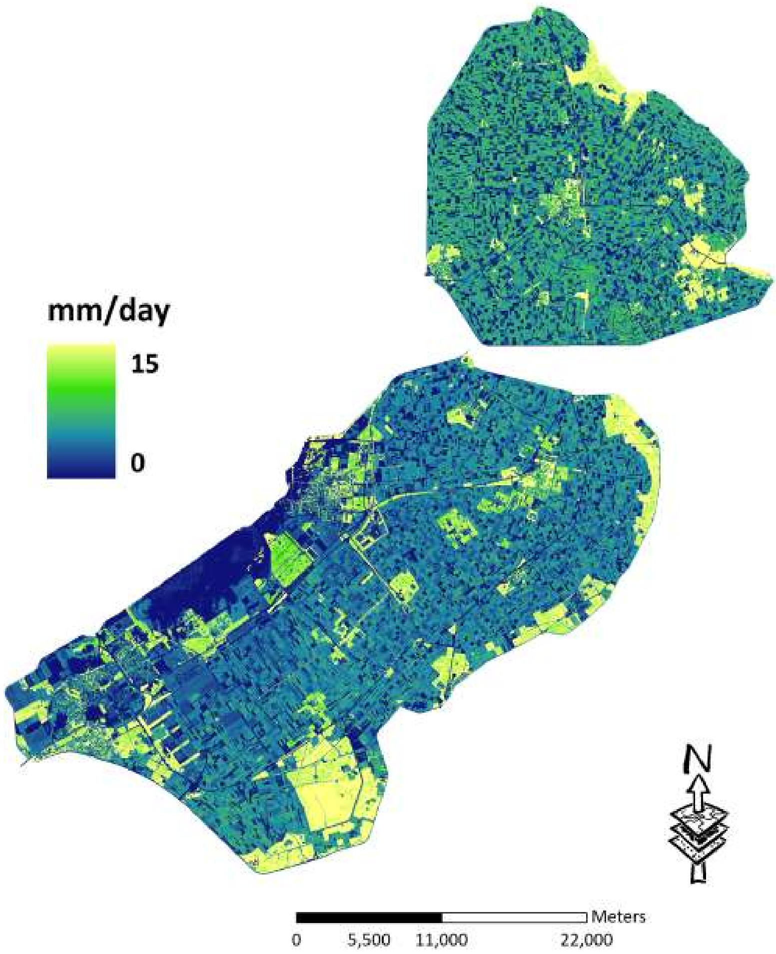


Figure 4.3 - ET_{def} map - 25th June 1995

The first thing it is assumed as long ET_{def} values are not 0 (pristine conditions), is that crops are experiencing water shortage. It should be stated clearly, that crops' water deficit is only related to that shortage of water. This shortage can fluctuate from being minimal to being quite extensive and crops experience water stressed conditions. In other words we encounter conditions where crops grow normally and on the same time environments where soil and plants are totally dry. Nevertheless ET_{def} values close to 0 imply that the rate of evapotranspiration is high and crops grow in almost pristine conditions. For June 1995 ET_{def} values were calculated (on a pixel by pixel basis) for each plot of each different crop type considered in the study, allowing us further to distinguish between wet and dry areas based exclusively on satellite data (figure 4.3).

4.3 Elevation – Target water level

Topography with all its variations and knowledge of the maintained summer water level in the polders are useful information in order to understand thoroughly the prevailing conditions. On the framework of the analysis these two different datasets become more revealing whenever they are combined. Particularly, it is very important to acknowledge the effect of the maintained target water level to the soil moisture. This information can only be deducted when the difference between the elevation and the maintained water level is calculated.

The newly created map illustrates accurately the distance of the top soil layer (crops root zone) to the water table level. In other words we can distinguish areas where soil's moisture is strongly affected by the maintained water level while others not. In addition we must bear in mind that all crop types within the area are typically agricultural, meaning that their rooting system cannot be extended more than 0.5 – 1 m below ground. For example when a crop's root system lies 3 meters above water's level then this is hardly influenced by water.

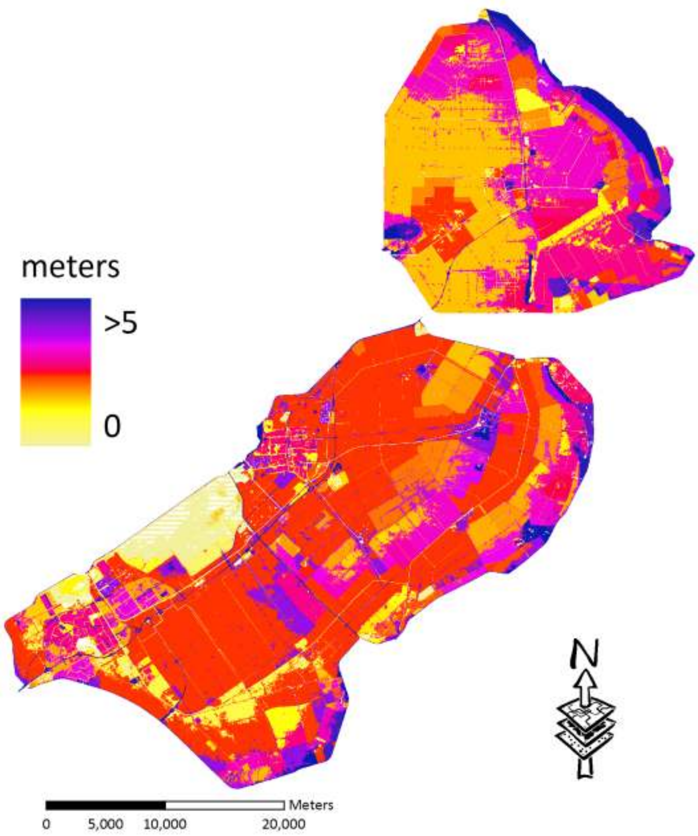


Figure 4.4 – Map showing the variation in differences between the elevation and maintained water level in the drains

4.4 Selection of crop types

The selection of suitable crop types, for which irrigation will be investigated, should be done carefully and meticulously. Inevitably, this implies the usage of *a-priori* knowledge for common irrigation practices in the area, by farmers. It wouldn't make sense for instance, to investigate irrigation for a certain crop type e.g. sugar beets when these crops are never irrigated. The reasons for such practices could be various; presumably adequate wet conditions in the area could be one possible explanation.

According to the land use map of the area, the most interesting crops from an irrigation point of view, which considered for the analysis, were:

- Potatoes
- Flower bulbs
- Maize
- Beets (sugar)
- Wheat
- Orchards
- Other arable crops

Without the use of a-priory knowledge for the common irrigation practices in the polders, it would be risky to initiate the analysis having just in mind that all the crops are potentially irrigated. And this proved accurate, as from the selected seven crop types only four of them are irrigated on a (more or less) regular basis. Specifically, it was revealed that maize, sugar beets and wheat are never irrigated by farmers. Present moisture in the area seems enough to cover crops' needs and to preserve high levels in the annual production. This consideration was also approved by local irrigation managers of the polders who confirmed the final crop selection.

On the other hand the classes of potatoes, flower bulbs, orchards and other arable crops are all of them irrigated. The intensity of irrigation is subject to each different crop type. For example, the majority of flower bulbs are always irrigated and this is supported by the fact that flower bulbs have very high economic value (e.g. 5 – 8 times more than potatoes). Consequently farmers in order to protect plantations and ensure that no losses will occur within their yield, they tend to irrigate regularly. Moreover, a-priori knowledge by authorities revealed that approximately a 25-35% of potatoes plots are also irrigated. Even if the accuracy of this percentage is questioned, it remains a sufficient indicator of applied irrigation. Other arable crops, as described before, consist mainly of onions, carrots, chicory and cabbages which are also usually irrigated for the largest part of them. Additionally it became known that all farmers who cultivate orchards (mainly apple trees) have installed drip irrigation systems. This fact by itself provides an extra reason to investigate whether these installations are actually used or not by farmers.

4.5 Temporal framework

Another important sub-question which needs to be answered, on the framework of this study, is *when does make more sense to investigate potential irrigated plots and on which parameter this decision should be based on*. It is rather obvious that if certain agricultural crops are irrigated, this would certainly be during their growing season when plants need sufficient water for their development. In general terms the period between April to August is in correspondence with the previous rationale but we should expect beforehand not all months to be informative with respect to irrigation.

So at this point, the challenge would be to distinguish within the same month and the same crop type different levels in soil moisture, indicative of potential irrigation. For example if we select June potatoes and we observe significant differences in soil's moisture then some of the plots must have been irrigated while others not. In order to do that, we need a parameter which is indicative of soil's moisture and consequently reveals different irrigation practices within the same crop type. This parameter is crop's water deficit (ET_{def}) and is the optimal choice given the available data sources. It is important to mention that ET_{def} as an indicator of soil's moisture bears some uncertainty, whether crops are irrigated or not, but with the support of a-priory knowledge for irrigated or not crop types, we can expect safer results.

To make things more concrete we refer to the examples of potatoes and flower bulbs (figure 4.5). Comparing the distribution of ET_{def} values, between successive months of May and June of 1995, we immediately notice differences in soil's wetness. Along the horizontal axis lie the various ET_{def} values, while on the vertical are the number of plots per crop type. Particularly, on May the majority of ET_{def} values are close to 0, without significant fluctuations. Thus the difference between ET_{pot} - ET_{act} is minimal. With a distribution like this it not likely to distinguish potentially irrigated plots. Additionally, the origin of wetness, at this stage, is impossible to be recognized with certainty but only conjectures can be made. On the other hand, June appears significantly more revealing. There is a noticeable group of plots which are dryer than others, allowing us to believe that the reason for this might be irrigation. In that way, it makes more sense to investigate irrigation on June rather than on May. For July and August of 1995 the distribution of ET_{def} values is similar to May's, both for potatoes and flower bulbs fields (Appendix D). Similarly was the situation for orchards and other arable crops which appointed June, as the most appropriate month, for irrigation's detection.

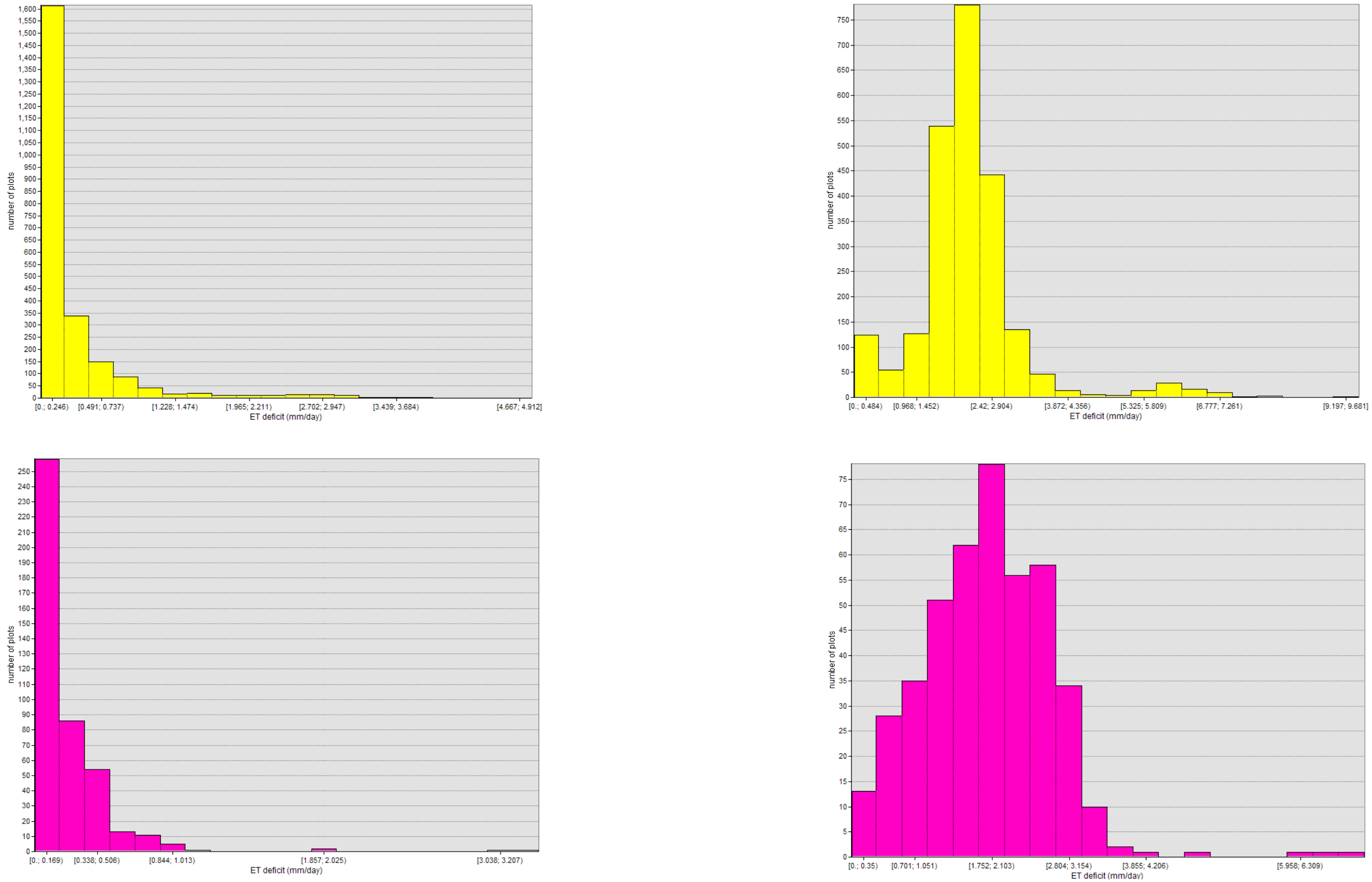


Figure 4.5 – Histograms of ET_{def} (mm/day) values for potatoes on 24th May (top left), 25th June (top right) and flower bulbs (bottom left and right) respectively

4.6 Data classification

On chapter 3 it was made clear that a significant amount of heterogeneous data will be shuffled in order to facilitate the distinction between irrigated and non-irrigated plots. This diversity of these data sources besides its valuable information, it also bears the danger of confusion and mistaken manipulation. Since this danger was realized at early stages of the analysis, it was decided to classify all the involved data. The classification was performed in a way that supports the analysis and is based on the special characteristics and meaning of each dataset.

All data sources were assigned to two basic categories, namely *primary* and *secondary* data. The category of primary data consists of the land use, the actual and potential evapotranspiration and finally the biomass production. As it is easily realized these data are direct products of Landsat images (land use map is also composed from satellite images). On the other side the category of secondary data is composed of maps of seepage, elevation, soil type, precipitation and the summer target water level as maintained by water boards of the area. The rationale behind this categorization is to combine and assess the information provided by satellites with other auxiliary water-related information.

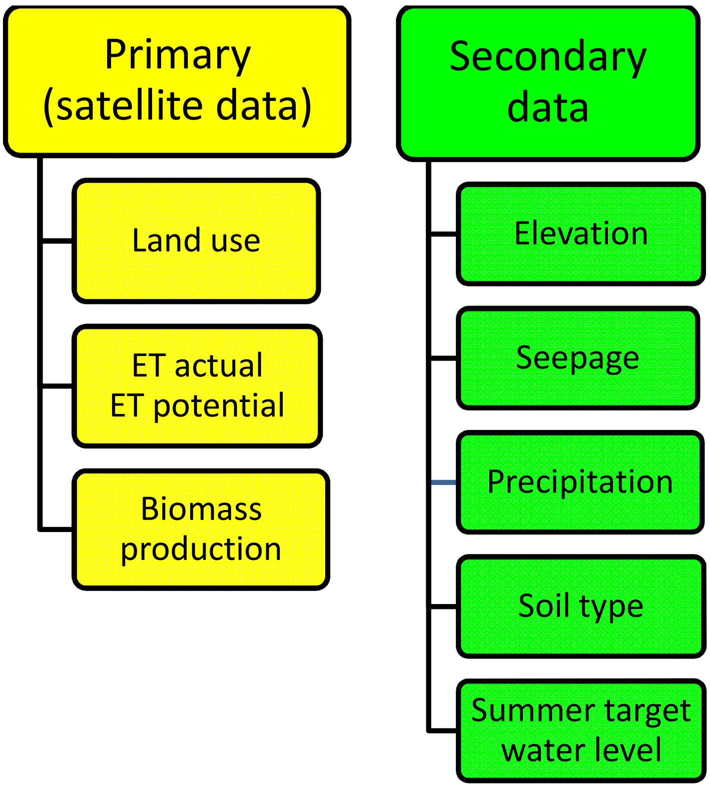


Figure 4.6 – Schematic representation of data classification

4.7 Methodology and results

4.7.1 Introduction

Before the description of the followed methodology, it is essential to clarify that answering whether certain plots are irrigated or not is not just a matter of yes or no. Satellite data may have the potentials to demonstrate wet and dry areas but the further interpretation of these zones is a vacillating issue. For example, it is possible certain locations to appear wet and the reason for this wetness to be high seepage values or precipitation. Normally this situation would comfort a farmer and relax him from the task of irrigation but finally whether he will do it or not is an issue that cannot be fully enlightened.

Dealing with a considerable amount of data sources, like it is the case in the current study, means automatically two things. Firstly it is assured that a large amount of diverse information can facilitate the analysis, providing multiple perspectives of the same area. Secondly it is very likely to get lost and encounter difficulties when manipulating data. In order to keep things tight and under control, a structured approach was considered for the analysis of data. The proposed methodology attempts to integrate all the necessary sources of information in a combined way in order to shed light, primarily on the issue of irrigation in polder areas, and secondly to quantify the amount of water which is actually used for irrigation by farmers.

The proposed methodology will be developed in two steps; the identification of wet and dry plots and following the identification of wetness origin. Primarily it is based on three parameters and these are:

- Land use
- Deficit evapotranspiration and
- Biomass production

4.7.2 Identification of wet and dry plots

After selecting suitable crop types and the temporal framework to investigate different irrigation practices, it is time to map polders according to wet and dry areas. This is the first and logical step to follow when irrigation is the issue. It is necessary to distinguish between wet and dry plots, independently of wetness or drought's origin. The driving factor in order to accomplish that would be the deficit evapotranspiration which is an excellent indicator of soil's moisture. Within each studied crop type there are certain plots which exhibit extremely small ET_{def} values (wet plots) while others significantly large (dry plots). One of the possible explanations for these differences is irrigation for which we are interested in.

Even though ET_{def} solely is a strong and reliable indicator of soil's moisture, it is rather tedious when it comes to the point where a certain threshold should be defined, which distinguishes between wet and dry plots. It proved that this threshold cannot be defined based only on ET_{def} values, since except from extreme differences e.g. 0.2 and 9 mm/day, the remaining ones cannot be classified with certainty. That problem is clearly realized if we consider the distribution of potatoes ET_{def} values on June 1995 (figure 4.7 and table 4.1). The same situation applies also for the classes of other arable crops, flower bulbs and orchards.

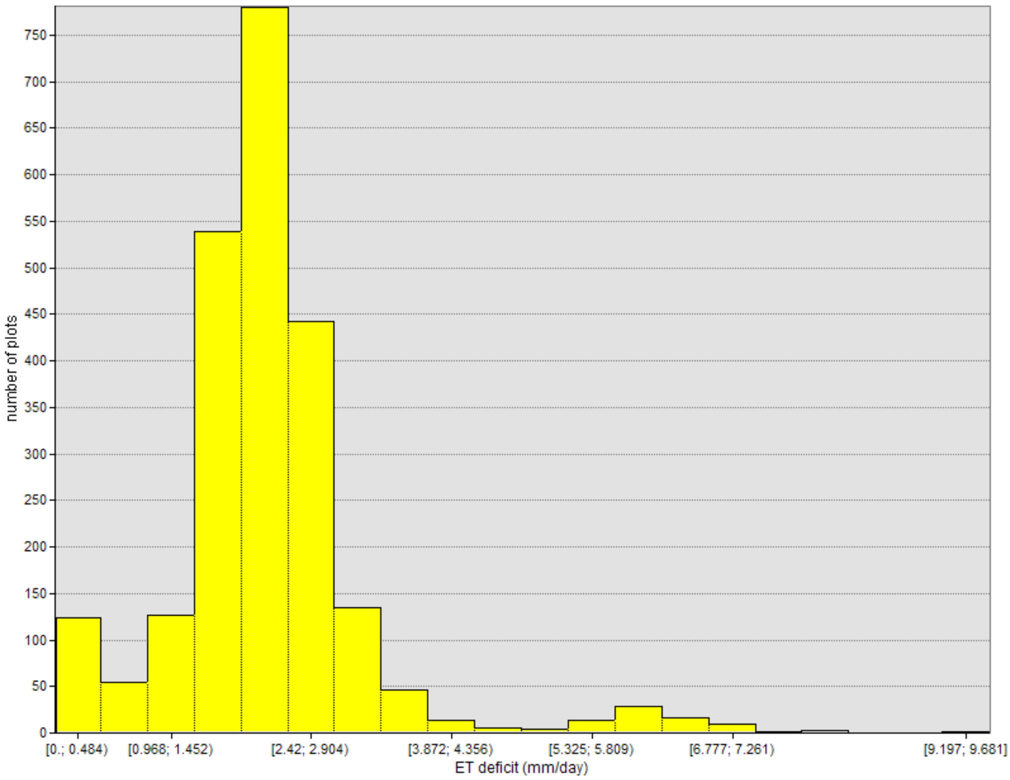


Figure 4.7 – Histogram of potatoes ET_{def} values – June 1995

Table 4.1 – Potatoes ET_{def} values - June 1995

Number of Plots	**ET_{def} (mm/day)**	**Number of Plots**	**ET_{def} (mm/day)**
124	(0 - 0.484)	5	[4.356 - 4.841)
54	[0.484 - 0.968)	4	[4.841 - 5.325)
127	[0.968 - 1.452)	14	[5.325 - 5.809)
539	[1.452 - 1.936)	29	[5.809 - 6.293)
780	[1.936 - 2.42)	17	[6.293 - 6.777)
443	[2.42 - 2.904)	9	[6.777 - 7.261)
135	[2.904 - 3.388)	2	[7.261 - 7.745)
46	[3.388 - 3.872)	3	[7.745 - 8.229)
14	[3.872 - 4.356)	2	[9.197 - 9.681)

Consequently, an extra parameter is necessary which could support ET_{def} and simultaneously facilitate the distinction between wet and dry plots. This parameter is biomass production, which is directly related to crop's growth and therefore to crop's water excess. For every ET_{def} plot value there is a corresponding biomass production one.

For the classes of potatoes (figure 4.8) and other arable crops (Appendix E) biomass production values (vertical axis) are plotted versus ET_{def} values (horizontal axis). The first thing one notice on those diagrams is that after a certain ET_{def} threshold biomass production values begin to decline while ET_{def} values increase. This is translated to the fact that biomass production reduces as long less moisture is available for crops. So as suspected from the beginning there is an inverse relationship between these two parameters.

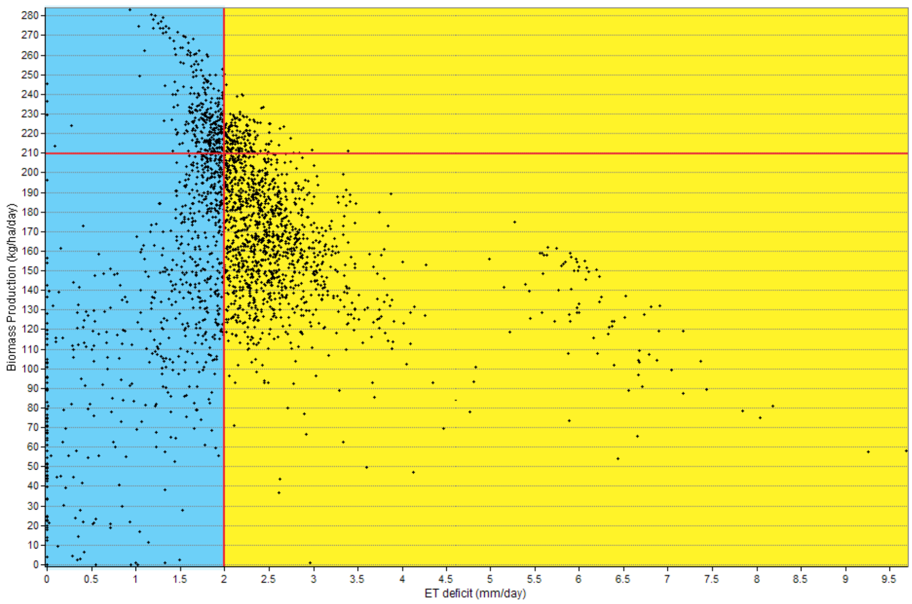


Figure 4.8 – Biomass production vs. ET_{def} values for potatoes on June 1995

In order to define that ET_{def} threshold we assumed the following: '*from the maximum range of the biomass production values (prosperous yield of wet plots) we accept a 10% reduction. After that 10%, farmers logically will begin to irrigate (the potentially dry plots) in order to preserve high production and reduce losses'.* Therefore, from the bio_{max} values we subtract the 10% which corresponds to accepted losses. Here it is mentioned that some extremely high values of biomass have not been taken into consideration as they probably are outliers. Potatoes bio_{max} was around 230 (kg/ha/day) and after 10% reduction dropped to approximately 210 (kg/ha/day). Many plots with different ET_{def} correspond to this biomass value, so the mean ET_{def} was selected. This $ET_{def/thr}$=2 (mm/day) is the threshold after which potatoes plots are considered dry and before that wet, based on Landsat satellite data. On figure 4.8 the yellow framework consists of plots considered dry, while on the blue plots considered wet. A graph of the same shape was also the result when values of biomass and ET_{def} were plotted for the class of other arable crops (Appendix E). The same assumption as previously was made and the resulted $ET_{def/thr}$=2 (mm/day) was considered as the threshold for the selection of wet and dry plots.

Regarding to the classes of flower bulbs and orchards the relationship between biomass production and ET_{def} was not as clear as before. The shape of the plotted values was somehow different and as so not applicable to the previous assumption. Luckily, the comfort news for these classes was the existence of a-priori knowledge with respect to their applied irritation practices.

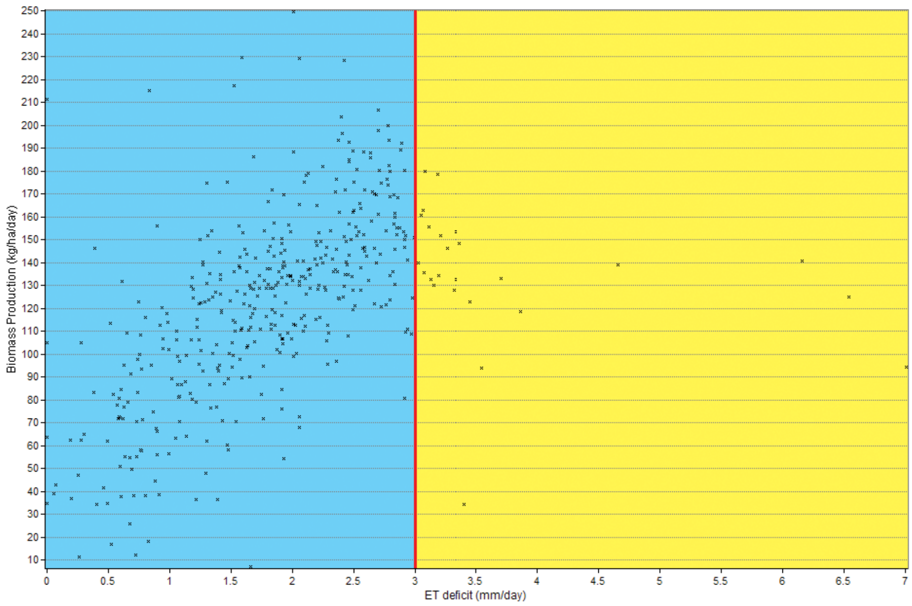


Figure 4.9-Biomass production vs. ET_{def} values for flower bulbs on June 1995

Field knowledge and experience pointed that all orchards (apple trees) are equipped with drip installations which are used on a regular basis. Furthermore flower bulbs are also irrigated permanently by farmers due to their importance as highly valuable species. For that reason it was decided to accept for both classes increased thresholds for ET_{def}. Consequently, for flower bulbs $ET_{def/thr}$ was set 3 (mm/day) and for orchards to 5 (Appendix E). As realized defining ET_{def} thresholds is a sensitive procedure which requires meticulous consideration. All the above decisions can only be fully approved after being validated. Figure 4.10 illustrates the locations of wet and dry plots after applying the selected thresholds. Our interest is focused only on wet, thus we discarded dry plots. The next challenge now would be to detect which of these wet plots are potentially irrigated by farmers and which not.

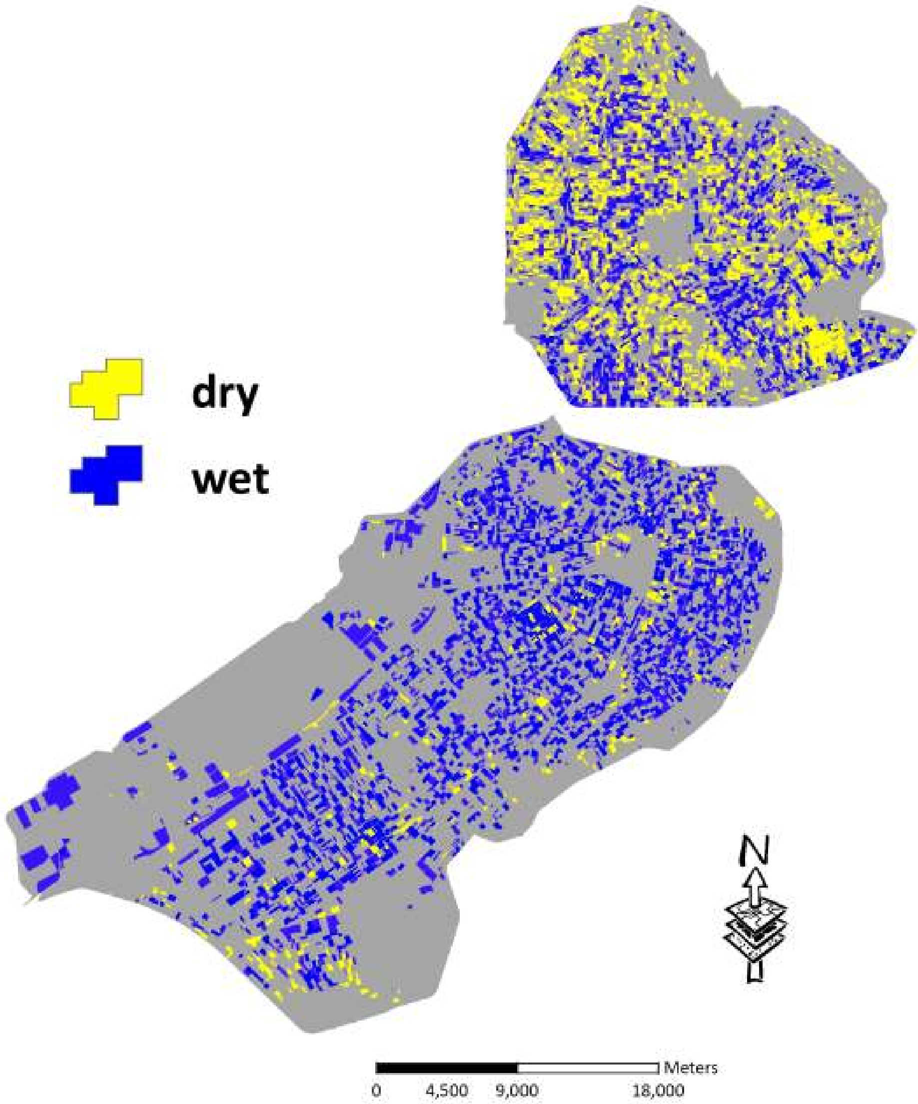


Figure 4.10 – Final map of wet and dry plots for all the classes considered in the study

4.7.3 Identification of wetness origin

The next equally important step for the analysis is the identification of wetness source. Wet pixels appear wet for some reason and this reason is vitally necessary to be identified. Consequently two critical sub questions need to be answered. The first one relates to the inventory of all wetness's contributors in the area and the second one relates to the development of a method which allows (if that is the case) the recognition of irrigation as the master responsible for soil's present moisture.

With respect to the former question as it can be seen at figure 4.11 ,the major sources which potentially contribute to plots (on a pixel basis for the analysis) moisture are seepage, rainfall, the maintained target water level in the drains, soil moisture and finally irrigation. For soil moisture it is implied the potential capability of the soil (depending on various soil types) to retain water or not and thus affect the final wetness profile. Moreover with respect to rainfall, it is considered a period of two weeks before the date of the image capture, so if rainfall is the case then it will be assessed in a safe mode.

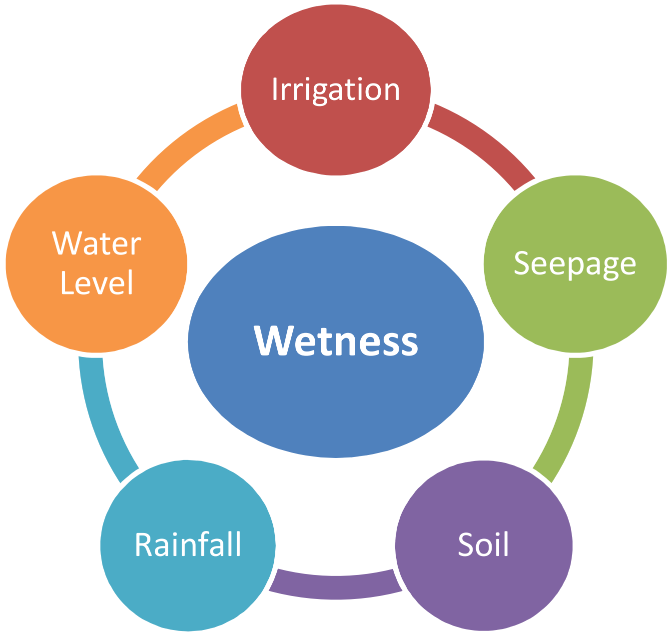


Figure 4.11 – Schematic representation of all potential sources of soil's moisture

At this point it should be clarified that the above wetness sources are indicative for Flevoland's polders but does not necessarily correspond to every agro-ecosystem around the world. As stated before Flevoland's polders exhibit some special relationship with irrigation since water is in abundance in the area.

But how can one attribute irrigation as the main contributor to crop's wetness without defying the rest? Irrigation can be appointed as wetness' origin, only when inferred as a residual from the main wetness contributors. For instance, if a certain area appears wet based on ET_{def} values (Landsat data) and the impact of all the other possible sources is set to minimal, then irrigation is the most likely answer. In that way irrigation can be identified, mapped and further investigated without ignoring the remains.

Clusters formation

Cluster analysis is an exploratory data analysis tool for solving classification problems like the one encountered here. Specifically, clustering is the classification of data (or objects) into different groups or more precisely, the partitioning of a dataset into subsets (clusters) so that the data in each subset (ideally) share some common characteristics. In fact it provides a convenient analytical tool for the classification, correlation and assessment of all soil's wetness sources.

So far we have come up with certain plots, which according to Landsat data are wet. Intentionally, for the moment we leave irrigation aside, and we deal only with the remaining sources of soil's wetness. For the purpose of the study it is necessary and effective to balance the impact of each source independently and simultaneously with each other so in the end an illustrative wetness profile would be produced for the study area.

When examining seepage, precipitation and elevation - water level values we clearly observe that their range support dry, wet but also intermediate soil conditions. An exact distinction of these values without previous geo-physical analysis was not possible; therefore it was decided to form three equally divided clusters by ranking each dataset from the smaller to the bigger occurrence. In that way we ended up with three equally proportional classes which support dry, intermediate and wet soil conditions. Each class was assigned a unique value of 0, 1 and 2 respectively.

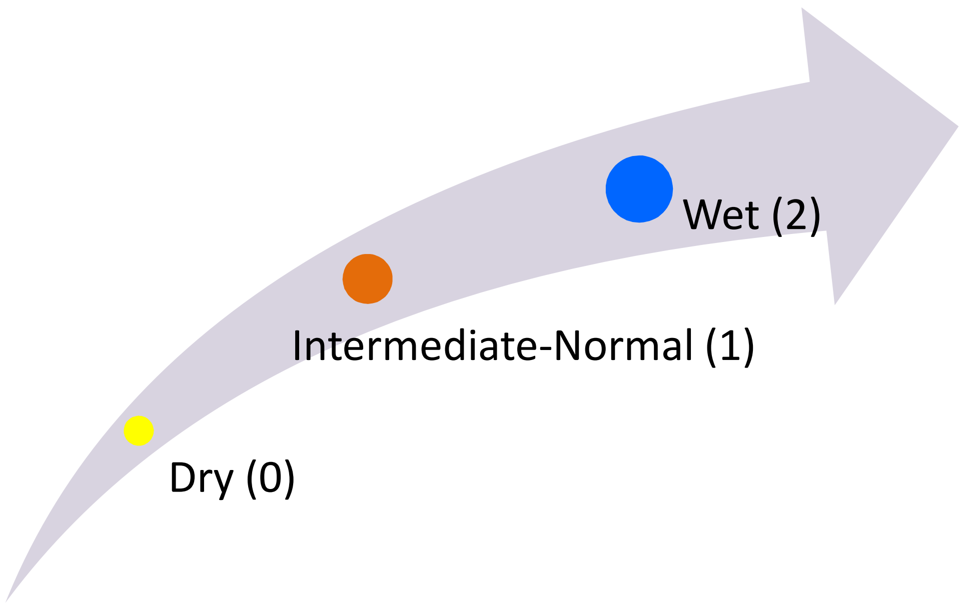


Figure 4.12 – Schematic representation of the clusters which support respectively a) dry b) intermediate – normal and c) dry soil conditions

After the reclassification of the original datasets (maps) of seepage, precipitation and elevation – water level, we could derive new thematic maps, composed each one of three classes. Consequently each plot now has been categorized to a certain wetness level group. Differently, from the previous three sets of interval data, the soil map of

Flevoland was consisting of nominal data (soil types). These data were also reclassified into three classes; each one representing soils which potentially support dry, intermediate and wet conditions. The results of the above described classifications for the whole area are presented in figure 4.13.

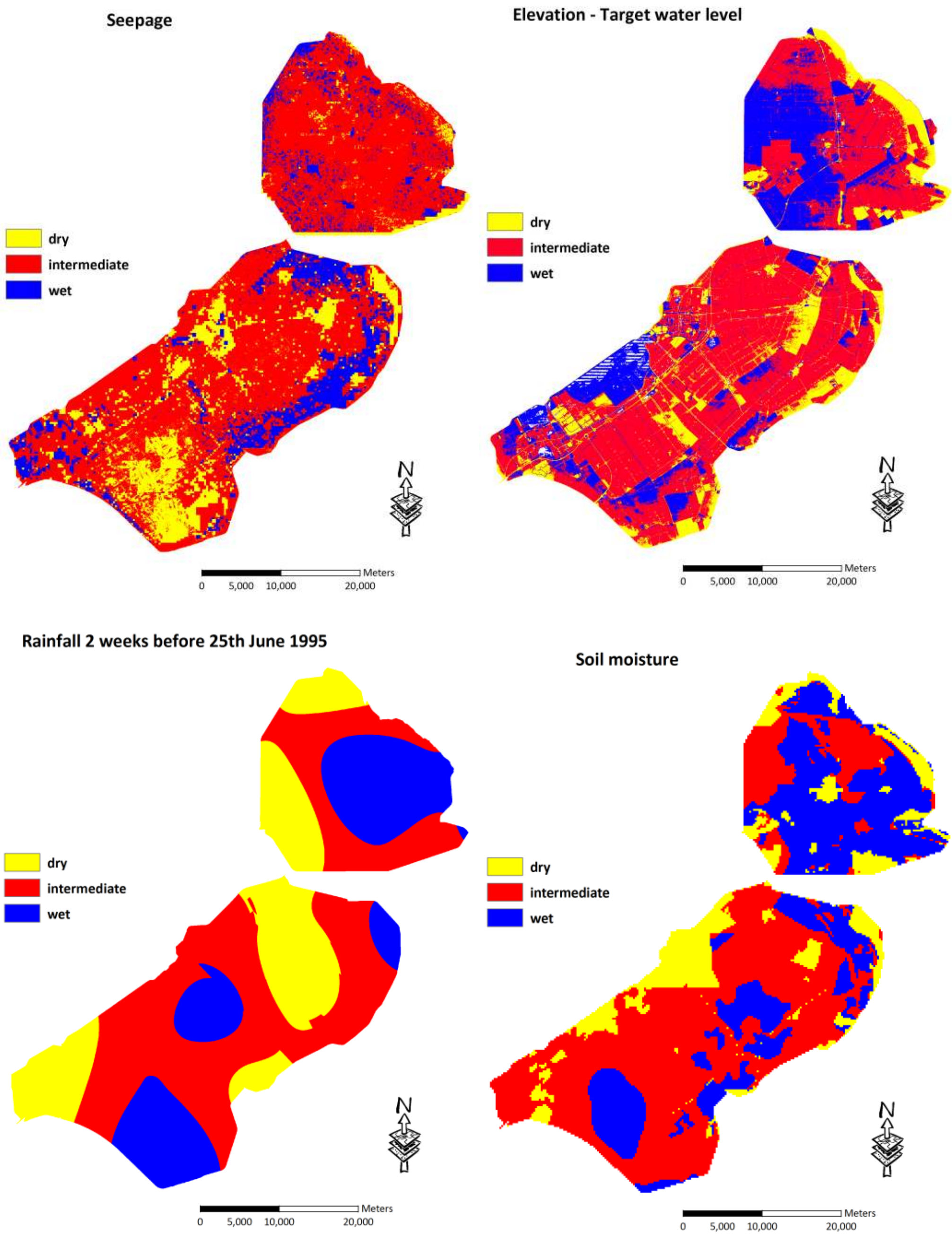


Figure 4.13 – Thematic maps of the potential wetness sources for 25th June 1995

These new maps constitute the key elements, for the production of one final irrigation map for each separate crop type. This could be accomplished by adding the four thematic maps into a new one, which consists of 9 distinct classes ranging from 0 to 8 and expressing different levels of potentially irrigated or non plots. Therefore, the impact of each distinct wetness source to the final soil profile can be assessed in an integrative way.

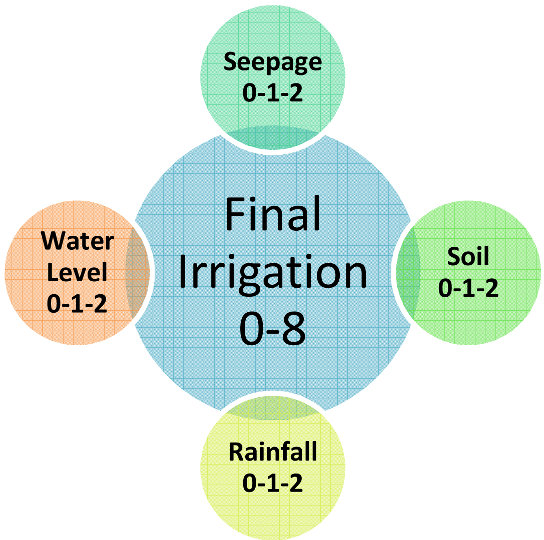


Figure 4.14 - Followed scheme for the production of the final irrigation map.

This approach is applied to each separate crop type so in the end we can estimate the total number of farmers who potentially irrigated their plots. On the other hand an overall estimation for both polders is also necessary with respect to the total number of irrigated plots. The final irrigation map which includes all the considered crop types for the area is presented in figure 4.16 while the ones regarding each crop separately on Appendix F. To illustrate the followed procedure better we refer to potatoes where by adding up the four key elements (figure 4.15) we can produce one final irrigation map (Appendix F).

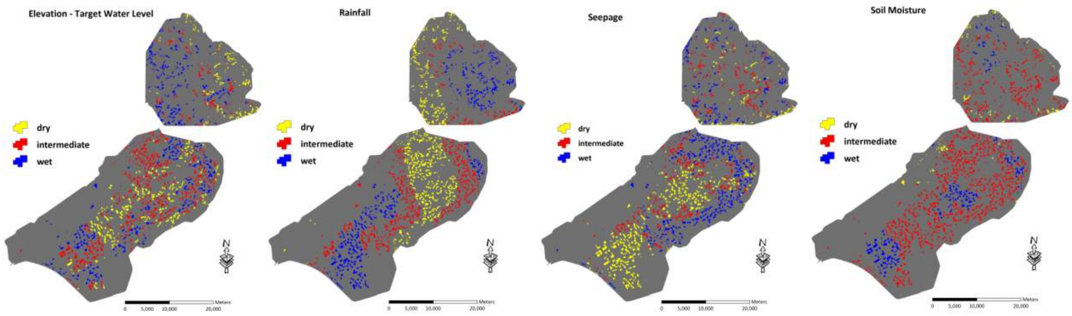


Figure 4.15 – Adding the four soil wetness sources

This final irrigation map manifests clearly the potentially irrigated and non plots. The class attributed to 0 corresponds to potentially irrigated areas (plots) while 8 to potentially non-irrigated. The in-between classes as ascending from 0 to 8 represent areas where we could expect less and less irrigated plots based on the assessment of the available sources.

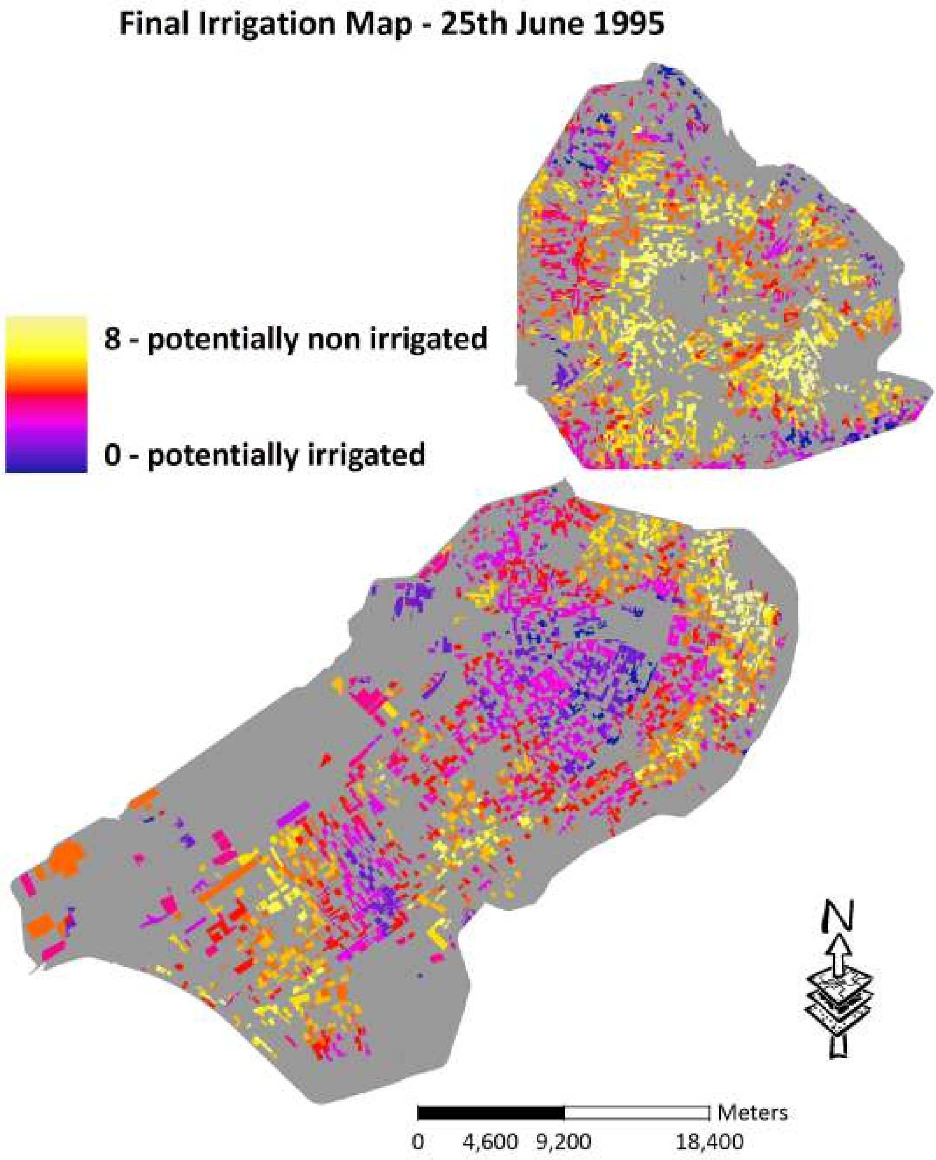


Figure 4.16 – Final irrigation map of the four different agricultural classes at Flevoland's polders on 25th June 1995

4.8 Water volume

So far we have managed to estimate which farmers have been irrigating on 25th of June 1995 when the satellite image was taken. In the final irrigation map we can clearly distinguish areas being potentially irrigated while others not. Consequently the developed decision model seems able to reciprocate to the major challenge of the current study. After that it would be beneficial if we could estimate the volume of water which was used for the irrigation of these plots. In that way the whole analysis would be more efficient since for the first time in the area irrigation water could be expressed with concrete figures. Simultaneously water authorities they could combine their field experience with volumetric estimations of irrigation for both polders.

For the quantification of the amount of water which corresponds to irrigation two major problems are considered. The first one relates to the validation of any calculated water volume with field or other related data, since at the moment no record exists. This is important since an indicative comparison could shed light whether our model simulates reality accurately or not. Secondly a number of assumptions are necessary if we wish to quantify the water from irrigated plots. Final results illustrate crops situation for a single day in June of 1995 for which also volumetric calculations will be applied.

In order to proceed we need to combine the results of the analysis with some data of the initial sources. As mentioned previously ET_{def} is a strong indicator of soil's moisture. Values close to 0 (mm/day) indicate highly wet conditions while greater values e.g. 7 (mm/day) are indicative of drought. Farmers always irrigate with one goal; to keep plants and their environment wet so their health and growth will not be affected. Therefore we assume that farmers irrigate their plots with an amount of water such that ET_{def} reduces to 0.5 (mm/day), level which ensures wet desirable conditions for growth.

Moreover from the final irrigation map for both polders (figure 4.16), plots have been classified to 9 distinct classes ranging from potentially irrigated to non-irrigated. We further assume that half of these classes ranging from 0 to 4 are surely irrigated. For these classes we will attempt to estimate the volume of water used for irrigation.

The total area of each plot is known as soon as we know the correspondent number of pixels per plot. Each pixel represents an area of 0.0625 ha, thus enabling us to easily calculate any requested area. Each plot belonging to one of the classes 0-4 is attributed with a computed ET_{def} mean value. The deviation of each $ET_{def/mean}$ from the 0.5 (mm/day) corresponds to the average amount of water a farmer irrigates. So from all the irrigated plots (of all crop types) we subtract 0.5 (mm/day). The resulted ET_{def} from irrigation when multiplied with the number of hectares (area) per plot reveals the amount of water delivered from irrigation for the 25th of June 1995 (table 4.2).

Irrigation efficiency

Irrigation engineers when designing an irrigation system they usually try to maximize the irrigation efficiency. Irrigation efficiency is defined as the ratio of the volume of water that is taken up by the crop to the volume of irrigation water supplied. At Flevoland polder two types of irrigation installations are mainly in use namely *mobile sprinklers* and *drip systems*.

Figure 4.17 – Drip system (left) and mobile sprinkler (right) installations

Drip irrigation systems have the potential to increase irrigation efficiency because the farmer can supply light and frequent amounts of water to meet crop's ET needs. In addition this system targets high accurately to the main root system of plants reducing therefore the losses. Extensive studies have shown that irrigation efficiency ranges from 80 to 90% when crops are irrigated with drip systems, as it is the case with orchards in both polders (Battikhi and Abu-hammad, 1994, Chimonides S.J., 1995). On the other hand, mobile sprinkles allow greater losses of water. Thus, irrigation efficiency for this kind of installations ranges from 60 to 80% (Chimonides S.J., 1995, Zalidis et al., 1997). For June 25th the water volumes which were consumed for irrigation are presented on table 4.2.

Table 4.2 – Volumes of water from irrigation

	Number of Irrigated Plots	**Irrigated (%)**	**Area (ha)**	**Irrigation efficiency (%)**	**Water Volume (m^3 day^{-1} ha^{-1})**
Potatoes	873	37.2	8654.87	70	83667.29
Flower bulbs	222	51.3	1062.31	70	10345.95
Orchards	52	44	1325.75	90	47232.28
Other arable crops	1284	37.1	8199.75	70	42983.49
Total	2431		19242.68		184229.01

On Appendix G detailed water volume maps are presented for each separate class. The proportional annotations illustrate better the water which was used by farmers in order to irrigate their land. From the above table it is concluded that at least half of the total plots of flower bulbs were irrigated on 25th of June 1995. The same applies also for the rest of the classes even though their percentages are slightly smaller.

5 Validation

5.1 Introduction

The absence of concrete data related to irrigation in polder areas, was initially one of the main reasons that triggered the current study. When it comes to the validation of the key findings, the same reason remains an obstacle and the developed model cannot be assessed for its accuracy. Field data which could validate the results could be either *quantitative* like volumes of water which correspond to irrigation, or *qualitative* like testimonies from water authorities or relevant organizations, which can provide an indication whether the findings correspond with their practice experiences.

Initially, it is very important and crucial to mention, that none of the related authorities to water management or irrigation, in the study area, had an exact or approximate estimation for the volume of water used in supplementary irrigation. The situation has been like that forever, probably because of the abundance of water in the area which frustrated local authorities from monitoring the water volumes used for irrigation. Until now the general climatic and agricultural conditions had not imposed urgent water management policies and the role of irrigation was always supplementary. Therefore, any possibility or attempt for quantitative comparison is impossible. This fact by itself constitutes the major limitation within the validation procedure.

On the other hand, what remains possible is to validate results qualitatively. This kind of validation, even though it is not the most accurate one, remains an alternative which cannot be omitted. Its reliability is subject to the knowledge, experience and frankness of the parties involved. After interviewing three water managers of both polders, it became clear that they are the most experienced and relevant representatives from which information should be extracted. The visited water authorities were:

- Water board Zuiderzeeland
- Regional water board office at Noordoostpolder
- Regional water board office at Flevoland

This kind of 'irrigation experience', can undoubtedly shed light to the findings of the current study and provide strong signs whether the final model performs well or guides to a wrong direction. The local water boards visited on May were extremely surprised by the fact that such an irrigation map had been constructed. Even though it referred to a period 13 years before, it sounded as a promising and helpful tool for water managers and farmers in the area. All the interviewed authorities, after a meticulous and careful examination of all the irrigation maps, concluded that these products correspond close to reality. The interesting part was at times when they could recognize certain plots and farmers who they acknowledged whether and how often they irrigate. They seemed surprised by how common maps can point who potentially irrigates and who not without having previous field knowledge and experience like theirs.

One of the first things that were made clear by the regional irrigation managers during the evaluation was that in 1995, irrigation in both polders originated mainly from surface water. The main reason for that is the favorable quality of surface water in comparison with the one coming from the ground. The latter one is brackish and salty due to the previous Zuiderzee (sea) and thus not preferred by the farmers in the area. Many farmers though today have their own wells, from where they can extract water to cover their various needs. In that way, ground water gives farmers more flexibility within their land. Unfortunately, the number of wells per plot is still not yet fully registered so only guesses can be made about them.

In general two types of potatoes are cultivated at Flevoland polders namely *seed potatoes* and *table potatoes*. Seed potatoes are mainly cultivated for the next year's production (serve as breeding materials), while table potatoes are those consumed within the same year of production. Nowadays, the ministry of agriculture forbids seed potatoes to be irrigated with surface water because of past disease incidents. There have been several infection incidents, and after 2003 it became mandatory to irrigate seed potatoes only with underground water. Moreover water boards ensured that almost none of the farmers had wells to extract underground water in 1995. Consequently, surface water can be considered as the dominant source of irrigation during the moment of images acquisition.

A direct question which rises with respect to the qualitative validation of the results is the following: '*since none of the local water boards have concrete volumetric figures to compare against, how can they deal with irrigation management?'*

Water boards are the ultimate authority, which control water supply irrigation. Every time a farmer needs to irrigate his land with surface water resources, he is obliged to ask for permission. In that way, water and irrigation managers know approximately how much water should be taken into the polder area. This is the current mechanism, with which irrigation managers supervise the water balance in the area. In the near future it is expected water boards to take over the responsibility for ground water from the Flevoland province. At the moment ground water is being managed by the province of Flevoland. One of their responsibilities is to record the number of wells which are owned by the farmers, and to estimate the total amount of water used for irrigation purposes. At the moment neither wells are fully registered nor do all farmers have meters to ensure accurate estimations. The province obliges farmers to pay 0.17 euros/m^3 after 20.000m^3 water consumption but this is impossible to be checked by authorities when they only rely on farmers' statements.

At the area of study, irrigation takes place mainly, through the following mechanisms:

- Mobile sprinkler systems
- Drippings
- Sub-surface drainage pipes

Surface water for irrigation in both polders is provided by water boards through surface drains (ditches). The water level in those ditches is arranged according to the needs. Consequently, mobile sprinklers and dripping systems extract water from these drains. Besides that many farmers have sub-surface drainage pipes. These are perforated pipes buried in the soil which end in ditches perpendicular to each plot. Initially they were installed to ensure the effective drainage of soil but simultaneously they serve as a means of water transport during periods of drought. In that way, crops have likely a more adequate soil moisture supply. For the validation of the results each polder was inspected separately. For that two reasons can be identified. One was that each polder belongs to separate administrative region and the other was that they constitute different systems from a hydrological point of view.

5.2 Northern polder (Noordoostpolder)

The first interview took place at the capital of Noordoostpolder, Emmeloord. At Emmeloord is located the regional office of water board. The reasons for contacting this authority are mainly the following:

- Direct responsible for the surface water irrigation management in the Noordoostpolder
- It is the official authority which provide permissions to farmers whenever they want to extract – use water for irrigation, hence they are aware of all the requests
- Fully aware of the number of farmers who cultivate irrigated crops within that polder, over the last 30 years

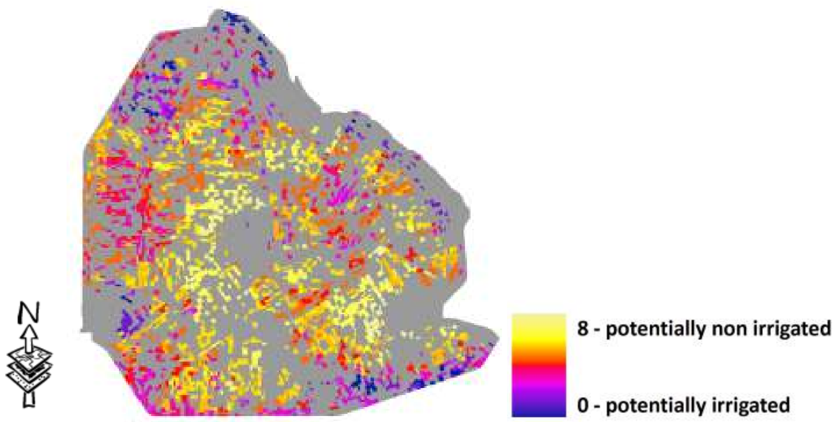


Figure 5.1 – Final irrigation map of all crops – Noordoostpolder

Water boards were asked to examine closely and meticulously the final irrigation maps and give their opinion based on their knowledge, experience and anything else that could be useful for assessing the results. They confirmed that all the peripheral part of the Noordoostpolder is indeed always irrigated on a regular basis by farmers. The final map also agrees with that as all the peripheral plots of the polder are blue, purple and red colored, having the highest chances of being irrigated. Additionally, they provided arguments in order to explain why these plots are always irrigated by farmers. The northern, eastern and southern peripheral part of the polder is composed mainly by sandy soils, as before the reclamation of land used to be coastal zone (beach). Sandy soils cannot retain moisture for long because of their drainage properties. This implies that crops grown on such soils need to be regularly irrigated in order to retain adequate wetness for their growth. This area is equipped with a sub-surface irrigation system. Sub-surface drains are used to transfer water into the soil. The area around Urk (south western part) appears to be dark colored for the same reason as Urk was previously an island (composed of beach sand).

Another important aspect is that water boards have installed *siphons* along the west and north boarder, in order to facilitate and provide farmers with enough and good quality water from the sea. These mobile siphons are located in various places on the dikes and allow the entrance of water automatically into the drains due to the different elevation between the polder and the sea level. This is the main reason why all the plots at the boundaries of the polder appeared dark colored. The excess water goes further inside the polder through drains and ditches, thus allowing the irrigation of plots located more to the centre of the polder. The remaining plots located around the centre of the polder are rarely irrigated either because of the limited availability of water sources, or the presence of clay and peat soils which can retain much more wetness than sandy soils, after intense rainfall.

In the final irrigation maps (figure 5.2), a clear irrigation trend can be distinguished starting from dark blue (potentially irrigated) to light yellowish plots (potentially non-irrigated), as we move from the area near the dikes to the centre of the polder. So near dikes we could always expect a greater number of irrigated plots than in the middle of the polder.

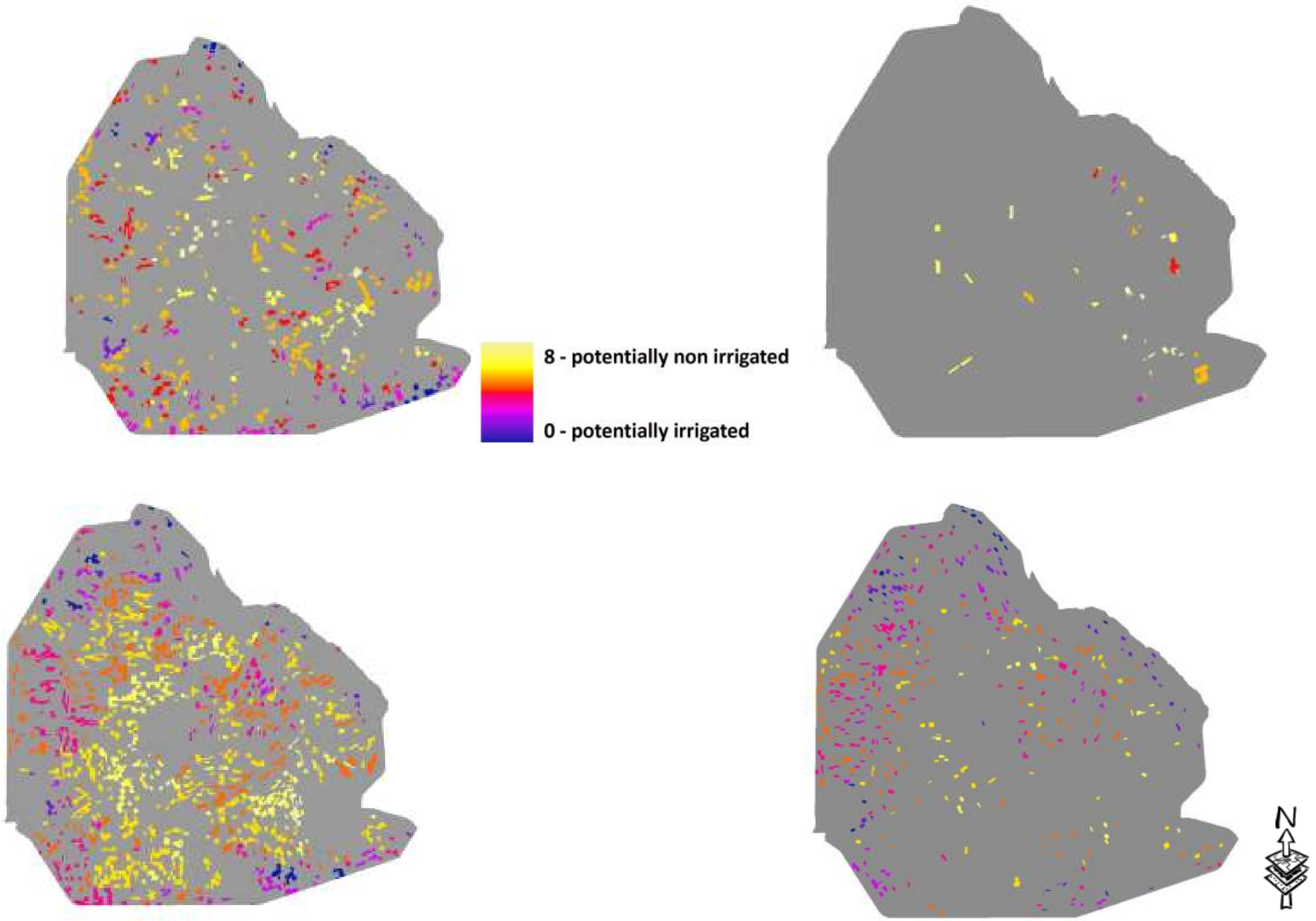


Figure 5.2 – Final irrgation map of Noordoostpolder, potatoes (top left), orchards (top right), other arable crops (bottom left) & flower bulbs (bottom right)

5.3 Southern & Eastern Flevoland

In order to validate the final irrigation map of Southern and Eastern Flevoland a visit at Lelystad local water board's office had been arranged. It appeared that quantitative validation was again impossible. Consequently, the best approach to validate so far results was qualitatively, by examining carefully the resulted maps.

In the north eastern part of the polder seepage values are significantly higher than in the rest of it. The cause of this phenomenon is attributed to the existing elevation difference between the polder and the mean sea level. As a result, this part of the polder experiences a remarkable amount of ascending water from the ground to the surface i.e. seepage. So the expected result of these high seepage values, would be plots located at these soils would never be irrigated. Truly, this expectation has been confirmed by the results as the majority of the plots are yellowish, indicating potential absence of irrigation. Water boards were very confident that farmers within that region are never irrigating their plots.

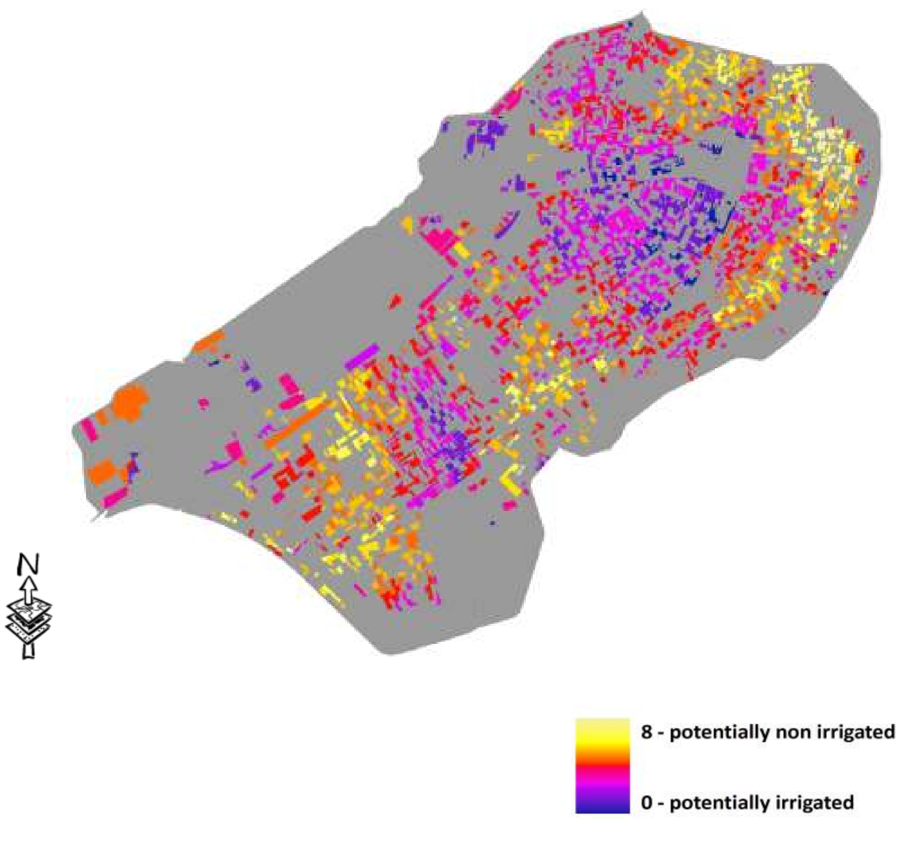


Figure 5.3 – Final irrigation map of all crop types considered for the study – Southern & Eastern Flevoland

It appeared that water boards have established new siphons along the main outlet drain, in order to distribute some excess drainage water further inside the polder where other farmers need water for irrigation. This excess water is being effectively used for irrigation as it appears on the final irrigation map. The surprising fact is a great number of farmers who irrigate using this indirect source of water. Just to remind at this point that irrigation at these polders is being done as well with surface water.

On the final irrigation map of orchards (figure 5.4) water boards were able to validate the results plot by plot. They knew precisely which farmers and how often they ask for water withdrawal permissions. Orchards, composed of apple trees have all of them installed drip irrigation systems, which are always used by farmers to irrigate except a few as shown in the map. Water inspectors were pleased to notice the indication of these few farmers who potentially do not irrigate, as they knew that they rarely ask for water withdrawals permissions. In general orchards are irrigated intensively for two reasons, one is to keep the temperature around plants low during the summers and the second is to keep high soil moisture levels. So for orchards it seems that the final irrigation map is high accurate according to the testimonies.

Water boards also revealed that in the south eastern part of the polder many farmers have wells in their land. These wells were established long time ago and they are used to cover farmers' needs for irrigation. The dark blue and reddish color of that plots seem to be in accordance with that clue. The issue is that authorities have not managed yet to control which farmers use this underground water and specify an equivalent volume. The province of Flevoland in order to keep track of the situation asks farmers to declare the volume of water they used per year. This approach though, is not trustworthy at all, since neither all farmers have meters to estimate the exact consumed volume, nor do they always reveal the truth. Province's policy is to apply charges after 20000 m^3 but unfortunately they do not have enough personnel to accomplish that.

It was also mentioned that nowadays there are much more flower bulb fields in these polders than it used to be. Inevitably this means more irrigation but no further details were available to investigate it further.

Finally local authorities are convinced that the eastern part of the polders (higher elevation) in general terms, is more irrigated than the western (lower elevations). This is attributed to the better quality of water which is available for these (eastern) farmers with respect to others who wait longer until they irrigate their plots. This general conclusion is also depicted in the final irrigation map of June 1995.

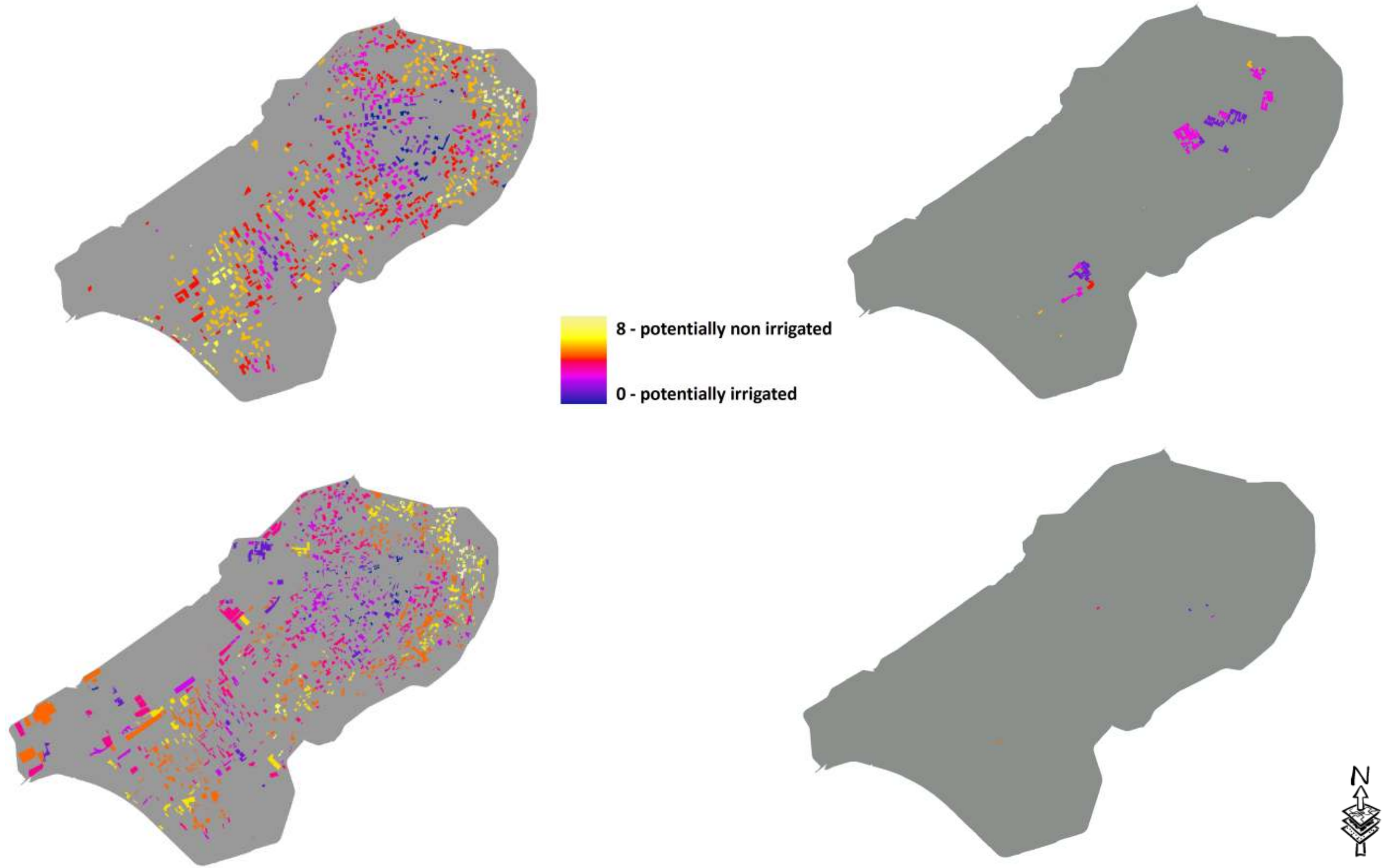
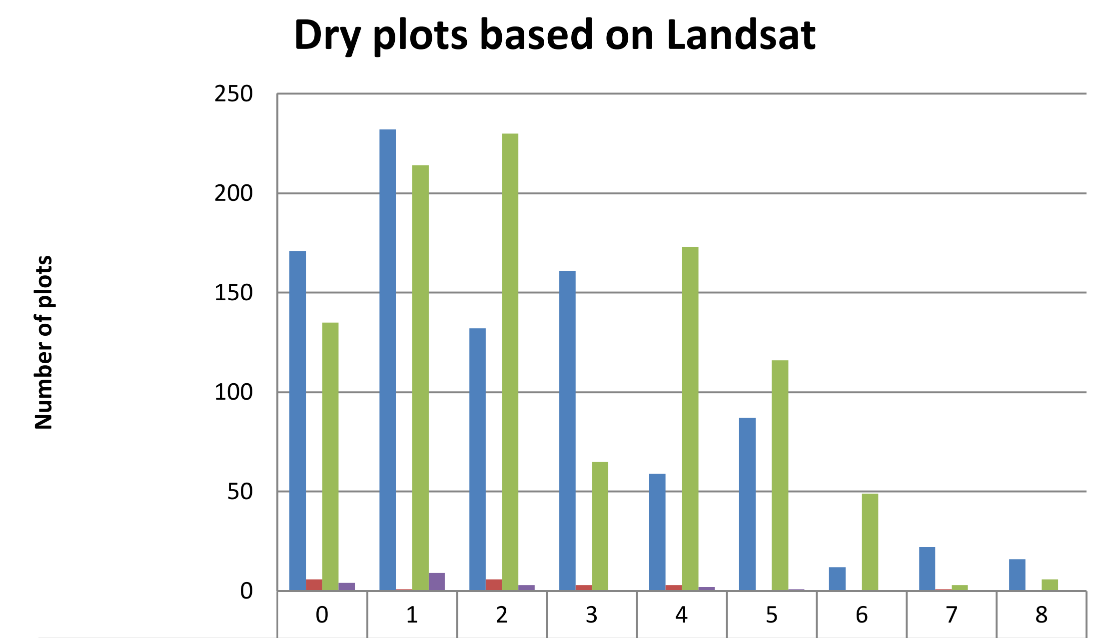


Figure 5.4 – Final irrgation map of S&E Flevoland, potatoes (top left), orchards (top right), other arable crops (bottom left) and flower bulbs (bottom right)

5.4 Consistency of ET_{def} thresholds

For the distinction between wet and dry areas based on Landsat data, certain ET_{def} thresholds had to be drawn among the four crop classes. These thresholds were defined according to a rationale which was explained thoroughly earlier. Additionally until now we have only dealt with plots which according to Landsat data considered wet. '*What about the dry ones?*' It would be equally interesting if we could say something about them as well. Specifically, if thresholds were set correctly and we apply again the previous methodology but to dry plots, then we should expect the majority of them to belong to the first classes of the classification, which represent dry areas. As a reminder classes from 0 to 4 represent dry areas due to the minimal input from each of the soil wetness sources (besides irrigation). In that way by performing the same approach to dry plots we would have a reliable indication for the consistency of wet and dry plots.



	0	1	2	3	4	5	6	7	8
Potatoes	171	232	132	161	59	87	12	22	16
Flower Bulbs	6	1	6	3	3	0	0	1	0
Other Arable Crops	135	214	230	65	173	116	49	3	6
Orchards	4	9	3	0	2	1	0	0	0

Figure 5.5 – Classification results of plots considered dry based on Landsat data

The classification results of dry plots are depicted on figure 5.5. Indeed, the majority of the plots is assigned to the first four classes, indicating that the proposed ET_{def} thresholds were satisfying. In total from 1922 plots which considered dry, 83.7% of them lie in locations where soil's moisture is minimal (not significant). This justifies why these plots appeared dry, with the consideration that irrigation was absent.

5.5 Discussion

At this point it would be beneficial to summarize the most important results so far. Undoubtedly, the major achievement is the production, for the first time, of an irrigation map for the polders. This map illustrates accurately the locations of potentially irrigated plots during a specific day in June of 1995. The proposed method in the end classifies plots, independently of crop type, in nine classes ranging from irrigated to non-irrigated. Specifically, this classification integrates the content of satellite with other water related data for the assessment of plots state.

Remote sensing by itself is an objective and powerful tool which can provide us accurate information for land surface processes. The potential of this information is boosted whenever it is used within a GIS environment with additional data. Various agricultural species are cultivated in Flevoland, but it appeared that only for some of them were meaningful to investigate irrigation. It also proved that June was the most revealing month with respect to different applied practices by farmers' side. Certain decisions around ET_{def} thresholds had to be taken in order to distinguish between wet and dry plots. The selection of these thresholds was proved consistent since the 83.7% of dry plots lie in locations where high wetness' levels cannot be supported by surrounding conditions. Results validation showed that on average the location of irrigated plots is correctly placed. Field experts and irrigation managers of the area confirmed this with high certainty. Field experience and detailed description of farmers' usual activities created a picture which is in accordance with the final irrigation map produced by satellite measurements.

Specifically it was found that 37.2% of potatoes, 51.3% of flower bulbs, 44% of orchards and 37.1% of other arable crops were irrigated on 25th of June 1995. These percentages are likely to be higher since farmers always try to preserve high production levels (by irrigating), even in cases where this is not completely necessary. Thus the supplementary role of irrigation is questioned. If the research was repeated, but for a broader period (more images), then it would be more disclosing for the prevailed conditions. Authorities concern for present and future water consumption is reasonable and further research on the topic could reveal more. The fact that volumetric calculations are feasible on the framework of the presented method, gives water managers an additional reason to invest on applying it. It is really important to realize the sustainable framework of water resources. Many areas around the world suffer from water shortage while others, as Flevoland polders, experience water abundance. In both cases water should be managed with provision. It is therefore crucial to develop policies which manage water stocks efficiently and rationally.

6 Conclusions and recommendations

This chapter presents the conclusions and recommendations of the study. In chapter 1 the main research objectives were defined as:

- *Is it possible to detect, which farmers have been irrigating their plots and which not for a certain period, based mainly on remotely sensed data?*
- *Is it feasible to quantify the amount of water which was used for irrigation?*

From the research questions, the main research objective of the thesis was derived:

- Developing a (decision) model which identifies irrigated plots of various agricultural crop types, based mainly on remotely sensed data. Additionally for the same period, the corresponding volume of water to irrigation was calculated.

In this chapter will be concluded if the research questions were sufficiently answered, if the main objectives were achieved and what recommendations for further research remain.

6.1 Conclusions

The research objective was pursued by investigating and assessing various data sources related to irrigation activities. The core of these data was remotely sensed with main relevance to agricultural and water management issues. The main goal of the research, which was the identification of irrigated plots, was innovative and unique for the area. A lot of discussions have been done around irrigation in polder areas, but none of these were ever expressed with concrete data or records. Water and irrigation managers, besides their valuable knowledge and field experience, they also need accurate and objective information for the management of the water resources in the area.

The proposed method appears capable of identifying irrigated plots and on the same time accounts for all the additional reasons which can deter irrigation. Moreover it is capable of calculating the amount of water which was used by farmers for irrigation. Therefore, local authorities can have unique information about farmers' activities and their water consumptions based solely on objective data.

The following summarized conclusions can be drawn from the presented research:

- Remote sensing has the potential to identify irrigated regions and shed light to the present problem. This can be done at varying scales ranging from individual plots to vast agricultural areas.
- Identifying supplementary irrigation in (wet) environments like polder areas is a complicated issue, which cannot be answered with yes or no. Instead of that, it is

possible to indicate areas where irrigation is the most likely answer for wetness presence, while in other cases not.

- Irrigation activities in polder areas cannot be detected solely by remotely sensed data but in addition water related data are necessary for the effective description of the area e.g. soil type, summer water level in the canals, precipitation etc. The final amount of data is large, thus special consideration should be taken when combining them.
- The proposed approach resulted in a new unique dataset, which holds comparative information for every plot individually and allows the characterization of any agricultural unit with respect to irrigation and water consumption.
- Findings are indicative for a specific day in June of 1995 but they can easily extend for longer periods e.g. the whole irrigation season of every crop type if more images are available. In that way, safer and efficient conclusions can be drawn for the water balance and the applied policies in polder areas. The working flow is present and can be utilized any given period.
- Results revealed that 37.2% of potatoes, 51.3% of flower bulbs, 44% of orchards and 37.1% of other arable crops were irrigated on the 25th of June of 1995. It is likely these percentages to be higher in reality since farmers' initiatives cannot always be predicted. Even though these numbers show intense irrigation activities if we consider that polders are characteristically wet environments.
- Defining the ET_{def} thresholds (among each crop type) for the distinction between wet and dry plots was not a straightforward process. Biomass production values facilitated significantly this selection but not to the full extend. Nevertheless, when dry plots were tested for their consistency, it proved that the majority (83.7%) was located at areas which couldn't support wet conditions, thus they were correctly classified as dry.
- During the assessment of soil's wetness origins it was assumed that each source contributes equally to wetness's profile. This was done intentionally in order to keep the analysis, at least on the first stages, as simple as possible. For instance we could have assigned different weights to each source but again we couldn't be sure which weight corresponds to each source. In the end after the validation process, it proved that final irrigation maps are in accordance with reality thus vindicating our approach.
- A-priori knowledge with respect to crops water needs and the general growing conditions was vital in order to avoid confusion and wrong assumptions. Also knowledge of the existed irrigation installations (independently of their use) on certain crop types facilitated the selection of suitable crops.
- The major bottleneck in the study was undoubtedly the weakness to validate quantitatively any estimation. For that reason, final irrigation maps were only validated qualitatively. Irrigation managers of the area and local water boards examined meticulously the results, which according to their field experience, depict reality very accurately.

- The production of final irrigation maps was enhanced by calculating the water volume which was used for irrigation. This amount of water even though it is representative of a specific day in June, indicates water consumption from irrigation. At the moment this volume is impossible to be validated but in the future, when more studies would be done this can change.
- It is necessary to investigate further the accuracy of the model and whenever need to refine it. This should be accomplished with the collaboration of the local water boards and irrigation managers who have the potential to monitor closely farmers' activities.
- The whole research so far has clearly revealed that irrigation can be detected with remote sensing, under the condition that advanced remote sensing products are available such as biomass production, ET_{act} and ET_{pot}. SEBAL is one among many algorithms which calculate water related parameters. The problem lies at water managers' side, who are ignorant of the possibilities of such products.
- Even though results represent a single day, they indicate that irrigation is an issue which needs further investigation. Therefore, water authorities' concern for accurate information with respect to present and future water consumptions is justified.
- When results are interpreted it makes us question about the supplementary role of irrigation in the area. Of course, in order to draw solid conclusions more research is necessary but at least now we do not lie in the dark as before.
- The current study managed to bridge a part of the gap between researchers and practitioners, by developing a tool with practical application, and by identifying one more problem that remote sensing could contribute.
- As organizations adapt to the information age and adopt emerging technologies such as cartography and GIS systems, water professionals should also be aware of the possibilities of remote sensing.
- Overall the most important achievement of the research is that for the first time information related to irrigation is available for Flevoland polders. This information derived from objective and independent sources which are not related to individual's opinions or considerations. Consequently the starting point has been set and it is up to authorities to steer it further.

6.2 Recommendations

There are some recommendations for further research and application, which have to be implemented to fully exploit the findings of this thesis. So far the model has been validated qualitatively and it proved that works sufficiently. This fact is a good indicator but not enough for the overall assessment of the method. It is crucial though, since the model exists, to test it further and estimate its accuracy quantitatively.

In order to do that authorities' collaboration is considered essential. For instance, it would be beneficial to design the implementation of the model in one of the next growing seasons as follows:

- Select certain agricultural crop type(s) for which irrigation is evident (preferably the same used this time)
- Select suitable month(s) on which crops' growth is at peak, thus irrigation activities are possible to happen
- Acquire frequent satellite images e.g. one per week and calculate ET_{act}, ET_{pot} and biomass production for the area on a pixel by pixel basis. Having 3-4 images per month will allow to draw safer conclusions and possible integrate individual maps into one, more representative of the period of interest.
- Simultaneously water authorities, for the same temporal framework, they can monitor farmers' activities more closely either by keeping records of the provided permissions for water withdrawals or by keeping a kind of irrigation calendar of farmer's activities.
- In that way, it would be possible to compare the results of the analysis with field data collected the same period the satellite images were taken.
- Moreover, it would be possible to investigate further the accuracy of the selected ET_{def} thresholds.
- By calculating water volumes from irrigation for specific days and acknowledging farmers' frequency of irrigation, it would be possible to estimate water consumption for the whole irrigation season per crop type. This calculation would be of maximum importance to water managers in order to realize quantitatively the consumption and distribution of irrigation water in the polders.
- It is also necessary for water authorities to have an approximate volume of the water used for irrigation and compare it with the one calculated by the model.

During the interviews with water boards it was mentioned that in the coming years the responsibility of under ground water will be transferred from the province to local water boards. It is therefore important, to force all farmers who own wells to install meters in order to calculate water consumption. As a result, in the end surface and under ground water will be controlled by one authority, making decisions more flexible and effective.

All the above actions require good planning and provision. It is up to water authorities to decide how much information they need for the management of water resources in the area. The design and implementation of new policies require as well accurate information. Consequently, the current study can be the starting point for further data collection and interpretation. Abundance of water does not necessarily mean that it will last forever or used without consideration.

Acknowledgements

I would like to thank all those who gave me the possibility to complete this research. Firstly, I would like to express my appreciation to my direct technical supervisor Wim Bastiaanssen, for his expert guidance and mentorship, for his encouragement and enthusiasm. His intelligent suggestions and friendship stimulated me during the whole process of research and writing of this thesis. Additionally I would like thank WaterWatch Company and Sander Zwart for providing the majority of data and explanations about the situation in Flevoland polders.

I also want to express gratitude to Nick van de Giesen and Olivier Hoes for the hospitality at Water Resources department of Civil Engineering. They provided me with all their support and guidance in order to transform the initial idea into a constructive research. Moreover I thank Ben Gorte from Optical and Laser Remote Sensing department for his valuable contribution and critics on the meetings during my thesis conduction. Moreover I thank water managers from Emmeloord and Flevoland water board offices, whose field experience and knowledge allowed me to validate my final results.

Furthermore I thank Katita Chrysanthopoulou, for the concept and design of my thesis cover as for her artistic advices on the final report. I also express gratitude to Areti for her endless tolerance and support throughout my studies. Big thanks to my true friends and amazing roommates Dimitris, Thanos and Chryso for making me smile all the time.

Finally I would like to deeply thank my parents, for supporting me all these years of studies and encouraged me to continue no matter the difficulties.

Without all of them, this thesis could not have been completed.

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Appendices

Appendix A

Table A1 – Sensors or satellites that provide images suitable for agricultural water management (W. Bastiaanssen, D. Molden, W. Makin, 2000)

Purpose	SPOT	IRS	TM	MSS	NOAA-AVHRR	ERS-SAR	Radarsat	ERS-ALT	ERS-ATSR	Meteosat	GOES	GMS	JERS-SAR
Cartographic information	•	•	•										
Irrigated area			•		•				•				
Cropping pattern			•			•	•						•
Land use	•	•	•	•	•				•				
Leaf area index	•	•	•	•	•				•				
Crop coefficient	•	•	•	•									
Transpiration coefficient	•	•	•	•	•				•				
Surface roughness						•		•					•
Crop yield	•	•	•	•	•				•				
Potential evapotranspiration			•		•				•	•	•	•	
Actual evapotranspiration			•		•				•				
Surface moisture						•	•						•
Root-zone moisture			•		•				•				
Soil salinity			•			•							•
Water logging	•	•	•	•		•							•
River discharge						•		•					•
Precipitation										•	•	•	

SPOT: Satellite pour l'Observation de la Terre; IRS: Indian Remote Sensing Satellite; TM: Thematic Mapper; MSS: Multi Spectral Scanner; NOAA: National Oceanic and Atmospheric Administration Satellite; AVHRR: Advanced Very High Resolution Satellite; ERS: European Remote Sensing Satellite; SAR: Synthetic Aperture Radar; ALT: Altimeter; ATSR: Along- Track Scanning Radiometer; GOES: Geostationary Operational Environmental Satellite; GMS: Geostationary Meteorological Satellite; JERS: Japanese Earth Resources Satellite

Appendix B

Table B.1 - Description of the soil map legend

	Soil Types
Code	**Simple Description of Soil**
Avk	Peat
bAFG	No data
cOPH	No data
gMOE	No data
gWAT	No data
hBEB	No data
hDIJ	No data
Hn21	Leemarm** and weak clay fine sand
kVc	Peat
kVd	Peat
kVz	Peat
kWp	Mineral deck with peat layer on sand
kWz	Mineral deck with peat layer on sand
KX	Keileem***
kZn	Leemarm** and weak clay fine sand
Mn12A	Light loam 8-17% lutum*
Mn15A	Light loam 8-17% lutum*
Mn22A	Heavy loam 17-25% lutum*
Mn25A	Heavy loam 17-25% lutum*
Mn35A	Light clay 25-35% lutum*
Mn45A	Heavy clay > 35% lutum*
Mn82A	Light clay 25-35% lutum*
Mo10A	No data
Mo80A	No data
Mv51A	Light loam 8-17% lutum*
Mv61c	Light loam 8-17% lutum*
Mv81A	Light clay 25-35% lutum*
Sn13A	Clay sand 5-8% lutum*
Sn14A	Clay sand 5-8% lutum*
uWz	Mineral deck with peat layer on sand
Vp	Peat
vWz	No data
Vz	Peat
Zn10A	Fine sand 50-210 μm
Zn21	Leemarm** and weak clay fine sand

Zn30A	Coarse sand 210-2000 µm
Zn40A	Fine sand 50-210 µm
Zn50A	Fine sand 50-210 µm
zVc	Peat
zVs	Peat
zVz	Peat
zWz	Mineral deck with peat layer on sand
	*lutum = clay fraction < 2 µm
	**leemarm = 0-8% lutum, 90-100% sand (50-2000 µm), 90-100% silt (2-50 µm)
	***compacted impermeable clay layer

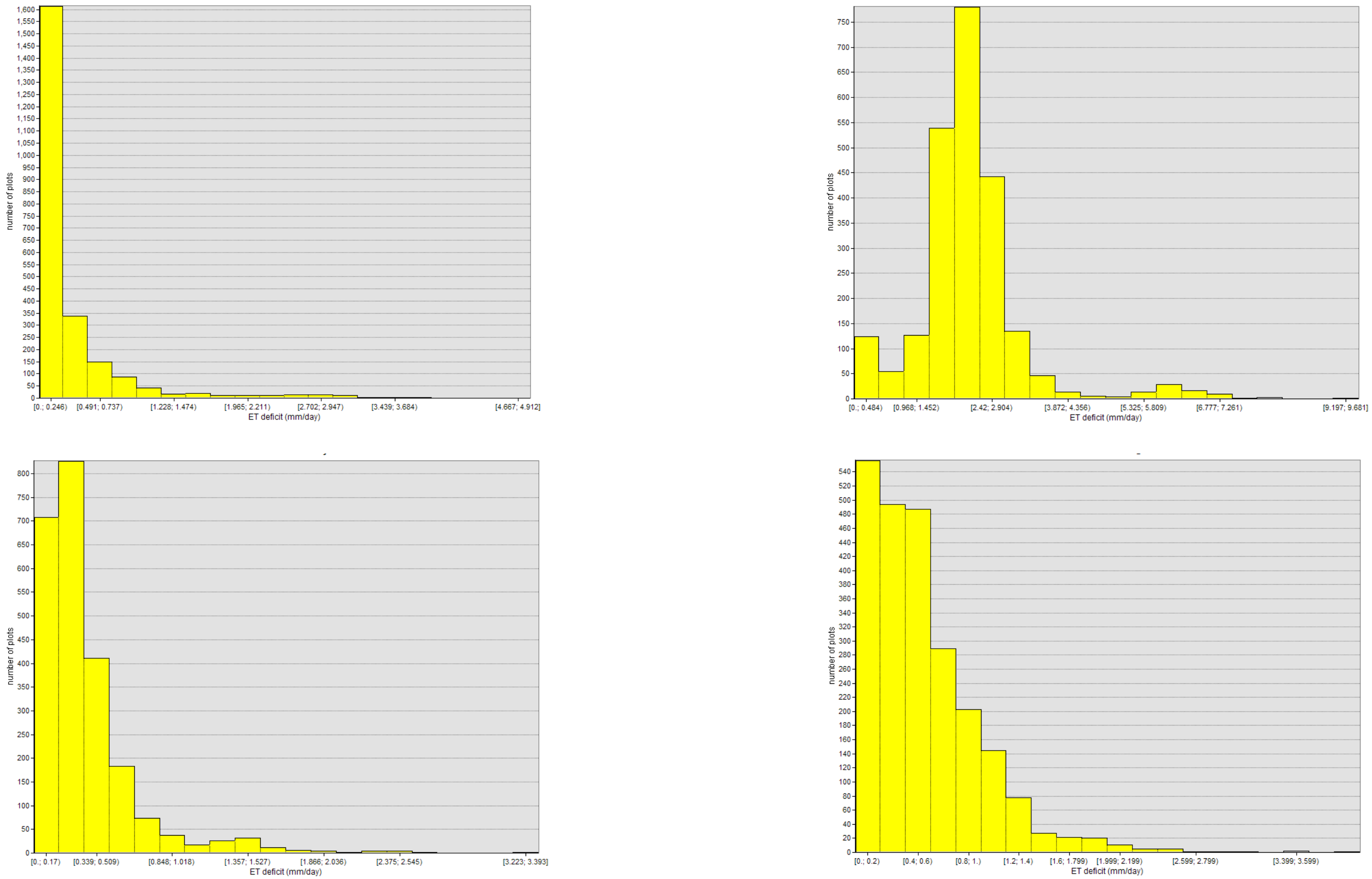
Appendix C

Table C.1 - Precipitation values from 14 meteo stations in Flevoland 2 weeks before 25th June 1995

Precipitation Values (mm) from Meteo Stations in Flevoland														
Station Number	**344**	**317**	**348**	**352**	**356**	**359**	**367**	**364**	**516**	**369**	**365**	**366**	**371**	**372**
11/6/95	3.9	21.2	31.7	9.2	7.5	6.1	4.4	14.4	6.2	8.8	9.0	7.7	5.6	31.1
12/6/95	1.0	1.0	1.3	1.2	2.2	0.1	9.1	0.2	6.3	4.6	2.2	1.5	19.0	4.9
13/6/95	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0	0.5	13.0	0.0	0.1	0.0	0.2
14/6/95	0.2	1.1	1.7	1.0	2.0	1.1	0.0	0.6	0.0	0.0	0.8	0.2	0.1	0.0
15/6/95	7.8	8.6	9.9	8.2	12.1	8.7	5.7	9.8	7.3	8.9	8.4	6.4	6.3	5.0
16/6/95	3.1	4.7	3.2	7.7	3.2	5.3	1.9	7.0	2.6	2.7	4.4	4.4	2.7	2.9
17/6/95	2.5	2.6	3.8	5.4	5.6	3.5	2.7	8.0	4.5	1.3	4.1	1.7	1.8	2.1
18/6/95	2.4	4.4	2.8	2.5	6.2	4.1	3.4	6.1	5.3	6.9	4.6	6.2	6.4	4.8
19/6/95	0.2	0.0	0.0	0.8	0.0	0.0	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0
20/6/95	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
21/6/95	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
22/6/95	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
23/6/95	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
24/6/95	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
25/6/95	0.1	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
Mean	**1.4**	**2.9**	**3.6**	**2.4**	**2.6**	**1.9**	**2.0**	**3.1**	**2.2**	**3.1**	**2.2**	**1.9**	**2.8**	**3.4**

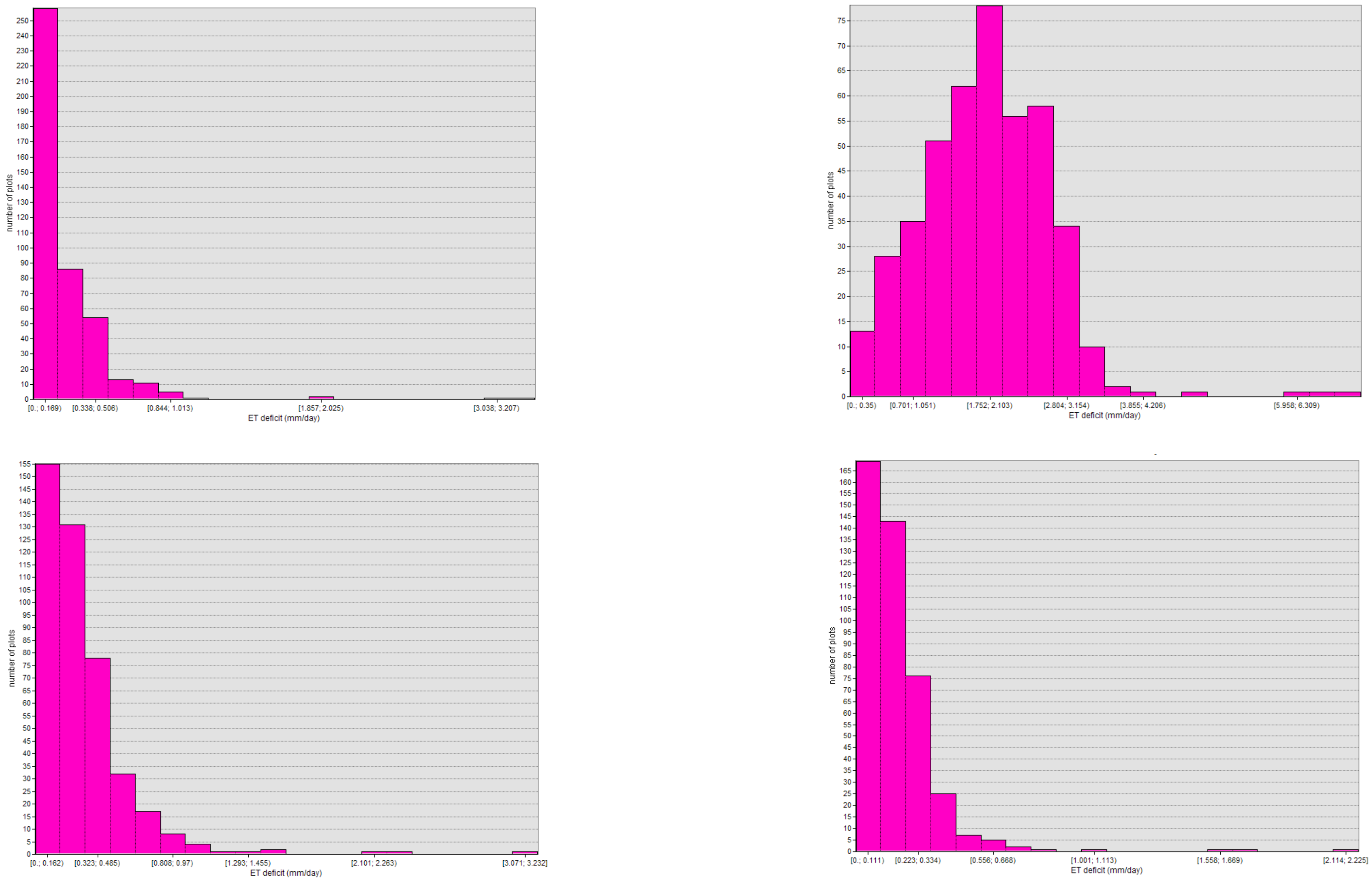
Appendix D

Figure D.1 - Histograms of ET_{def} values for potatoes



24th May (top left), 25th June (top right), 11th July (bottom left) and 12th August (bottom right) 1995

Figure D.2 - Histograms of ET_{def} values for flower bulbs



24th May (top left), 25th June (top right), 11th July (bottom left) and 12th August (bottom right) 1995

Appendix E

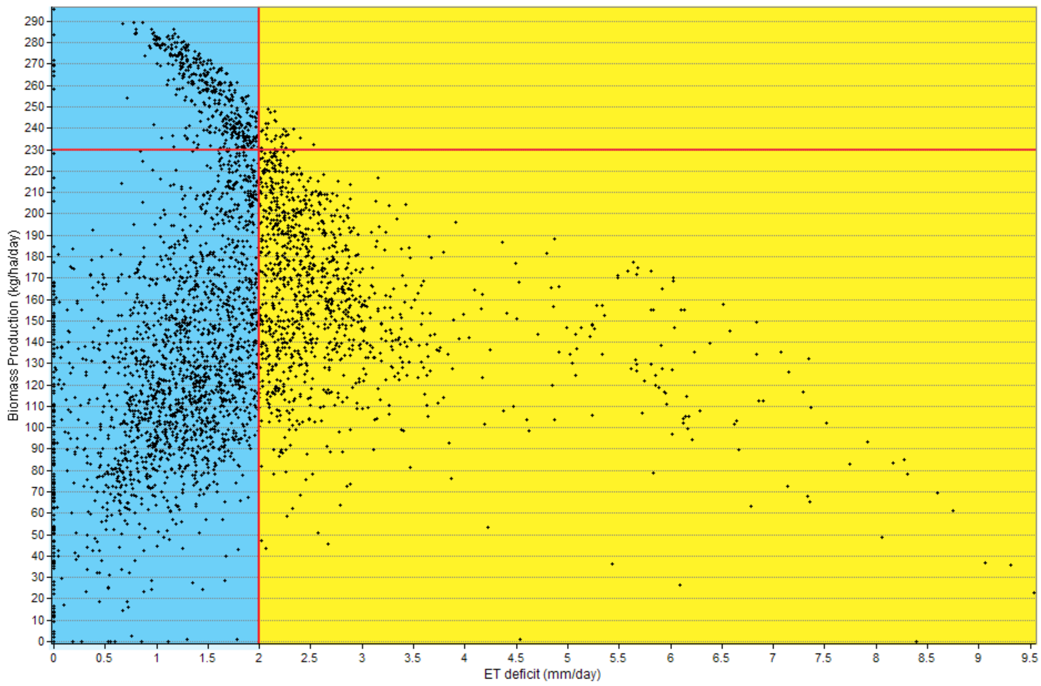


Figure E.1 - Biomass production vs. ET_{def} values for other arable crops on June 1995

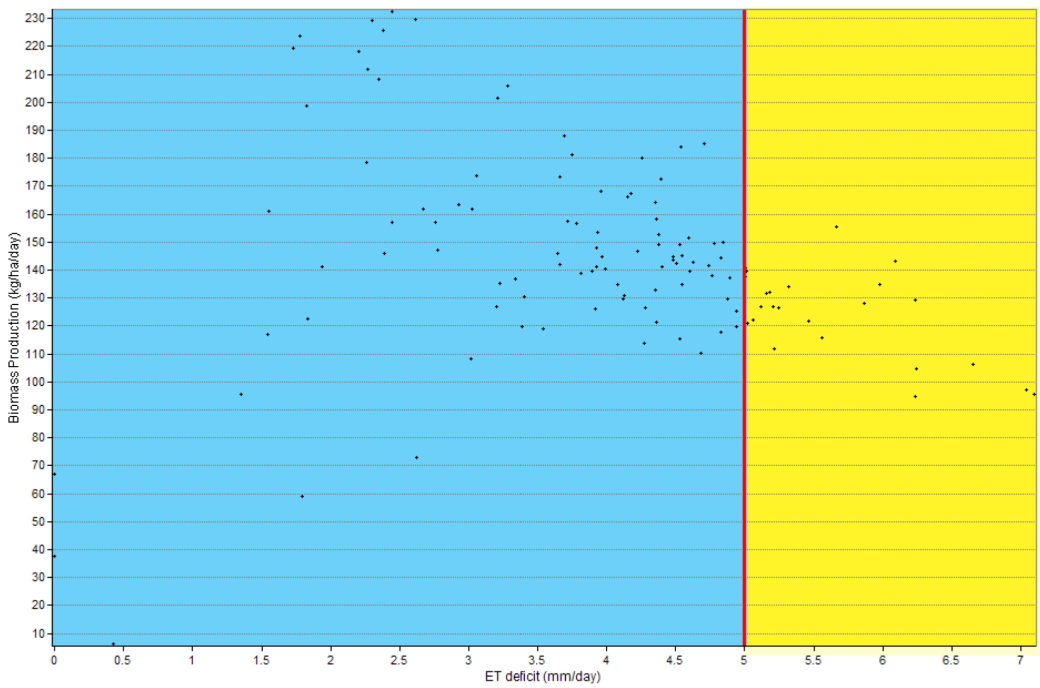


Figure E.2 - Biomass production vs. ET_{def} values for orchards on June 1995

Appendix F

Final irrigation maps for each crop type considered in the study

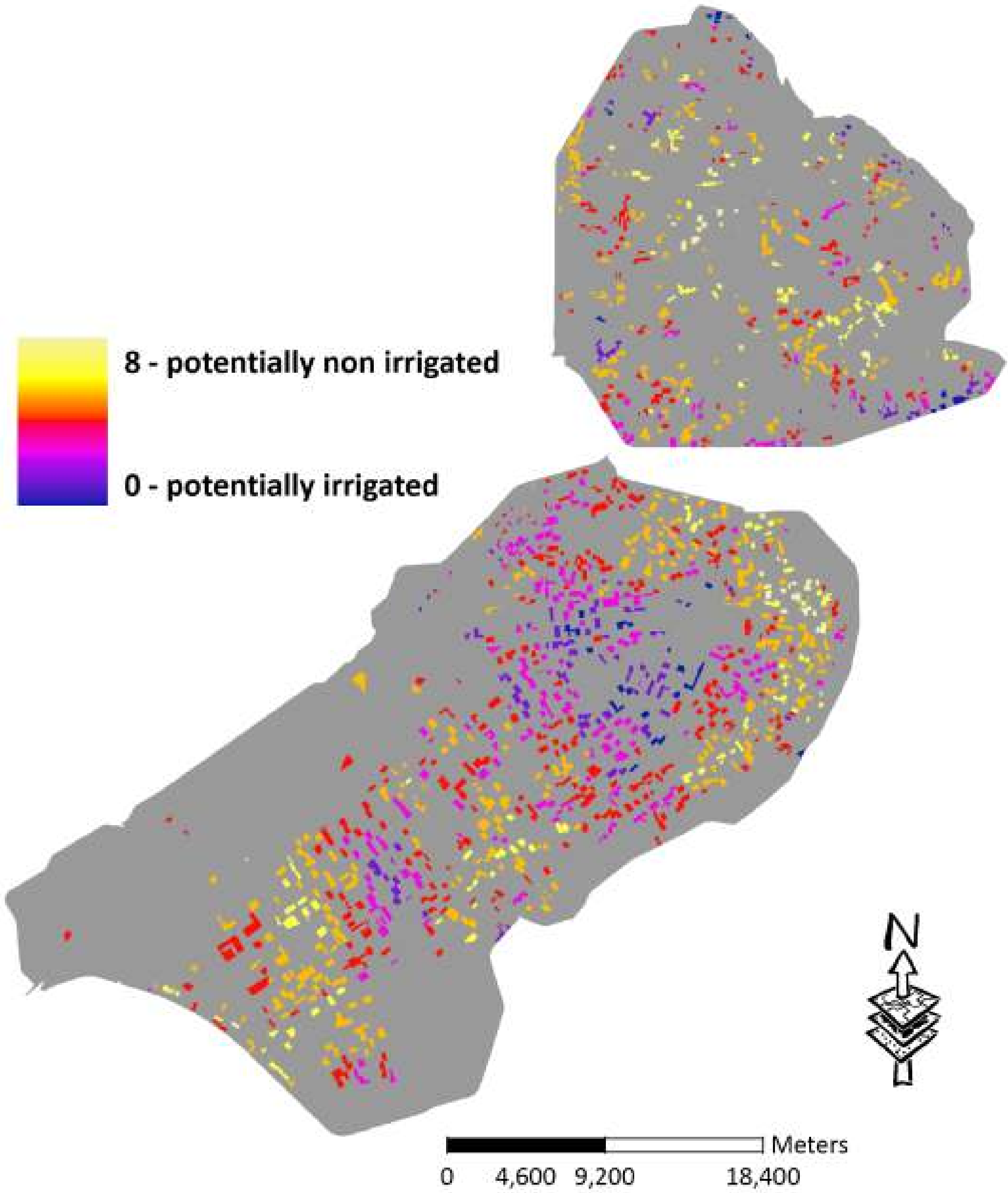


Figure F.1 - Potatoes 25th June 1995

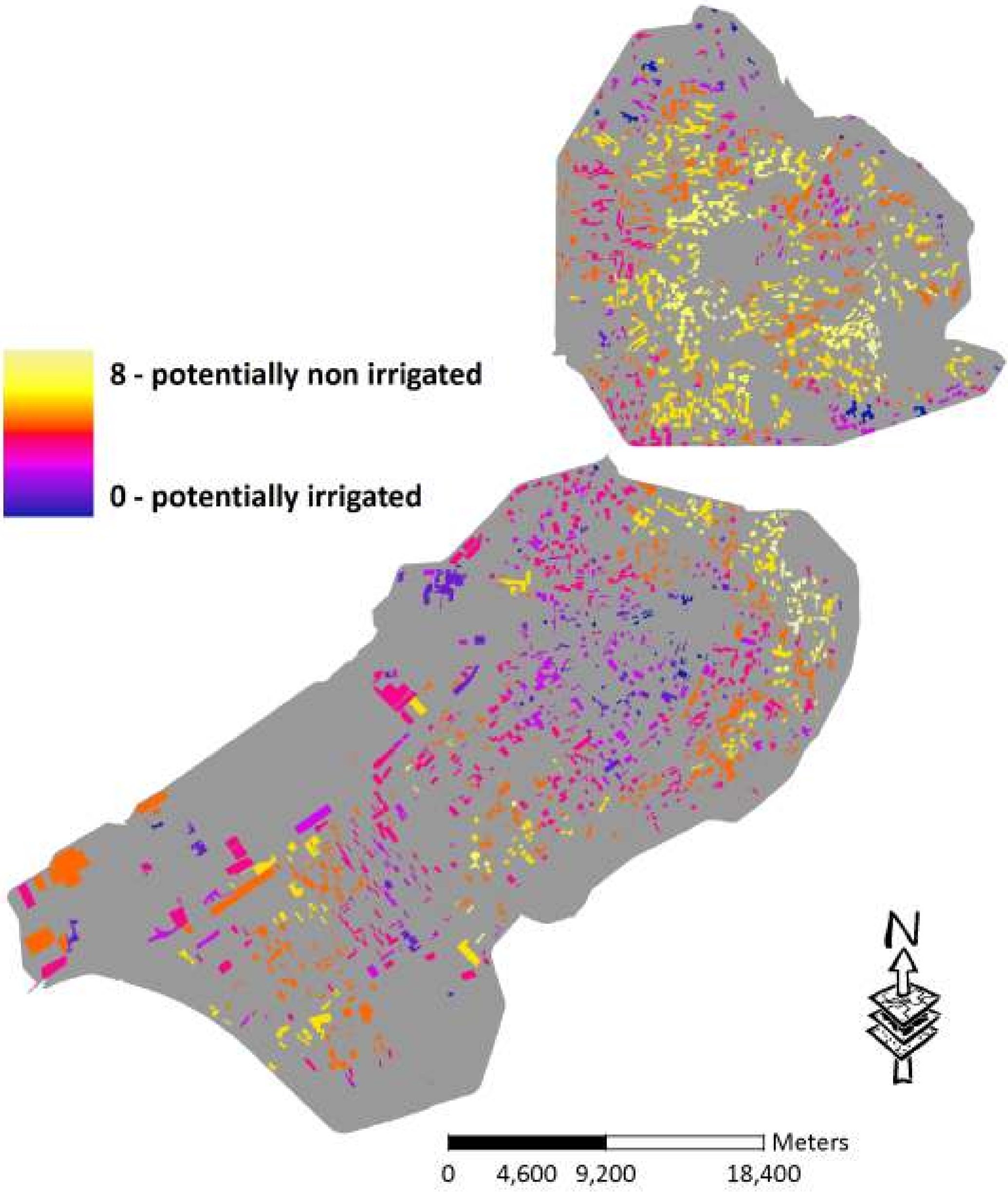


Figure F.2 - Other arable crops 25th June 1995

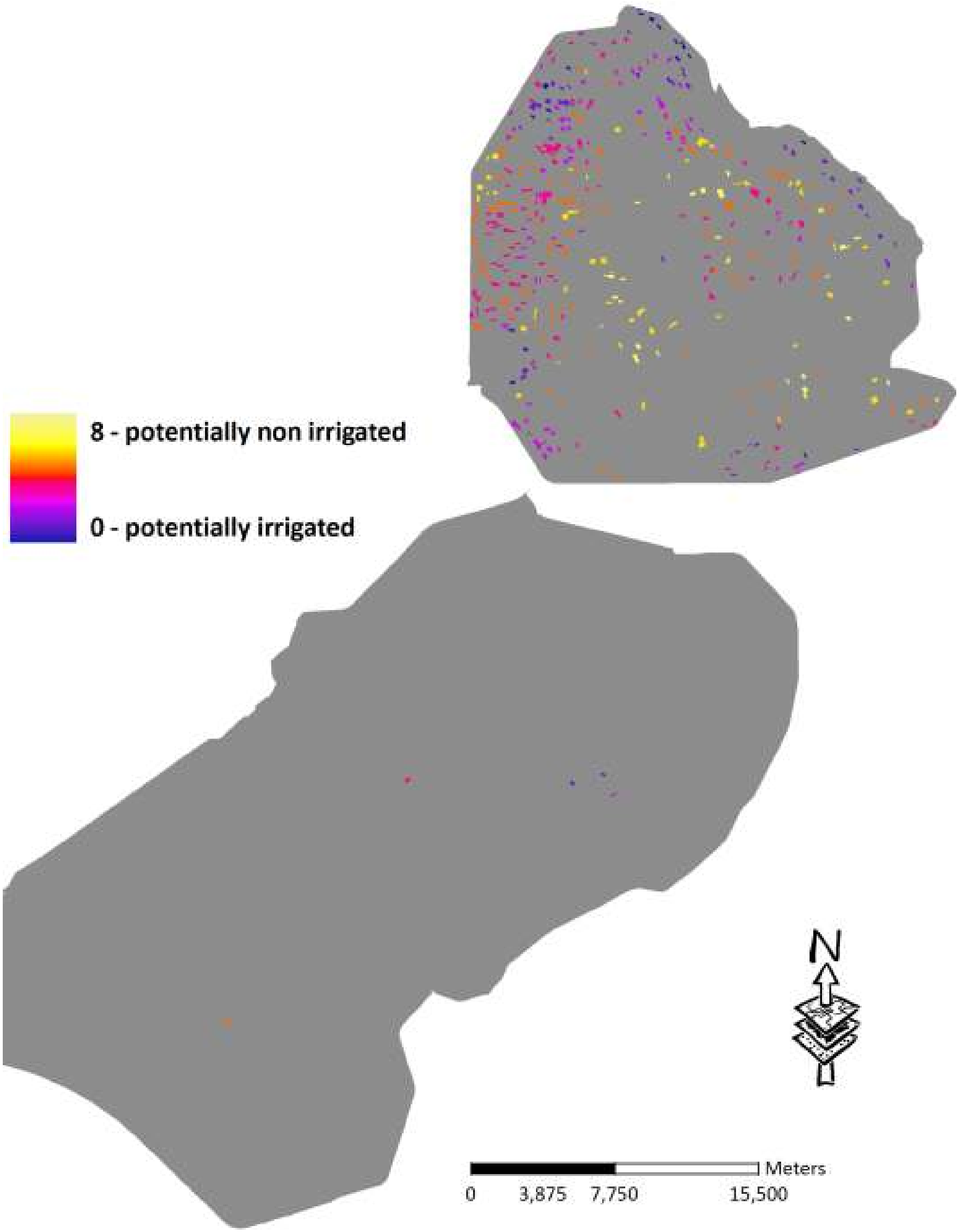


Figure F.3 - Flower bulbs 25th June 1995

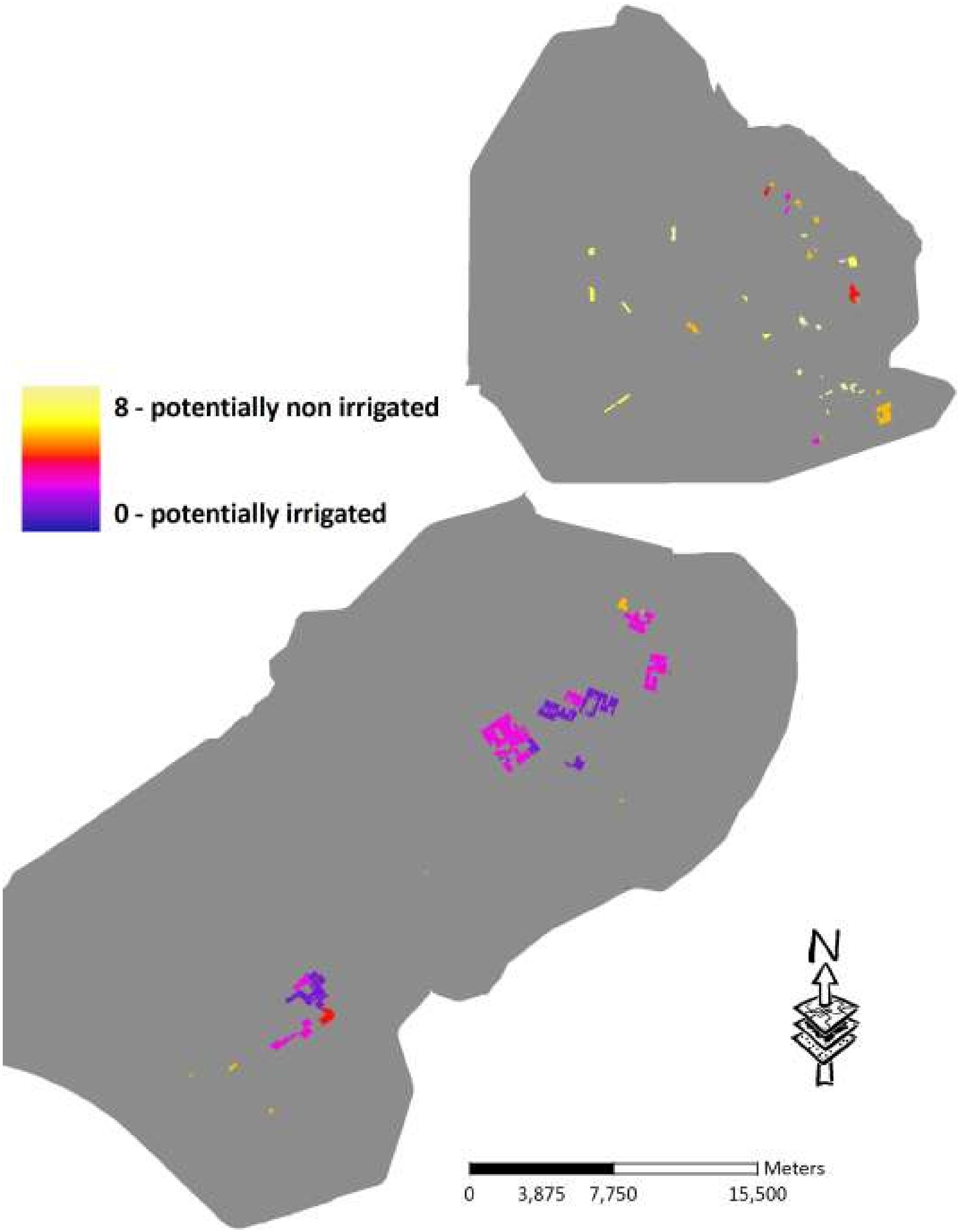


Figure F.4 - Orchards 25th June 1995

Appendix G

Water volumes from irrigation activities – 25th June 1995

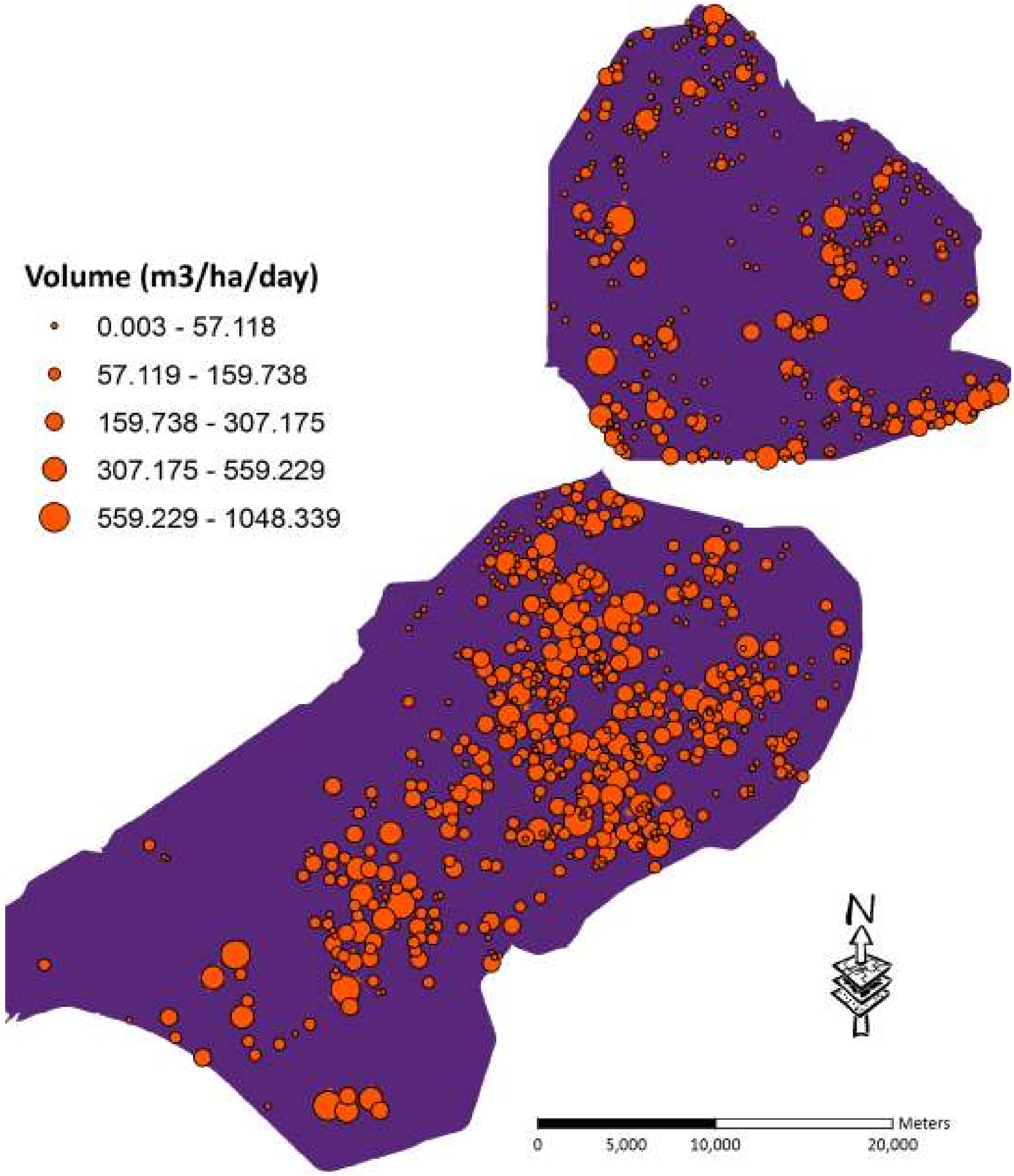


Figure G.1 - Potatoes

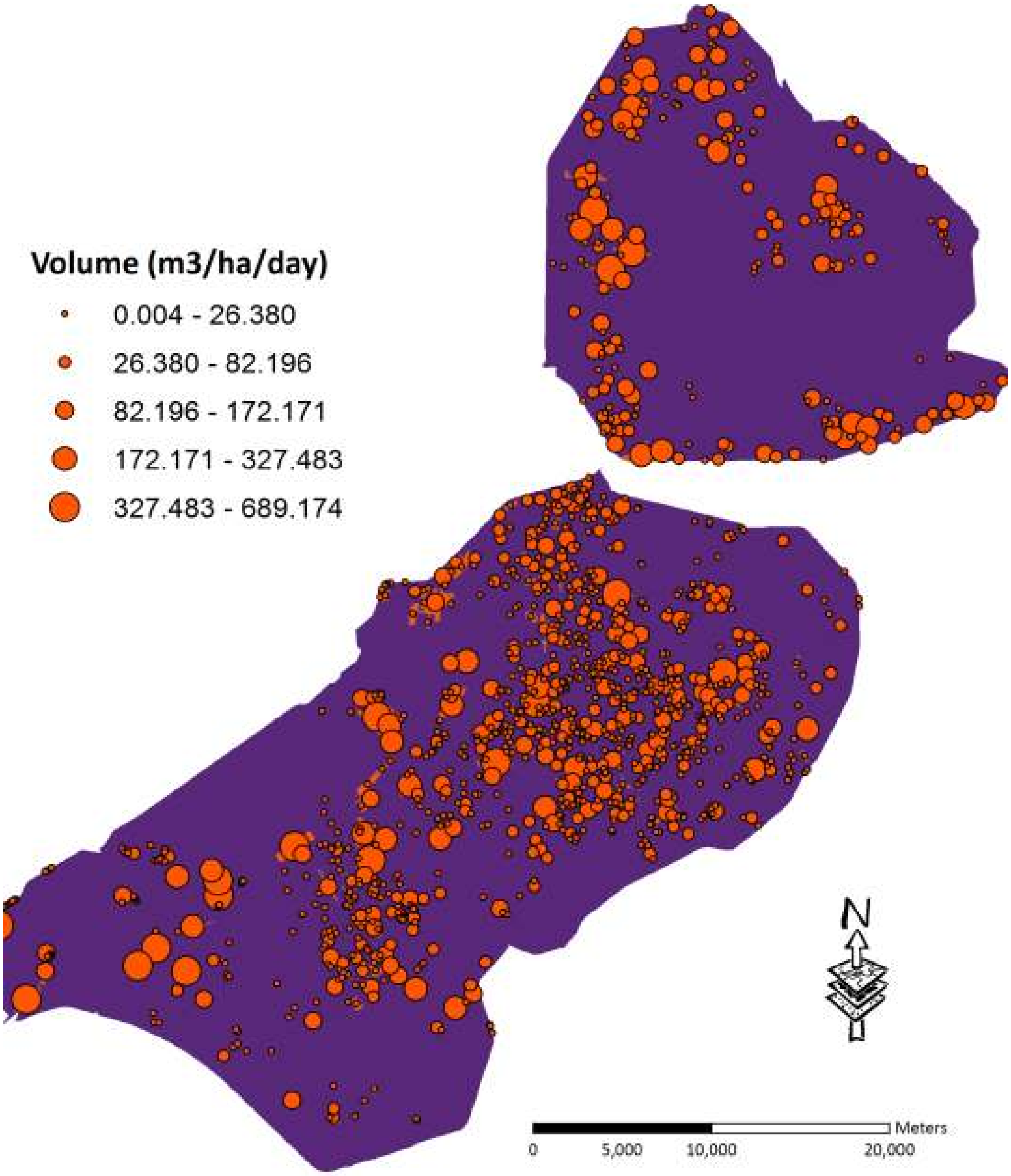


Figure G.2 - Other arable crops

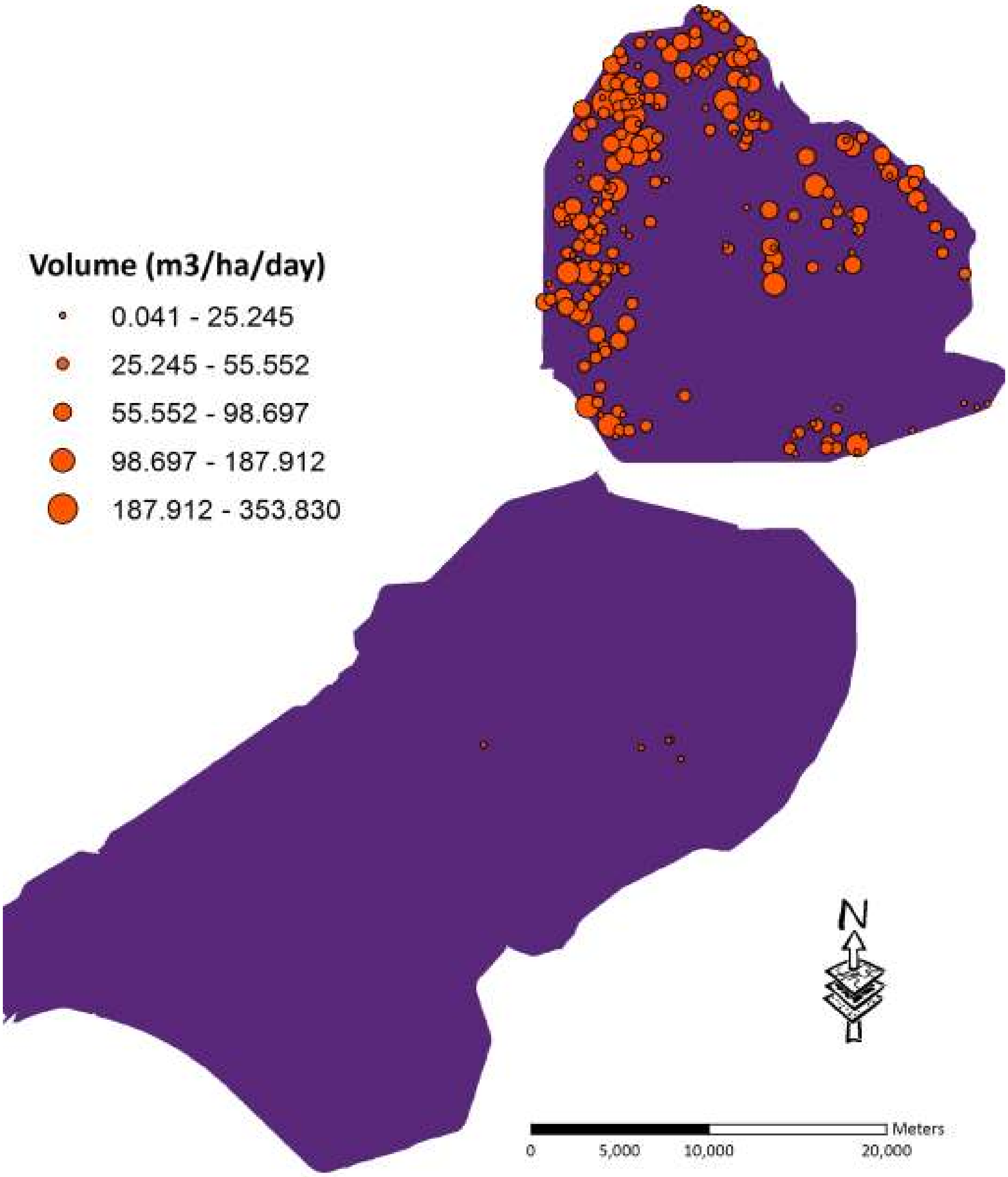


Figure G.3 - Flower bulbs

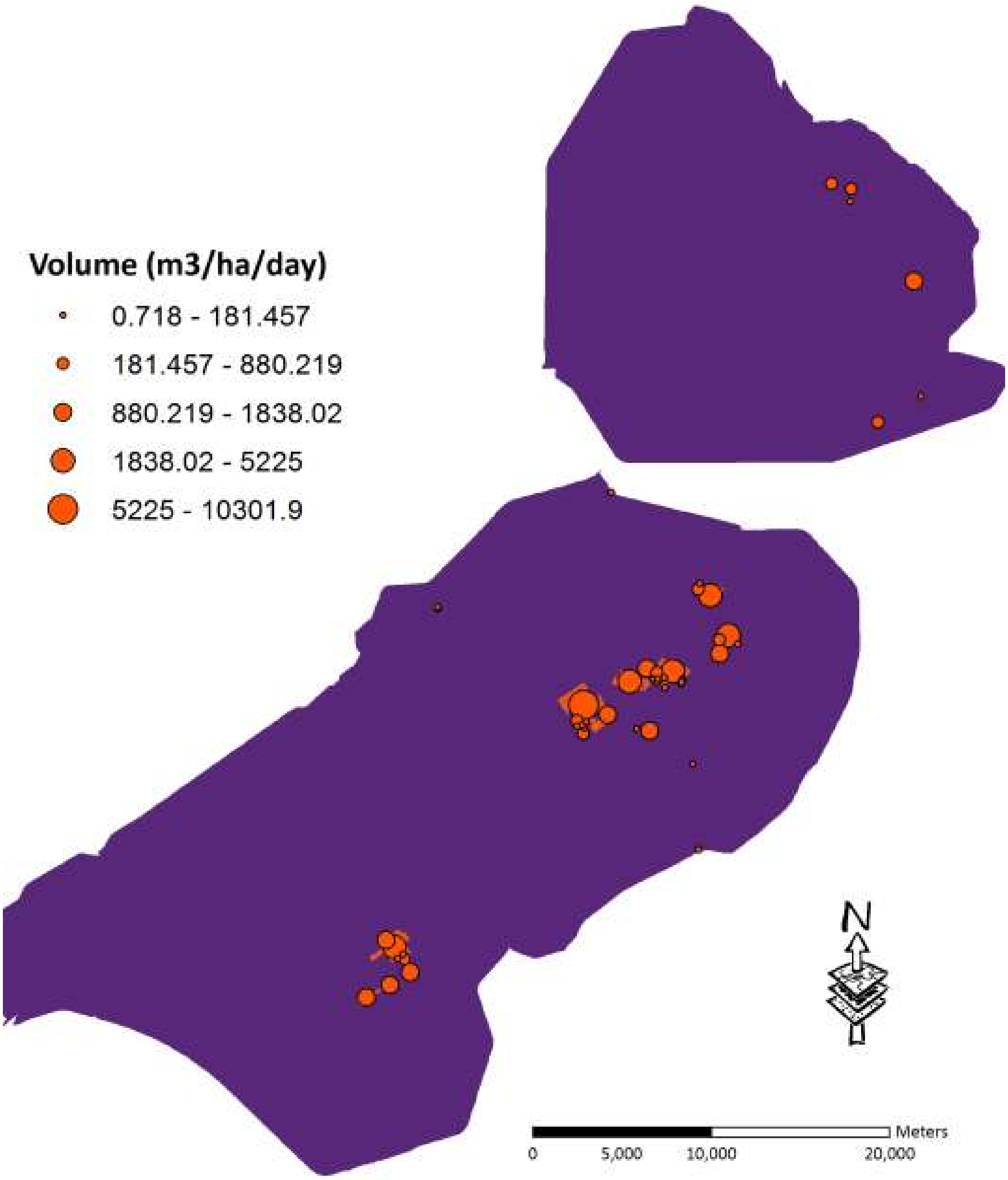


Figure G.4 - Orchards