Estimating the influence of on-farm Conservation Practices on the Water Balance:

Case of the Mzinyathini Catchment in Zimbabwe

Lennart Woltering
Delft, September 2005

Integrated Water Resource Management For Improved Rural Livelihoods
CGIAR Challenge Program on WATER & FOOD
WATERnet
UNESCO-IHE Institute for Water Education
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TU Delft
Delft University of Technology

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Delft University of Technology

A thesis submitted for the degree of Master of Science
in the Faculty of Civil Engineering
Delft University of Technology
Department of Water Resource Management,
Section Hydrology
Delft, September 2005

Supervisor	Title	Institution
H.H.G. Savenije	Prof.dr.ir.	Delft University of Technology
S. Uhlenbrook	Prof.dr.ir.	UNESCO-IHE
M.L. Mul	ir.	UNESCO-IHE
D. Love	mr.	University of Zimbabwe
W.M.J. Luxemburg	ir.	Delft University of Technology
J.C. van Dijk	Prof.ir.	Delft University of Technology

Preface

When browsing through this thesis one sees pictures of crops, farmers and tillage equipment in an African setting. The first question that comes in peoples mind is: "Why is this guy not studying at the agricultural university in Wageningen?". To be honest, I asked myself the same question many times when I had to go deep into the rainfed agriculture subject. In particular the last word "agriculture" sounded very distant for a hydrology student in Delft who is used to working on a catchment scale rather than zooming in on small farm plots. In hindsight, I am very happy that I graduated in this subject, because it qualified me for my first job in Niger for ICRISAT, an international organization for science based agricultural development. Furthermore, I had to explain people that I wanted to go to Zimbabwe, "isn't that that country where Mugabe is ruling?". Only after a few emails home with pictures of the beautiful country and nice people I met, my Dutch friends and family felt at ease.

First, I would like to thank Marloes Mul, for her hospitality, friendship and swimming pool. Besides making me feel at home, she was also a very helpful supervisor. Many thanks to prof. Savenije for his advice and especially for corresponding with the University of Zimbabwe (UZ) on such short notices when I was in trouble. Thank you David Love for facilitating me on the UZ, although you almost killed me by having me taste Chibuku (warm beer). Prof. Uhlenbrook and ir. Luxemburg were always available for comments and advice, many thanks for that. Furthermore, I would like to thank the people of WaterNET (Lewis Jonker, Arjen Hoekstra, Admire, Martha and other *tockoloshi's*), staff and students of the Civil Engineering department, ZINWA, DA Esigodini and the Meteorological Department. Steve Twomlow and Andre van Rooyen at the ICRISAT office in Bulawayo helped me on the right track for my thesis. I cannot think of Zimbabwe without thinking of Marieke de Groen, Frank Jaspers and Pieter van der Zaag who gave their party spirit, fatherly advise and farmers-point-of-view on all kind of occasions. After my 4.5 months in Zimbabwe, Pieter van der Zaag arranged a working place for me at the IHE-office in Delft. I enjoyed it very much there. *Tatenda* Gumbo, for letting me be your paranimf.

All this would not have been possible without the financial support of RELMA in Nairobi, The Lamminga Foundation in Delft and my parents in Zeeland, thank you for having granted me this opportunity.

Lennart Woltering
Delft, 6 September 2005

TU Delft

Delft University of Technology

Abstract

The Sub-Saharan region can be characterised by erratic rainfall and high population growth. Nevertheless, 95% (FAO, 2004) of the cultivated land is solely dependant on rainfall. Food security can only be reached when more crops per drop is achieved instead of increasing the stress on the available *Blue* water resources.

Given the limiting soil and climatic conditions, there exists a yield gap between what *is* (0.5-1 t/ha) and what *can* (1.5-2 t/ha) be produced on a farm. This gap can be minimized when farmers alter their management practices and realize that their socio-economic conditions are amenable to changes. Conservation farming groups water, soil and crop management practices, which focus on sustainable farming. Conservation farming contributes to yield stability and dry spell mitigation in drought prone regions. Tillage is an important aspect of conservation farming, because it changes the surface conditions such as pore space and roughness, affecting the potential for infiltration and runoff. However, the key to successful conservation farming is the integration of tillage within the total production system. This means that besides applying, for example, zero tillage, mulching or ridging, it is also important to focus on measures that increase the water uptake capacity of the plants, such as, pest management, crop rotations, weeding, etc. Research from several countries show significant improvements in crop yields and reduced soil erosion after the introduction of alternative tillage practices for conventional mouldboard ploughing. Thus, the risk of crop failure as a result of water stress can be decreased significantly, moreover the willingness to invest more in their crops in terms of fertilization eventually leads to even higher yields. However, with equipment and know-how available adoption of conservation practices is still very low due to lack of adequate labour, insecure land tenure systems, limited access to credit and markets, and failing technology transfer. Proper socio-economic conditions and land management increase the resilience against calamities, so that, for example, droughts not always lead to social disaster.

The catchment water balance consists of physically based equations for interception, transpiration and surface runoff, the base flow component is calculated using a statistical multiple linear regression model. The rainfall partitioning on farm scale is linked to the input variables from the multiple linear regression model. The input variables can be adjusted to represent the effects of different farm management implementations on rainfall partitioning. This way farm management innovations that work on a farm scale can be used for the water balance on a catchment scale. There is considerable more *Green* than *Blue* water available in the catchment, so there is a lot of potential for optimising rainfed agriculture. The goal of the farm management practices is to maximize the transpiration. It appeared to be effective to increase the plant available soil moisture, but this reduces the river recharge through base flow. Tied ridging stop surface runoff from the plots, when applied on a larger scale this has similar effects on the river recharge. Decreasing the interception losses through minimum tillage or mulching provides more water for transpiration and runoff. The water is transformed from interception loss to usable water for plants, besides that, the effects for river water users downstream are minimized.

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List of Acronyms and Abbreviations

ARDA:	Agricultural and Rural Development Authority
AREX:	Department of Research and Extension Services
CGIAR:	Consultative Group on International Agricultural Research ()
CP:	Challenge Programme
CWR:	Crop Water Requirements
DAP:	Draught Animal Power
DOI:	Department of Irrigation
EIA:	Environmental Impact Assessment
FAO:	Food and Agriculture Organization of the United Nations
SAFR:	Sub-Regional Office for East and Southern Africa
FEWS NET:	Famine Early Warning Systems Network
GMB	Grain Marketing Board
GWR:	Green Water Requirement
HIV/AIDS:	Human Immune-deficiency Virus / Acquired Immune Deficiency Syndrome
ICRISAT:	International Crops Research Institute for the Semi-Arid Tropics
IHE:	Institute of Hydraulic Engineering
LAI:	Leaf Area Index
M. Sc.:	Master of Science
MARD:	Ministry of Agriculture and Rural Development
MLR:	Multiple Linear Regression
MRRID:	Ministry of Rural Resources and Infrastructural Development
MRRWD:	Ministry of the then Rural Resources and Water Development
PhD:	Doctor of Philosophy
SADC:	Southern Africa Development Community
ZINWA:	Zimbabwe National Water Authority

1 Introduction

1.1 Background

The Food and Agriculture Organization of the United Nations (FAO) estimated that in Sub-Saharan Africa 204 million people, one third of the total population, were undernourished in 2000-2002 (FAO, 2004). Ongoing population growth and large scale poverty reinforces additional stresses on scarce and proper food resources. The bulk of these people live in the rural areas and are dependant on rainfed agriculture, which covers 95% of Africa’s sub-Saharan total agricultural land. Annual rainfall figures often show sufficient water for high crop yields, however soil moisture is not always available at crucial periods in the maturing stage of crops, leading to crop failure. Poor water and land management on communal farms in Zimbabwe result in low yields of 0.5-1.5 t/ha, even though Rockström (2003b) claims that there is a potential to generate 3-5 t/ha. Rockström (2002a) stated that as long as farmers live “at the mercy of rainfall” one should not be surprised at the extremely low level of investments in improved crop varieties, pest management and fertilisers (less than 20 kg/ha/year in sub-Saharan Africa).

Before 1990 increased food production was reached through expanding agricultural land and irrigated areas. The area of land fit for expanding agricultural land reached its limit. Moreover, irrigation development implies high capital costs, regional water scarcities, limited benefits to the poor, and negative environmental impacts. The need for raised yields per unit of soil and unit water became apparent in the last decade. Trying to maximize the ratio of productive to non-productive water flow after rainfall became the credo. Techniques which improve crop production by elongating soil moisture contents and increasing infiltration have been implemented and tested thoroughly. Currently the success for poor farmers of these soil and water conservation practices, such as minimum tillage, ridging and weeding is recognized by many. However, Rockström (2002a) stated, the fact remains that hydrological implications at catchment scale of upscaling system innovations such as water harvesting are still unknown and require further research. Human interference directed at changing rainfall partitioning at farms will affect the hydrological regime in terms of amount and distribution of water in the river. With knowledge on downstream consequences of certain land use and management options, well-informed decisions can be made on catchment planning. While the aim is to increase food production, other stakeholders in the catchment should not be neglected. The challenge is to identify to what extent technologies can be implemented without jeopardising other users and functions downstream (Mul, 2004).

1.2 Scope of the study

1.2.1 Thesis

This thesis forms the last necessity for finalizing the 5-year study of Civil Engineering, specialization Water Resource Management and more in particular Hydrology, at the Delft University of Technology in the Netherlands. When appreciated adequately by the examination commission, the student graduates in the degree of Master of Science.
The data gathering and first phase of the write up took place in Harare, at the University of Zimbabwe, between November 2004 and March 2005. ICRISAT-Bulawayo provided assistance and satellite imagery from Matopos to obtain a land use map. The modelling and final write up was done at UNESCO-IHE and Delft University of Technology in the Netherlands.

The fundamental research question in this thesis largely coincides with the ongoing Ph D research of ir. M. Mul on the Makanya catchment in Tanzania. The results will be important for that Ph D research, but first of all it forms a contribution to the WaterNET project under the CGIAR Challenge Program (CP17) on Water and Food for the Mzingwane catchment.

1.2.2 Challenge Program

(Extracted from Love, 2004)
WaterNET is leading a trans-institutional trans-disciplinary project under the CGIAR Challenge Program, taking on the challenge of developing a framework for a new IWRM based water governance from village to basin scale in the Limpopo basin, which integrates green and blue water management for improved rural livelihoods. Participatory on-farm research will focus on productive use of alluvial management, shallow water tables, and surface runoff, using water harvesting systems. The focus is on adaptive management for risk reduction, water productivity and yield improvements. Trade-offs between upstream-downstream water uses and options for improved irrigation efficiencies downstream will be studied.

The project will focus on pilot catchments in Zimbabwe (Mzingwane), Mozambique (Chókwè) and South Africa (Olifants). The project will generate a new knowledge base on appropriate agricultural water management, and catchment management to support this. Guidelines for catchment management will be developed and upscaled to a needs-based IWRM framework for sustainable water for food development at basin scale throughout Sub-Saharan Africa.

1.3 Problem Analysis

1.3.1 Problem Description

Improvement of food security and rural livelihoods in Sub-Saharan Africa can be achieved by upgrading the widespread rainfed agricultural sector in the region. Experience with simple in-situ farming techniques show that more crop per drop is established. However, the impact on the catchment hydrology after applying these new techniques on a large scale is not clear.

1.3.2 Objectives

The main objective of this research is to:

- Estimate the influence of on-farm conservation practices on the water balance in a catchment in Zimbabwe.

The specific objectives are:

- Literature review on experiences with in-situ conservation farming practices in Africa.
- Derive land use map of Mzinyathini Catchment from *LandSat* images
- To investigate how different types of farming technologies influence the rainfall partitioning on field scale.
- Derive a rainfall runoff relation, so the terms in the water balance can be modelled.
- Translate the rainfall partitioning on farm scale to a water balance on catchment scale.

1.3.3 Research Questions

The following research questions function as a guideline to fulfil the objectives mentioned in the previous section.

- What are the reasons behind the food deficit in Sub-Saharan Africa?
- What are the dominating terms in the rainfall partitioning scheme in the catchment?
- What types of in-situ conservation practices are applicable for the catchment under consideration?
- What terms in the rainfall partitioning change significantly after appliance of different farming practices?
- To what extent does an alteration in rainfall partitioning on a farm plot influence the water balance on catchment scale?

1.3.4 Hypothesis

Improved farming practices maximize the ratio of productive over unproductive rainwater use. Surface runoff and evaporation are regarded as the unproductive part of the rainfall, because they do not contribute to crop growth. If less water evaporates or runs off over the surface, then there shall be more water left for infiltration. Infiltrated water can be used entirely for transpiration by crops or it can percolate further to the groundwater storage. Increased groundwater recharge leads to more seepage to the river. This base flow is filtered by the soil and therefore better for the water quality than surface runoff that enters the river directly. In addition, annual river runoff will be more evenly distributed, due to slower travel times compared to surface runoff. Consequently, more water and more evenly distributed availability of water in the river throughout the year reduces the occurrence of conflicts when water gets prioritised for certain functions (agriculture, environment, etc.). Less surface runoff will not only decrease the amount of water flowing to water bodies, but also the discharge peak after heavy rainfall. Discharge peaks cause flooding and erosion. The decrease in surface runoff is expected to have a more dominant effect on the annual river discharge than extra base flow.

1.3.5 Justification

This research project will contribute to the knowledge necessary in securing the future food demands and provides an insight into the changes occurring in the physical system due to the implementation of system technologies. Some paragraphs from recent publications that recognize the importance of this research are presented next:

- *The Seeds staff from the UN Development Programme, World Health Organization, UN Food and Agriculture Organization (http://seedpublishers.org/he2000glst.html)*

Often it takes just a few simple resources for impoverished people to be able to grow enough food to become self-sufficient. These resources include quality seeds, appropriate tools, and access to water. Small improvements in farming techniques and food storage methods are also helpful.

- Lørup, J., 1998, in: *Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe*

His study found that although an increase in population was noticed and a change in hydrology, it was not as a result of land use change. He suggested the management of the land, especially concerning small-scale agriculture, was responsible for the shifts. Different management techniques consist of applying rainwater harvesting techniques and small-scale diversion and storage structures, changing rainfall partitioning and the hydrological regime of the catchment.

- Kijne, J., 2001, in: *Preserving The (Water) Harvest: Effective Water Use In Agriculture*

Human-induced soil degradation also occurs at farm and field level. Fallow periods, reduced recycling of organic matter to the root zone, and generally low fertility status of the soil all contribute to crust formation, increased runoff and reduced water holding capacity of the soil profile. Analysis of long term records of how rainwater is partitioned, e.g. those by Rockström et al. (1998) in Niger mentioned above and for Zimbabwe by Savenije (1998), would help to identify the rate of change in partitioning, and the scale on which it is significant (i.e., field or catchment).

- Rockström, J., 2003a, in: *Water for Food and Nature in Drought-prone Tropics: Vapour Shift in Rainfed Agriculture*

However, the fact remains that the hydrological implications at watershed and river basin scale of upscaling system innovations such as water harvesting are still unknown and require further research.

1.3.6 Report Structure

The preceding sections have explained that the main objective of this thesis is to estimate the influence of on-farm conservation practices on the water balance in a catchment in Zimbabwe. In Chapter 2 the study area within Zimbabwe is discussed. In Chapter 3 it is stated that the different hydrological cycles are all based on the same water balance; IN equals OUT plus change in STORAGE. Furthermore the yield gap is analysed, and solutions for increased food security are introduced. Chapter 4 gives an overview of different conservation practices, farm management techniques and socio-economic constraints in Africa. Results of several on-farm experiments with different conservation practices are summarized in a table. In Chapter 5 the water balance model, based on the rainfall partitioning on catchment scale, is discussed. This model can interpret the changes in the catchment water balance as a result of changes in farming practice in the catchment. Finally, Chapter 6 presents conclusions and recommendations for further research.

2 Study Area

2.1 Introduction

Zimbabwe today is not the granary of Africa as it was once known. Not only the land reforms, but also widespread AIDS and hunger changed the country. Even today the country is far from stable and newspapers in the Netherlands publish alarming stories almost every day. The data presented in this chapter is as up to date as possible. First the history and different sectors in Zimbabwe are discussed, before the selected study catchment is explored.

2.2 Zimbabwe

2.2.1 History

Colonial time

A large settler community of European origin, mainly British, existed from the initial creation of the state of Southern Rhodesia in 1890. The Land Apportionment Act of 1930 set aside 51% of land for these white people while the black people were restricted into Native Reserves. The reserves were to eventually become today's communal lands. Over time a pattern of settlement was established which saw low density white settler farmers existing on the best land, with an increasingly marginalized and impoverished black community existing in high density settlements on less favourable communal land. In 1896 and 1966 the native people rose up against the white settlers and gathered forces to drive the enemy from their land in what is called the first and second *Chimurenga* ('War for Liberation'). The second *Chimurenga* ended in 1979 with the signing of the Lancaster Agreement, paving the way for independence in 1980. At independence white commercial farmers, constituting less than 1% of the country's population, occupied 45% of the country's agricultural land while over 700,000 black farmers occupied less than 50% of the agricultural land (Moyo, 2004).

Independence

When Robert Mugabe came to power in 1980, he promised to resettle 162,000 black families on white-owned land. Under the 'willing buyer, willing seller' scheme, which operated through the 1980s, the government was able to buy back the land at market prices. After ten years, the government changed the law to permit compulsory acquisition of land for redistribution and resettlement at prices set by a committee. By 1997, only 71,000 families out of a targeted 162,000 had been resettled on roughly 3.5 million hectares of land. In response to persistent demands for assistance by the Zimbabwe Liberation War Veteran's Association (WVA) the government announced that it planned to compulsorily acquire nearly 1500 farms (3.9 million hectares). By 1999, only 35 of the nearly 1500 targeted farms had been purchased for resettlement, leading to violent seizures by impatient black farmers from marginal areas (Human Rights Watch, 2003).

Fast track land reform

In July 2000, president Mugabe announced the fast-track land reform program. Under the program, the government acquired five million hectares of land from commercial large scale farmers and divided it among the people. Agricultural production was especially disrupted, because the people who took over the land had little experience or training how to manage the equipment. Irrigation lines were destroyed and farmers were unable to obtain the constituent ingredients for fertilizer, due to the lack of foreign exchange and raw materials (Human Rights Watch, 2003). Targeted international sanctions, combined with a withdrawal from development cooperation by the International Monetary Fund, the World Bank and most donors, worsens prospects for economic recovery.

2.2.2 Geography

Zimbabwe is a land-locked country in the Southern African Region, bordered by Zambia, Mozambique, South Africa, Botswana and Namibia (Figure 2.1). Zimbabwe has a total area of

390,580 km2, stretching 725km east west, and 825km north south. It is situated between 15 and 22° south latitude and 26 and 34° east longitude.

Figure 2.1: Zimbabwe is a landlocked country in Southern Africa (Scale 1:10,000,000)

The only significant mountainous region is the Eastern Highlands, forming the border with Mozambique. Zimbabwe's highest peak, Mt. Nyangani, is 2592m high, while the lowest point is 162m, at the confluence of the Save and Runde Rivers in the south. Most of the country lies between 900m and 1700m above sea level. A low ridge across the country from the Mvurwi Range in the north-east to the Matobo Hills in the south-west marks the divide between two of Africa's great river systems, the Zambezi in the north west and the Limpopo in the south-east. Approximately one-third of Zimbabwean soils are derived from granitic rocks. Many of these soils are sandy and infertile, low in weatherable minerals and especially deficient in *N*, *P* and *S*. Wilson (2001) observed that rock outcrops, in the form of granitic domes, are common in communal areas of Zimbabwe, sometimes even occupying up to one-third of the land area. They are statistically correlated with erosion and generate high rates of runoff. Sheet wash and gullying are common in agricultural fields at the base of these domes and remaining subsoil strata is susceptible to continued physical degradation. Results of the Zimbabwe erosion survey (Whitlow, 1988) indicated that there were 1.8 million ha of eroded land of which 80% was located on communal lands. Intense cropping practices on infertile soils on communal lands of Zimbabwe has led to significant soil removal and general declines in crop yields.

2.2.3 Climate

Climatic conditions are largely sub-tropical with one rainy season, between November and March. Rainfall reliability decreases from north to south and also from east to west. The rainfall in Zimbabwe is strongly related to the seasonal fluctuations of the Inter-Tropical Convergence Zone (ICTZ), the zone where the airstreams originating in two hemispheres meet. The ICTZ is a complex, ever changing band of growing and disintegrating convergences. The position, width and depth varies geographically, seasonally and even daily related to the position of the sun. The convergence within the ICTZ induces convection, which is the movement of air upwards due to warming at ground level. Convection accounts for perhaps 90% of the Zimbabwean rainfall (De Groen, 2002). The upward movement of air is compensated for by the downward movement of air in areas around it. Convection thus only occupies a maximum of 10% of the area, with dimensions in the order of 5 to $10(km)^2$. Therefore, the spatial scale of daily rainfall is very small.

The Eastern Highlands receive high rainfall (>1500mm/a) due to both their high altitude and proximity to the Indian Ocean. The central watershed receives moderately high rainfall due to its high altitude. The northern parts receive more rainfall than the southern parts (400mm/a) since both the Congo Air and north-eastern monsoons will have discharged most of their moisture when they get to the southern parts. The mean annual rainfall in Zimbabwe is 650mm/a. Only 37% of the country receive rainfall considered adequate for agriculture. For the rest of the country the rainfall pattern is inadequate, erratic and unreliable making water management a crucial discipline for food security. The country is split up in several agro-ecological zones on the basis of the spatial distribution of climate, topography and soil types as shown in Table 2.1 and Figure 2.2 (FAO & SAFR, 2000).

Table 2.1: The five natural regions of Zimbabwe, each with their dominant type of agriculture (FAO & SAFR, 2000)

Region	% of Land	Attributes
I	1.5	Very high rainfall, above 1000mm/a; low temperatures, below 15°C. Forestry, wattle, tea, coffee, deciduous fruit, barley and potatoes. Intensive beef and dairy farming.
II	18.7	High rainfall, 700 to 1000mm/a; warm summers, cool winters. Maize, tobacco, cotton, winter wheat and market gardening - intensive farming. Intensive beef and dairy farming.
III	17.4	Moderate rainfall, 550 to 700mm/a; high temperatures and dry spells. Drought resistant cotton, soya and sorghum. Beef farming and breeding.
IV	33.0	Low rainfall, 450 to 600mm/a; seasonal droughts. Irrigation of drought resistant crops. Semi-extensive controlled grazing.
V	29.0	Very low erratic rainfall, below 500mm/a; very hot. Sugar, citrus, cotton and wheat irrigation schemes of lowveld.

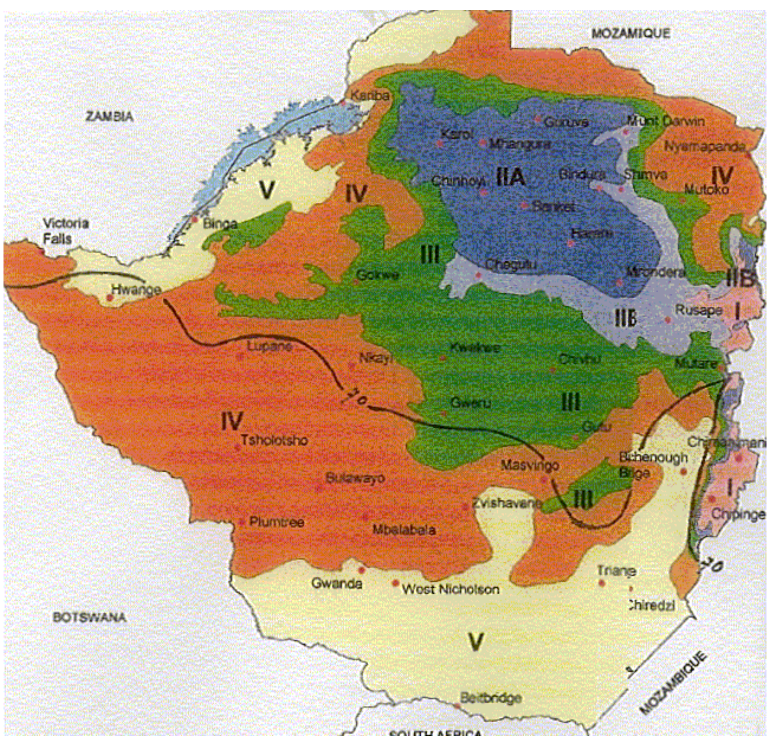

Figure 2.2: Natural regions, which relate climate, soils and topography to appropriate farming systems

Regions IV and V, which receive low rainfall, are the ones with the highest inter-annual rainfall variability. Droughts are therefore an inherent characteristic of the climate of

Zimbabwe. Lack of water affects every aspect of environmental health and human activity, including agriculture, natural areas and development projects. The 1991-1992 drought which ravaged most of southern Africa, killed more than one million cattle in Zimbabwe. Rivers and lakes shrink and food sources for fish decrease, resulting in low breeding rates and smaller catches for fishermen. The drop in water supplies in dams and rivers also affects the quality of water. The cholera outbreak that affected almost every country in the region during 1992 and 1993, claiming hundreds of lives, may have been compounded by the drought.
The semi-arid nature of the climate in Zimbabwe is indicated by a greater potential evapotranspiration than rainfall in all months of the year.

2.2.4 Population

The total population of the country is estimated at about 12.6 million, of which 64% is rural (2004). The estimated annual growth rate is about 1.02%. Table 2.2 shows information from the CIA World Factbook (last update February 2005) about Zimbabwe (last national census in 2002) and the Netherlands, for comparison purposes.

Table 2.2: Information on population and economy in Zimbabwe and the Netherlands (CIA,2005)

		Zimbabwe	**The Netherlands**	
Area		390,580	41,526	km^2
Population		12,671,860	16,318,199	persons
Age	0-14yr.	39.4	18.3	%
	15-64yr.	57	67.8	%
	65-	3.6	13.9	%
Total Median age		19.1	38.7	years
Births		30.05	11.4	/1000 pop.
Deaths		23.3	8.67	/1000 pop
Total Infant mortality		67.8	5.11	/1000 live births
Life Expectancy at birth		37.82	78.68	years
HIV/AIDS-adult prevalence rate	15-49yr	24.6 (UNAIDS Zimbabwe, 2003)	0.2	%
Population below poverty line		70	0	%
Inflation rate		625	2.1	%
Unemployment		70	5.3	%

The high death rate and in particular high infant mortality can be attributed to hunger and AIDS. The HIV/AIDS adult prevalence rate is calculated by dividing the estimated number of adults (aged 15-49) living with HIV/AIDS at yearend by the total adult population at yearend. This means that more than two million Zimbabweans are infected by the HIV virus. Research performed by the UN in December 2003 indicates a 43% HIV/AIDS prevalence rate on farms compared to a national infection level of 24.6%, with the highest number of HIV-positive people in the 15 to 23 age range, the core of the agricultural labour force.
The impact of HIV/AIDS on agriculture includes the loss of agricultural extension workers through death, illness and discharge on medical grounds, while a significant amount of man-hours have been lost through increased absenteeism because of illness, caring for the sick or attending funerals. This leads to 23% of labour losses among farming communities due to HIV/AIDS (UN, 2003).

2.2.5 Agriculture and Economy

Zimbabwe's economy is driven by agriculture and about 70% of the population depends on it for their livelihood. Irrigation is important for successful crop production in the country as the greater part of the country (Natural Regions III, IV and V) receives inadequate rainfall for agriculture. Supplementary irrigation is also used to extend the growing season of certain crops or ensure the early planting of such crops as tobacco and cotton. The major irrigated crops in the country are wheat, cotton, sugarcane, tobacco, soya beans, fruit, vegetables and maize. Of the total irrigated area in Zimbabwe it was estimated in 1999 that 112,783ha is under sprinkler irrigation (including center pivots), 46,849ha under surface irrigation and 13,881ha under localized irrigation. Yet, only 6% of the total cultivated area (3,350,000 ha) is being irrigated (FAO, 2005). About 80% of the rural population live in regions where agriculture is dependent on erratic and unreliable rainfall. The success rate of rainfed agriculture in these regions has been known to be in the order of one good harvest in every four to five years. In years of good rainfall the country produces enough food to feed the nation and enjoys surpluses for export, in years of drought the reverse is the case. Crops should be rigid and capable of withstanding extreme conditions. For example, the maize type SC401, is recommended in natural regions III, IV and V, because of its good heat tolerance and early maturing (Table 2.3)

Table 2.3: Standability and Tolerance Scores: 1 = Excellent, 9 = Very Susceptible (SeedCo Specialist, 2000)

		Height (m)		**Standability**		**Tolerance**					**Grain**	**Days to**		**Yield range**
	Grain Colour	Cob	Plant	Root	Stalk	Leaf Blight	Cob Disease	Heat & Drought	Maize Streak	Grey Leaf spot	Drying Rate	Silk	Mature	(t/ha)
SC401	White	1.2	2.4	1	2	2	2	2	8	9	Fast	60	126	1-6

FAO (2005) states that there are four broad categories of farming sectors under full or partial irrigation. These are:

- Large-scale commercial schemes: land owned by private individuals or groups including estates and plantations (80,854ha);
- ARDA (Agricultural and Rural Development Authority) schemes: government-owned estates and farms for agricultural development in rural areas (11,084 ha);
- Smallholder irrigation schemes: group of farmers irrigating together sharing the same water source and supply line. However there is individual control of irrigation and farming activities by each farmer in his/her plot. Plot sizes are normally 0.1-2 ha (11,861 ha);
- A1 and A2 irrigation schemes: this is a new type of irrigators in the country. The land reform undertaken by government has increased the area under smallholder irrigation. The reform has split up commercial irrigation schemes and ushered in two new groups of farmers, namely A1 who irrigate small areas at times with shared infrastructure and A2 who are the breed of commercial irrigators. In some cases, the A2 farmers also share irrigation infrastructure (69,714 ha).

The agricultural sector contributes about 17% to the country's Gross Domestic Product (GDP), 60% of the raw materials required by the manufacturing industry and 40% of the total export earnings.

2.2.6 Water resources and management

(partly extracted from FAO, 2005)
The overall groundwater resource is small when compared to estimates of surface water resources, mainly because the greater part of Zimbabwe consists of ancient igneous rock formations where groundwater potential is comparatively low. The estimated groundwater potential is between 1 and 2 $(km)^3$/a. Total annual water withdrawal is estimated at 4.2 $(km)^3$ in 2002. Agriculture is the greatest water user in Zimbabwe accounting for 79% of total water use. Agricultural water uses are for irrigation, fish farming and livestock watering. Most irrigation schemes in the country depend on water stored in dams. Other important sources are boreholes or deep wells, the river, shallow wells, springs and alluvial aquifers. At national level the responsibility for the planning, coordination, management of water resources and delivery of water is vested with ZINWA in conjunction with catchment councils. The Zimbabwe National Water Authority (ZINWA) is supervised by its parent ministry the Ministry

of Rural Resources and Infrastructural Development (MRRID). There are seven catchment councils in the country and each is supposed to represent all stakeholders in a given catchment. Irrigation schemes, both smallholder and large-scale commercial schemes, are represented in some of these catchment councils. As well as the MRRID the Ministry of Agriculture and Rural Development (MARD) is very important for the overall development and implementation of the Government's policy on agriculture and irrigation.
The MARD is directly involved through its departments and parastatal bodies as follows:

- The Department of Research and Extension Services (AREX) provides extension services to all irrigators and its research section is responsible for soil surveys and testing for irrigation development;
- The Agricultural and Rural Development Authority (ARDA) is a parastatal responsible on behalf of government for the operation of government-owned irrigated estates and farms. It works closely with the Department of Irrigation;
- The Grain Marketing Board (GMB) is a parastatal in charge of marketing of the country's strategic crops. All controlled crops such as maize and wheat from irrigation schemes are sold to GMB at regulated prices. The parastatal also administers the government input credit scheme to irrigators;
- The Department of Irrigation (DOI) is a new department which was initially in the Ministry of the then Rural Resources and Water Development (MRRWD) and was recently moved to MARD. The Department is mandated with all the irrigation activities in the country which include planning, identification of schemes, designing, construction, operation and management of existing irrigation schemes

The departments of AREX and DOI play a central role in providing extension and training to the irrigation sector. These departments are represented at provincial level and in the case of AREX also at district level.

Recent milestones in water- and land-related legislation are:

- The Water Act (1998) has reformed the water sector to ensure a more equitable distribution of water and stakeholder involvement in the management of water resources. Water now can not be privately owned. The "priority date water right system" has been replaced by water permits of limited duration which will be allocated by catchment councils. Water is now treated as an economic good and the "user pay principle" applies. Pollution of water is now an offence and the "polluter pays" principle applies.
- The Zimbabwe National Water Authority Act (1998) led to the establishment of ZINWA.
- The Land Acquisition Act (2000) has empowered the government to compulsorily acquire any land for resettlement purposes under the land reform. The land redistribution carried by the government has resulted in an increase in the land under irrigation in the smallholder sector as commercial irrigated farms have been acquired and split into smaller pieces. This has ushered in two new groups of farmers namely A1 who irrigate small areas with shared equipment and A2 who are the new breed of commercial farmers. In some cases the A2 farmers also share irrigation infrastructure;
- The Environmental Management Act (2002) empowers the government to command public and private development institutions to undertake an Environmental Impact Assessment (EIA) before undertaking any activity and adhere to mitigating activities to protect the environment as recommended in the EIA. Irrigation development is one such prescribed activity which requires an EIA.

From an international point of view Zimbabwe is cooperating with other members of the Southern Africa Development Community (SADC) on the shared management of the region's river systems. The country is a signatory to the recent Shared Water Course Systems Protocol, which provides the basis for the management of international rivers in SADC. The country is actively participating in the formation of the Limpopo and Zambezi basin commissions which will oversee joint management of these international rivers.

2.3 Mzinyathini Catchment

2.3.1 Geography

The Challenge Program focuses on the Mzingwane catchment, which drains south into the Limpopo river, the Mzinyathini catchment is one of the uppermost small sub-catchments close to Bulawayo (see Figure 2.3). It is 448(km)^2 and lies between 1100m and 1480m above mean sea level.

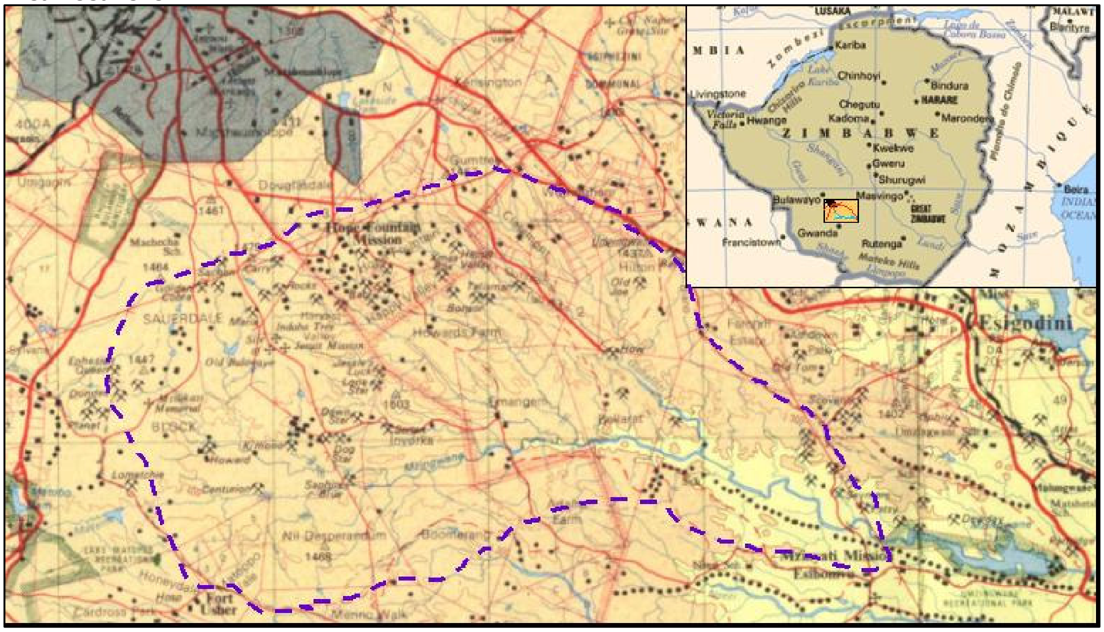

Figure 2.3: Location of Mzinyathini catchment in Zimbabwe (Scale: 1:300,000

Figure 2.4 shows the Digital Elevation Map of the catchment plotted using Aguila software. The relief can be characterised as hilly.

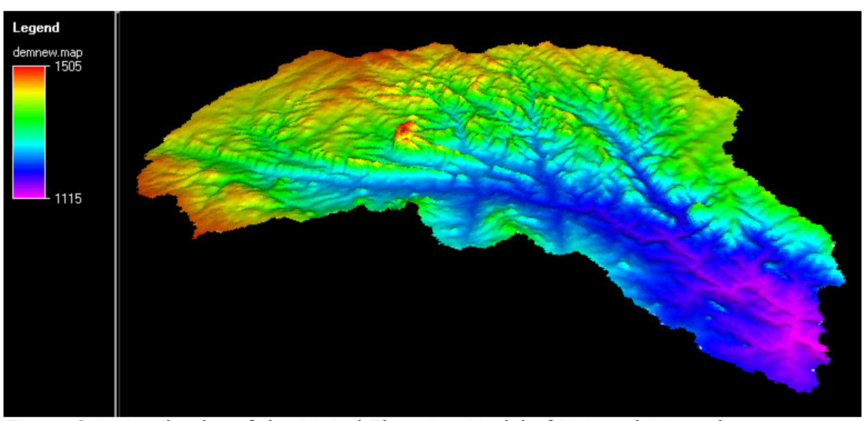

Figure 2.4: Aguila plot of the Digital Elevation Model of Mzinyathini catchment

The Gabalozi river joins the Mzingwane river which fills a big reservoir dammed by the Umzingwane Dam. The dam was built in 1962 to secure the water supply of the city of Bulawayo.

The geology of the catchment is characterised by large expanses of undifferentiated gneisses and granites, with numerous mineralised Greenstone intrusions underlain by the Zimbabwe Craton. The soil mainly consist of moderately shallow, coarse-grained kaolinitic sands derived from the granites and shallow clays formed from the Bulawayo Greenstone Belt.

2.3.2 Climate

Temperature, humidity and wind

The average daily maximum and minimum temperature in Bulawayo is respectively 26.6 and 13.4°C. From Figure 2.5 it can be observed that the average monthly temperatures in summer (September to March) are about 5°C higher than in winter (April to August).The high relative humidity between November and March coincides with the rainy season in Zimbabwe. Monthly average wind data for Bulawayo indicate wind speeds of 2m/s throughout the year.

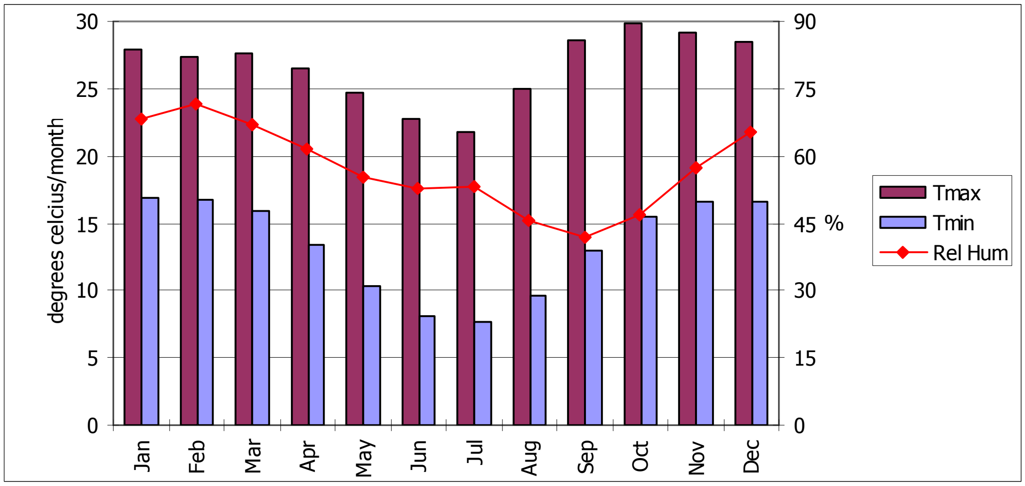

Figure 2.5: Average maximum and minimum temperature and relative humidity measured at Bulawayo (1988-2001)

Rainfall

Eight rainfall stations are located in the vicinity of the Mzinyathini catchment. Only one of them, Umzingwane Dam Station, is actually located within the catchment boundary. Figure 2.6 shows the locations of the runoff station, rainfall stations and the catchment boundary.

Figure 2.6: Mzinyathini Catchment with all nearby rainfall stations and one runoff station B30 (Scale: 1:400,000)

Data from stations in Esigodini, Bulawayo and Matopos are considered applicable for this research, this is explained in Chapter 5 in more detail. Observations are made daily at 08.00

hrs after which they are coded and send to the collection centres. The reliability of the rainfall data is analysed for the period between 1988 and 2001.
Rain conditions are influenced by the occurrence of a high pressure zone in the upper air above Botswana. This Botswanean Upper High causes an anticyclonic movement of air masses against the cyclonic Indian Ocean air in the region and therefore has a rain-inhibiting stability (De Groen, 2002). The distribution of the rainfall in a year for the catchment is shown in Figure 2.7. It is observed that basically two distinct periods can be discerned: a wet period from November to March and a dry period from April to October. The relative standard deviation is always higher than 0.5 indicating a substantial variability in rainfall from year to year. The hydrological year in Zimbabwe runs between October and September.

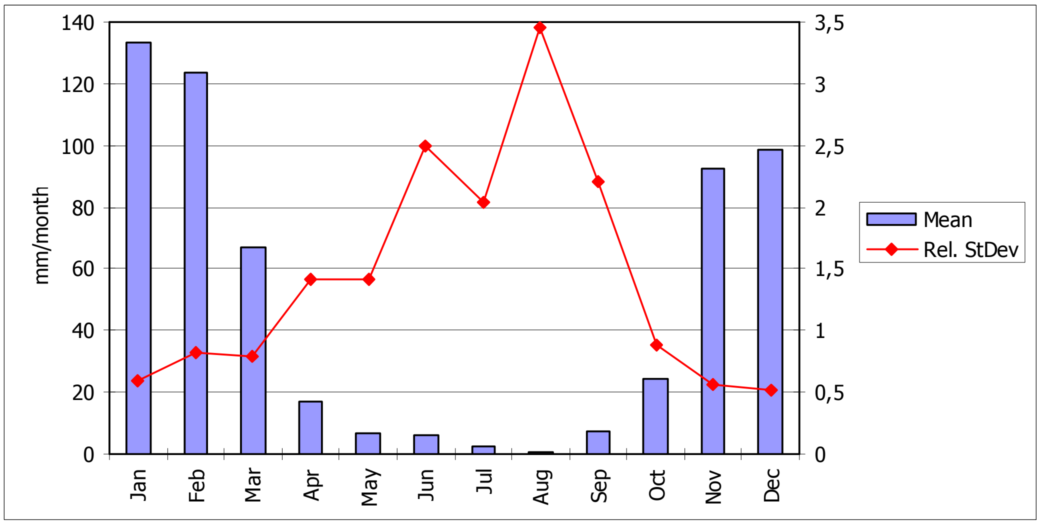

Figure 2.7: Average Monthly rainfall of Esigodini, Bulawayo and Matopos and relative standard deviation over 1988 to2001

The annual rainfall for the three stations for the period 1988-2001 is shown in Figure 2.8. Season 1991-1992 can be recognized as a very dry year, while 1999-2000 was a very wet year, due to the cyclone *Eline* that hit Zimbabwe in February 2000. The mean annual rainfall for Esigodini, Bulawayo and Matopos is respectively 553mm/a, 575mm/a and 563mm/a. Thus, the absolute difference between rainfall totals per station is not very large.

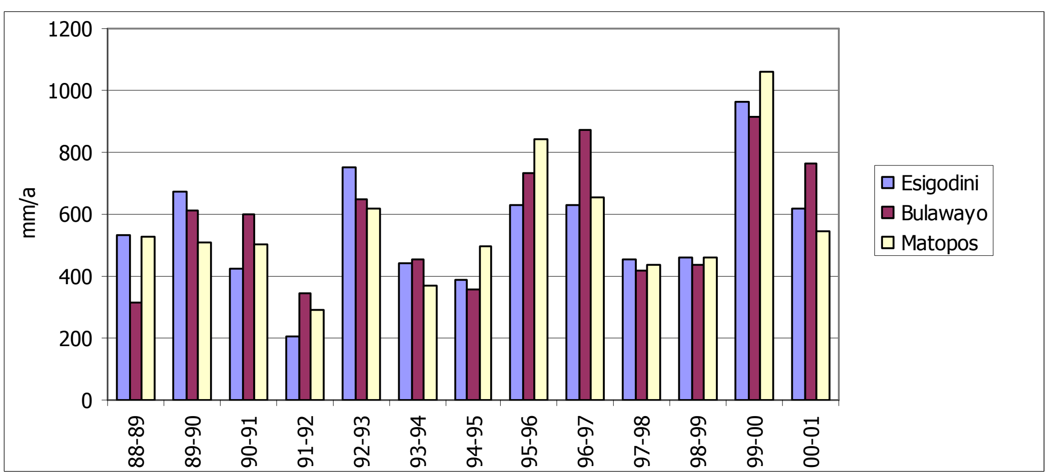

Figure 2.8: Rainfall totals of Esigodini. Bulawayo and Matopos over a hydrological year (1988-2001)

TU Delft
Delft University of Technology

Evaporation

Evaporation occurs when water in liquid form is converted into water vapour. At the evaporating surface energy is required to break the hydrogen bonds between the water molecules to let them escape from the surface. The energy is mainly delivered by net radiation. Supply of energy however is not sufficient to sustain a high rate of evaporation. Aerodynamic factors like wind and vapour pressure difference between the surface and lower atmosphere control the conditions for transfer of water vapour away from the evaporating surface. In Zimbabwe evaporation is estimated from class A pan evaporation measurements. All pans are covered by chicken wire to prevent animals drinking from the pan. The chicken wire reduces the pan evaporation by about 10% (De Groen, 2002). The average daily pan evaporation in Bulawayo on a rainy day is 4.1mm/d, while it is 6.1mm/d on a dry day. Figure 2.9 shows the average monthly pan evaporation and rainfall in Bulawayo for the period 1988-2001. It can be seen that pan evaporation is much higher than rainfall throughout the year.

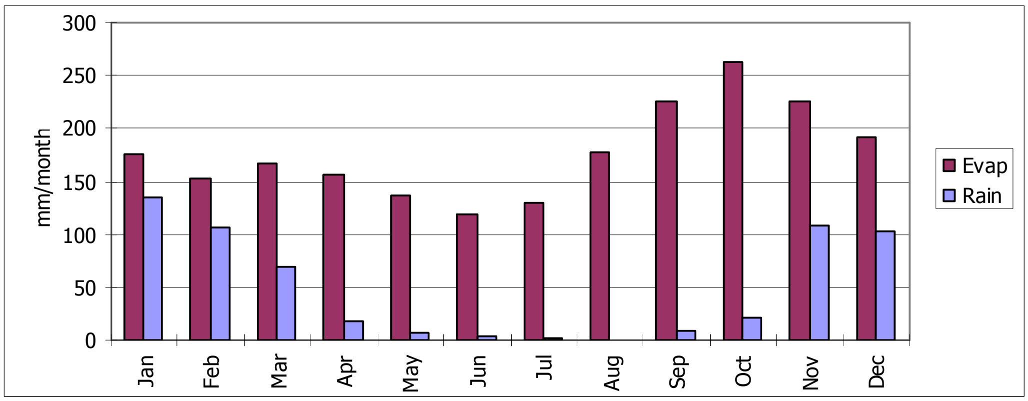

Figure 2.9: Average monthly evaporation and rainfall at Bulawayo for 1988-2001

However, it should be noted that the actual evaporation from the catchment is only a fraction of the measured pan evaporation. This overestimation is caused due to the fact that the pan evaporation measures open water evaporation from an unlimited amount of water and it is not restricted by any resistance. Figure 2.10 illustrates the relation between annual pan evaporation and rainfall in Bulawayo. Annual pan evaporation seems to decrease at higher annual rainfall totals. This might be explained by the lower need for moisture by the atmosphere at increasing rainfall events.

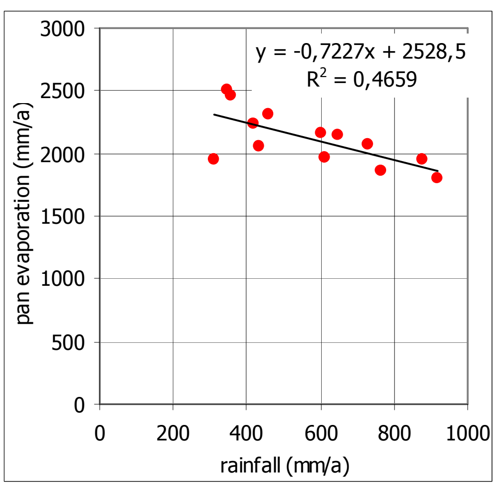

Figure 2.10: Annual pan evaporation and rainfall in Bulawayo (1988-2001)

2.3.3 Runoff

The Mzinyathini catchment is defined as the drainage area upstream of weir B30. Downstream of the weir a big reservoir and recreational lake is situated. The reservoir secures the water supply to the city of Bulawayo. The catchment has two main rivers, the Gabalozi river merges with the Mzingwane river 11km upstream of weir B30, which is the only weir in the catchment. Figure 2.11 shows the longitudinal profile of the two rivers, the mean slope of the Gabalozi and Mzingwane river is respectively 1.5% and 1%.

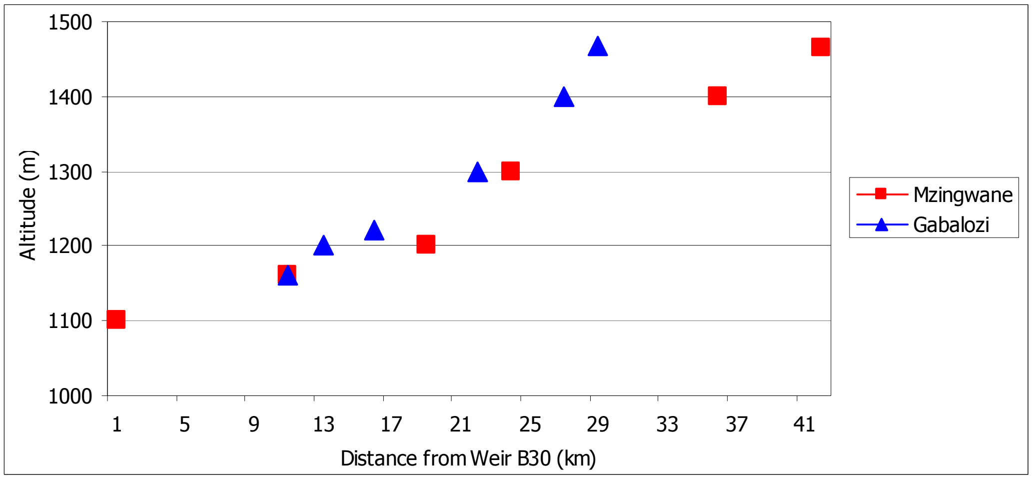

Figure 2.11: Altitude (+MSL) of points in the Gabalozi and Mzingwane river bed related to the distance upstream from weir B30

The rivers are considered ephemeral rivers, because they dry up during rainless periods (see Figure 2.12). This is also an indication that it is an influent river, meaning that water from the riverbed infiltrates the soil and not reaches the weir. So not all the water that enters the river is gauged, due to re-infiltration further downstream of the area that generated runoff.

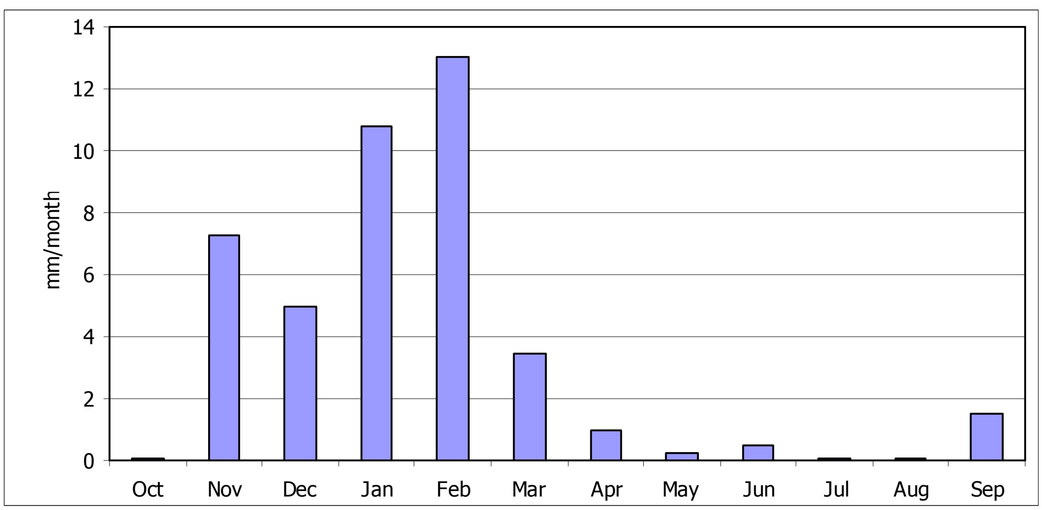

Figure 2.12: Average monthly runoff measured at weir B30 (1988-2001)

Figure 2.13 shows the flow duration curve of the Mzingwane river, the X-axis is categorized in class intervals of recorded runoff and the Y-axis gives the percentage of time the discharge is exceeded. The figure implies that only 33% of the time water is observed flowing over the weir. The flow duration curve may be regarded as a probability curve, which may be used to estimate the percentage of time that a specified discharge will be equalled or exceeded in the future (Savenije, 2003). At the 16th of February 2000 the highest recorded flow at weir B30 was 100m^3/s, which equals 19.6mm over the total catchment area.

In 1984 the Ministry of Water Resources and Development in Harare made an assessment of the surface water resources of Zimbabwe. Catchment run-off parameters of every hydrological zone and sub-zone are estimated and published. It was found that the mean annual virgin runoff (includes abstractions for irrigation purposes) was 50mm with a coefficient of variation of 100% (WRD, 1984). The mean annual runoff over 1988-2001 is smaller, 42mm with a coefficient of variation of 87%. This is because no abstractions are taken into account, but in addition, a lot of small dams have been built by farmers in the area increasing the evaporation from open water but also from the irrigation fields.

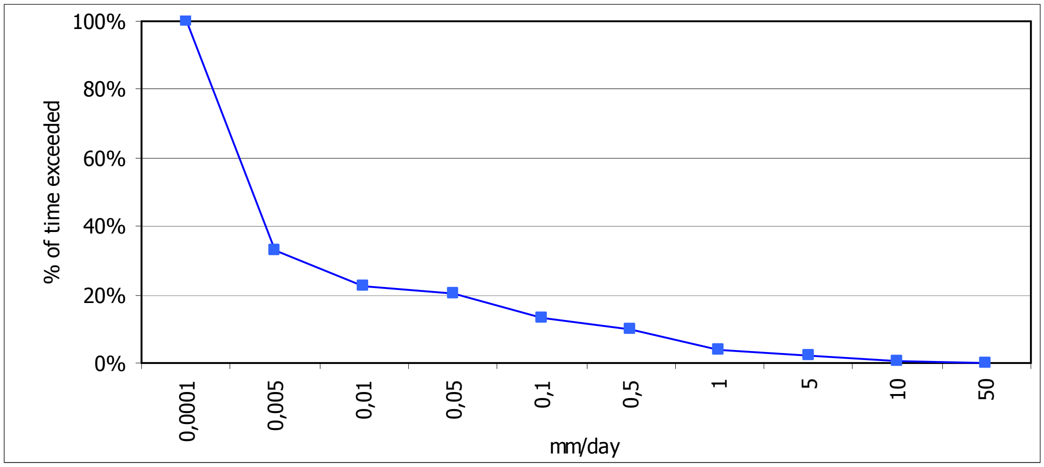

Figure 2.13: Flow duration curve Mzingwane river (1988-2001)

The runoff data is collected by ZINWA, they are currently digitising the automatic gauging data from the weir. Errors in the data used for this research can be attributed to:

- A malfunctioning gauge (clogging, mechanical problem, no maintenance, etc.)
- Errors in observations (miscalculate the date, wrong list, etc)
- Errors while digitising (misinterpretations, miscalculation in dates, wrong list, etc.)
- The rating curve is not representative anymore

2.3.4 Land and Water management

A large part of the catchment is part of the Mzinyathini Communal Land, which means that the land is owned by a large community where many farmers work on small plots. Subsistence agriculture takes place in the communal areas where mainly maize, groundnut and beans are grown during the wet months, in addition with livestock farming (Mwenge Kahinda, 2004). Figure 2.14 shows a picture of children herding the cattle alongside the Mzingwane river.

Figure 2.14: Cattle in the catchment (23-12-2004)

The land tenure system in Communal Areas in Zimbabwe today is a result of an evolution of the traditional customary tenure system existing in the pre-colonial days. Under traditional tenure, land rights are defined for groups, households and individuals based on traditions and customs evolving over time. Access to land was regulated through kraal heads and chiefs. This system worked because of social pressure (van der Zaag, 1998). Generally, individual families enjoyed more clearly defined spatial and temporal rights over the use of several parcels of land and the natural resources on it. Tenure today is administered by local level institutions, each with its own boundaries and drawing on different sources of legitimacy. Until a few years ago, Zimbabwe had a dual system of land ownership: large commercial, intensively managed crop- or grazing land, mostly white-owned; and small-scale/subsistence, tribal or communal lands, usually not intensively managed and characterized by low productivity (Louw, 2003). This duality presumably imposes large productivity and socio-economic costs. A further problem is the lack of purchasing power for acquiring critical farm inputs such as feed, fertilizers and seed, particularly among resource-poor small-holders. The obvious solution, establishment of communal schemes to pool resources, is usually fraught with such problems as management disagreements and waste of resources.

One of the most successful smallholder schemes of Zimbabwe, the Mzinyathini scheme, is also situated in the catchment (FAO & SAFR, 2000). The scheme was a result of an agreement made between the Bulawayo town municipality and the government Department of Native Affairs in 1959. It started to operate in 1965, after the construction of the Umzingwane Dam, from where it draws its water through gravity. The success of Mzinyathini irrigation scheme (32ha large with 81 plot holders, each having 0.4ha) is claimed to be the result of good planning and group cohesion. A comparative analysis of yields showed that irrigators get much higher yields than non-irrigators. Table 2.4 gives the average yields for the two types of farmers during the 1995-96 cropping season

Table 2.4: Irrigation and rainfed crop yields in the Mzinyathini scheme during the 1995-96 season (Source: Farmers and Extension workers record books, 1998)

	Irrigation yields (t/ha)	Rainfed yields (t/ha)
Maize	6 - 8	0.6 - 2
Groundnuts	2	0.7 - 1

FAO & SAFR (2000) concluded from Table 2.4 that the higher yields obtained under irrigation, apart from additional water, are attributed to the high levels of inputs used in irrigation. In rainfed agriculture, farmers confirmed that they are scared of using fertilizers, because they will burn their crops due to lack of rainfall. This is a legitimate concept given the limitations posed by weather on their cropping activities. In Mzinyathini scheme, irrigated maize is applied with 400 kg/ha fertilizer as opposed to 100 kg/ha in the rainfed areas. Groundnuts are given on average 300 kg/ha gypsum as opposed to nothing or very little in rainfed agriculture.

Figure 2.15 shows a land use interpretation in IDRISI of the catchment in 2000. The catchment boundary is indicated with the dotted line. The light color is defined as *Rangeland*, characterised by sandy soil with scattered bush. In some cases poor farmers use this soil for agricultural purposes. Agriculture is most extensive in the purple areas (*Fields*). The large area of Degraded land is due to overgrazing and intensive agriculture. Altogether it is assumed that about 40% of the area is used for some sort of agriculture. In the upper left corner the city of Bulawayo can be distinguished, in the catchment itself there is no significant urban area, dwellings are scattered through the catchment. An attempt to fully utilize runoff has led to an extensive dam construction programme. While these reservoirs are used as sources of domestic water, some supply water for irrigation and mining purposes. The Mzingwane sub-catchment is the most intensely mined in the Limpopo Catchment in Zimbabwe. Mines extent water retention in the catchment and negatively affect the water quality. The main activities are nickel, cobalt and gold mining, with potential acid mine drainage polluting the environment. All three of these are associated with the greenstone belts, as is the medium level of environmental impact of numerous smaller gold mines. There is also alluvial gold mining in the river beds.

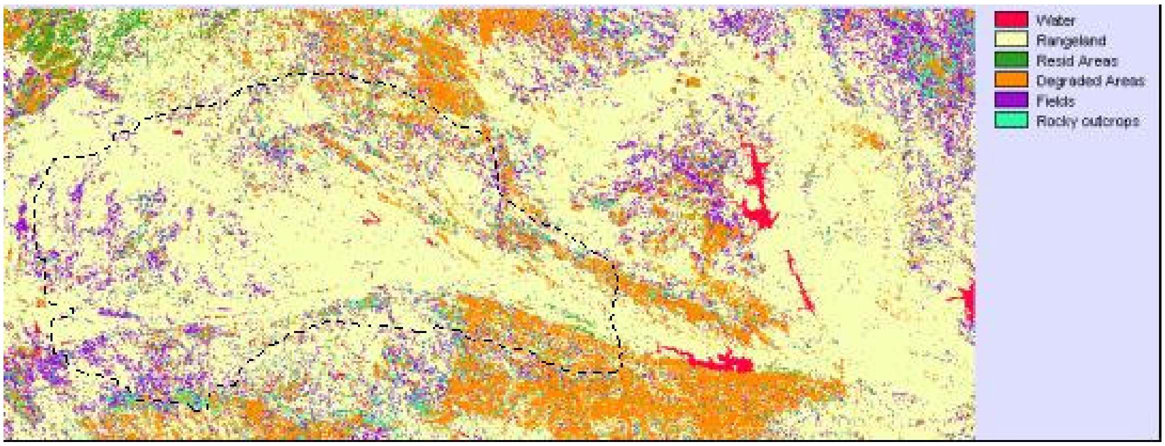

Figure 2.15: Land use map derived from LandSat images from 2000

3 Rainfed Agriculture

3.1 Introduction

Crop growth goes hand in hand with the availability of water, either through irrigation, direct rainfall or a combination of these. Rainfed agriculture refers to those agricultural areas where rainwater is the sole water source for crops, constituting a significant impact (60%, Savenije, 1998) on global food production. Yet, productivity in rainfed agriculture is often low in semi-arid climates. This chapter focuses on what hampers on-farm yields, and perhaps most importantly, how much can yields realistically be increased?

3.2 Hydrological Cycles

3.2.1 Global Scale

Precipitation, evaporation and vapour transport are the major pathways in the global water cycle, shown in Figure 3.1 (adapted from an illustration which originally appeared in *Scientific American*, September 1989, p.82). Water is taken up by the atmosphere from the earth's surface in vapour form through evaporation. The wind transports the vapour until it is condensed back to its liquid phase to form clouds. Water then returns to the surface of the earth in the form of precipitation. Water transport can also take place on or below the earth's surface by flowing glaciers, rivers, and ground water flow.

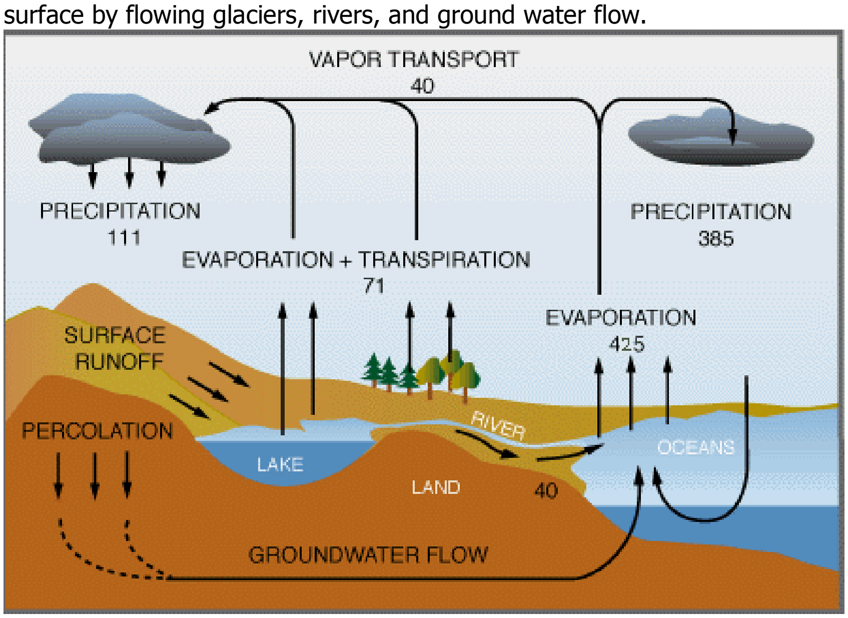

Figure 3.1: Concept of Hydrological cycle (Scientific American, numbers represent estimated annual fluxes on a global scale Gm^3/a)

Another approach to look at the spatial distribution of water on a global scale is splitting them into different colour categories based on its occurrence on the globe.

Rainbow of water

Falkenmark (1995) first introduced the concept of distinguishing between *Green* and *Blue* water flow in the hydrological cycle as a practical analytical tool for analysis of water flow partitioning on the local, regional and global scale. Figure 3.2 shows the rainbow of water, it is made up of *White*, *Green* and *Blue* water resources (Savenije, 1998).

White water is defined by Savenije (1998) as the part of rainfall that directly feeds back to the atmosphere through evaporation from interception.

Blue water is the sum of the water that recharges the groundwater and the water that runs-off over the surface. It occurs as renewable groundwater in aquifers and as surface water in water bodies.
Green water is water that is stored in the unsaturated soil, the process through which it is consumed is called transpiration *(T)*. As green water is transpiration resulting directly from rainfall, it is important for, rainfed agriculture, pasture and forestry. Green water has an average residence time of about four months in the unsaturated zone and is defined as the ratio of storage to transpiration flux, depending on soils, climate and topography. Green water is responsible for by far the largest part of the world's food and biomass production (Savenije, 1998).

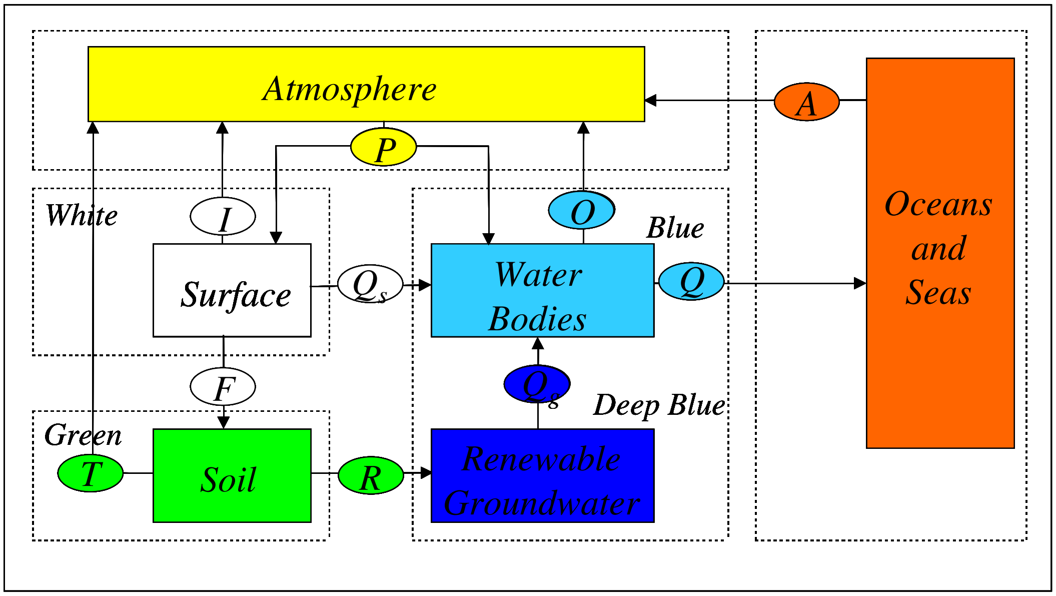

Figure 3.2: Rainbow of water: Global water resources; Blue, Green and White (Savenije, 1998)

3.2.2 Farm scale

Without proper understanding of water partitioning at farm scales, it is difficult to identify sources of inefficiency and to upgrade rainfed agriculture in semi arid regions. Rainfall partitioning on the farm zooms in on the routes rain water follows after it falls on the plot.

Figure 3.3 shows that the rainwater encounters two separation points. At the first separation point rainfall can be intercepted and evaporated directly back to the atmosphere or it can infiltrate in the soil. However, when the infiltration capacity is exceeded, Hortonian overland flow is generated to local flow paths.
The infiltrated rainwater reaches the second separation point where the water is transported back to the atmosphere through evaporation (capillary water) and transpiration by vegetation or it recharges the groundwater.

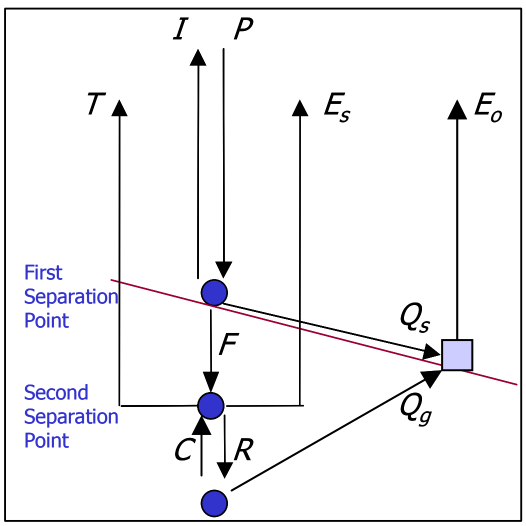

Figure 3.3: Rainfall partitioning on field scale

Table 3.1 shows the definitions of symbols related to rainfall partitioning, with the most important hydrologic processes described more extensively.

Table 3.1: Terms in rainfall partitioning on field scale per separation point

	Symbol	Definition
First Separation Point	P	Rainfall
	I	Interception
	F	Infiltration
	Q_s	Surface Runoff
	E_s	Evaporation from soil
Second Separation Point	T	Transpiration
	R	Groundwater Recharge
	C	Capillary Rise
	Q_g	Base and Rapid Subsurface flow
	E_o	Surface Water Evaporation

Interception I

Interception is defined as the amount of rain that evaporates on the day it falls (Savenije, 2004). For the rainfall runoff process this comes down to that part of the rainfall that does not infiltrate or runs off, because it is temporarily stored on natural or artificial ground cover until it is evaporated back to the atmosphere. In rural areas interception consists of precipitation stored on leaves of trees, and on or in mulch on the ground. Interception is considered an unproductive flux, because this part of the precipitation is lost for plant growth. Yet, interception is not a loss from a global water resource perspective, because it is mainly responsible for moisture recycling that sustains continental rainfall.

Soil evaporation Es occurs mainly from the top few centimetres of the soil. When these have dried out, the hydraulic conductivity of the top soil reduces considerably, which hampers capillary rise of water to the surface. Obviously, physical parameters of the soil play a deciding role. This top part of the soil should not be considered part of the soil moisture that feeds the transpiration process. Due to the fact that soil evaporation is completed within a day after the rainstorm, it is regarded part of the interception (De Groen, 2002). However, Figure 3.3 shows that there is also soil evaporation from the unsaturated zone, this is attributed to moisture feedback through capillary rise. The channels in which capillary rise occurs are mostly disturbed by grubbing on fields. The evaporated amount is negligible in relation to soil evaporation on the day it rains, which is included in the interception term *I*. The amount of interceptions is largely dependent on the type of vegetation and on the intensity, duration, frequency and form of precipitation. Interception is generally proportional to leaf area index (LAI) with forests having a larger LAI then shrubs or grasses.

Surface Runoff Q_s

The water that can not be stored in the soil flows down the slope, there are two different types of surface runoff:

- Saturation overland flow: No more infiltration is possible because the unsaturated zone is completely saturated. The groundwater level reaches the surface level and additional water flows over the surface because it can not be stored anymore.
- Hortonian overland flow: the intensity of net precipitation is higher than the infiltration capacity. The water does not have the chance to infiltrate and flows down in thin sheets, mostly because of surface crusting.

FAO (1993) claims that surface crusting results from three processes:

- Physical disintegration of soil aggregates and their compaction, caused by the impact of raindrops.
- Chemical dispersion of the clay particles. The low electrical conductivity of the rainwater as well as the organo-chemical bonds between the primary particles of the surface aggregates, control the rate and degree of dispersion.
- An interface suction force which arranges the once suspended clay particles into a continuous dense layer.This almost impermeable layer can form at the very surface of clay soil or in the immediate sub-surface washed-in layer and can reduce the infiltration capacity of soils dramatically during rainstorms.

Runoff is the greatest water management problem on rainfed crop lands because not only is it the loss of a potential water resource but it may cause damaging soil erosion (FAO, 1993).

Infiltration F

Infiltration involves the process of a water flux trough the soil-atmosphere interface, driven by gravity. Pores in the soil are filled and the water becomes part of the unsaturated zone. The amount of water that infiltrates in a certain time span is called the infiltration rate; the maximum infiltration rate is called the infiltration capacity. The infiltration capacity depends on the type of soil, soil structure, vegetation and porosity. Macro pores in the topsoil and soil crusts have a large effect on the infiltration rate.

Transpiration T

Plant growth occurs through the process of photosynthesis, or CO_2 assimilation. In photosynthesis organic materials (carbohydrates, $(CH_2\ O)_n$) is manufactured in green plant leaves, through reduction of carbon dioxide (CO_2) from the air by means of solar energy in the presence of H_2O:

$CO_2 + H_2O$ *+ solar energy ->* $CH_2\ O + O_2$ *(See Figure 3.4)*

Photosynthesis itself uses a negligible amount of water. Soil moisture is abstracted by plant roots activating a nutrient flow through the stem to the leaves, which transpire the water back to the atmosphere (Figure 3.5). In brief, transpiration is evaporation of water from plants through the stomata of the leaves and involves a biological process. The time scale of transpiration is determined by the soil moisture stock, which can last weeks or months depending on the soil depth.

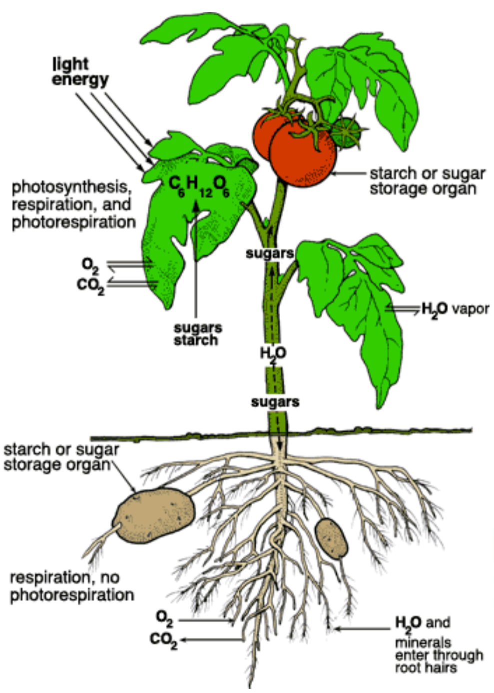

Figure 3.4: Photosynthesis, respiration, leaf water exchange and translocation of sugar in a plant

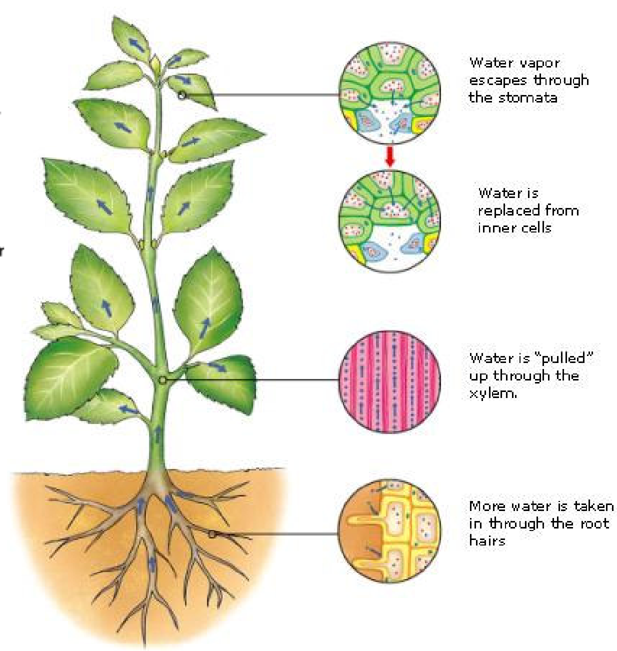

Figure 3.5: Water uptake through the roots and discharge through the stomata of the leaves

Evaporation E

Evaporation is the amount of water that transfers from the liquid to the gaseous state by physical processes. The driving forces are solar energy and wind, which create an atmospheric demand for water vapour from the surface. The total evaporation *E* in a catchment is often described as the sum of a number of different processes: evaporation from interception *I* (including surface evaporation from the soil E_s), transpiration *T* and open water evaporation E_o, which is not relevant on a farm scale. These processes are very different in terms of time scale, time of occurrence, physical characteristics, climatic feedback and isotope composition. However, some scientists, such as Falkenmark and Rockström (2004), include interception as a part of the green flux. Moreover they use the term: evapotranspiration to account for all evaporation processes together. Savenije (1998), strongly disagrees with combining these processes and notes that open water evaporation is a physical process and transpiration is a biological one, which can not be clustered in one term. Furthermore, interception works more or less like a threshold above which productive use can be made from rainfall, including it in the term evaporation or even evapotranspiration gives a false sense of water use by crops.

Rockström (2001) stated that for semi-arid rainfed farming systems in sub-Saharan Africa, on average 70-85% of the rainfall is not used in agricultural biomass production. Figure 3.6 shows the poor rainfall partitioning in the sense that the rainfall does not infiltrate properly due to a combination of human induced land degradation and high intensity rainfall events. Evaporation *E,* either from the surface or from the soil, accounts for 30 to 50% of rainfall *R*. At the same time, surface runoff R_{off} may be as much as 10-25% and groundwater recharge *D* varies around 10-30% of rainfall. The result is soil water scarcity in the root zone manifested in biomass-producing transpiration *T* of merely 15-30 %.

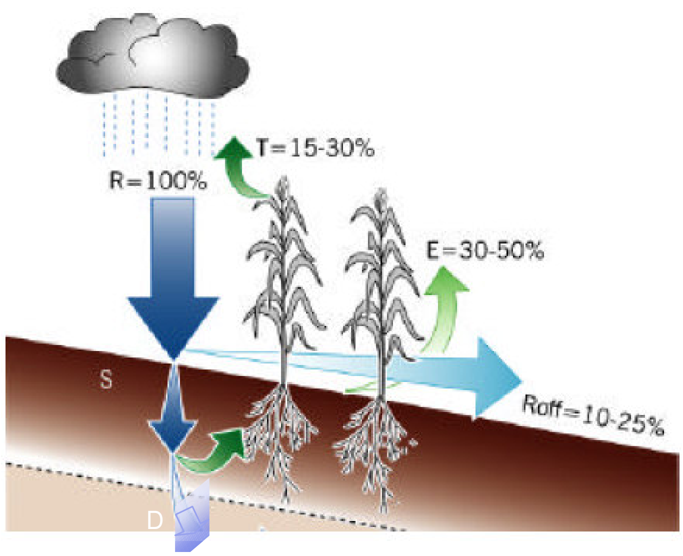

Figure 3.6: General overview of rainfall partitioning in farmers' fields in semi-arid savannah agro ecosystems in sub-Saharan Africa (Rockström, 2001)

3.3 The Yield Gap

3.3.1 Crop growth

The amount of water consumed by a crop equals the amount the crop transpires through the leaves and the amount of water the soil evaporates, the latter amount is negligible under proper crop management. The so called maximum transpiration T_m [mm/d], a term often used by agronomists, can be expressed in terms of the reference evaporation (E_0).

$$T_m = K_c * E_o \qquad \text{Equation 3.1}$$

E_o expresses the evaporating power of the atmosphere at a specific location and time of the year, solely dependant on meteorological conditions not considering crop characteristics and soil factors. The crop coefficient K_c on the other hand incorporates crop characteristics and averaged effects of evaporation from the soil. Changes in vegetation and ground cover mean that the crop coefficient K_c varies during the growing period. The trends in K_c during the growing period are represented in the crop coefficient curve shown in Figure 3.7. Only three values for K_c are required to describe and construct the crop coefficient curve: those during the initial stage ($K_{c\ ini}$), the mid-season stage ($K_{c\ mid}$) and at the end of the late season stage ($K_{c\ end}$).

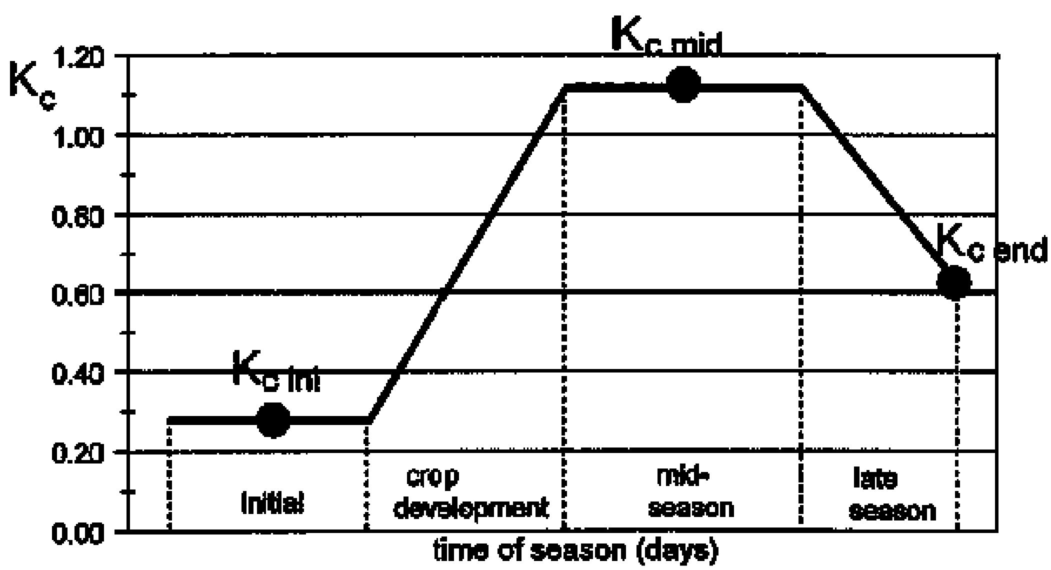

Figure 3.7: The crop coefficient K_c changes depending on the growing stage of the crop

Van der Zaag (2003) states that crop yield Y is a function of incoming short wave radiation R_s and maximum transpiration T_m, and inversely related to the moisture in the air, expressed as the difference between the saturation vapour pressure e_a and actual vaporation pressure e_d

$$Y = f(R_s, T_m, \frac{1}{e_a - e_d}) \qquad \text{Equation 3.2}$$

In this relationship, maximum transpiration is of greatest interest since this is the term which can be influenced by humans most: more water available to the crop translates to more transpiration and to higher yields, provided nutrients are not in short supply.

3.3.2 Current Situation

It has been estimated that food makers in developing countries will have to more than double yields over the next 25 years, just in order to keep pace with population growth (FAO, 1995). This is an enormous challenge as most land is already put under the plough and as there are indications suggesting that yield levels have tended to stagnate rather than increase in several developing countries, because of land degradation (Rockström, 2001). Besides that, the question remains whether there is enough water available on-farm to enable this doubling. In Sub-Saharan Africa the observed on-farm yields are a factor 4-8 below experienced yields on experimental stations, and a factor 8-16 times lower than commercial farmers who often operate at yields levels of 6-8 t/ha.

The yield gap Y_g is a term denoting the difference between maximum yield Y_m and actual yield Y_a, based on an assessment of the site-specific characteristics.

$$Y_g = Y_m - Y_a$$ *Equation 3.3*

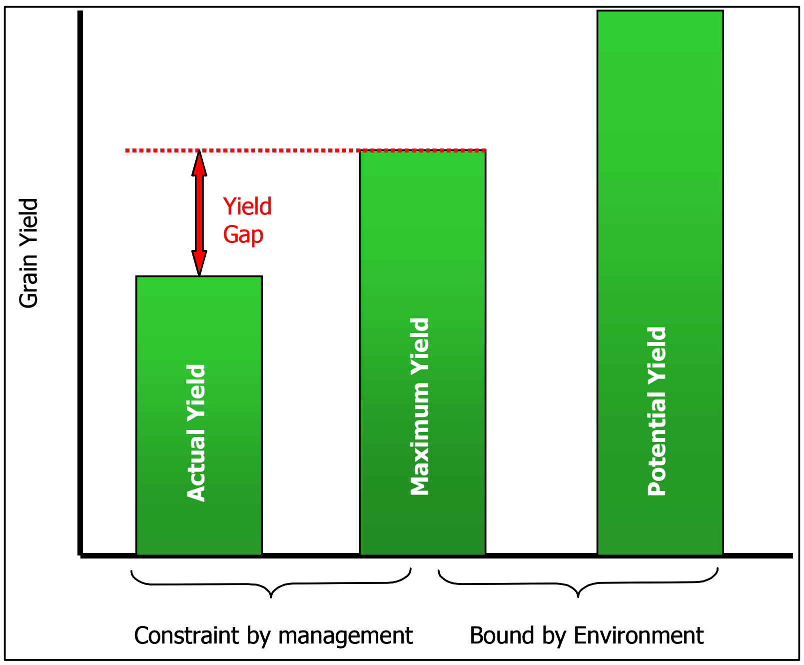

Figure 3.8: Three categories of yields

However, Figure 3.8 shows three categories of yields.

- The potential yield Y_p is the highest possible yield obtainable with ideal management, soil, and climate (around 6 t/ha). It is the genetically limited yield.

- The maximum yield Y_m is defined as the yield of a crop planted at the optimal plant density for a given soil type and climatic conditions with nutrient supply not limiting and pests, diseases, weeds, soil damage and other factors amenable to management control (around 3-5 t/ha).

- The actual yield Y_a is the observed yield, considering social, technical and economical constraint of the system on top of the environmental constraints (around 0.5-1.5 t/ha).

Thus, rainfall and soil conditions in rainfed agriculture are responsible for the gap between maximum and potential yield.

Rainfall
While total seasonal rainfall is usually more than sufficient to grow an annual crop in arid regions, only part of the precipitation is available for crop growth, due to the following factors:

- much of the rainfall comes in high-intensity storms and the soil is unable to absorb and store it all.
- rain falls in summer, when temperatures are the highest and most of rainfall evaporates before being used by the crop.
- midseason dry spells in crucial stages of the growing season are devastating for crops.
- Extreme temporal rainfall variability makes planning for start of planting and tillage difficult. In dry-planting, for example, seeds are planted before the rains start to make the best use of limited rainfall (FAO, 1991).

Soil
Determining soil factors affecting maximum yield are

- Soil texture and structure, which determine rooting depth, infiltration and water holding capacity. Figure 3.9 shows the relative amounts of water available and unavailable for plant growth in soils with textures ranging from sand to clay. Dense packing of soils reduces infiltration and increases the draught requirement for tillage operations.

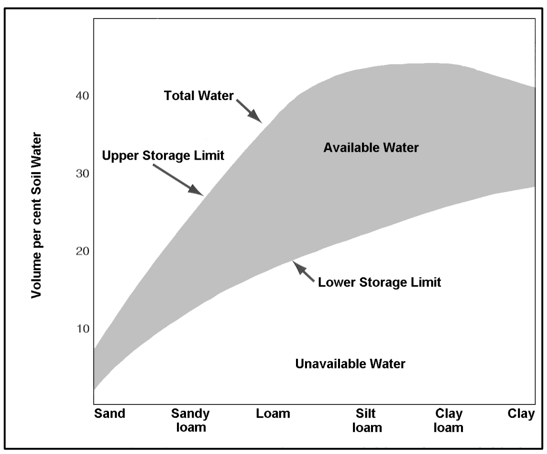

Figure 3.9: The relative amounts of water available and unavailable for plant growth in soils with textures from sand to clay

- Soil fertility, which is in dry areas usually the second most limiting crop production factor after moisture stress. It is very important to maintain levels of organic matter by adding animal manure or compost to the soil. An alteration due to the improvement in the supply of water available to plants can lead to depletion of soil nutrients. Inorganic fertilizers are seldom economic for subsistence crops grown under water harvesting (FAO, 1991). Some water harvesting systems actually harvest organic matter from the catchment and therefore build up fertility. This can most clearly be seen with stone bunding techniques which filter out soil and other organic particles, thereby building up fertile deposits.

Rockström (2003b) claims that there is ample evidence showing that the yield gap between what is presently produced on-farm (generally 0.5-1.5 t/ha) and what can be produced (generally 3-5 t/ha), is not explained by biophysical conditions, but rather due to sub-optimal management. The sub-optimal management factors refer to poor land and crop management and socio-economic constraints which enlarge the yield gap between actual and maximum yield.

Land management

- Poor cultivation practices cause a deterioration of the infiltration rate, permeability and retention capacity of the soils. This is explained in Chapter 4 more extensively.
- Land tenure, in particular in Zimbabwe, is greatly affected by the large scale resettlement program that took flight in 2000. Uncertainties related to whether one farmer can keep his land next season hampers incentives to invest in fertilizers, equipment, and other farming necessities.

Crop management

- Weeds compete for the scarce water with the crops, especially at the start of the season, therefore early weeding is extremely important.
- Pest and diseases holds back root systems and canopy development.
- Several farming practices like crop rotations, interplanting and timing of operations enhance the soil fertility status for example, but this is explained more extensively in Chapter 4.

Socio-economic framework

Providing tools and equipment does not automatically mean that the next step is implementation. Socio-economic considerations should always be taken into account.

- the level of education is important for extension of know how and innovation in farming
- Perceptions on outside involvement and gender issues
- The poverty trap. Poor people living in a marginal environment try to survive by avoiding damage resulting from hazards. Risk avoidance generally results in maximizing the use of labour while minimizing the use of capital intensive resources. Often the poor can not afford to invest sufficiently in their crops or in their natural resource base. This behaviour leads on the one hand to economic inefficiency but it also leads to exploitation and degradation of the resource base, both of which, in turn, sustain their poverty (Savenije, 1998)
- Availability and adequate access to markets.
- Smallholder farmers in semi-arid Zimbabwe rely heavily on timely availability of labour and draught animal power, together with well-maintained, correctly used implements.

3.3.3 Increasing the yield

Low yields indicate serious land degradation, in terms of erosion, desiccation and soil fertility depletion. There remains an enormous potential for increasing yields. In the framework of constraints in rainfed agriculture presented in the previous section, water management plays an important role in improving yield levels. The focus is on achieving more crop per drop by reducing non-productive water losses, such as interception, runoff and deep percolation (see Figure 3.4 in Section 3.2.2).

The evaporation flux from interception is non-productive, whilst the transpiration flux is required to produce biomass. Transpiration is very conservative, and tends to increase linearly with plant growth and crop yield at a rate that is closely related to the physiological characteristics of the plant and the climatic conditions where the plant is grown. Transpiration productivity for a crop in a certain hydro climatic condition is thus very difficult to influence. While transpiration increases linear, evaporation losses will progressively decline with increased yields. The effect is a progressive improvement in water productivity, defined as the amount of water required to produce one unit of biomass (Rockström, 2003b). This has to do with the fact that with increasing yields, crops will have more leaves that increasingly shade the soil surface and create micro-climatic effects that diminish energy gradients decreasing the evaporative demand of the topsoil.

This means that the relationship between on the one hand $I + T$ and biomass production on the other hand follows a non-linear 'diminishing returns" type of relationship. Thus at increased yield levels water is used more efficiently, therefore the most efficient strategy is to increase the yields of existing arable lands before extending the area under cultivation.

Rockström proposes the following relationship to model this relationship and quantify the contribution of the non-productive evaporation to the total evaporation $I + T$:

$$\mathrm{G}_{\mathrm{i+t}} = \mathrm{PG}_{\mathrm{t}}(1 - e^{(b*Y)})$$, and *Equation 3.4*

$$T = \frac{1000 * Y}{PG_t}$$ *Equation 3.5*

Where

G_{i+t} = Green water use efficiency, expressed as the amount of crop produced per unit of evaporation water consumed [kg/m3]

PG_t = Productive Green water use efficiency, expressed as the amount of crop produced per unit of transpiration water consumed [kg/m3]

b = climate dependant factor (between –0.3 and 0 for dry hot climates where evaporation remains significant, while smaller than –0.3 in cooler and more moist systems with denser vegetation)

Y = crop yield [t/ha]

T = transpiration, or productive green water[m3/ha]

Note: In Section 3.2.1 Green Water is defined as transpiration resulting directly from rainfall, here Green Water is defined as the total of interception and transpiration. Transpiration is referred to as "productive Green Water".

Figure 3.10 shows the green water productivity, or biomass production per total of interception and transpiration for a maize ($E_{y,t}$ = 1.25 kg/m^3) cultivated plot in Zimbabwe (b = -0.25) (Rockström, 2003b). It can be seen that the water productivity increases faster at low yields, than at higher yield levels.

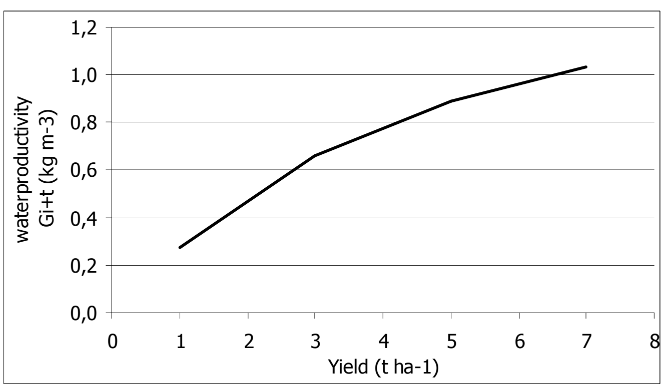

Figure 3.10: Evaporation water productivity at different yield levels for a maize field in Zimbabwe

Every management effort in terms of water, soil and crop management will automatically result in improvements of green water productivity at least for a lower yield range (from about 0 to 3 t/ha). The decrease in water requirement is largest in the lower yield range, because evaporation is highest. This shows an interesting path for water productivity improvements in the presently low-yielding rainfed farming systems in the world. Figure 3.11 shows how the consumptive water use interception I, transpiration T and the sum E+T behave at different yield levels. The unproductive part of evaporation decreases at higher yield levels and the productive part increases. In brief, water loss decreases at higher yield levels.

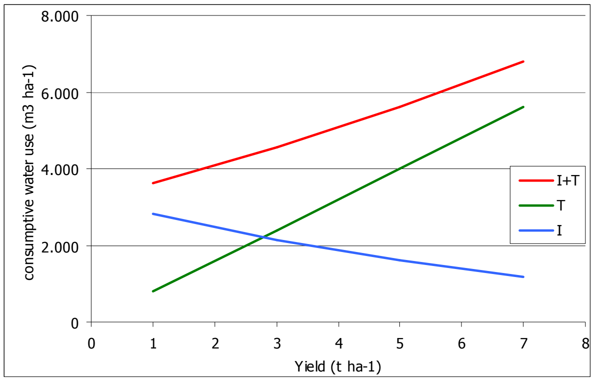

Figure 3.11: Productive and unproductive consumptive water use at increasing yield levels

In a very simplified situation without storage transfer over the year and annual rainfall *P* equals the sum of transpiration *T*, interception *I*, Surface Runoff Q_s and deep percolation *D* the downstream available water ($Q_s + D$) can be calculated:

$$P = I + T + (Q_s + D) \qquad \text{Equation 3.6}$$

This equation is applied in Table 3.2 for the season 1995-1996 (717mm/a of rainfall). *E* and *T* are calculated according to Eq. 3.4. The runoff coefficient decreases from 20 to 5% for yields between 1 and 7 t/ha, as a result of increasing roughness with more crops on the plot. At a yield level of 1 t/ha almost half of the rainfall flows directly or indirectly to the river and is considered lost for the farmer. At a yield level of 7 t/ha almost 95% of the annual rainfall is turned into interception and transpiration, no water is left to runoff or percolate.

Table 3.2: Annual rainfall partitioning of 717mm/a on a maize field in Zimbabwe

constants	PGt = 1,25 kg/m3								rainfall: 717 mm/a					water availability	
	b = -0,25														
Y ton/ha	*Gi+t* kg/m3	*1/Gi+t* m3/kg	*1/PGt* m3/kg	*1/Ge* m3/kg	*I+T* m3/ha	*T* m3/ha	*I* m3/ha	efficiency *T/(I+T)*	runoff coeff.	*P* m3/ha	*Qs* m3/ha	*I+T* m3/ha	*D* m3/ha	m3/ha *Qs+D*	mm *Qs+D*
1	0,28	3,62	0,80	2,82	3617	800	2817	22%	20%	7170	1434	3617	2119	3553	355
3	0,66	1,52	0,80	0,72	4549	2400	2149	53%	15%	7170	1076	4549	1546	2621	262
5	0,89	1,12	0,80	0,32	5606	4000	1606	71%	10%	7170	717	5606	847	1564	156
7	1,03	0,97	0,80	0,17	6778	5600	1178	83%	5%	7170	359	6778	34	392	39

Rockström and Falkenmark (2004) developed an analytical tool to assess the options available to improve crop yields in semi-arid tropics from a hydrological perspective. In Figure 3.12 the general situation of maize cultivated in a semi-arid tropical savannah agro-ecosystem is presented growing period of 120 days, daily potential evapotranspiration =8mm/d, seasonal rainfall =550mm/season, based on the rainfall partitioning range of Figure 3.6 (Rockström, 2001)). Water, soil and plant deficiencies together affect two main crop processes which determines crop growth and yield. To improve yields it is important to assess how much water is required in crop production and what water management options should be adopted. In Figure 3.12 reference is made to crop water availability (Y-axis) and crop water uptake capacity (X-axis).

The X-axis stands for the percentage of productive green water to total green water (ratio of *T* to *I+T* flow), or in other words, the plant water uptake capacity. Just because there is water in the soil does not mean that the crop is taking up water at an optimum rate. The plant needs to have a well developed root system and a good canopy in order to maximize benefits from available water in the root zone. This is an indicator on grain yield of the impact of crop management such as soil fertility, crop species, timing of operations and pest management (Van der Zaag, 2003). A low value for *T/(I+T)* corresponds with a low leaf area index (LAI).

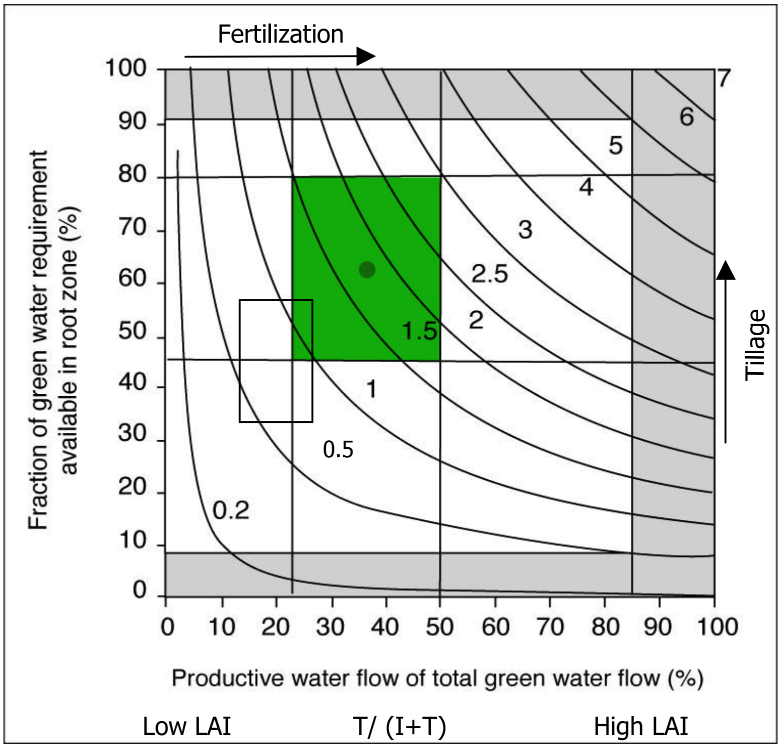

Figure 3.12: Maize grain yields under semi-arid conditions at variable plant water uptake capacities and available soil moisture (Rockström, 2001)

The Y-axis shows the percentage of crop water requirement (CWR) available in the root zone, and is an indicator of the impact of good land management on crop yields. This is determined by the amount of rain that infiltrates in the soil and how much of that infiltrated water can be held in the soil and made available to the crop.

The grey zone shows boundary conditions of the model. The upper horizontal line represents the maximum ratio of average seasonal rainfall *(P)* to green water requirement *(GWR)*

$$\left(\frac{P}{GWR} * 100\%\right) \qquad \textit{Equation 3.7}$$

or in other words, the maximum long-term achievable yields if assuming that all rainfall infiltrates and is available for root uptake. The lower horizontal boundary represents the percentage of plant available soil water that is consumed, before any crop yield can be attained, generally as direct evaporation from bare soil early in the crop growth season. The final boundary condition, given by the vertical line in Figure 3.12 shows the upper realistic seasonal *T/(I+T)* ratio in cropping systems that reach full canopy cover.

The concave lines are isolines of equal grain yield (t/ha), with the lowest yield line in the lower left corner, and the maximum yield isolines in the upper right hand corner. The achievable yield level in this semi-arid case amounts to 5 t/ha grain yield (given by the point where the upper yield isoline intersects the upper boundary conditions). Actual observed yield levels based on the rainfall partitioning data in Figure 3.6 are shown by the large square. The average experienced yield level amounts to 1.5 - 2 t/ha. The common on-farm reality is shown by the smaller square, with an experienced yield range of 0.5 - 1 t/ha. In the on-farm case only some 35 - 55 % of crop water requirement is available in the root zone (due to high runoff and deep percolation) and productive green water amounts to only 15 - 25 % of total green water flow (indicating large evaporation losses).

The objective is to move to the upper right corner of the Figure. Moving upwards along the Y-axis confirms to better rainfall partitioning as a result of land management, achieved by:

- Maximizing infiltration, thus raising the potential for green water use through soil conservation measures.
- A decreasing runoff coefficient through obstructions or increased roughness.
- Improving the soil texture enabling deep root penetration. Water can be taken up instead of percolating to deeper layers where the roots can not reach it anymore
- Improve the water holding capacity of the soil. This increases the amount of water available to plants over time so dry spells can be mitigated.

Moving to the right along the X-axis, or establishing better plant water uptake capacity by crop management corresponds to increasing transpiration at the expense of interception.

- Increase canopy cover through fertilization and intercropping (several crops grown at the same time, for example beans and maize to rapidly develop crop coverage). This reduces early season evaporation through shading of the surface and decreasing evaporative demand of the topsoil, because of improved micro-climatic conditions between the canopy and the soil.
- Increase rooting densities and depth, so roots can access additional soil nutrients and soil moisture, reached by preventing compaction and soil nutrient deficiencies.
- Reduce early season evaporation through mulching

The analysis suggests a large scope for improving yield levels within the available water balance in rainfed farming systems. When farmers act innovative in crop, land and water management, it is very well possible to enable a huge and stable yield increase from, for example, 0.5 t/ha to 2 t/ha (a quadrupling of yields) in semi-arid environments. Thus, water productivity is not static, but highly dynamic, and people have the ability to make changes.

Droughts and dry spells will affect both soil water availability (Y-axis) and plant water uptake capacity (X-axis). The size of reduction in transpiration and the subsequent effect on crop yield will vary depending on which development stages of the crop are hit by water stress.

3.4 Droughts and dry spells

Crops in rainfed agriculture are primarily dependant on rainfall, additional irrigation water is negligible. Rain in Zimbabwe often falls as convective storms, with high rainfall intensity and extreme spatial and temporal variability. A high rainfall year can have several times higher rainfall than a dry year, as can be seen from Figure 3.13.

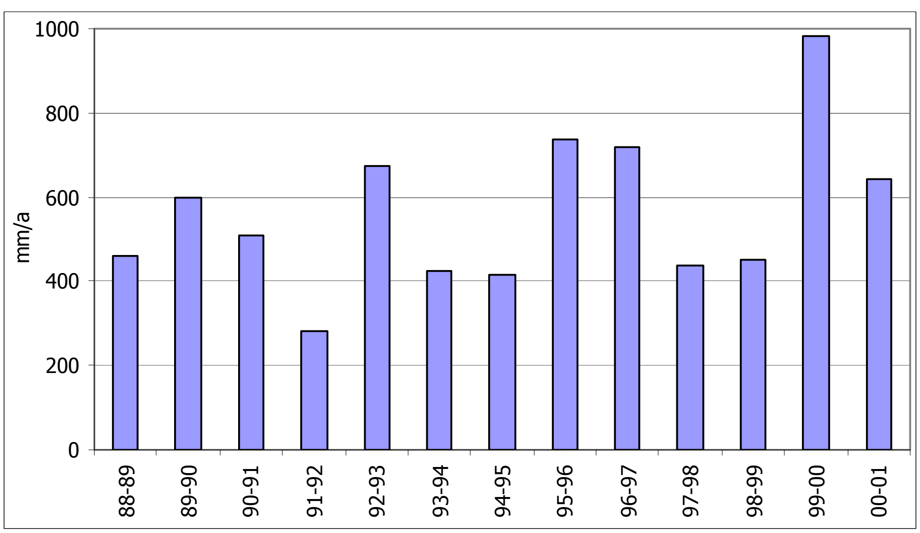

Figure 3.13: Average of annual rainfall measured at Esigodini, Bulawayo and Matopos

A climatic study by Unganai (1996) using Global Circulation Models (GCM) indicated that, between 1900 and 1993, total precipitation over Zimbabwe declined with 10% on average. Climatic variability, enhanced by climate change and climatic phenomenon like El Niño, increases the potential for drought occurrence. Wilhite and Glantz (1985) describe four types of drought:

- Meteorological drought: defined as a period during which less than a certain amount, generally 70%, of the normal precipitation is received over any large area for an extended period. Statistically, complete crop failure in semi-arid regions due to meteorological droughts occurs almost once every 10 years (Rockström, 2002). A meteorological drought is generally unmanageable. There is simply not enough water to produce food. The 1991-92 season can be classified as a meteorological drought year for the Mzinyathini catchment, because precipitation (271mm/a) was less than 70% of the normal annual precipitation of 550mm/a.
- Agricultural drought: A reduction in water availability below the optimal level required by a crop over each subsequent growth stage, resulting in impaired growth and reduced yields. In semi arid regions, severe crop reductions due to dry spells occur once or twice in every 5 years (Nyamudeza, 1998; Rockström, 2003b).
- Hydrological drought: The impact of a reduction in precipitation on natural and artificial surface and subsurface water resources. It occurs when there is substantial deficit in surface runoff below normal conditions or when there is a depletion of groundwater supplies. Hydrological drought reduces the supply of water for irrigation, hydro electrical power generation, and other household and industrial uses.
- Socio-economic drought: The impact of drought on human activities, including both indirect and direct impacts. This relates to a meteorological anomaly or extreme event of intensity and/or duration outside the normal range of events taken into account by enterprises and public regulatory bodies in economic decision-making, thereby affecting production and the wider economy.

Meteorological droughts and dry spells result from poor rainfall distribution. They can be managed by supplemental irrigation through groundwater or rainwater harvesting techniques. Rainwater harvesting is the process of concentrating, collecting and storing local precipitation for later use. This can be achieved by means of

- *Micro-catchment systems* concentrating on rainfall collection within 30m of the field (FAO, 1991). Techniques involve rooftop harvesting, surface and underground storage tanks and diversions from streams, gullies and footpaths for either storage or direct field irrigation.
- *Macro-catchment systems* on the other hand involve large scale harvesting of water through floodwater or river diversion, hence needing large storage structures for regulated irrigation.

Hatibu (2003) notes that the general problem of land shortage within the region forces people to concentrate on much smaller runoff producing areas hence the most appropriate systems are the micro-catchment systems where source of water is very close to the field plot.

Agricultural droughts and dry spells result from poor rainfall infiltration, low water holding capacity and weak crop development. Bridging crop water deficits during dry spells can be reached by supplemental irrigation from groundwater or water harvesting systems, or in-situ systems, which prolong soil moisture availability by reducing field runoff and competition for soil water. Techniques to achieve this include mulching, infiltration pits, strip zone tillage and ridging that increase infiltration and reduce surface runoff. Weed control is also very important for reducing competition for transpiration, nutrients and light between crops and weeds (Twomlow, 1997).

Rockström (2003b) and Van Oosterhout (1996) found through analysis of rainfall data that water-related problems in semi-arid tropics are often associated with intra-seasonal dry spells during critical stages of crop growth, rather than cumulative rainfall. Dry spells, short periods of 2-4 weeks with no rainfall, are detrimental to crop yields if their occurrence coincide with critical phases of crop development. In semi arid regions, severe crop reductions due to dry spells occur once or twice in every five years (Nyamudeza, 1998, Rockström, 2003b). For example, a study of five semi-arid districts in Zimbabwe by Van Oosterhout (1996) showed that years with the highest total rainfall did not coincide with years of highest crop yields. An earlier study by Unganai (1990) had indicated that approximately 480mm of rainfall, well distributed within the growing season was sufficient for successful production of sorghum and maize.

Figure 3.14 shows the distribution of rainy and dry days in a hydrological year in Esigodini. It can be seen that in the dry year 1991-92 there were 346 dry days, consequently there were only 19 days that year where rainfall was higher than 0mm/d. Most rain in Esigodini fell in 1999-2000 (966mm/a, see Figure 3.13), but the most rainy days (43) occurred in 1989-1990 when 687mm/a fell.

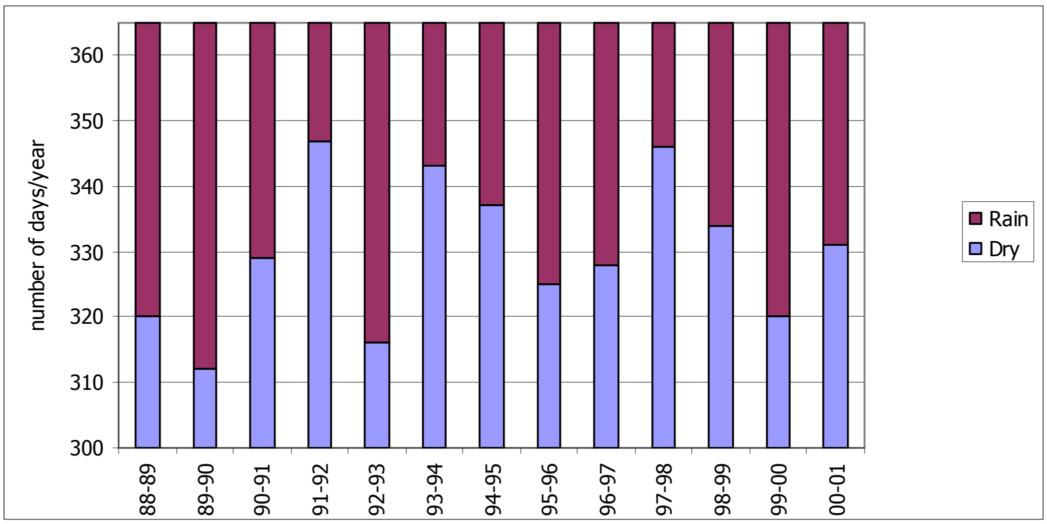

Figure 3.14: Number of rainy and dry days in Esigodini per year, assuming a maximum of 365 days

Figure 3.15 shows the probability that a dry spell of a duration longer than *t* does occur at least once in a growing season in Esigodini. Appendix A shows the calculation table to come to this figure. The growing season is assumed to run between November and March (150 days). So, the probability of occurrence of an at least 25 day period with no rain in a growing season (November to March) in Esigodini is 50%, this probability far exceeds that of seasonal droughts. As a result of the unpredictability of dry spells, farmers tend to avert risks. For many smallholder farmers in the semi-arid tropics it is not worth investing in external inputs such as fertilizers, as the risk of total crop failure remains a reality once every five years and the risk of severe yield reduction occurs once every two years (Rockström, 2002). Mitigating dry spells is thus vital to improved water productivity in rainfed agriculture in semi-arid environments.

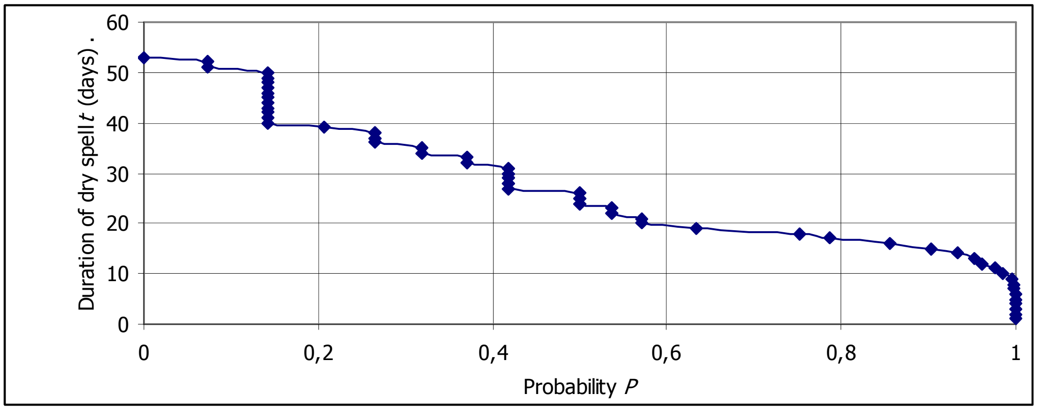

Figure 3.15: Probability P that a dry spell of a duration longer than t does occur at least once in a growing season (November- March, 1988-2001) in Esigodini

However, for successful and sustainable implementation of water system innovations for poor, vulnerable communities they should be easy to operate, and have minimum operational and maintenance costs. The focus of this thesis is on agricultural droughts, in the next sections several in-situ conservation practices will be discussed that improve the resilience against dry spells.

3.5 Conclusions

There are many ways to distinguish different hydrological processes within a cycle. The most recent approach is based on the colours of the water resources; *Blue* for surface water, *Green* for soil water and *White* for water in the atmosphere. On a more detailed scale one can distinguish many different processes, such as interception, transpiration, runoff, etc. Plant growth is dependant on the available water in the soil, the *Green* water stock. The goal is to maximize the infiltration at the expense of unproductive water fluxes such as surface runoff and interception. After that, it is important to enable plants to efficiently withdraw water through their root system. As a result the yield gap, between what *is* (0.5-1 t/ha) and what *can* (1.5-2 t/ha) be produced on a farm, can be closed. How this can be achieved in practice is explained in Chapter 4.

Chapter 3 also made clear that water-related problems in semi-arid areas are often associated with intra-seasonal dry spells during critical stages of crop growth, rather than cumulative rainfall. Dry spells, short periods of 2-4 weeks with no rainfall, are detrimental to crop yields if their occurrence coincide with critical phases of crop development. The probability of occurrence of an at least 25 day period with no rain in a growing season (November to March) in Esigodini is 50%. Sufficient storage of water in the soil is essential for bridging dry spells.

4 Conservation Farming

4.1 Introduction

Conservation farming groups a wide set of integrated farming practices, which focus on sustainable farming. This entails preventing land degradation, and ensuring suitable soil conditions for food production. Apart from good farm management and proper socio-economic conditions, tillage is crucial in rainfed agriculture. This chapter discusses the most applied tillage and crop management techniques in Africa. The effects on the rainfall partitioning on farm scale have been investigated and presented in Section 4.2.4.

4.2 Conservation Practices

4.2.1 Tillage

Tillage operations change soil properties that are important for the soil moisture conditions such as pore size distribution and roughness. For example, tillage can improve water holding capacity and fertility conditions of a sandy soil by ploughing to depths that bring the fine material to the surface. However, the effectiveness of tillage in soil and water conservation depends on the conditions under which it is carried out and its frequency. It is important to cultivate only when soil conditions, particularly the soil moisture content, are right to avoid structural breakdown and smearing (FAO, 1993). The pulverizing effect of conventional tillage can be minimized by reducing the number of operations on the land. This can be achieved by cultivating only the small strips of land required for seedbeds (strip zone tillage), by carrying out tillage with a mulch retained on the ground (mulch tillage) or completing as many activities as possible in one pass (minimum tillage). There is ample evidence indicating that the conventional farming system in the tropics, based on soil inversion using plough and hoe, contributes to soil erosion and soil desiccation. Plough pans impede soil infiltration and root penetration, and frequent soil inversion results in accelerated oxidation of organic matter and soil erosion by wind and rain (Landers, 1998).

In Zimbabwe and the Sub-Saharan region in general, conservation tillage has been loosely used to refer to any tillage system whose objective is to conserve or reduce soil, water and nutrient loss or which reduces draught power input requirements for crop production. Kijne (2001) states that conservation tillage is a promising system for redirecting the components of the water balance in favour of infiltration and thereby crop transpiration. Water use efficiencies can be substantially improved, while at the same time soil productivity is restored. Different tillage methods result in different top soil conditions with respect to pore space and roughness, affecting infiltration, runoff and the potential for erosion. Through improved rainwater use efficiency, conservation tillage contributes to yield stability and dry spell mitigation in drought prone regions.

Conservation tillage results in increased and sustained crop yields, this can be attributed to improvements in:

1. Soil characteristics, such as:
    - Improved soil fertility
    - Building of soil biology
    - Improved soil aeration
    - Erosion control
    - Alleviation of compaction and crusting
    - Evaporation suppression
    - Water infiltration enhancement

2. Plant growth conditions, such as:
    - Deeper root penetration

- Seedbed preparation
- Weed control
- Management of crop residues
- More intensive cropping, avoiding long fallow periods, because of better soil moisture regimes.

3. Farm management, such as:
   - Conservation of energy (draught power)
   - Conservation of labour time and costs
   - Long term resilience building
   - Ability to use land formerly at risk of erosion for more intensive crop production, rather than for pastures or in long-term rotations.

The next section gives descriptions of different conservation practices. For any given location, the choice of a conservation practice will depend on soil, climatic, crop and socio-economic factors shown in Table 4.1 (FAO,1993).

Table 4.1: Factors affecting the choice of a conservation practice

Soil Factors	**Climatic Factors**
Relief (slope)	Rainfall amount and distribution
Erodibility	Water balance
Rooting Depth	Length of growing season
Texture and Structure	Temperature (ambient and soil)
Organic Matter content	Length of rainless period
Mineralogy	
Crop factors	**Socio-Economic factors**
Growing duration	Availability of labour
Rooting characteristics	Government policies on e.g. land tenure
Water requirements	Access to cash and credit facilities
Seed	Markets
	Objectives and priorities

4.2.2 Existing techniques

Traditional tillage

The FAO (1993) states that ploughing with a single furrow mouldboard plough drawn by oxen is the most widely used land preparation practice in Zimbabwe communal areas. It is estimated to be used on 73-90% of the cultivated area. About 5-25% of the remaining area is estimated to be ploughed by hired tractor, 1-15% cultivated by hand hoe and less than 1% is under any form of conservation tillage, typically ridging parallel to the contour or ripping into bare ground. The mouldboard plough is usually drawn by a single ox or a span of two oxen. Ploughing with a mouldboard plough leaves a rough soil surface and it creates a small ridge-and-furrow profile, improving water storage capacity on the soil surface. On the other hand more exposed soil increases the evaporative surface and combustion of organic matter results in loss of nutrients through increased aeration. Frequent soil inversion at the same depth result in plough pans which impede soil infiltration and root penetration. It is normally used in conjunction with hand hoeing for instance to construct pot holes on freshly-ploughed land, to close the planting line, or to perform additional in-row weeding. Shortage of draught animals is one of the major ploughing constraints, with up to half the farmers in some areas having to hire oxen for land preparation (Van der Meer, 2000). Under these circumstances ploughing is normally done once late in the season (December-January) after the rains have penetrated deeply enough to facilitate ploughing (FAO, 1993).

The hand hoe is traditionally a vertical metal blade attached on a wooden handle (Figure 4.1). Hand hoe planting only takes place when no Draught Animal Power (DAP) is available because it is labour intensive and slow, thus reducing the scope for timely planting. Weed infestations are slashed before and during planting, while crops are planted at regular intervals. Soil disturbance is limited to the planting holes The working depth is restricted and the level of soil disturbance is further limited as it generally does not result in a blanket disturbance of the soil surface.

Figure 4.1: Woman with a hand hoe

Zero Tillage
In this approach, the land is not tilled at all. Weeds are controlled by means of adding chemicals to the soil. This tillage technique conserves water in the soil profile since the soil is not tilled and exposed to the drying in the atmosphere. The moisture is retained within the soil profile. The new crop is generally planted directly into the stubble of the previous crop (Thornton, 1998). Zero tillage saves energy and time, but the cost of herbicides counterbalances this. Compared to traditional tillage, zero tillage is effective in reducing erosion and conserving moisture.

Minimum Tillage
Minimum Tillage refers to reducing tillage operations, and therefore labour, to the minimum by using a ripper tine which opens only a narrow planting furrow (Figure 4.2).

Figure 4.2: Ripper with direct seeding tray

The ripper implement consists of a 60mm wide, 260mm long reversible tine under a low 15° angle mounted on a standard plough assembly and is pulled by two oxen when working on lighter soils, four animals may be needed on heavier soils (ATNESA, 1999). The furrow that is left after the planting operation is very shallow and the redistribution of surface water into this furrow will primarily take place during the early stages of development only. However, the soil surface between the ripper tines is generally degraded and has little surface relief, thus promoting the shedding of water into the planting furrows. The speed of the operation, together with the relatively shallow planting depth, makes it possible to achieve timely planting over a large area. The limited soil disturbance means that the planting operation does not control weed growth between the rip lines, which means that the use of the ripper tine needs to be followed by a good weeding regime.

Deep tillage
Available moisture to crop roots can be increased if the rooting depth is increased by tilling deeper in the soil. Seeds can be planted deeper, delaying germination until good rains have fallen. Deep tillage requires great draught power which is usually in short supply in semi-arid areas.

Strip zone tillage
The seedbed is divided into a seedling zone and a soil management zone. The seedling zone (5 to 10cm wide) is tilled to optimise the soil for germination (Thornton, 1998). The inter-row zone is left undisturbed and protected by close growing grasses (or other ground cover crop) slowing down runoff and filtering out soil washed from the tilled row. This control of runoff also allows increased opportunity for infiltration of the runoff. The strip widths can be varied depending on the soil type and slope.

Mulch Tillage
Mulch farming is a system of maintaining a protective cover of vegetative residues such as wheat straw, maize stalks and stubbles on the soil surface at all times. The ground is opened with a ripper to create a narrow (2-3cm wide) strip for seed placement to ensure adequate seed/soil contact, this is also called no-tillage. No-tillage involves a one-pass planting and fertilizer operation in which soil and surface residues are minimally disturbed. The system is particularly valuable where a satisfactory plant cover cannot be established at the time of year when erosion risk is greatest. The beneficial effects of mulching include protection of the soil surface against raindrop impact, decrease in flow velocity by creating roughness, and improved infiltration capacity (Figure 4.3). It also enhances burrowing activity of insects which improves transmission of water through the soil profile preventing surface crusting and soil moisture storage in the root zone. And in closing, the mulch prevents spontaneous development of other plants, like weeds. In a 1993 report from the World Bank it is claimed that with good management and adoption of other recommended practices, application of crop residue mulch can increase yields by a factor of three to ten.

The quantity of mulch required for maintenance of favourable infiltration capacity and structural stability depends on the rate of residue decomposition, climate, soil properties, relief and rainfall characteristics. Studies relating soil loss to bare ground indicate that about 70% of the soil surface must be covered by mulch to be effective (FAO, 1993).

Figure 4.3: Mulch resists splashing raindrops and washing

Yet, Kaoma-Sprenkels (1999) observed that in Zambia the availability of enough mulch was a major bottleneck. Many farmers clean their fields by burning old weeds and residues of previous crop, after first having taken away the bulk of stover for use as building material and animal feed or by allowing their animals to graze on it. Even without burning, the quantities of stover remaining on the fields are normally too small to form a protective mulch cover. Weeds will quickly overgrow the field and get out of control, particularly on fields that are too large to allow complete eradication of weeds by hand hoe.

Sub-soiling
A sub-soiler is a narrow tine with an adjustable angle mounted on a steel plough frame and works 20cm deep in the soil which is deeper than the standard plough that can only go 15cm deep. It is draft animal powered and manually controlled. This implement is designed for braking the hard pan which was formed through ploughing at the same depth for successive years either with a hand hoe or animal drawn plough in dry areas. Water from rain will enter rapidly in the shattered rows to improve lateral redistribution in the soil profile. In general the chisels improves the soil surface roughness by 20 to 60%, cutting down runoff during the first rains of the season (ATNESA, 1999).

Johnson (1998) found that sub-soiling in trials in a semi-arid part of Tanzania (Babati), where only the plough-pan was broken in one single action, resulted in maize yields 2.7 times higher than in the control. This increase was obtained for a fertilized crop during a rainy season with good rainfall distribution.

Ridging
Contour ridges are small earthen ridges, 15 to 20cm high, with an upslope furrow which accommodates runoff from a catchment strip between the ridges (See Figure 4.4). Ridges can be kept in place as a semi-permanent feature for a number of years, although maintenance of the ridge structure is required and often they are re-created each season (Van der Meer, 2000)

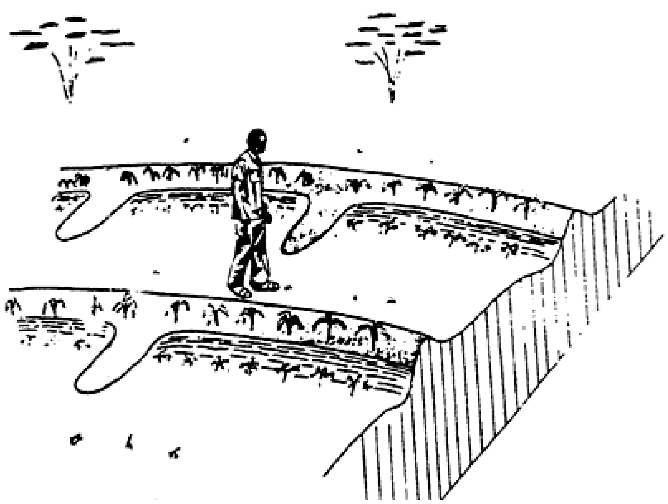

Figure 4.4: Contour ridges as used in Kenya (Critchley, 1992; Thornton 1998)

The yield of runoff from the very short catchment lengths is very efficient and when designed and constructed correctly there should be no loss of runoff out of the system. Ridges may be 1 to 10m apart, depending on slope and expected rainfall. Crops are planted on both sides of the furrow. Planting in the furrow bottom, however, prohibits the use of animal drawn weeding, while planting on the ridge top can lead to limited water availability to the crop during the early stages of development. The main crop (usually a cereal) is seeded into the upslope side of the ridge between the top of the ridge and the furrow. At this point, the plants have a greater depth of top soil. An intercrop, usually a legume, can be planted in front of the furrow (see Figure 4.5). It is recommended that the plant population of the cereal crop be reduced to approximately 65% of the standard for conventional rainfed cultivation (FAO, 1991). The reduced number of plants thus have more moisture available in years of low rainfall.

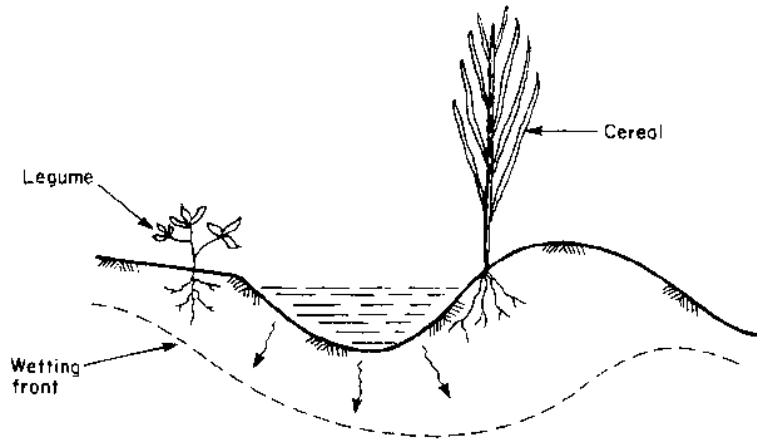

Figure 4.5: Planting configuration on ridged field

When small earthen ties are made within the furrow at 2 to 5m intervals to prevent lateral flow, the system is referred to as a tied ridge system (see Figure 4.6). The implement for doing this type of work is the tie-ridger and a single donkey is adequate to haul it. The operator moves behind the implement directing it within the furrow or in between planting stations. As the implement moves forward it bulldozes soil that is released by raising the implement vertically using the handle bars making the tie ridge (ATNESA, 1999). The objective of the system is to collect local runoff and store it within the soil profile in the vicinity of plant roots.

Twomlow (2000) states that the major disadvantage with ridges are higher soil temperatures and incomplete wetting of the tied ridges early in the season, which can result in poor crop establishment and growth.

Figure 4.6: Tied ridges

Motsi (2004) experimented on sandy loams on three different sites in Natural Region IV and V in Zimbabwe with water holding capacities ranging from 6 to 10mm/m. It was found that the average yield of maize from tied ridges was 3.4 t/ha compared to 1.5 t/ha for conventional tillage.

Infiltration pits

Infiltration pits are deep trenches dug along the contour ridge to trap run-off and increase infiltration. The pits are filled with grass or stover that is covered by a thin layer of soil so that the organic material can decompose to form compost. The pits trap rain and then water infiltrates down slope thereby providing moisture to the crops in the field. Figure 4.7 shows a Zaï pit, which harvest runoff in pits filled with manure, termite activity improves the infiltration capacity of the soil.

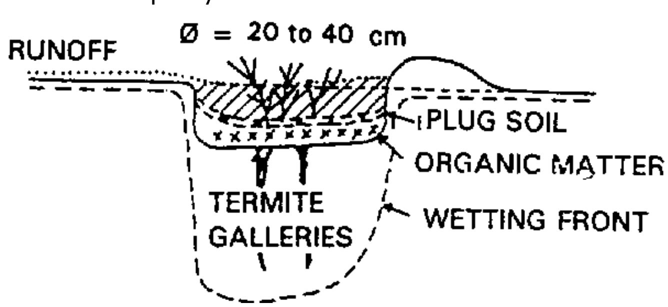

Figure 4.7: Infiltration pit in the Sahel (FAO, 1993)

TU Delft
Delft University of Technology

4.2.3 Farm Management

Conservation tillage will not be successful in isolation of other factors involved in farm management presented in this section.

Improved pest management

Crop pests include, in order of priority, weeds, insects and diseases. The goal of pest management is to reduce crop loss and not specifically to reduce pest numbers. Means to control pests for small scale farmers are using pest resistant varieties, natural enemies, entomopathogens (including bacteria, fungi and viruses used for control of insects and mites), and introduction of selective pesticide applications (Bajwa, 1990)

Crop rotations

Crop rotation is changing crops from year to year on the same field. The advantages of applying crop rotations on the fields are:

- Nutrient use can be optimised by synergy between different crop types and by alternating shallow-rooting crops with deep-rooting ones.
- Reduced cost for pesticides because of the natural breaking of the cycles of weeds, insects and diseases.

The disadvantage of crop rotations is that additional planning and management skills are required, increasing the complexity of farming.

Interplanting

Interplanting is combining crops with different planting times and different length of growth periods on the same field at the same time. Interplanting of cereals with legumes, sorghum with cowpeas for example, can also lead to higher overall yields as well as soil fertility maintenance (FAO, 1991).

The advantages of applying interplanting are:

- spreads the labour requirement of planting and of harvesting
- allows mid-season change of plan according to the rain in the early part of the season
- higher overall yields
- soil fertility enhancement, because different crops can benefit from each other when they replenish and take up different nutrients.

Timing of operations

Timing of farming operations is very important in areas where the rainfall is erratic, because yields can be dramatically affected by planting or cultivating at the right time. Common problems are having to wait for rain to soften the ground because it is too hard to plough when dry, and perhaps then not being able to plant because the ground is too wet. Or a family with only one ox having to wait to borrow another one. (FAO, 1987).

Dry planting

in regions where the onset of rains can be predicted land preparation starts as early as possible in the dry season. The first rains will be fully utilised, optimising the productive flow of water, and labour can be spread effectively over the season. The biggest concern when applying dry planting is the loss of input (fertilizer, seeds, labour) when the predicted rains do not come.

Application of fertilizer

Manure not only provides nutrients for plants to grow but it also attracts termites that break the crust on the soil surface and create good macro-pore networks in the soil to facilitate infiltration (Nagano, 2001). In a household survey, ZIDS (1989) found that as many as 90% of the farmers in the semi-arid regions of Zimbabwe did not apply fertilizers. Van der Meer (2000) states that the chemical fertility of the soil should be regarded as a socio-economic rather than a biophysical variable, because its use is closely related to the use of credit.

Weeding

Weeds are competing with crops for nutrients, light and soil moisture. Most weeding takes place during the first two months after crop emergence. Later in the cropping season, crops tend to have a competitive advantage and prevent further weed growth (Van der Meer, 2000). Smallholder farmers remove the weeds with the hand hoe, when there is no DAP available for weeding with an ox-cultivator or plough. Riches (1997) found that weeding accounts for up to 60% of the pre-harvest labour input for maize production in semi-arid Zimbabwe. Weeding improves the infiltration capacity of the soil surface, as the surface crust is broken up and the roughness of the soil surface is increased.

Figure 4.8 and Table 4.2 show the results of weeding experiments at the Makaholi Experimental station in Zimbabwe for December 1991 up to November 1993 (Twomlow, 2000). One plot was kept weed free for two seasons and on the other plot there was no weed control at all. Biomass production appeared three to four times higher for maize fields where weeds were constantly removed. The water use efficiency, defined as the ratio of biomass production to total water use, was four times higher for weed free maize fields.

Table 4.2: Total crop biomass, total crop water use and water use efficiency in response to weeding at Makaholi Experimental Station (Twomlow, 2000)

	1991-1992			1992-1993		
Weeding treatment	**Biomass**	**Crop water use**	**Efficiency**	**Biomass**	**Crop water use**	**Efficiency**
	kg/ha	*mm/a*	*kg/ha/mm*	*kg/ha*	*mm/a*	*kg/ha/mm*
Weed free	1805	164	11	3178	393	8.1
Unweeded	489	210	2.3	1014	465	2.2

In Figure 4.8, blocks indicate the depth of water when the maize field is kept weed free, whereas circles indicate available soil water when no weeding is applied. As expected the driest profile and lowest yields were observed for the unweeded plot.

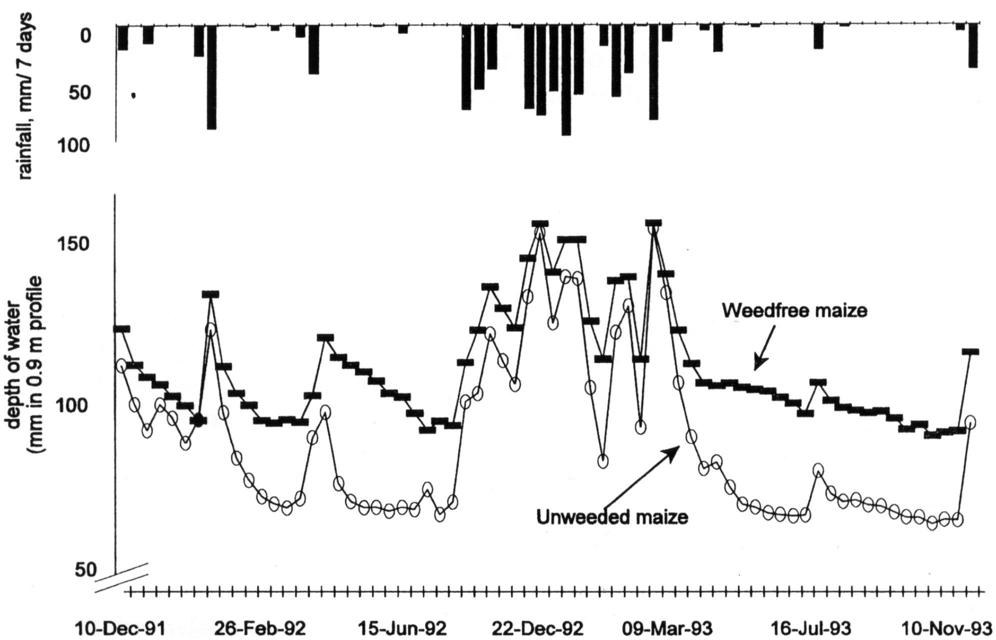

Figure 4.8: Impact of weed on the soil water regimes that develop for a 0.9m deep profile under a maize crop grown on the Makaholi sand (Twomlow,2000)

4.2.4 Experience with tillage in Africa

Research from several countries show significant improvements in crop yields and reduced soil erosion after the introduction of alternative tillage practices. The key to successful conservation farming is the integration of tillage within the total production system. The change from inverting the soil with a plough to only ripping up planting lines, makes changes in most farm operations necessary like weeding, application of fertilizers, timing of planting, and pest management (Rockström, 2003b).

Table 4.3: Recapitulation of in-situ conservation practices

	Characteristic	**Advantage**	**Disadvantage**
Traditional Tillage			
• Hand Hoe	Digging planting holes	Cheap	Labour intensive
			Slow
• Mouldboard plough	Considerable soil inversion	Faster than Hand hoe	Pan impedes soil infiltration
		Rough surface	Linked to cattle ownership
Zero Tillage	No soil tillage at all	Saves time and energy	High cost of herbicides
		Reduces soil loss	Chemicals can harm environment
Minimum Tillage	Only a narrow planting furrow	Saves time and energy	Needs good weeding
		Reduces soil loss	
Deep Tillage	Seeds are planted deep in the soil	Delays germination until good rains have fallen	Requires great Draught Animal Power (DAP)
Strip Zone Tillage	Division in tilled and undisturbed zone	Little soil loss	Strip can harbour pests
		Increased infiltration	
Mulch Tillage	Plot fully covered with plant residue	Reduces competition from other plants	Mulch is not always available
		Reduces fluctuations in soil temperature, reducing seedling mortality	Lack of implement which can plant or drill through the mulch
		Enhance soil fertility	Rapid oxidation of organic mulches
		Increases macro pores through insects	Pest, disease or nitrogen lock up
		Controls erosion, traps wind borne dust	
Sub-soiling	Shatters hard pans in dry areas	Improves surface roughness	Requires great DAP
		Regenerates soil productivity	
Tied ridge	Rainwater is accumulated between ridges	Good weed control early in growing season	Poor crop establishment due to incomplete wetting early in season
		Simple and easy to use equipment	High input of labour and DAP
			High soil temperatures
Infiltration pits	Gradually infiltrating water from deep trenches	Subsurface storage of water; less evaporation	High labour input and maintenance

Table 4.3 gives an overview of the different tillage practices with their major advantages and disadvantages described in section 4.2.2. It can be seen that many practices, such as zero and strip zone tillage, aim at decreasing the roughness as to minimize the evaporative area of the soil. While tied ridging, aims to increase the roughness as to maximize surface water retention and ability to infiltrate. A similar break even point is apparent with respect to canopy cover. A low canopy cover facilitates a lot of bare soil evaporation, but restrains water loss due to interception from the leaves. A high canopy cover on the other hand shades the soil surface and creates micro-climatic effects that diminish energy gradients decreasing the evaporative demand of the topsoil. Wallace (1999) states that when annual rainfall is low, the

saving in soil evaporation due to canopy cover may be greater than the leaf interception loss. The exact point at which the two effects completely offset each other will depend mainly on rainfall intensity and soil type.
Many of the presented practices have been extensively studied in Africa by different researchers and over different time periods. Most of the research focused on runoff and the directly proportional soil loss, because this triggers persistent land degradation.

- *Twomlow, S., 1999 in Sustainable Dryland Smallholder Farming in Sub-Saharan Africa*

Twomlow (1999) investigated soil loss and maize yields for five different tillage techniques in Makaholi, Zimbabwe. Table 4.4 shows the average maize yield and annual soil loss over five years (1988-1994), with an average rainfall of 490mm/a over the same period. Makaholi sand is qualified by the FAO as Ferralic Arenosol, and can be characterised as deep coarse grained granitic sand with low available water capacity.

Table 4.4: Effects of tillage on yield and soil loss (Twomlow, 1999)

	Mean Maize Yield	**Annual Soil loss**
	t/ha	*t/ha*
Mouldboard ploughing	3.3	10
Hand hoeing	1.9	5
Minimum Tillage	2.9	4
Mulching	3.2	1
Tied ridging	2.5	1

Twomlow concluded that despite the obvious conservation of soil, the different conservation systems had no significant impact on crop yields. In fact, highest yields were consistently recorded on the conventionally ploughed treatments.

- *Nagano, T., et al, 2001 in Changes in Surface Runoff Due to Crust Formation and Land Conservation Techniques: The Case of On-Farm Study in Niger, West Africa*

Nagano (2001) experimented in Niger on sandy soil (slope 2.8%), where weeding was carried out twice during the season on four experimental plots (20mx2m). He observed that the bare and millet cultivated plot showed similar runoff characteristics until the leaf area index of the millet became significant to intercept the rain. Until the first weeding both of these plots generated far more runoff than the millet field which was covered with manure and mulch (see Table 4.5). Application of manure in combination with mulch was found to greatly reduce runoff at the onset of the season, due to attraction of termites that break the crust on the soil surface and create good macro-pore networks in the soil to facilitate infiltration. Similarly, weeding tillage had a very positive effect on infiltration because of destruction of the soil crusts on the surface. Stone lining is effective in breaking the speed of flow and this results in better infiltration. Since rainfalls at the onset of season is vital for the establishment of millet, reduction of runoff in the beginning of the season seems very important.

Table 4.5: Seasonal runoff rates and soil loss at annual rainfall 512mm/a (1998) and 684mm/a (1999)

		Runoff	**Soil loss**
		As % of rainfall	*t/ha*
Millet cultivated with manure	1998	13.4	1.77
	1999	-	-
Millet cultivated with manure and mulch	1998	-	-
	1999	5.8	1.36
Millet cultivated	1998	15.3	1.31
	1999	13.5	2.18
Bare plot	1998	22.8	4.23
	1999	21.3	2.85
Bare plot with stone lines as tied ridges	1998	-	1.33
	1999	13.3	0.85

- *FAO,1993 in Soil Tillage in Africa: Needs and Challenges*

Similar research in Ghana in 1979 (no data on rainfall total), is presented in Table 4.6. Mulching refers to a mulch cover of 70%. Kwadaso soil is characterised as coarse sandy-loam (Paleustult), the soil in Ejura is somewhat finer (Oxisol).

Table 4.6: Effects of farming practices on runoff and soil loss in Ghana (1979)

	Runoff		**Annual Soil Loss**	
	As % of rainfall		*t/ha*	
	Kwadaso	Ejura	Kwadaso	Ejura
Bare Fallow	50	36	313	18
Zero Tillage	3.4	0.5	2	9
Mulching	1.4	0.3	0	2
Ridging	1.9	1.3	3	5
Minimum Tillage	1.7	1.1	5	4
Mixed Cropping	13.2	5.1	34	2.5

It can be seen that runoff is consistently lower for the finer soils of Ejura, however soil loss is only significantly greater when zero tillage or mulching is applied. This might be attributed to the sieving capacity of the ground cover. The effect of farming practices on annual soil loss is significant, soil loss in Kwadasa even reduced to zero tonnes per hectare compared to 313 t/ha for the bare fallow.
The spectacular decrease in runoff and thus soil loss is similar for investigated soils in C'ote d'Ivore and Nigeria shown in Table 4.7.

Table 4.7: Effects on runoff and soil loss of mulching and bare fallow land in Nigeria and C'ote d'Ivore

	Runoff			**Annual Soil Loss**		
	As % of rainfall			*t/ha*		
	Cote d'Ivore	Nigeria (20% slope)	Nigeria	Cote d'Ivore	Nigeria (20% slope)	Nigeria
Bare Fallow	36	29	42	18	410	233
Mulching	0.3	0.1	2.4	2	1	0

- *Thornton, J., et al., 1998 in A Source Book of Alternative Technologies for Freshwater Augmentation in Africa*

Thornton experimented with fields that were conventionally tilled and tied ridge in four rainy season in Domboshawa, an area about 30km north of Harare. The average annual rainfall ranges from 800 to 1000mm/a, 90% of it falls between October and March. As can be seen in Table 4.8, runoff at the tied ridge plot is less than 50% than that of the conventionally tilled plot.

Table 4.8: Effects on runoff and soil loss of conventional tillage and tied ridging for the rainy seasons between 1988 and 1992

		Runoff		**Soil Loss**
		mm/a	*%*	*t/ha*
Conventional tillage	1988-89	7	7	2
	1989-90	274	23	10
	1990-91	15	2	1
	1991-92	9	2	1
Tied Ridging	1988-89	2	0	9
	1989-90	117	10	2
	1990-91	1	0	0
	1991-92	0	0	0

- *Kaumbutho, P., et al, 1999 in Overview of Conservation Tillage practices in East and Southern Africa*

Oldreive (1993) simulated two storm trials and observed that higher energy tillage methods led by conventional tillage, leads to increased surface runoff, hence soil loss. From Table 4.9

it can be concluded that mulching is very effective in fighting soil loss, because only an increase in mulch cover from 10 to 30% already results in 35% less runoff. For the second simulated storm the tractors could only get in after two days at the conventionally tilled plot, due to the danger of soil destruction. At the zero tilled plot, the tractors could already go in and work after four hours. This can be attributed to faster infiltration and deeper storage of the water in the soil at the zero tilled plot.

Table 4.9: Effect of two simulated storm trials on run off and soil loss (Oldreive, 1993)

		Runoff	Soil loss
		%	*t/ha*
1. 63mm rain in 1 hour on 4% slope			
	Deep ploughed	90	29
	Ripped and disked, 10% mulch cover	70	7
	Chisel ploughed and cultivated, 30% mulch	34	2
	Zero-tilled, 80% mulch cover	6	1
		Infiltration	
2. Two consecutive day treatments; total of 125mm applied in 2 hours			
	Conventional Till	52mm	
	Zero Till	122mm	

On the basis of these studies, Table 4.10 can be set up as a general overview of the influence of a tillage technique on surface runoff compared to traditional tillage with the mouldboard plough.

Table 4.10: Reduction in surface runoff from a farm plot compared to mouldboard ploughing

	Reduction in Surface Runoff
Hand hoe	50%
Zero Tillage	70%
Minimum Tillage	60-80%
Tied ridging	70-90%
Mulching	90-100%

From these studies it can be concluded that water erosion processes on cultivated land are affected by the soil roughness caused by human intervention. Applying conservation practices decrease surface runoff and thus soil loss. Reduced surface runoff is proportional to the increase in infiltration, which is the main goal of the conservation practices. The residence time of runoff flow in the catchment is increased. This, in general has positive environmental as well as hydrological implications downstream. River runoff will be more evenly distributed over the year, and the chance of erosion and flooding through discharge peaks will diminish. Water quality in the river improves, because base flow water is filtered through the soil, whereas surface runoff transports litter and sediments from the surface. On a farm scale it can be concluded that through good crop and soil husbandry a large part of the water that otherwise would have flown off the plot now comes available for infiltration. Higher crop production is possible through the higher potential for transpiration and smaller risk of crop failure due to dry spells, because more water is stored in the soil. In addition to smaller risks of crop failure the farmers may be willing to invest more in their crops in terms of fertilization. The combined effect of more water and more nutrients may result in even higher yields. However, it should be noted these studies are mostly restricted to experiment stations, and can be influenced by the effect of seasonal variations due to their relatively short time span. Besides that, the validity of coverage over a wider area and local practical farming conditions needs to be taken into account.

4.3 Socio-economic Aspects

4.3.1 Adoption of Conservation Farming

As already stated in Table 4.1 there are various biophysical factors affecting the choice of the most appropriate conservation practice. Socio-economic considerations, however, should always be taken into account in decision making for the adoption of one practice over another. Yet, Nyagombo (1998) comments that adoption of conservation practices in Southern and Eastern Africa is still very low due to lack of adequate labour, insecure land tenure systems, limited access to credit and markets, and failing technology transfer.

Labour

Availability of labour and Draught Animal Power (DAP) are the key resources for crop production in small farm systems. They determine the area that is cropped, the timelines of operations, the utilization of other inputs and therefore the productivity of the farming system. The availability of labour is influenced by household composition, labour productivity and other claims on household time, notably household duties and off-farm work. Labour productivity is influenced by sex, age, nutritional status, health, food availability and off-farm income opportunities. Overall it is estimated that women contribute 60-80% of the labour for food crops (FAO, 1995).

Traditionally tasks and tools are gender specific in Zimbabwe. Ploughs, axes and shovels are generally considered to be men's tools. Hoes and sickles are women's tools. Weeding was, in the past, equally shared between men and women. However, due to the current economic hardship and the HIV/AIDS pandemic, the workload of farming women has tremendously increased. Weeding, the hardest and most time-consuming task, is rapidly becoming a "woman's job".

"Weeding shows your ability to grow a crop and it's the hardest task which takes the longest time to finish, we really overwork ourselves when we are weeding, the back has to ache to conquer the weeds, Oh, weeding is the most taxing job, both in energy and time. You have to bend down and work carefully not to damage the crop and at the same time you want to finish the operation before the weeds outgrow the crop. To win a crop you have to disregard the backache!"

This fragment from a farmer discussion group, where women comment on weeding labour (9 Mar 2004 FAO Reliefweb) shows the need for taking women seriously. The role of women should be taken into account in design of tools and planning of tillage systems.

Most farm families are large. The availability of cheap labour hinders the adoption of labour-saving technology. On the other hand, High local population densities are essential for providing the necessary labour to work the land, control weeds, feed animals and spread manure. Ching (2002) observed that as population densities increase, farmers intensify their cooperation systems, grouping to tend each other's fields at busy periods, lending and borrowing land, livestock and equipment, and swapping seed varieties. People thus invest heavily in creating and maintaining social networks, regarding land, labour, cattle, technology and cash.

The FAO estimated in 1993 that as much as 80% of the arable land in sub-Saharan Africa is cultivated manually. Large farms cannot be worked on effectively by hoe and machete. Farmers with access to draught animal power can prepare many hectares of their land and achieve timely planting. The problem is that the peak demand for DAP coincides with the time that animals are in their weakest condition after a long dry season.

Tenure

Practically all rainfed agricultural area is situated on communal land, whereas all commercial farms have access to additional irrigation water. The focus of this research is on the small-scale farmers on the communal lands whose sole source of water is rainfall. Community ownership and transient rights to use land do not encourage investment to improve farm conditions. Where the land is owned by the village chief, the right to cultivate it can be withdrawn at will (FAO, 1993).

Investments
Investment in farm development and production technology appears to be generally low. Farmers appear to be either unaware of the possibilities or not motivated to invest in enhancing the productive capacity of their land (FAO, 1993). Savenije (2000) speaks of the poverty trap. Poor people living in a marginal environment try to survive by avoiding damage resulting from hazards. Risk avoidance generally results in maximizing the use of labour while minimizing the use of capital intensive resources. Often the poor can not afford to invest sufficiently in their crops or in their natural resource base. This behaviour leads on the one hand to economic inefficiency but it also leads to exploitation and degradation of the resource base, both of which, in turn, sustain their poverty. Where markets are unreliable or difficult to access, households will continue to regard self-sufficiency as the wisest strategy for food security, again, sustaining their poverty.

Market
An increase in rural income from rainfed agriculture and subsequently an increase in capacity to invest in the resource base is only possible if there is sufficient demand for the products that can be grown. This may require the creation of markets at the appropriate scale and adequate access to these markets. The FAO (1993) observed that farmers have been slow to develop marketing practices to take advantage of the opportunities for diversified and higher-value crops. There have been some successes in the development of market linkages between large groups of farmers and large buying and trading companies but there has been less success in linking small groups of farmers with medium- and small-scale trading entrepreneurs. In order to create opportunities for diversification and shifts to high-value crops, market development should be supported by attention to infrastructure and services.
Roads are essential to enable commercial intercourse, farmers with reasonable access are more productive and better off than those without.
(FAO, 2003)

Technology transfer
There are a number of preconditions for a good transfer of on-farm research to farming in practice by smallholder farmers. The most important is to know what the farmers actually want. The FAO (1987) observed that possible new techniques should have the same basic characteristics as traditional practices, they should be easy to understand, simple to apply, have low inputs of labour or cash, and must show a high rate of return. Besides the fact that communities prefer to continue growing traditional staple food crops, the farmers prefer a long term reliable yield over a maximum yield.

It is important to note that:

- Every community has different customary laws (mentality, witchcraft)
- A traditional preference to high-input over low-input farming hampers development of more efficient techniques (ReliefWeb, 2004).
- Most farmers are illiterate, and often unaware of improved systems of soil and crop management and best use of received inputs (Figure 4.9). This is not to say that uneducated farmers cannot comprehend the usefulness of science-based technology (FAO, 1993)
- The purchase of inputs presents problems and risks to less-secure farmers
- Appreciation by the communities is necessary, because without popular participation and support, projects are unlikely to succeed.

Thus, selection of an inappropriate approach with regard to the prevailing socio-economic conditions restrains proper appliance of conservation tillage. Cook book recommendations and solutions were being resented by farmers in the last decades. Participatory technology development and extension with farmers is probably the only way forward. Figure 4.10 shows the result of integration of farmer training into relief budgets. Farmers need to be taken as partners and equals in research and the basis for innovation should be farmers indigenous technical knowledge (ATNESA, 1999).

Figure 4.9: Illustration from a pamphlet on fertilizer use, distributed to 160 000 farmers across Zimbabwe

Figure 4.10: Technology transfer through farmer training

4.3.2 Resilience in Rainfed Agriculture

The combination of population growth, poor land management practices and weak land policies on a vulnerable natural resource base form the basis of large scale land degradation in Sub-Saharan Africa. Land degradation affects the resilience of agricultural and natural ecosystems, or, the capacity of an ecosystem to absorb shocks while maintaining structure and function. Conservation farming assists in building resilience, making agro-ecosystems more resilient, for example, to agricultural droughts. Davies (2000) claims that droughts causing production failures in agriculture do not automatically result in famines unless they coincide with other socio-economic factors. A drought leads to social disaster only if social resilience is eroded to the extent that the society is left with no capacity to absorb the shock. Or as Rockström (2003b) puts it, the society becomes extremely vulnerable to even small climatic or social disturbances, which suddenly turn into disasters.

The 1991/92 drought that hit southern Africa was also experienced as the worst drought in living memory in Zimbabwe. It led to water and electricity shortages, a 25% reduction in volume of manufacturing output and 6 % decline in foreign currency receipt (FAO, 2004b). The impact of drought in Southern Africa is presented in Table 4.11.

Table 4.11: Overview of impacts of the 1991-92 drought in Southern Africa (FAO, 2004b)

Primary impacts	Secondary impacts
SOCIAL	
Disrupted distribution of water resources	Migration, resettlement, conflicts between water users
Increased quest for water	Increased conflicts between water users
Marginal lands become unsustainable	Poverty, unemployment
Reduced grazing quality and crop yields	Overstocking; reduced quality of living
Employment lay-offs	Reduced or no income
Increased food insecurity	Malnutrition and famine; civil strife and conflict
Increased pollutant concentrations	Public health risks
Inequitable drought relief	Social unrest, distrust
Increased forest and range fires	Increased threat to human and animal life
Increased urbanization	Social pressure, reduced safety
ENVIRONMENTAL	
Increased damage to natural habitats	Loss of biodiversity
Reduced forest, crop, and range land productivity	Reduced income and food shortages
Reduced water levels	Lower accessibility to water
Reduced cloud cover	Plant scorching
Increased daytime temperature	Increased fire hazard
Increased evapotranspiration	Crop withering and dying
More dust and sandstorms	Increased soil erosion; increased air pollution
Decreased soil productivity	Desertification and soil degradation (topsoil erosion)
Decreased water resources	Lack of water for feeding and drinking
Reduced water quality	More waterborne diseases
ECONOMIC	
Reduced business with retailers	Increased prices for farming commodities
Food and energy shortages	Drastic price increases; expensive imports/substitutes
Loss of crops for food and income	Increased expense of buying food, loss of income
Reduction of livestock quality	Sale of livestock at reduced market price
Water scarcity	Increased transport costs
Loss of jobs, income and property	Deepening poverty; increased unemployment
Less income from tourism and recreation	Increased capital shortfall
Forced financial loans	Increased debt; increased credit risk for financial institutions

Source: Adapted from Vogel, Laing and Monnik (1999)

4.4 Conclusions

Conservation farming contributes to yield stability and dry spell mitigation in drought prone regions through improved soil characteristics, plant growth conditions and farm management. Tillage is an important aspect of conservation farming, because surface conditions can be adapted with respect to pore space and roughness, affecting the potential for infiltration and runoff. However, the key to successful conservation farming is the integration of tillage within the total production system. This means that besides applying, for example, zero tillage, mulching or ridging, it is also important to focus on pest management, crop rotations, weeding, etc.

Research from several countries show significant improvements in crop yields and reduced soil erosion after the introduction of alternative tillage practices for conventional mouldboard ploughing. Runoff is the greatest water management problem on rainfed crop lands because not only is it the loss of a potential water resource but it also causes damaging soil erosion. Mulching, covering the plot with plant residue, appeared to be very effective in reducing the surface runoff (90-100%) in experiments throughout Africa. Furthermore, weeding improved the infiltration capacity of the soil surface significantly, as the surface crust is broken up and the roughness of the soil surface is increased. Thus, the risk of crop failure as a result of water stress can be decreased significantly, moreover the willingness to invest more in their crops in terms of fertilization eventually leads to even higher yields.

However, with equipment and know-how available, adoption of conservation practices is still very low due to lack of adequate labour, insecure land tenure systems, limited access to credit and markets, and failing technology transfer. Proper socio-economic conditions and land management increase the resilience against calamities, so that, for example, droughts not always have to lead to social disaster.

5 Runoff Modelling

5.1 Introduction

The effect on the on-farm water balance of applying different farm practices has been discussed in the previous chapters. This chapter goes into the effects on the catchment scale. In Section 5.2 it is explained how the rainfall and runoff input data is acquired. Section 5.3 describes the rainfall runoff relation on different scales. In Section 5.4 and 5.5 Multiple Linear Regression is explained and how this is used to separate the different terms in the rainfall partitioning in the catchment. The main issue in this Chapter is to properly relate likely changes on farm plots to the bigger scale.

5.2 Data Validation

5.2.1 Missing Data

Eight rainfall stations are located in the vicinity of the Mzinyathini catchment. Only one of them, Umzingwane Dam Station, is actually located within the catchment boundary (see Figure 2.6). In Appendix B the data availability for all the stations is shown. There is a considerable amount of missing data. Where possible, these are filled with data from the neighbouring station. So, for example, missing data from Bulawayo Goetz is filled with data from Bulawayo Waterworks. Correlation analysis between all pairs of neighbouring stations shows considerable relation between them, justifying this data filling. When both stations have missing data, data from another station with similar rainfall characteristics for that period is used. For hydrological research a substantial period is necessary, in order to get a good feel about the rainfall variability in the catchment, which is quite high in these areas. The data series of Mbalabala and Umzingwane are not taken into account, because there are too many data gaps and the time period is too short. The stations in Esigodini, Bulawayo and Matopos do have enough data and can be used for this study. Figure 5.1 shows the station locations and the catchment boundary.

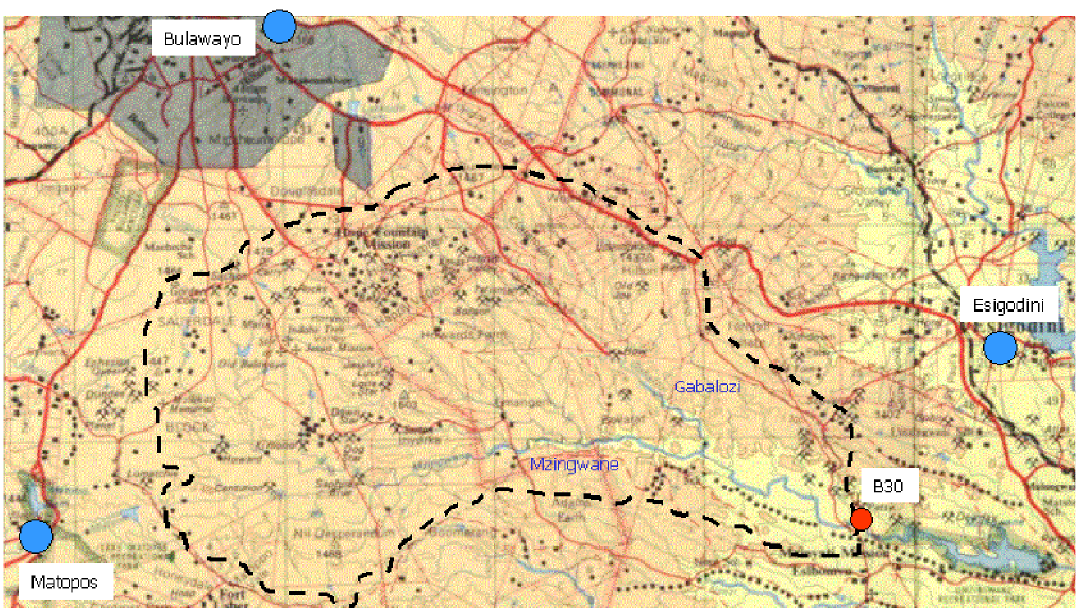

Figure 5.1: Mzinyathini Catchment with most important rainfall stations and weir B30 (Scale 1:300,000)

The different colours in Table 5.1 show per station per year to what extent data is compiled. For example, when several months of data are missing these gaps are filled with data from the nearest station, this is classified as considerable manual data filling. Little manual data filling stands for the case when only a few days in a particular year are missing. Daily rainfall data from Esigodini, Bulawayo and Matopos will be used as a basis for modelling. A hydrological year in Zimbabwe runs between October and September, therefore the rainfall period includes October 1988 up to September 2001.

Table 5.1: Annual availability and completeness of rainfall data

	Alt.	Lat.	Long.	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
Esigodini	1160	20-17-30	28-56-30																		
Bulawayo	1340	20-09-00	28-37-00																		
Matopos	1400	20-23-00	28-30-00																		

Alt. = Height in meters above Mean Sea Level		No data available
Lat. = Lattitude in degrees - minutes - seconds		Considerable manual filling of data gaps
Lon. =Longitude in degrees - minutes - seconds		Little manual filling of data gaps
		Original data

Runoff data is obtained from weir B30 upstream of the Umzingwane Dam reservoir. The data serie shows no data gaps. There is hardly any correlation with the runoff data downstream of the big reservoirs weir. This is due to unknown abstractions from the reservoir to the city of Bulawayo. The period from October 1988 to September 2001 is taken as input data, with respect to available rainfall data and the fact that runoff data before 1988 is largely missing. Despite the fact that there are three rainfall station versus one runoff station the observed runoff data is assumed to be correct. All inconsistencies concerning the rainfall runoff relation are therefore attributed to the rainfall series.

5.2.2 Spatial homogeneity

The data has to be analysed before it can be used for further calculations. A fast and simple method to indicate inhomogeneities, such as jumps in the time series, is the double mass analysis. The principle of double mass is to plot the accumulated rainfall of one station against another station over the same period of time. This is done for the three stations in Figure 5.2 for daily rainfall records between October 1988 and September 2001.

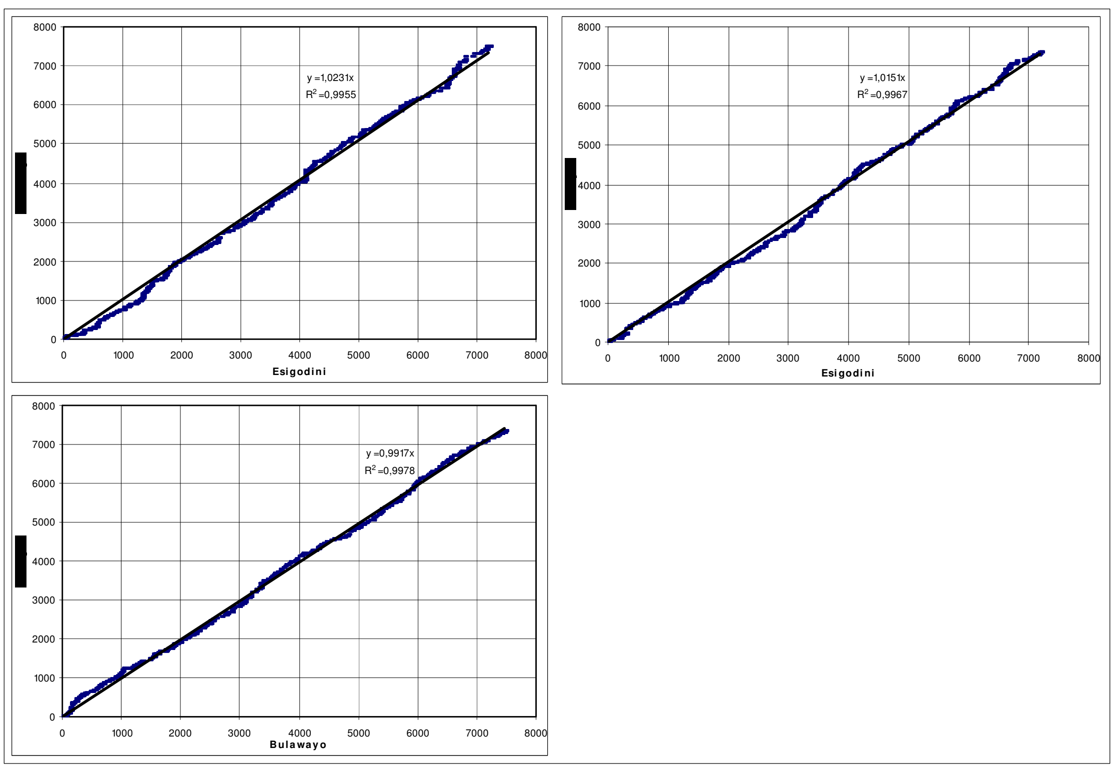

Figure 5.2: Double mass analysis, cumulative daily rainfall of: Bulawayo vs Esigodini, Matopos vs Esigodini and Bulawayo vs Matopos.

It can be seen that total rainfall over the 13 years under consideration amount to up to more than 7000mm for all stations, which means an average of more than 540mm/a. Besides that, the trend line gives a directional coefficient close to 1 and based on the fact that the coefficient of determination lies between 0.99 and 1, it can be concluded that rainfall amount and distribution over time is quite similar for the three stations. However, the curves for Esigodini against respectively Bulawayo and Matopos, show an unusual jump around 6000mm of accumulated rainfall. This amount was accumulated in December 1999. The difference between all sets of two stations confirms the suspicion that some inconsistency appears in the data from December 1999 onwards (see Figure 5.3). The peaks show a large difference in rainfall between two stations. There are more peaks for Matopos and Bulawayo minus Esigodini, than when Bulawayo and Matopos are compared. Especially the height and amount of peaks from the end of 1999 onwards for Esigodini minus Bulawayo and Esigodini minus Matopos require further investigation.

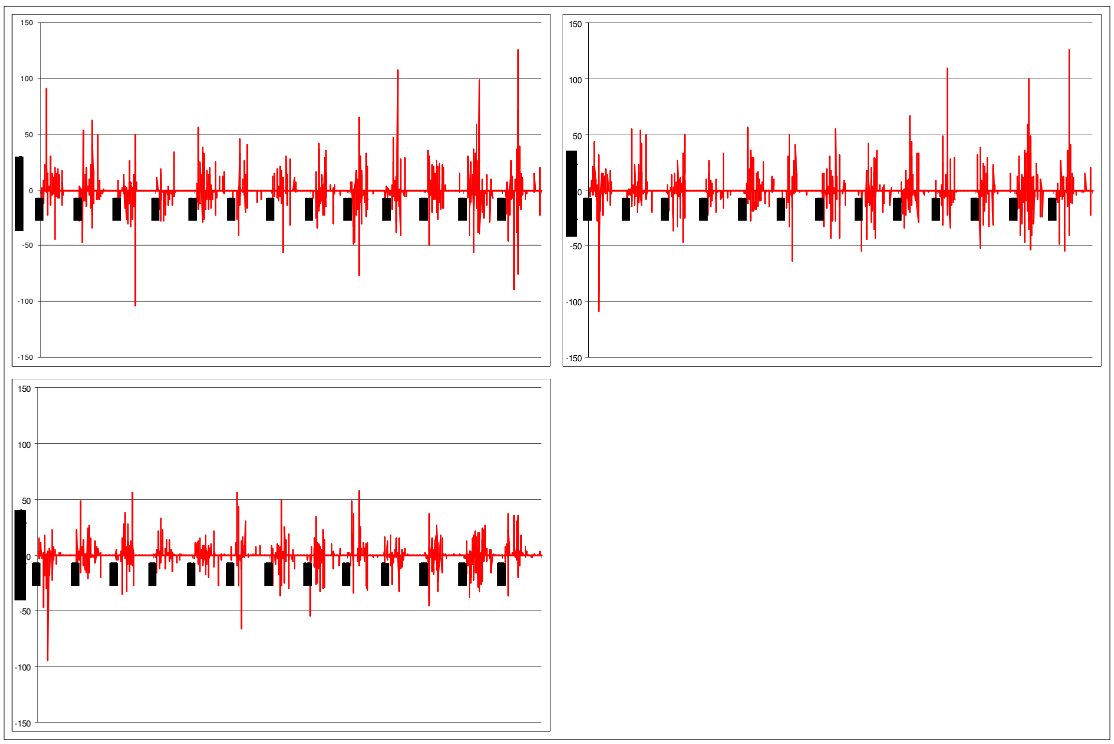

Figure 5.3: Absolute difference in daily rainfall between Esigodini-Bulawayo, Esigodini-Matopos and Bulawayo-Matopos for 1988 to 2001 (mm/d)

Figure 5.4 shows the observed rainfall of the three stations in February 2000. Peak rainfall or dry days in Esigodini do not coincide with peaks or dry days in Bulawayo and Matopos.

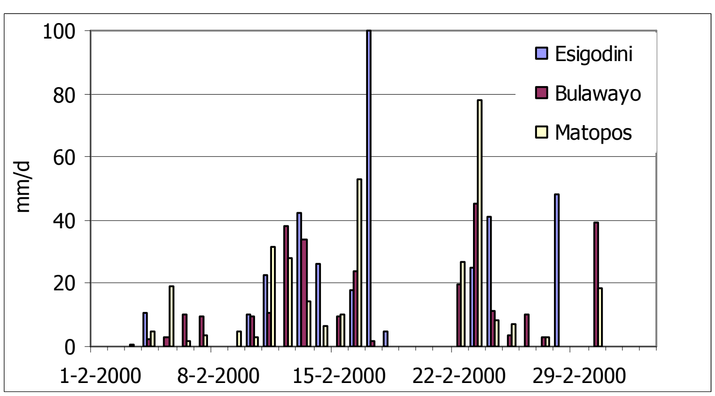

Figure 5.4: Observed rainfall in February 2000

After thorough visual inspection of Figure 5.2, 5.3 and 5.4 it is suspected that either the observer or the person digitising the data made a mistake with assigning dates. Esigodini rainfall data from December 1999 onwards should be shifting back one day, because it will be more consistent with the data set of Bulawayo and Matopos. Figure 5.5 shows the rainfall in the same period when the Esigodini data is shifted back one day. Besides that the rainfall peaks at the end of February 2000 are spread out over the preceding days, because they are suspected to be aggregates of preceding days. It is assumed that the observers were too occupied with other activities after the cyclone *Eline* hit Zimbabwe at the 22nd of February 2000. They probably did not bother to empty the gauges.

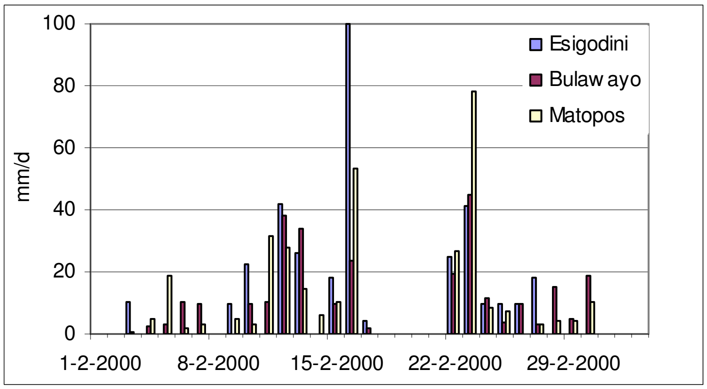

Figure 5.5: Observed rainfall after day-shift and removing peaks

Figure 5.6 shows cyclone *Eline* that originates at the Indian Ocean. Cyclones are frequent phenomena, but this time it penetrated exceptionally far inland.

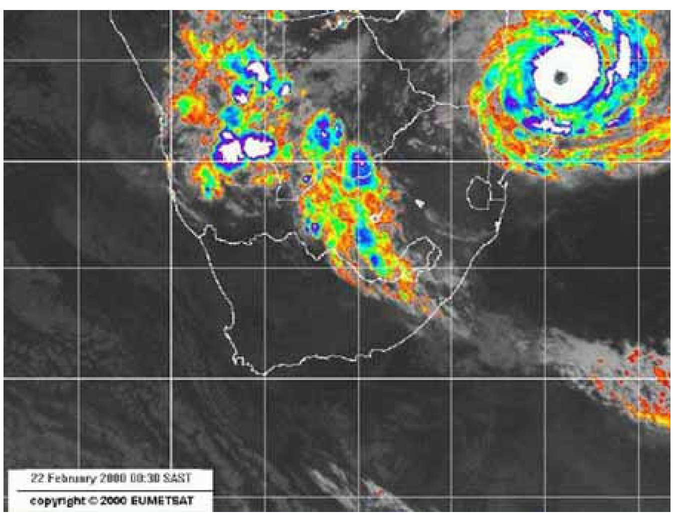

Figure 5.6: Cyclone Eline hits Zimbabwe (www.weathersa.co.za)

5.2.3 Areal Rainfall

The three selected stations are all located outside the Mzinyathini catchment, this makes it very difficult to describe the rainfall behaviour in the catchment itself. Table 5.2 gives the distance between two stations.

Table 5.2: Distance between rainfall stations in km

Station	Bulawayo	Matopos
Esigodini	40	45
Bulawayo	-	30

Interpolation of observed rainfall records to the catchment area can be performed using Thiessen polygons. It is based on the hypothesis that, for every point in the area, the best estimate of rainfall is the measurement closest to that point. The lines perpendicular to lines connecting each two stations draw a set of closed areas known as Thiessen polygons. The proportion of the area one of these polygons occupies, is a weight factor for the relevance of that particular station. The weights per station are calculated using PCRaster (2005), Figure 5.7 gives a graphical representation of the Thiessen polygons and the corresponding weight factors.

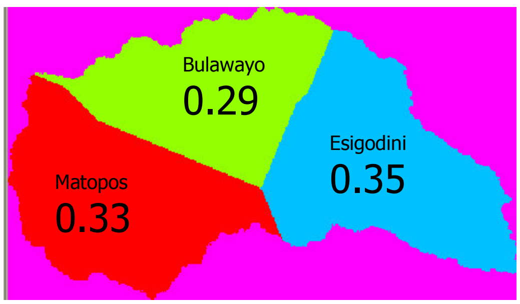

Figure 5.7: Thiessen polygons with weight factors for the three rainfall stations

The areal Thiessen rainfall is calculated using the weights and rainfall for the three stations:

$$P_{area} = 0.35 * P_{Esigodini} + 0.29 * P_{Bulawayo} + 0.33 * P_{Matopos}$$ *Equation 5.1*

In Figure 5.8 the observed runoff is plotted against the areal rainfall calculated from the original data, whereas Figure 5.9 shows the areal rainfall for the manipulated data (day-shift) explained in the previous section. It can be seen that for the manipulated data rainfall peaks coincide better with runoff peaks, for example, in the original data the runoff peak at the 16th of February occurs while the most rainfall falls the day after.

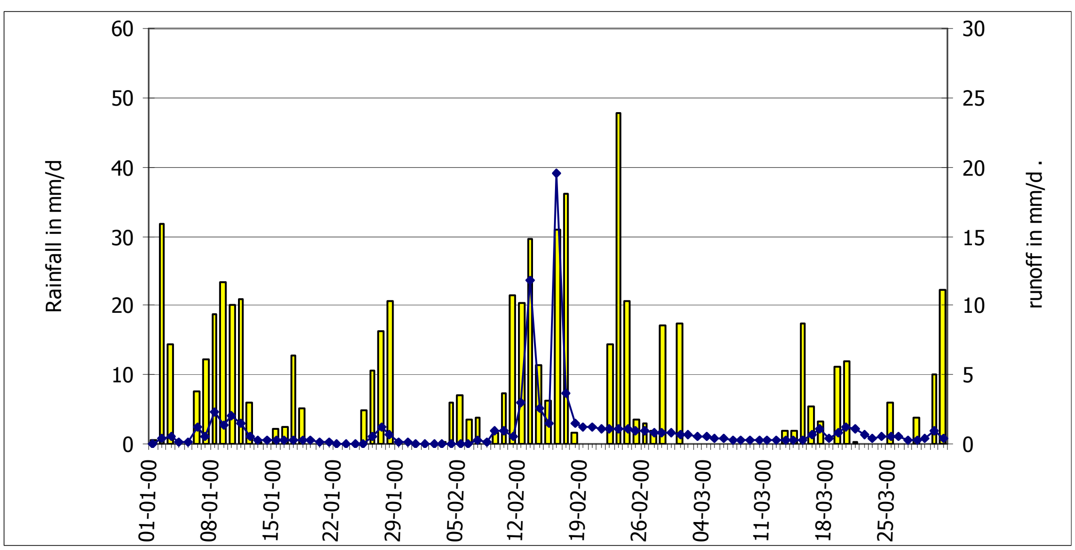

Figure 5.8: Observed runoff and areal rainfall (January – March 2000)

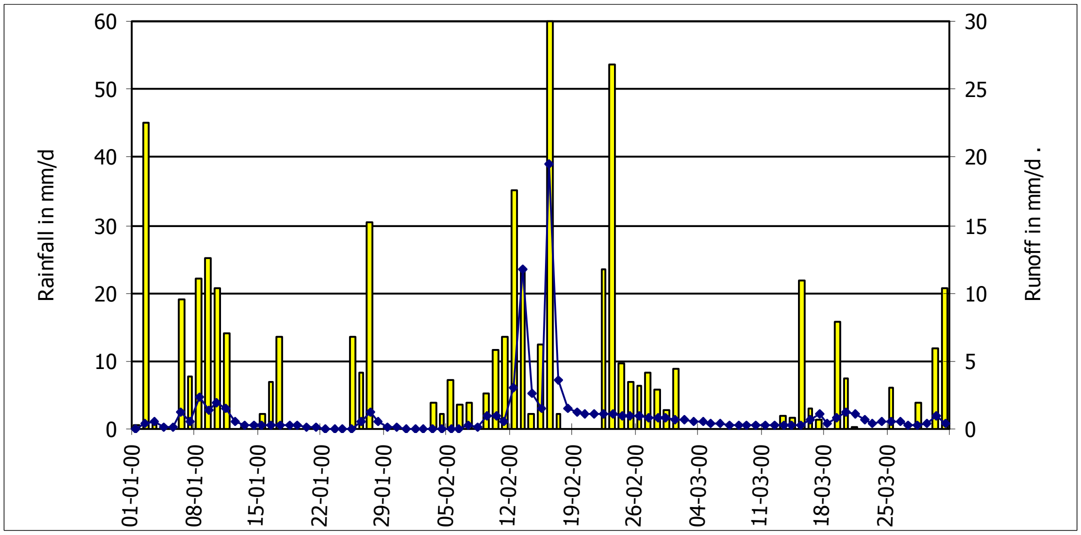

Figure 5.9: Observed runoff and manipulated areal rainfall (January – March 2000)

The *Eline*-rainfall peak at the 23rd of February attracts attention, because there is no runoff peak as a result of that rainfall. The chance that no rainfall occurred in the catchment is rather small, because all three stations experienced rain that day. Storage in the catchment might explain the absence of runoff, due to a preceding week with hardly or no rainfall. The most realistic reason is probably failing runoff gauges after the severe storm.

From now on the manipulated data set is regarded as the correct rainfall data set, and will be used as such in the next sections.

5.3 Rainfall Runoff relationship

5.3.1 Hydrograph

When analysing observed data it will be noted that a certain amount of rainfall is always required before any runoff occurs. The preceding chapters explained that runoff is only a small portion of the rainfall partitioning in semi-arid Africa. The annual runoff coefficient can be used as an indicator for what portion of the rainfall can eventually be observed in the river, it is defined as the ratio between total annual runoff and rainfall.

$$c_{annual} = \frac{R_{annual}}{P_{annual}}$$ *Equation 5.2*

The time of concentration, defined as the time needed for a drop of water to reach the outlet of a catchment from the most remote location in the catchment, is approximately ten hours (assuming a stream velocity of 1m/s over 40km). However, a rainfall peak is mostly followed by a runoff peak within the same day or up to two days later. This can be seen in Appendix C, where daily areal rainfall and runoff at weir B30 are shown. Within one day after the last rainy day in the rainfall event there is no more runoff recorded that can be attributed to that particular event. In relation to the rainfall peak it can be seen that the effect on the runoff of that peak is gone within seven days. This rather short reaction time is due to the fact that the

Mzinyathini catchment consists of a small top layer on permeable hard fractured rocks. This results in little release of stored water, because there is only a small saturated zone and water can be stored in cracks disabling further groundwater seepage to the riverbed. The water that recharges the river through the subsurface gets delayed in the soil. This delay does not only affect the delay in runoff peak, but it also smoothes out the river recharge after rainfall. Figure 5.10 shows the daily response of the river runoff to the rain that fell in the beginning of 2000. The response on the cyclone *Eline* (16th of February) can be characterised by a rising limb, resulting in a peak, followed by a period of decreasing river runoff (recession). This can still be distinguished on a daily scale, observing this behaviour on an hourly basis is more interesting, nevertheless, only daily data is available. It can be seen that the time lag, or time difference between maximum rainfall and runoff is not more than one day for this event. Besides that it can be seen that the second rainfall peak (23rd of February) shows no effect on the observed runoff. This is very remarkable, and should be attributed to failing runoff gauging.

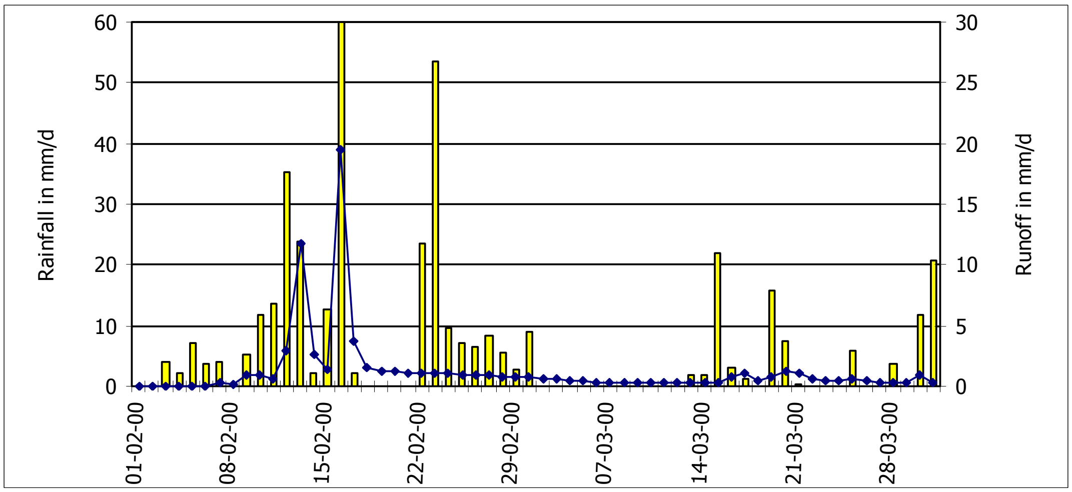

Figure 5.10: Hydrograph for February 2000

In general, climatic and site specific factors determine the shape and volume of the runoff peak.

Climatic factors, such as:

- Rainfall intensity: The type of storm, such as, cyclones, convective or frontal storms, all have different rainfall intensity distribution. Convective storms, which are common in Zimbabwe, have the highest intensity at the beginning of the storm and die out gradually. When the infiltration capacity of the soil is exceeded by the rainfall intensity the water will directly add up to the peak discharge and runoff volume.
- Rainfall duration and amount: The runoff contributing area increases over the catchment with increasing rainfall. For small catchments almost all rainfall will become runoff if a storm lasts long enough.
- Distribution of rainfall on the catchment: If the area of high rainfall is near the weir, this results in a rapid rise, sharp peak and rapid recession of river runoff. When most rain falls in the upper reaches, the water has more time to spread out and there is a big chance that it re-infiltrates again downstream from the riverbed to the soil. The same effect is also experienced for a storm moving either upstream or downstream over a catchment.

Site specific factors, such as:

- Slope: Steep hill slopes in the catchment trigger soil erosion and rapid surface runoff. The average slopes of the Mzingwane and Gabalozi rivers are not very steep, respectively, 0.9% and 1.5%.

- Soil: The infiltration capacity is dependant on porosity of different soil types and moisture content prevailing in the soil at the start of the rainstorm. Initial high infiltration rates reduce surface runoff, but as rain continues it reaches a constant value as the soil profile becomes saturated. In particular for soil types with a high clay or loam content subject to high intensity storms, the infiltration capacity of soil is seldom reached, due to soil crusting. FAO (1991) states that kinetic energy of raindrops hitting the soil increases considerably with increasing intensity of a rainstorm, due to expansion of raindrops. Soil aggregates breakdown and disperse leading to redistribution of fine soil particles into the upper soil pores. This results in clogging of the pores, forming a thin compacted layer at the surface which highly reduces the infiltration capacity.
- Land use: An area densely covered with vegetation, yields less runoff than bare ground. This is caused by improved infiltration capacity and increasing interception loss with higher vegetation cover. Peugeot (1997) recapitulates by stating that runoff is negatively related with vegetation density and positively related with soil crusting. Ultimately, land management, like tillage, described extensively in Chapter 3 and 4, show a considerable influence on runoff.
- Catchment size and shape: Large or long catchment areas have a long time of concentration, so the water is exposed to infiltration and evaporation for a long duration before it reaches the measuring point. Small areas have a shorter time of concentration, thus runoff can already be produced from short storms. Figure 5.11 demonstrates the general trend between the volume of runoff per unit of area and catchment size. The larger the size of the catchment the longer the time of concentration and the smaller the runoff efficiency.

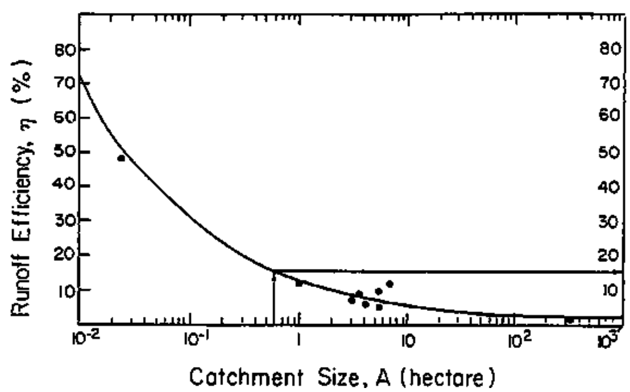

Figure 5.11: Relation between runoff efficiency and catchment size in the Negev Desert in Israel (FAO, 1991)

5.3.2 Scale in hydrology

A scale problem is introduced in hydrology because different processes are dominant at different scales. This was already mentioned for the influence of catchment size on runoff processes. Negi (2001) states that hill slope runoff processes dominate at sub-catchment scale, while the channel network geometry becomes important in meso-scale basins (up to the order of $100(km)^2$) and in large basins the spatial variability of precipitation becomes important. Therefore process descriptions that have been derived at the experimental plot do not necessarily hold true at the catchment scale. The physical conditions of a catchment area are not homogenous, even at the micro level, for example, there are a variety of different slopes, soil types and vegetation covers. Runoff plot studies in Cˆote d'Ivoire (Van de Giesen, 2000) show that not all water that is observed on the surface during a rainstorm reaches the bottom of the hill slope. For example, on small $1m^2$ plots in Cˆote d'Ivoire as much as 40% of the annual rainfall became runoff, but at the bottom of 100m hill slopes less than 4% of the rain was found as runoff. Stomph (2002) found that the reduction in runoff was also observed elsewhere, such as in Nigeria, Burkina Faso, Burundi and Israel. The substantial reduction of runoff per unit length can be explained by an extended residence time of overland flow. The residence time changes with slope length and with resistance to overland flow. This means that the water is exposed for a longer duration to infiltration and evaporation before it reaches the measuring point. Besides increased surface retention, heterogeneity of infiltration capacity results in additional processes such as water storage in the micro-relief, or infiltration in more pervious areas.

Consequently, the observed runoff at weir B30 does not provide much insight into the hydrologic processes on the farm plot. On the farm plot, direct surface runoff occurs when the infiltration capacity of the soil is zero. This can be the result of soil saturation or the fact that crusts prevent water from infiltrating at all. The only solution to model the runoff from farm plots well is to increase the gauging network extensively. Based on different experiments throughout Africa, Table 4.10 gave an overview of the extent to which surface runoff is affected by a certain tillage practice. It was found that tillage-induced roughness significantly affects runoff and soil erosion. Furthermore, Takken (2001) states that, it also has an important effect on the spatial patterns of runoff and erosion. On tilled fields, water flow is often directed along the tillage lines instead of in topographic direction. Moreover, borders between fields may act as water collectors and water flow may be routed along linear features, such as roads, even if these are oriented more or less parallel to the contour lines. Therefore, the actual runoff pattern can be very different from the runoff pattern that would be predicted from topography alone. Due to the fact that runoff patterns define the locations where water will concentrate, as well as the effective slope gradient (the slope in flow direction), erosion patterns and rates are also affected.

In addition to the spatial scale problem, there is a temporal scale problem, which refers to the different time scale on which processes in the rainfall partitioning work. The time scale of transpiration is determined by soil moisture stock, which can last weeks or months depending on the soil depth. Interception and surface runoff processes work only on rainy days, whereas base flow can be found in the river a few weeks after the last rain. Modelling with a small time step is very complicated because one has to split processes up in, for example, daily steps. Lumping these processes on a weekly or monthly scale improves the practicability of the model.

5.4 Multiple Linear Regression

5.4.1 General structure of Multiple Linear Regression models

Multiple Linear Regression (MLR) is a method used to model the linear relationship between a dependent variable *y* and one or more independent variables ($x_1, x_2,..,x_n$).

$$y = a + b_1 * x_x + b_2 * x_2 + ... + b_n * x_n \qquad \textit{Equation 5.3}$$

The coefficients b_i are found through multiple stepwise backward regression. A relationship is found such that the sum-of-squares of differences between observed and predicted values is minimized. This means finding the equation of the straight line that is best fitted to *n* observed points, or from a mathematical point of view; ξ needs to be minimized:

$$\xi = \sum_{i=1}^{n} \{y_i - \hat{y}_i\}^2 \qquad \textit{Equation 5.4}$$

The regression line is a best fit to the data points, see Figure 5.12.

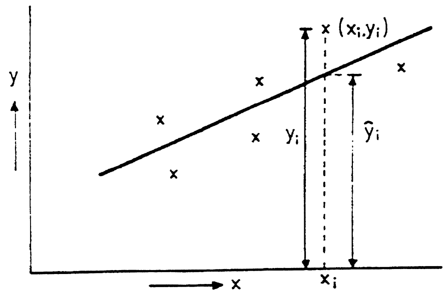

Figure 5.12: Principle of the regression line

The correlation coefficient *r* is used to indicate the deviation of a linear relationship between variables. Between two variables *x* and *y, r* can be defined as:

$$r = \frac{\sum^{n}(x_i - X)(y_i - Y)}{\sqrt{\sum^{n}(x_i - X)^2}\sqrt{\sum^{n}(y_i - Y)^2}}$$ *Equation 5.5*

where,

r	= correlation coefficient
x_i	= *i*-th observation of variable *x*
y_i	= *i*-th observation of variable *y*
X	= mean for all *x*
Y	= mean for all *y*
n	= number of values

The value of *r* is such that -1 < *r* < 1. Negative values for *r* stand for a negative linear correlation, so that as values for *x* increase, values for *y* decrease. If there is a random, non-linear relationship between the two variables, *r* is close to 0. Perfect correlation of ± 1 occurs only when all data points lie exactly on a straight line. A correlation greater than 0.8 is generally described as strong, whereas a correlation less than 0.5 is weak.

The coefficient of determination, r^2, is described as the proportion of variance accounted for by regression, or in other words, a measure of how well the regression line represents the data. Parallel to *r*, perfect fit is reached when r^2 approaches 1.

Soil crusting (Section 3.2.2) and soil moisture content influence runoff resulting from rainfall. Soil moisture can be built up over a couple of weeks, as it increases, the infiltration rate of a soil declines and potential for runoff increases. Savenije (1997), developed a MLR model that expresses monthly runoff as a function of the effective rainfall in previous months. Observed runoff at weir B30 in the Mzinyathini catchment is considered a function of rainfall in the current and previous months. Here, the dependent variable is observed runoff and rainfall is the independent variable:

$$R_{t-i} = Q_{s,t-i} + \sum_{i=1}^{n} b_i * P_{eff,t-i}$$ *Equation 5.6*

Where

$i \in [1,2,..,n]$	= counter of backward time steps from the start of the rainfall at time step *t*
R_{t-i}	= calculated runoff, taking into account rainfall up to *i* months ago [mm]
$P_{eff,t-i}$	= Effective (rainfall minus interception) rainfall of *i* months ago [mm]
Q_s	= Surface runoff occurs when moisture storage threshold is exceeded [mm]
b_i	= partial runoff coefficient

Two alterations were made compared to the model Savenije described (Savenije, 1997).

- Savenije uses one maximum monthly interception value throughout the year over the total data base. The model used for this study recognizes interception as a function of the number of rainy days per month, daily interception threshold and monthly rainfall described in the next section. The interception equation of de Groen (2002) calculates a different threshold for every month.
- When accumulated moisture in the catchment exceeds a certain threshold, additional rainfall runs off instantly in that time step. Consequently, this part of the rainfall is not available for the subsurface system. Savenije did not separate the instant surface runoff from the groundwater seepage.

Consequently, the daily interception and surface runoff threshold can be modified until the highest coefficient of determination r^2 is found for the model. In Savenijes model, the only variable is the monthly interception threshold.

The characteristics of the catchment can be described without using a lot of input data in this lumped empirical model. The input of this MLR model is observed rainfall over the period 1988-2001. The calculated runoff can then be compared to observed runoff and the coefficient of determination r^2 quantifies the analogy between them.

5.4.2 Model concept

The concept of the model is presented in Figure 5.13. Rainfall first has to pass the interception threshold, before it reaches the surface system. There, rainfall has to pass a storage threshold above which surface runoff occurs or it can enter the subsurface system. From here water can directly percolate deeper or it can add up to the subsurface storage from where it becomes available for plants. This latter flux T is of course the most important one in this research. From the deeper subsurface storage delayed runoff is generated. Table 5.3 shows a fragment of the Excel sheet, where the parameters from Figure 5.13 are calculated. All parameters from this sheet will be discussed in this section.

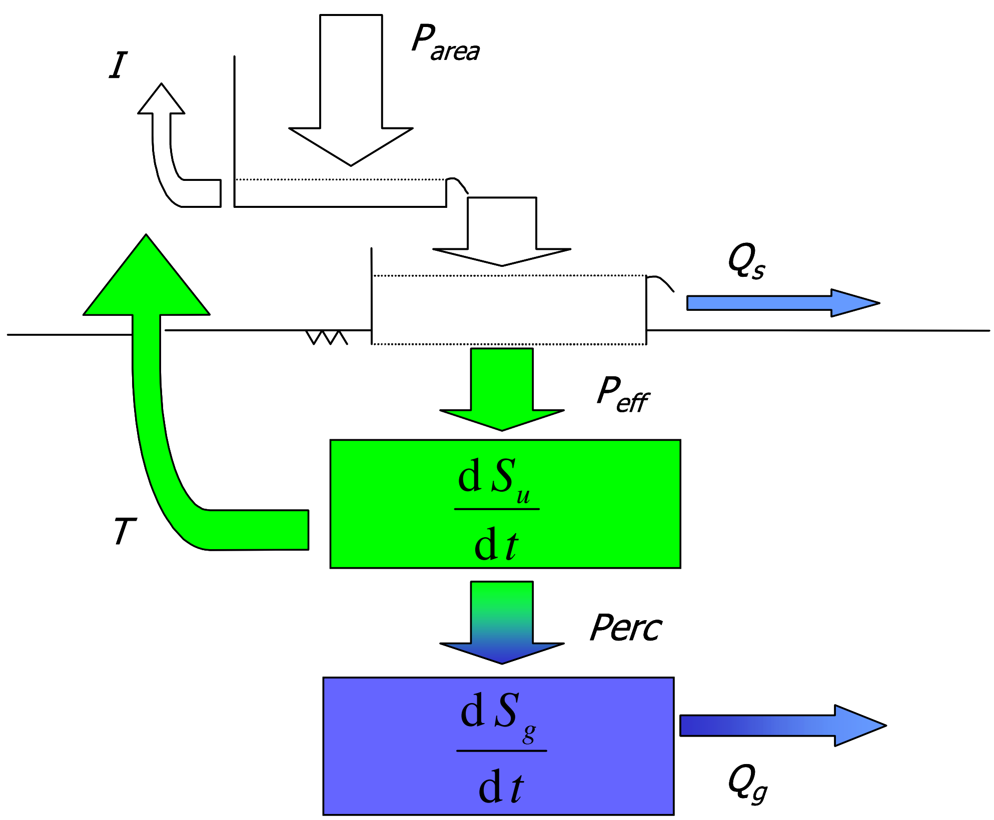

Figure 5.13: Model concept, colours indicate the type of resource discussed in Section 3.1

Table 5.3: Results from regression calculation for a memory of up to four months (Monthly data, 1988-2001, D=3mm/day, L=3mm/day and D_s =220mm)

	Runoff	**Rainfall**					Memory	1	2	3	4
Month	*Robs*	*Parea*	*Nr*	*Im*	*Pnet*	*Qs*	*Peff*				
	(mm)	*(mm)*		*(mm)*	*(mm)*	*(mm)*	*t*	*t-1*	*t-2*	*t-3*	*t-4*
sep-88	*19*	*0*			*0*		*0*				
okt-88	0	27	7	14	13	0	13	0			
nov-88	0	83	6	16	66	0	66	13	0		
dec-88	0	59	9	22	37	0	37	66	13	0	
jan-89	0	97	8	22	75	0	75	37	66	13	0
feb-89	0	135	13	35	100	0	100	75	37	66	13
mrt-89	0	21	4	9	12	0	12	100	75	37	66
...	...	...	...	...	...	...	...	...	...	...	...
feb-01	14	317	17	48	269	0	269	48	16	68	2
mrt-01	12	71	8	20	51	0	51	269	48	16	68
apr-01	1	10	4	7	3	0	3	51	269	48	16
mei-01	0	6	2	4	2	0	2	3	51	269	48
jun-01	0	0	0	0	0	0	0	2	3	51	269
jul-01	0	7	3	5	2	0	2	0	2	3	51
aug-01	0	0	0	0	0	0	0	2	0	2	3
sep-01	0	26	2	5	22	0	22	0	2	0	2

Month
The MLR model calculates runoff on a monthly time scale. De Groen (2002) states that the spatial correlation of daily rainfall data in Zimbabwe is low and the density of the rain gauge network is not adequate to provide good estimates of daily rainfall. This is not surprising, because perhaps 90% of the total rainfall in Zimbabwe, occurs from convective storms, with limited areal extent. Furthermore, water resource planners interest in daily variability of runoff is small, because uncertainties in the socio-economic scenarios, with a larger time scale, play a more important role in planning strategies.

R_{obs}
R_{obs} is the observed runoff measured at weir B30 upstream of the Umzingwane Dam reservoir. The period October 1988 up and including September 2001 is taken as input data, with respect to available rainfall data and the fact that runoff data before 1988 is largely missing.

P_{area}
P_{area} is the monthly areal rainfall, calculated by using Thiessen polygons (Section 5.2.3) on the rainfall stations in Esigodini, Bulawayo and Matopos.

n_r
n_r is the number of days in a month on which rainfall occurred. The value for n_r is derived from the average value for the number of rainy days per station, because areal rainfall is applied.

I_m
I_m is the monthly interception threshold. De Groen (2002) used Markov Chains to prove that the relationship between monthly rainfall and the transition probability of a rain-day after a rain-day is spatially homogeneous in Zimbabwe. This justifies the use of the following equation for the monthly interception threshold:

$$I_m = P_{area}\left(1-\exp\left(\frac{-D*n_r}{P_{area}}\right)\right) \qquad \textit{Equation 5.7}$$

where

D = daily interception threshold [mm/day]

n_r = number of rainy days per month

P_{area} = monthly areal rainfall [mm/month]

Figure 5.14 gives a graphical representation of Eq. 5.7, for different parameter values. It can be seen that the maximum monthly interception is largely influenced by the number of rainy days. The water that is intercepted evaporates in the course of a day and the interception storage volume is free for the next rainfall event.

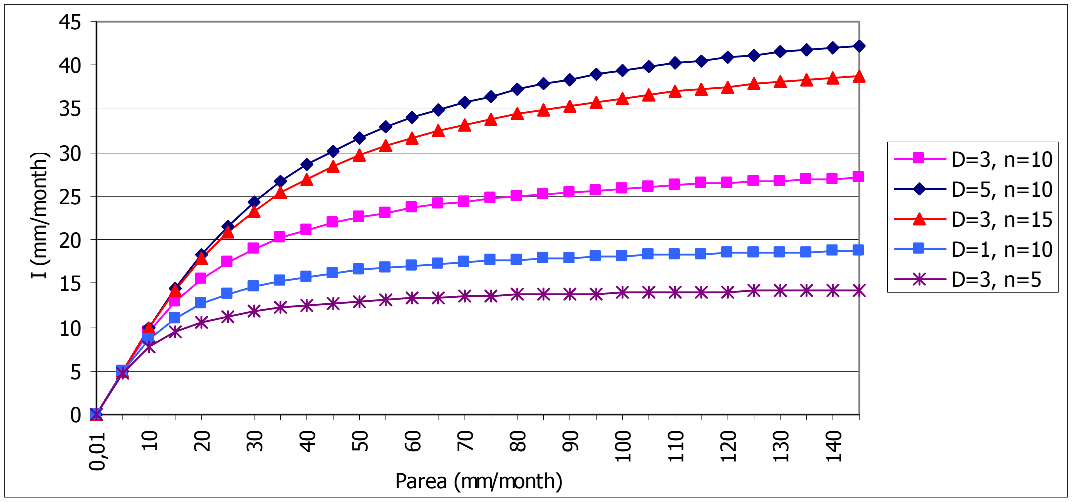

Figure 5.14: Relation between daily interception threshold D, number of rainy days n, monthly rainfall P and interception I according to Eq. 5.7

Interception works on the scale of a day, therefore it is more realistic to set a daily threshold *D* instead of setting a constant monthly threshold. Furthermore, when there are only a small number of rainy days, interception on a monthly basis is also small. *D* is dependant on local land cover conditions, such as soil and vegetation, and growth stage. A cereal crop, for example, has a smaller interception storage capacity than a dense grass cover. Pitman (1973) states that the value for *D* in Southern Africa can reach 8mm/day for densely vegetated areas. De Groen (2002) considers 2-5mm/day as appropriate for areas in Zimbabwe. Savenije (2004) observed that a sandy area occupied by traditional farmers in the Mupfure catchment in Zimbabwe, consisting of cropland with isolated trees, has an interception capacity of 4-5mm/day. The threshold *D* is determined iteratively until maximum r^2 is obtained.

P_{net}

Net rainfall, P_{net} , is that part of the rainfall that is left after subtraction of the interception threshold. On a monthly basis:

$$P_{net} = P_{area} - I_m \qquad \textit{Equation 5.8}$$

Q_s

Direct surface runoff occurs when the infiltration capacity of the soil is zero. This can be the result of soil saturation or the fact that crusts prevent water from infiltrating at all. Surface runoff water flows to the riverbed during and just after a rainstorm. Most of the surface runoff water does not make it to the riverbed and not in the least all the way to the gauge location. This is caused by depression storage and re-infiltration either on its way to the river or to the alluvial aquifer. Consequently, $Q_s = 0$ does not mean no surface runoff occurred anywhere in the catchment, it only means no surface runoff is recorded over the weir.

The value for Q_s is dependant on a certain threshold D_s, above which the soil is completely saturated and local depressions in the catchment are filled. D_s is referred to as the saturation threshold of the entire catchment above which additional rain runs off instantly. Please note that the calculations for surface runoff are on a daily basis. Calculation of the daily surface runoff goes as follows. First, daily net rainfall, defined as the areal rainfall P_{area} minus the daily interception threshold D, is calculated.

$$P_{net,d} = Max(P_{area} - D, 0)$$ *Equation 5.9*

Moisture storage S is supplemented with this daily net rainfall after subtraction of daily leakage L. This leakage should not only be regarded as a downward movement of water in the topsoil, but caters for percolation, transpiration and evaporation. As a result of leakage new storage opportunities occur for water upstream of the gauging location amounting up to L mm/day. So when no rain occurred on a day, the additional moisture storage is negative, namely $-L$

$$\Delta S = P_{net,d} - L = S_t - S_{t-1}$$ *Equation 5.10*

$$Q_s = \max(S_t - D_s, 0)$$ *Equation 5.11*

The storage at time step t S_t can not become higher than D_s, the threshold for maximum storage, all additional rainfall then runs off the surface instantly. The fact that the threshold has first to be surpassed explains why not every rainstorm produces surface runoff. Figure 5.15 shows an example of how instant surface runoff is calculated for two events. Daily interception is assumed 4mm/day, leakage 8mm/day and the saturation threshold of the catchment is set at 40mm. It can be observed that storage has to be built up before any surface runoff can occur. The first peak is only 10% higher than the second, but because of built up storage from previous days this results in a three times higher surface runoff peak.
Daily surface runoff values are accumulated for the month under consideration, resulting in the monthly Q_s. When surface runoff occurs, it flows down the river immediately and leaves the system in the same time step.

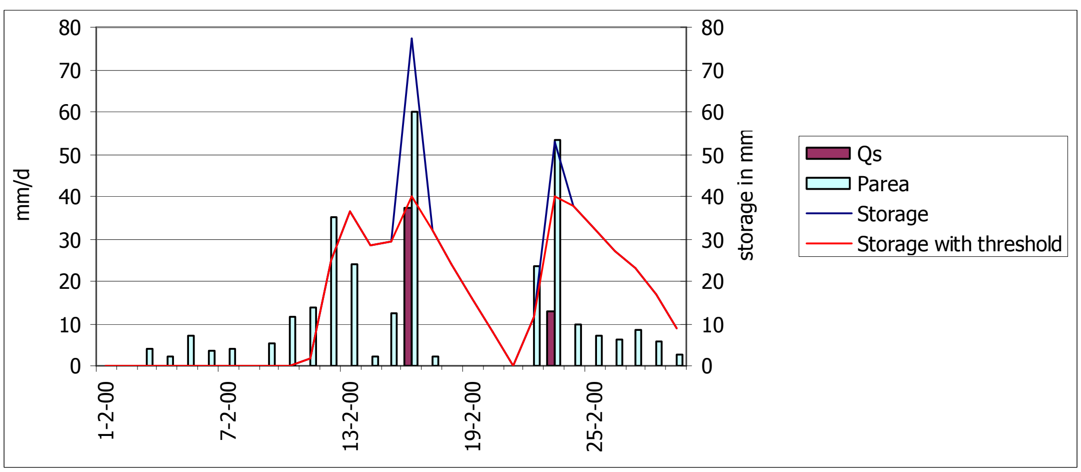

Figure 5.15: Surface runoff occurs when the catchment saturation threshold D_s is exceeded (here: 40mm)

P_{eff}
Effective rainfall P_{eff} is defined here as the part of the rainfall that is not intercepted and does not runoff directly. Effective rainfall is rainwater that infiltrates the soil and feeds transpiration T and subsurface runoff Q_g processes.

$$P_{eff} = P_{net} - Q_s$$ *Equation 5.12*

In Eq. 5.6 P_{eff} is defined for several months, *t-2* for example, stands for the effective rainfall of two months ago.

5.5 Model Calculations

5.5.1 Monthly

To sum up, Table 5.4 shows the three variables that are to be found through iteration, to reach maximum r^2. The variables have a physical meaning and are therefore subject to iteration boundaries set by the environment. The presented range for the daily interception threshold was discussed in the previous section. Leakage consists of evaporation and percolation. The average daily pan evaporation is 5mm/day and the estimated maximum daily percolation is 3mm/day. To be at the safe side the maximum possible leakage is set at 10 instead of 8mm/d (5mm/d + 3mm/d) constituting the upper boundary value of the leakage *L*. The boundaries are set at a safe range, when additional depression storage in the catchment is also taken into account. The maximum amount of storage in the catchment is set at 500mm, based on the rocky conditions of the catchment.

Table 5.4: Model variables and their calculation range

			Min.	**Expected range**	**Max.**
Daily interception threshold	D	mm/d	0	2-5	8
Leakage	L	mm/d	0	2-6	10
Catchment saturation threshold	D_s	mm	0	50-250	500

The model is now applied to find the best fit for the partial runoff coefficients (b_i's from Eq. 5.6). The coefficient b_i determines the contribution of the effective rainfall in month *t-i* to the subsurface runoff Q_g in the current month *t*. The total amount of months taken into account should not exceed six months, because there exists a fictive correlation due to seasonality. When the rainfall of the previous months does not influence runoff for the current month, the memory of the model is referred to as 0. Table 5.5 shows some calculation results when a memory of up to four months is considered. Physically it is not possible for the *b*-values to become negative, because this would imply that the rainfall in a certain month results in a decrease in river runoff several months later. In this case, the runoff system has a memory of one month, only rainfall of the previous month affects the runoff of the current month, because negative values appear for longer memories. The coefficient of determination between observed and calculated runoff is very low, indicating that the model calculations are not very consistent with runoff observations. The accompanying calculated runoff, together with observed runoff and areal rainfall is plotted in Figure 5.16 on the next page.

Table 5.5: Results from regression calculation for a memory of up to four months (Monthly data, 1988-2001, D=3mm/d, L=3mm/d and D_s =220mm)

memory	*t* *b1*	*t-1* *b2*	*t-2* *b3*	*t-3* *b4*	*t-4* *b5*	*c*	*r^2*
0	0,094	0	0	0	0	0,094	0,220
1	0,066	0,044	0	0	0	0,111	0,244
2	0,068	0,057	-0,022	0	0	0,103	0,249
3	0,069	0,056	-0,028	0,009	0	0,107	0,251
4	0,068	0,057	-0,027	0,014	-0,008	0,104	0,252

The effective runoff coefficient *c* is the proportion of runoff to effective rainfall. The individual partial runoff coefficients *b* determine the contribution of the corresponding effective rainfall to the runoff. Together they equal the total fraction of rainfall that comes to runoff through the subsurface system, therefore Eq. 5.13 applies.

$$c = \sum_{i=1}^{n} b_i$$ *Equation 5.13*

As stated before, the effective rainfall is that part of the rainfall that actually contributes to soil moisture and comes available for transpiration and groundwater runoff. The effective runoff coefficient *c* multiplied by the effective rainfall gives the part of the rainfall that percolates and is eventually discharged from the subsurface in a hydrological year. Equation 5.14 holds only for hydrological years when moisture transfer from one hydrological year to another is considered negligible.

$$Perc = Q_g = c * P_{eff}$$ *Equation 5.14*

The rest of the effective rainfall remains in the soil, from where it can transpire through plants. Abstractions by humans for supplementary irrigation, mining and drinking water, either for themselves or cattle, is not taken into account here. The term transpiration should therefore be considered as a potential transpiration rather than an actual one.

$$T = (1 - c) * P_{eff}$$ *Equation 5.15*

The observed runoff is comprised of water originating from groundwater and surface runoff. The partial runoff coefficients are calculated based on the least squares difference between observed runoff and effective rainfall. Calculated runoff is obtained through adding up the separately calculated Q_g (effective rainfall multiplied by *b*-values for some bygone months) and Q_s. So, the partial runoff coefficients do not take Q_s into account for the calculated runoff, even though they are based on the observed runoff which is comprised of groundwater and surface runoff. As a result, the *b*-values do not fully represent the contribution of rainfall to runoff. Nevertheless, during calculation runs it became apparent that additional runoff due to surface runoff did not occur very often. So, the values for *b* are not corresponding exactly with actual calculated runoff, but it is assumed to be a sufficiently good approximation.

Nevertheless, as stated in Section 5.4.1 the regression calculated in the case of Table 5.5 (0.244) can be qualified as weak. Figure 5.16 shows the areal rainfall, observed runoff at B30 and calculated runoff plotted against time for the period 1988-2001.

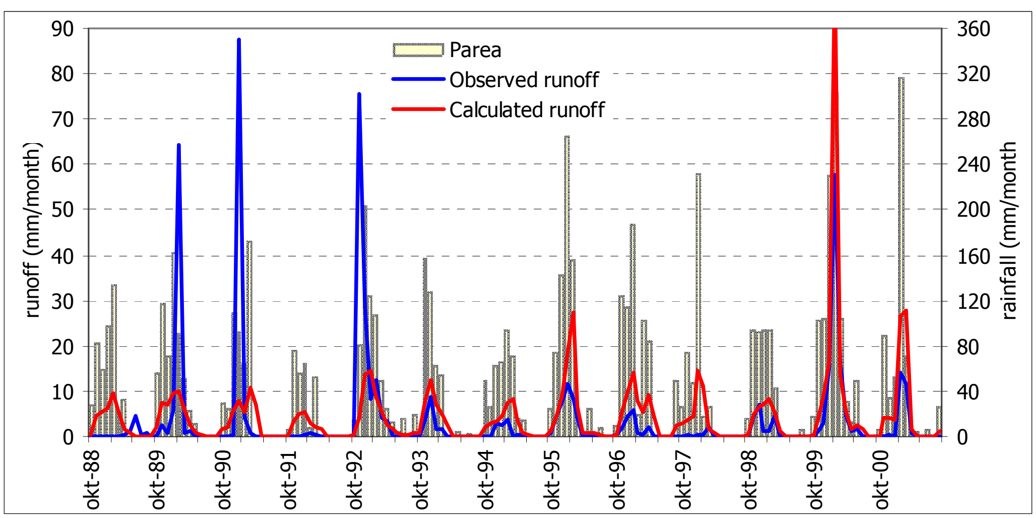

Figure 5.16: Areal rainfall, observed and calculated runoff (1988-2001)

When looking at this relation between rainfall and runoff a number of remarks can be made.

- The observed peak runoff normally occurs some three or four months after the first considerable rains. The small peak in the hydrological year 1988-1989 looks suspicious, because it occurred in June, while considerable rain fell between October and April. The runoff peak of 75mm in November 1992 also looks doubtful, because only 16mm/month and 82mm/month of rain fell in respectively October and November.
- The runoff coefficient, or the ratio between observed annual rainfall and runoff, normally lies between 0.01 and 0.06 (see Figure 5.17). The years 1989-1990, 1990-1991 and 1992-1993 show a runoff coefficient of respectively 0.13, 0.19 and 0.20. These high values are dubious, because there is no abnormality in the amount of rain for these years, moreover the rainfall quantities are close to the average annual rainfall of 550mm/a. The low runoff coefficient in 1991-1992 can be explained by the low rainfall in 1991-1992. While season 1997-1998 has considerable rainfall amounts, the low runoff might be explained by errors in the data series or large abstractions by humans.

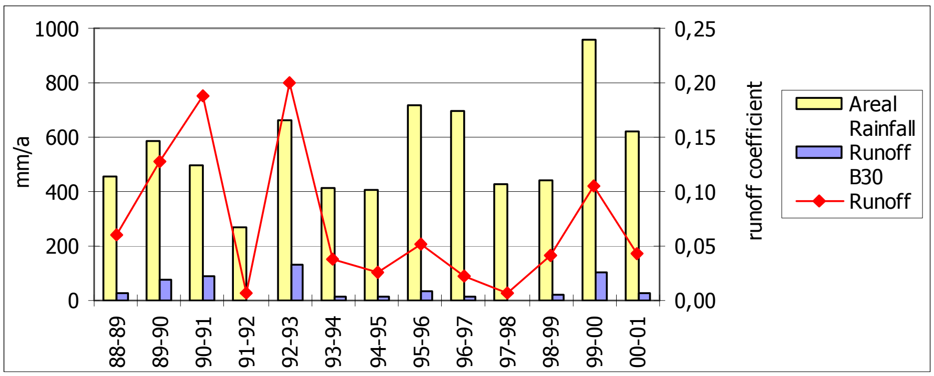

Figure 5.17: Rainfall and runoff per hydrological year with runoff coefficient

Consequently, data from 1988-1990 and 1992-1993 is now discarded and new calculations are made. The maximum coefficient of determination is found after several iterations, the values for *D*, *L* and D_s are respectively 2mm/day, 3mm/day and 240mm. Table 5.6 shows the calculation results, some remarks can be made when this table is compared to the Table 5.5 where the entire data set was used:

- the rainfall runoff relation also has a memory of 1 month, because the b_3-value is negative.
- From the values for b_1 and b_2 it can be stated that the contribution of the rainfall to the runoff in the current month is 1.5 times higher than that the rainfall in the previous month contributes to the current runoff.
- The *c*-value of 0.078 means that over a year 7.8% of the effective rainfall comes to runoff.
- The highest coefficient of determination was found for a very low daily interception threshold (*D*=2mm/d)
- For a memory of one month the r^2 is almost four times higher, namely 0.914 versus 0.244

Table 5.6: Results from regression calculation (Monthly data, 1991-2001, D= 2mm/day, L= 3mm/day and D_s = 240mm)

memory	*t* *b1*	*t-1* *b2*	*t-2* *b3*	*t-3* *b4*	*t-4* *b5*	*c*	*r^2*
0	0,066	0	0	0	0	0,066	0,871
1	0,045	0,033	0	0	0	0,078	0,914
2	0,046	0,037	-0,008	0	0	0,075	0,909

Rainfall and observed and calculated runoff are plotted in Figure 5.18. Please note that season 1992-1993 is left out of the time series. It can be seen that overall runoff is overestimated, especially in the wet 1997-1998 season substantial runoff was expected but hardly any runoff was observed. The calculated peaks of 1999 up to 2001 fit the observed runoff peaks remarkably well. This is due to the soil moisture threshold which was exceeded in February 2000 and not in 2001, additional instant surface runoff contributed to achieving an almost equal amount of runoff in 2000. The linear relation between effective rainfall and runoff is described in Eq. 5.16

$$R_{M,t} = Q_{s,t} + 0.045 * P_{eff,t} + 0,033 * P_{eff,t-1}$$ *Equation 5.16*

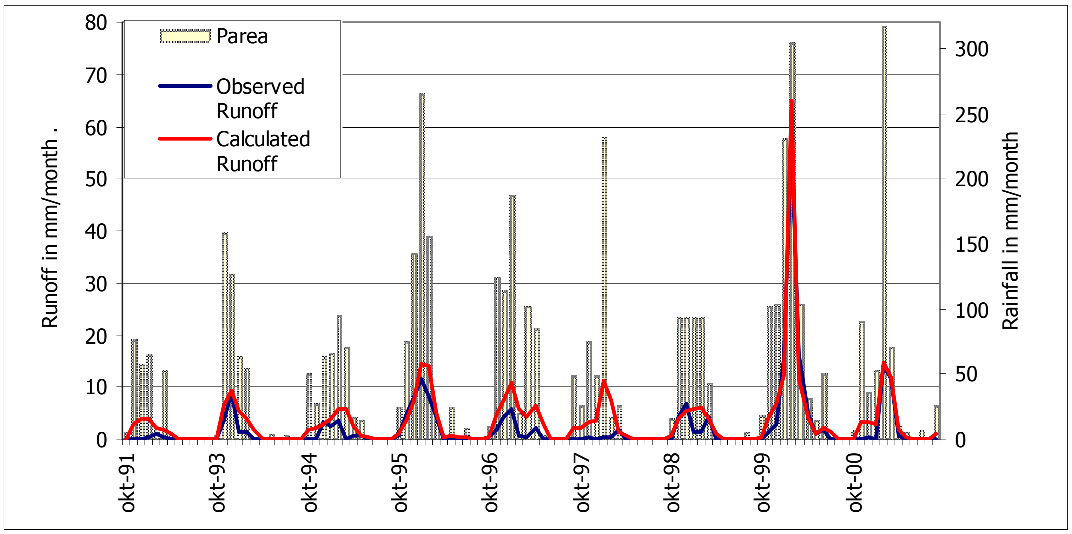

Figure 5.18: Areal rainfall, observed and calculated runoff (1991-2001)

5.5.2 Weekly

Hydrological processes appear to be more regular on a monthly than on a weekly time scale. Variability in the catchment characteristics have a serious influence on the hydrological response on a small time scale. On larger time scales these variability's are evened out due to lumping of the hydrological response over a time step. Data peaks and other indications of variability within the time step get averaged out, leaving little to no trace of what actually happened. From the monthly calculations in the previous section it became apparent that the memory of the system is not longer than one month. Modelling on a weekly basis might also make more clear about the memory of this catchment.

Areal rainfall is now defined as the accumulated rainfall over a week, calculated with Thiessen polygons. The weekly interception threshold I_w is assumed to be in accordance with the calculation for the monthly threshold I_m. Consequently, the number of rainy days in a month has to be calculated on a weekly basis.

$$I_w = P_{area}\left(1 - \exp\left(\frac{-D * n_r}{P_{area}}\right)\right)$$ *Equation 5.17*

Modelling over the period 1991-2001 results in a maximum r^2 of 0.7113, found for D, L and D_s values of respectively 3mm/d, 2mm/d and 190mm (Table 5.7). It can be seen that the memory of the system is two weeks and that the coefficient of determination is adequate.

Table 5.7: Results from regression calculation (Weekly data, 1991-2001)

memory (weeks)	*t* *b1*	*t-1* *b2*	*t-2* *b3*	*t-3* *b4*	*t-4* *b5*	*c*	*r^2*
0	0,051	0	0	0	0	0,051	0,714
1	0,039	0,030	0	0	0	0,069	0,711
2	0,039	0,029	0,001	0	0	0,069	0,711
3	0,037	0,027	-0,003	0,015	0	0,075	0,713

In accordance with the *b*-values from Table 5.7 and the Multiple Linear Regression equation 5.6 presented in section 5.4.1 the following Equation gives the best linear estimation between effective rainfall and runoff in the Mzinyathini catchment.

$$R_{W,t} = Q_{s,t} + 0.039 * P_{eff,t} + 0.029 * P_{eff,t-1} + 0.001 * P_{eff,t-2} \qquad \text{Equation 5.18}$$

From this Equation it becomes clear that the effect of the rainfall in the current and previous ($P_{eff,t}$ and $P_{eff,t-1}$) weeks is far more dominating on the current river runoff than the rainfall of two weeks before. The areal rainfall, observed runoff and calculated runoff (Eq. 5.18) for a memory of two weeks is plotted in Figure 5.19. Figure 5.20 zooms in on the low values of observed and calculated runoff, it can be seen that the model results approach the observed runoff quite well.

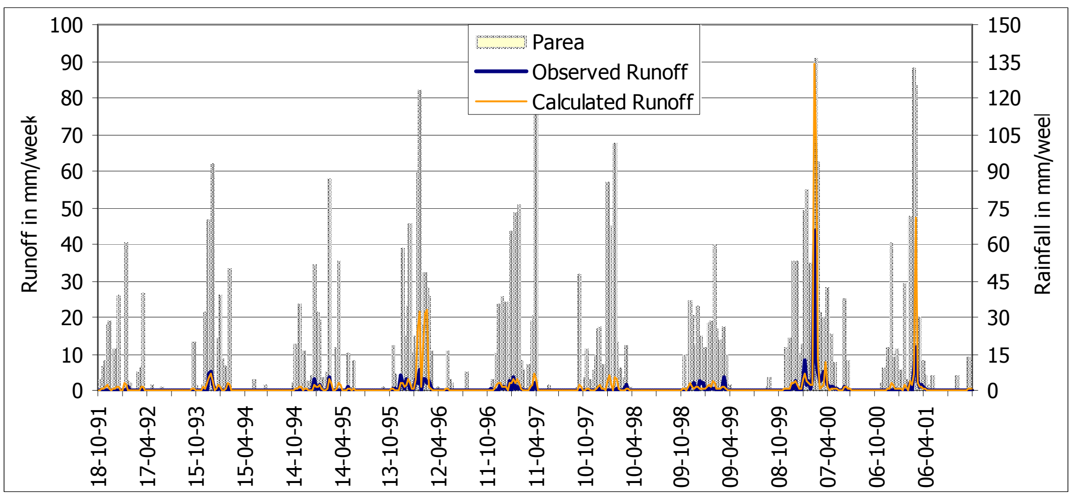

Figure 5.19: Areal rainfall, observed and calculated runoff calculated with weekly time step (1991-2001)

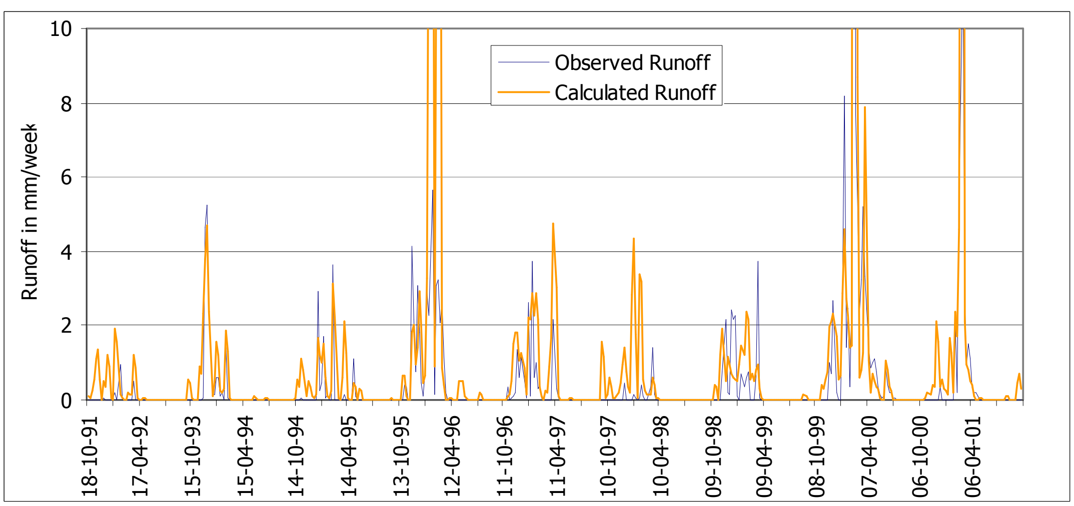

Figure 5.20: Low values of observed and calculated runoff calculated with weekly time step (1991-2001)

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Appendix D gives an overview of results from different variable values for the total data period 1988-2001, 1991 until 1999 and 1991 until 2001. The coefficient of determination for monthly data is consistently higher than for weekly data. This was already anticipated, because on larger time scales processes appear to work more regular, due to evening out of the variability's of the hydrological response.

5.5.3 Catchment Water Balance

The multiple linear regression model that describes observed runoff best on a monthly and a weekly basis can now be used to quantify parameters in the catchment water balance. The general water balance of a catchment is made up of incoming rainfall *P* and outgoing fluxes such as evaporation *E* and river discharge *Q*, the difference between these two fluxes is attributed to a change in storage:

$$\frac{dS}{dt} = P - E - Q \qquad \textit{Equation 5.19}$$

where,

S = the total storage of moisture in the catchment, $S = S_s + S_u + S_g$ [mm]

S_s = the surface water storage [mm]. This is considered negligible, because the Mzinyathini catchment does not have a lot of open water.

S_u = the part of the storage in the unsaturated zone that is available for transpiration (exceeding the wilting point) [mm]

S_g = groundwater storage is the remaining subsurface storage [mm]

Evaporation *E* consists of interception I and transpiration *T*, while *Q* consists of surface runoff Q_s and base flow from the subsurface Q_g. Equation 5.19 can be elaborated in line with the parameters from the previous sections.

$$\frac{dS_u}{dt} = P_{area} - I - T - Q_s - Q_g - \frac{dS_g}{dt} \qquad \textit{Equation 5.20}$$

From Eq. 5.9 and 5.12 follows that

$$P_{area,t} - I_t - Q_{s,t} = P_{eff,t} \qquad \textit{Equation 5.21}$$

It is assumed that percolation occurs in one time step without delay, Q_g on the other hand discharges with a delay of one or more time steps:

$$Q_{g,t} = b_1 * P_{eff,t} + b_2 * P_{eff,t-1} + b_3 * P_{eff,t-2} \qquad \textit{Equation 5.22}$$

$$Perc = c * P_{eff} = Q_g + \frac{dS_g}{dt} \qquad \textit{Equation 5.23}$$

The numerical form of the catchment water balance can now be written as:

$$S_{u,t} - S_{u,t-1} = P_{eff} - T - c * P_{eff} = (1-c) * P_{eff} - T \qquad \textit{Equation 5.24}$$

So far, the transpiration *T* is only defined over a hydrological year (Eq.5.15). To be able to use *T* in a catchment water balance on a smaller timescale it is important to realize that transpiration is dependant on soil moisture storage. De Groen (2002) states that transpiration is equal to potential transpiration T_p, unless the available soil water content is below a certain limit. This limit S_b is usually 0.5-0.8 of the maximum available soil moisture content in the root zone S_{max}, depending on the soil and vegetation. Below that limit the transpiration decreases proportionally to the available soil water content. The typical form of the equation relating soil moisture and transpiration is (see Figure 5.21):

$$T = T_p * Min\left(\frac{S_u}{S_b},1\right)$$ Equation 5.25

where

S_b = the available soil moisture content below which transpiration is soil moisture constrained [mm]

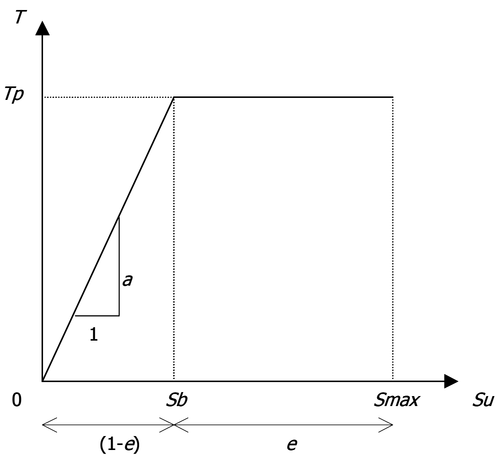

Figure 5.21: Typical form of relationship between soil moisture and actual transpiration

De Groen (2002) assumed the potential transpiration to be equal to measured daily pan evaporation, however in this thesis daily pan evaporation is considered equal to potential evaporation E_p. This is done, because for calculation the effective rainfall is applied, where interception is already subtracted. Daily pan evaporation data is only available for the meteorological station in Bulawayo. These values are assumed valid for the whole catchment. Daily potential transpiration is considered to be the difference between E_p and actual interception in mm/day.

$$T_p = E_p - I$$ Equation 5.26

From Figure 5.21 it can be observed that below S_b transpiration is assumed linear proportional to the coefficient *a*. This proportionality factor is a function of the maximum available soil moisture S_{max} and the proportion *e* of the available soil moisture in the root zone that is readily available for transpiration.

$$a = \frac{1}{(1-e)S_{\max}}$$ Equation 5.27

$$S_b = (1-e) * S_{\max}$$ Equation 5.28

Due to lack of data concerning moisture storage capacities in the Mzinyathini catchment values for *e* and S_{max} are assumed equal to the ones Savenije (1997) used for the Bani catchment in West Africa. Savenije found *e*=0.5 and S_{max}= 500mm, resulting in a proportionality factor of *a*=0.004 mm^{-1}. Equation 5.25 can now be written as:

$$T = Min(a * S_u * T_p, T_p)$$ Equation 5.29

When this equation is inserted in the water balance equation (Eq. 5.24) and this is solved stepwise, the following equation can be solved:

$$S_u(t) = S_u(t-\Delta t) + (1-c) * P_{eff} - Min(a * S_u(t-\Delta t) * T_p, T_p) \qquad \text{Equation 5.30}$$

Appendix E gives an overview of the equations used in the catchment water balance modelling. In Eq. 5.30 the actual transpiration is calculated on the basis of the moisture storage in the unsaturated zone of the previous time step Δt. This is a direct effect of the difference in time scale in which transpiration works compared to effective rainfall and storage processes. De Groen (2002) states that the time scale of transpiration is in the order of ten days to a month. So, Eq. 5.30 is very much suitable when a time step of one month is selected.

Figure 5.22 shows the monthly calculated partitioning of rainfall for values of *D*, *L* and D_s of respectively 2mm/d, 3mm/d and 240mm and a value for *c* of 0.0781 (r^2=0.9142), as presented in Section 5.5.1. Monthly interception *I*, transpiration *T*, calculated runoff R_{calc} and areal rainfall are plotted in one figure for the period 1991 up to 2001. Transpiration is calculated according to Eq.5.29 with Δt = 1month. It can be seen that areal rainfall mainly ends up in transpiration and interception, runoff constitutes only a small part of the monthly rainfall.

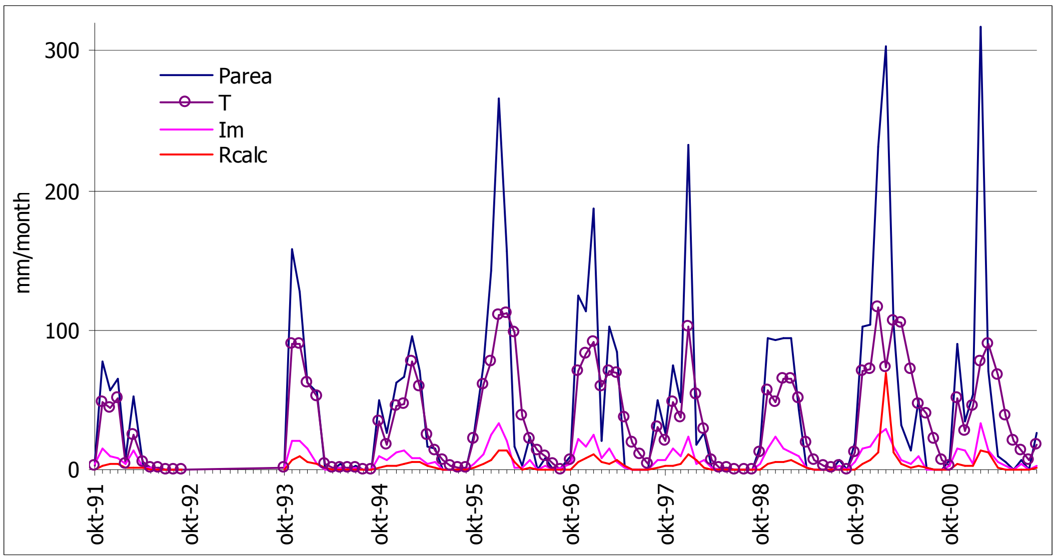

Figure 5.22: Areal rainfall P_{area}, Transpiration T, Monthly interception I_m and calculated runoff R_{calc} (1991-2001)

Figure 5.23 gives an impression of how interception and transpiration relate, and their relative contribution to total evaporation *(I+T)*, for different amounts areal rainfall for calculations with a weekly (left) and monthly (right) time step. The scatter plots for the

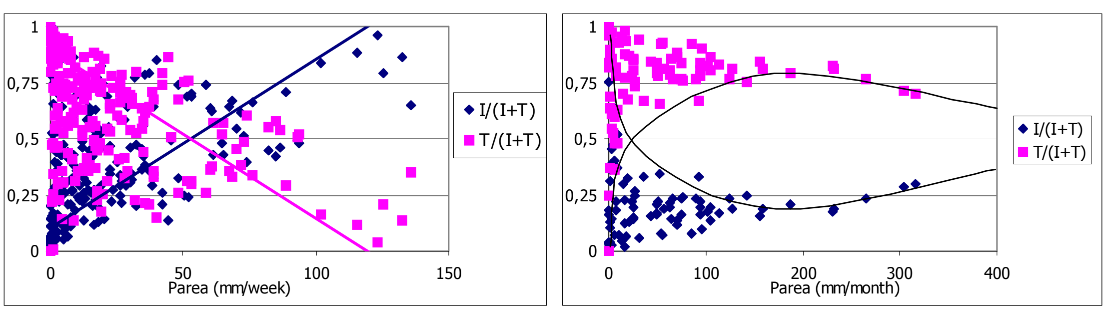

Figure 5.23: Relative contributions of interception and transpiration to monthly evaporation I+T, based on the weekly (left) and monthly model (right) (1991-2001)

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weekly and monthly model look very different. This can be ascribed to the way weekly interception is calculated. In Eq. 5.16 the number of rainy days n_r in a week accumulates faster to the maximum of seven days in a week than that the monthly maximum is ever reached. Weekly interception I_w approaches the maximum interception faster than I_w does, for monthly interception. The daily interception threshold for the weekly model is 3mm/d instead of 2mm/d which is used in the monthly model. Regarding the monthly model, Savenije (2004) found a similar picture for his research in the Mupfure catchment. He commented that one can distinguish scatter dots and dots that appear to follow a pattern depicted by the drawn line. The scatter dots in the low rainfall months are the result of delayed transpiration from deeply rooted vegetation at the end of the wet season. The drawn line on the other hand represents the contributions of interception and transpiration to the fast evaporation, occurring within one month. The line shows that there is a tendency for interception to become dominant in wet months, this is due to the fact that wet months have more rainy days from where interception can be generated. This is supported by the linear trend lines drawn in the left figure for the weekly model. Again transpiration is dominant, but only significant below weekly areal rainfall amounts of 80mm, although the trend line suggests 50mm.

Figure 5.24 shows that the amount of storage in the unsaturated zone S_u is in line with the peaks and dips of the rainfall. Therefore, the assumption that no moisture storage is transferred from one hydrological year to another is acceptable.

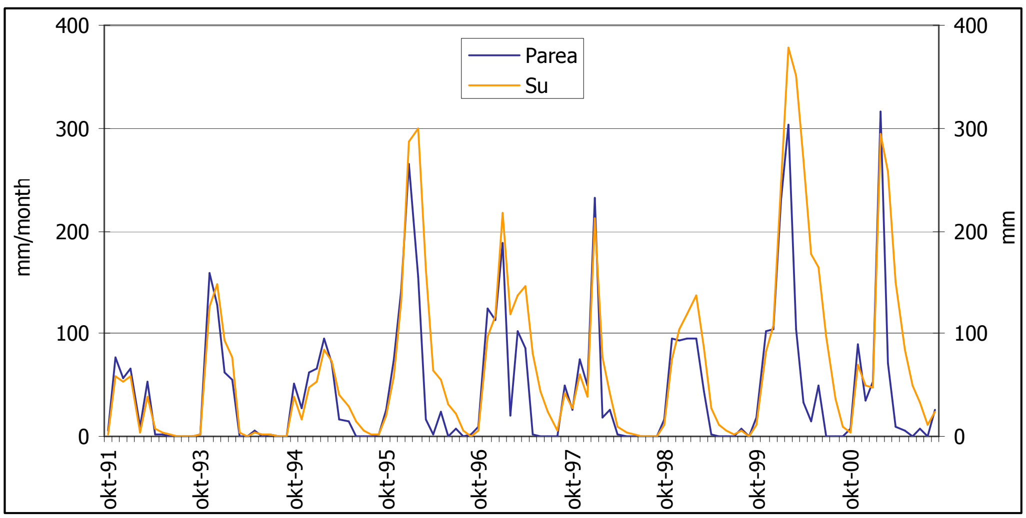

Figure 5.24: Storage in the unsaturated zone S_u [mm] and areal rainfall [mm/month]

Figure 5.25 shows that accumulated transpiration over a year calculated with a weekly time

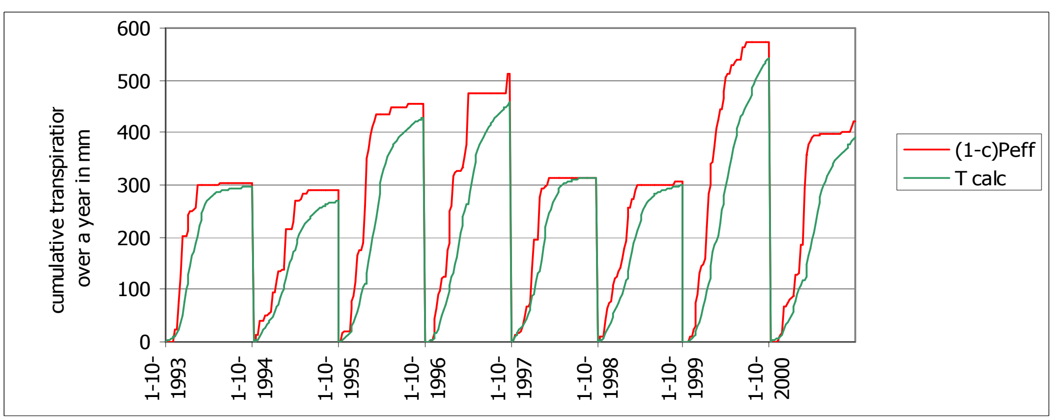

Figure 5.25: Weekly accumulated transpiration calculated with Eq.5.29 and 5.19 give similar totals

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step dependant on the soil moisture content in the unsaturated zone (Eq. 5.29) adds up to almost the same annual T-value when $T=(1-c)*P_{eff}$ over a year is used. From Figure 5.24 and 5.25 it becomes clear that for an annual water balance storage fluctuation components can be left out:

$$P_{area} = I + T + Q_s + Q_g \qquad \textit{Equation 5.31}$$

In Figure 5.26 the terms of the annual rainfall partitioning are plotted against the areal rainfall. On the left side the partitioning is based on the weekly model and on the right the monthly model.

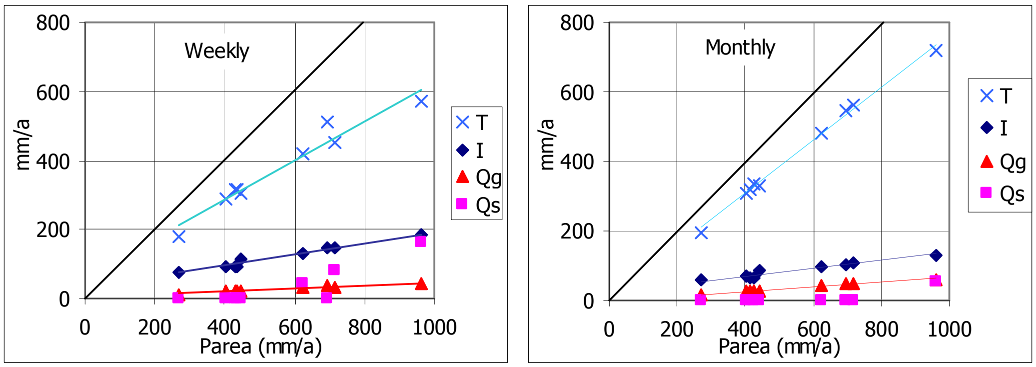

Figure 5.26: Annual rainfall partitioning into transpiration T, interception I, base flow Q_g and surface runoff Q_s

As already concluded from Figure 5.23 transpiration is the dominant process in the rainfall partitioning. But it is more dominant in the monthly model, where the daily interception threshold was higher and therefore less interception occurred. The contribution of the interception is also higher for the weekly model.

Table 5.8 shows the relative contributions of interception, transpiration and runoff relative to areal rainfall for the monthly and weekly model. The data is presented from low to high annual rainfall. The contribution of interception is highest for dry years and gradually declines when rainfall increases. This can be attributed to the small amount of rainfall events exceeding the interception threshold. The contribution of transpiration on the other hand is very stable, with only a small standard deviation. The same goes for the groundwater flow. Surface runoff is more evident in the weekly model, because the moisture threshold D_s is lower.

Table 5.8: Rainfall partitioning relative to areal rainfall over 1991-2001, for a monthly and weekly time step

Hydr. year	Parea mm/a	Monthly *I*	Weekly *I*	Monthly *T*	Weekly *T*	Monthly *Qg*	Weekly *Qg*	Monthly *Qs*	Weekly *Qs*
91-92	271	0,21	0,28	0,73	0,67	0,06	0,05	0,00	0,00
94-95	405	0,17	0,23	0,76	0,72	0,06	0,05	0,00	0,00
93-94	414	0,16	0,21	0,78	0,73	0,07	0,05	0,00	0,00
97-98	428	0,16	0,21	0,78	0,73	0,07	0,05	0,00	0,00
98-99	443	0,19	0,26	0,74	0,69	0,06	0,05	0,00	0,00
00-01	623	0,16	0,21	0,78	0,67	0,07	0,05	0,00	0,07
96-97	695	0,15	0,21	0,78	0,74	0,07	0,05	0,00	0,00
95-96	717	0,15	0,21	0,78	0,63	0,07	0,05	0,00	0,11
99-00	962	0,13	0,19	0,75	0,59	0,06	0,04	0,06	0,17
Average	551	0,16	0,22	0,76	0,69	0,06	0,05	0,01	0,04
St.dev	214	0,02	0,03	0,02	0,05	0,00	0,00	0,02	0,06

For further calculations in this chapter only the water balance model based on a weekly time step is used. This weekly model estimates the hydrological processes in the catchment well, while the calculating with a monthly time step lumps hydrological responses in one time step.

Savenije (2003) applied this model first and found for the Mupfure catchment, some 400km east of Bulawayo, that interception constituted 62% of annual rainfall, while transpiration was only 23%. Table 5.9 shows the separation of rainfall into *White*, *Green* and *Blue* water (see Section 3.1) and their contribution to the partitioning. Apart from the fact that the interception threshold for the Mupfure catchment was set at 5mm/d, it can not be explained why interception accounts for such a big component of the rainfall in that case. The *White* (interception) and *Green* (transpiration) water together form the vertical component of the water cycle, as opposed to the *Blue* water, which is horizontal. It can be seen that there is considerably more *Green* than *Blue* water available. This endorses the view that the focus must lie on development of rainfed agriculture over irrigated land.

Table 5.9: Water resource partitioning and variability in the Mzinyathini catchment based on the weekly model

Mzingwane River Catchment Area: 440*10^6m^2 Record length: 1991-2001	**Source**	**Vertical Component**		**Horizontal component**
Resource type	Rainfall (*P*)	*"White" (I)*	*"Green" (T)*	*"Blue" (Q)*
Mean annual flux (μ)	553mm/a	120mm/a	374mm/a	59mm/a
Partitioning	100%	22%	68%	11%
Standard deviation (σ)	214mm/a	35mm/a	124mm/a	63mm/a
Interannual variability (σ/μ)	39%	29%	33%	107%

Figure 5.27 shows the annual cumulative water resource partitioning for the period 1991-2001. The contribution of the *Blue* water is very small, especially in dry years. It can be seen that all rainfall is intercepted when rainfall is less than 40mm/a. Runoff begins to play a role at more than 350mm/a of rainfall.

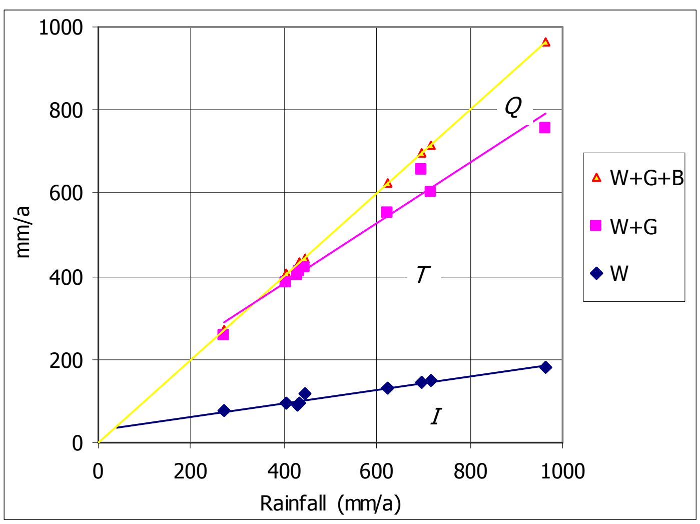

Figure 5.27: Partitioning of rainfall between "White", Green" and "Blue" water between 1991-2001 (Δt=1 week)

5.5.4 Model Appliance on Farm Scale

From Chapter 3 it became clear that there is a large scope for improving yield levels in rainfed farming systems within the available water balance. The difference between required and available crop water should be as small as possible. This entails minimizing surface runoff, interception and deep percolation on the plot and maximizing infiltration. After that it is crucial to use available water as efficient as possible by increasing root densities and depths. In terms of the presented modelling approach this entails: minimizing Q_s, I and c (Q_g) all aiming at optimising the availability for T. However, the model is limited to say something about the rainfall partitioning on a catchment scale, rather than on farm scale. Rainfall might have eroded a farm plot far in the catchment considerably, but due to re-infiltration of the water on its way to the river or to the alluvial aquifer the surface runoff from the plot will not be recorded at the catchment outlet. In the model, surface runoff is only considered when the catchment saturation threshold D_s is exceeded. Besides that, the catchment transpiration T should actually be regarded as the residue of everything that is not interception or runoff. Grouping all residual water to transpiration does not do justice to human interference in the water balance accounting. Human activity entails groundwater abstractions, small rainwater harvesting systems, additional irrigation from the river and water use for the extensive mining in the area. Nevertheless, the presented lumped model is the only applicable model, which characterises the catchment well. The implementation of a change in farm management can only be significant on the catchment scale when the implementation is performed over a large part of the catchment area. In line with the land use map presented in Chapter 2 (Figure 2.15), the farming area comprises 40% of the total area. Different on-farm measures are assumed to apply to the total farming area. Table 5.10 gives an overview of the possibilities the model offers to change the rainfall partitioning in favour of transpiration. The corresponding on-farm measure and major intended result, which were extensively dealt with in Chapter 4, are also presented.

Table 5.10: Goals, measures and results of interventions

Minimize	Measure in model	Measure on farm	Major result
Q_s	Increase D_s	Ridging, mulching	Increased roughness holds water on plot
	Increase L	Ridging, Infiltration pits, strip zone tillage	Maximize infiltration capacity
I	Decrease D	Mulching, Zero tillage, Minimum tillage	Reduce early season evaporation losses
Q_g	Change c	Deep tillage, fertilization, pest management, crop rotations	Increase rooting depth and density

Consistent with Table 5.5 where the physical boundaries for the model variables were given, Table 5.11 shows the variables that are used to calculate the terms in the rainfall partitioning. The range indicates the freedom of movement of plausible variable values. The range for the saturation threshold is limited by the capacity of how much the farm measures can influence the surface runoff. The range for the variables will be discussed further on in this section. The calibrated effective runoff coefficient c is very low, namely 6.9%, while Rockström (2001) stated that for semi-arid rainfed farming systems in Sub-Saharan Africa groundwater recharge varies around 15-40% of effective rainfall. Deeper and denser root systems as a result of farm management practices decrease this coefficient in favour of transpiration. On the other hand, ongoing land degradation might increase the coefficient, leading to more percolation to the groundwater.

Table 5.11: Model variables and the range in which they can vary

		Calibrated value		Range
Saturation threshold	D_s	190	mm	170-230
Leakage	L	2	mm/day	1.5-2.5
Daily Interception threshold	D	3	mm/day	2-4
Effective runoff coefficient	c	0.069	-	0-0.4

Table 5.12 gives an overview of the variables for different scenarios, the model results show annual rainfall partitioning in mm and in percents of average annual rainfall (553mm/a). The scenarios are based on the physically possible range shown in Table 5.11. Scenario 1 refers to the base case, in which the variables give the highest correlation (see Section 5.5.2).

Scenario 2 & 3

In the previous chapter it was stated that after appliance of a mulch cover the surface runoff on farm plots decreased by 100%. When a homogeneous areal contribution to surface runoff is assumed and only 40% of the catchment is agricultural land and can be tilled as such, the total catchment surface runoff becomes 60% of the original surface runoff. This corresponds to a threshold value of 230mm, which is applied in scenario 2a. A decrease in surface runoff corresponds to an increase in effective rainfall (see Eq. 5.21). Consequently more water can be stored in the soil or in depressions in the catchment, from where it comes available for transpiration and groundwater runoff. Increasing the leakage L to 2.5mm/d (scenario 3a) has a similar effect on surface runoff, but the cause is now assigned to a faster storage depletion in the catchment instead of a change in threshold value. So scenario 2a and 3a both decrease the surface runoff for the entire catchment with 40%, resulting in only a 2% increase in available water for transpiration.

Ongoing land degradation, due to surface crusting and little root penetration, diminish the possibilities for water to be stored or infiltrated in the catchment (D_s and L decrease). In scenarios 2b and 3b D_s and L are taken 25% lower than in the base case, Q_s increased respectively to 8% and 9% of rainfall. The change in surface runoff is bigger than the change in annual transpiration and base flow (5%) compared to scenario 1, this is due to the fact that surface runoff constitutes only a small portion of the rainfall. However, this forms a threat for the water supply in Bulawayo because of decreasing inflow in the reservoir downstream of the weir B30.

Table 5.12: Change in annual average rainfall partitioning (553mm/a) for different scenarios

	Qs		*I*	*Qg*	Model Results			
	Ds	*L*	*D*	*c*	*I*	*T*	*Qg*	*Qs*
Scenario	mm	mm/d	mm/d	-	mm/a	mm/a	mm/a	mm/a
1	190	2	3	0,069	120 22%	374 68%	28 5%	32 6%
2a	230	2	3	0,069	120 22%	387 70%	29 5%	18 3%
2b	150	2	3	0,069	120 22%	361 65%	27 5%	46 8%
3a	190	2,5	3	0,069	120 22%	386 70%	29 5%	18 3%
3b	190	1,5	3	0,069	120 22%	356 64%	26 5%	51 9%
4a	190	2	2	0,069	85 15%	392 71%	29 5%	47 9%
4b	190	2	4	0,069	151 27%	356 64%	26 5%	19 3%
5a	190	2	3	0,01	120 22%	398 72%	4 1%	32 6%
5b	190	2	3	0,2	120 22%	322 58%	80 15%	32 6%

Scenario 4

As already discussed in Chapter 3, interception can be influenced by:

- the canopy cover. A high leaf area index stands for higher evaporative area by the leafs, but on the other hand it creates high favourable micro-climatic conditions for moisture in the soil. Mulching prevents water that infiltrates in the soil to easily evaporate back to the atmosphere likewise.

- disturbance of the top soil through tillage. Ploughing, for example, turns the topsoil over increasing the evaporative area of the plot significantly.
- increasing the infiltration capacity of the soil, so water can be stored in the soil instead of on the surface where evaporation is highest.

In scenario 4a the interception threshold *D* of the catchment is 2mm/d instead of 3mm/d, maybe due to giving up traditional ploughing practices over new techniques like minimum tillage. This results in a reduction in average annual interception from 120mm in the base case to 85mm. More water reaches the soil and can run off. The ratio of transpiration to total rainfall is now 0.71, which means that on an average year 71% of all rainfall is evaporated back to the atmosphere through transpiration. The opposite can be seen for scenario 4b, where *D* is 4mm/d, for example, as a result of ploughing with a mouldboard disc. Interception increases and the other terms in the rainfall partitioning decrease.

Scenario 5
The partitioning of the effective rainfall on an annual basis is modelled very simple. The effective runoff coefficient *c* determines the proportion that leaves the soil moisture storage through transpiration and what seeps through to the groundwater, feeding the base flow. The relation between transpiration and groundwater replenishment on the farm plot is largely dependant on the condition of the root system. A deep and dense root system can reach more water in the soil. Fertilization and pest management keep the plants healthy, while deep tillage enables a deep rooting depth, because the seeds are planted deep in the soil. In scenario 5, the *c* is lowered to 0.01, which means that 99% of the effective rainfall is used for transpiration and only 1% becomes river discharge. Now only 4mm/a out of the annual average rainfall of 553mm/a enters the river in the form of base flow. This water comes available in the river slowly and is extremely important for humans and environmental purposes. A decrease in base flow has more negative effects than a decrease in surface runoff, because surface runoff leaves the river in the same day it occurred from rainfall. Scenario 5b simulates the situation when there is little transpiration, due to weak root systems or fallow lands (*c*= 0.02). Q_g is now almost three times higher than in the base case.

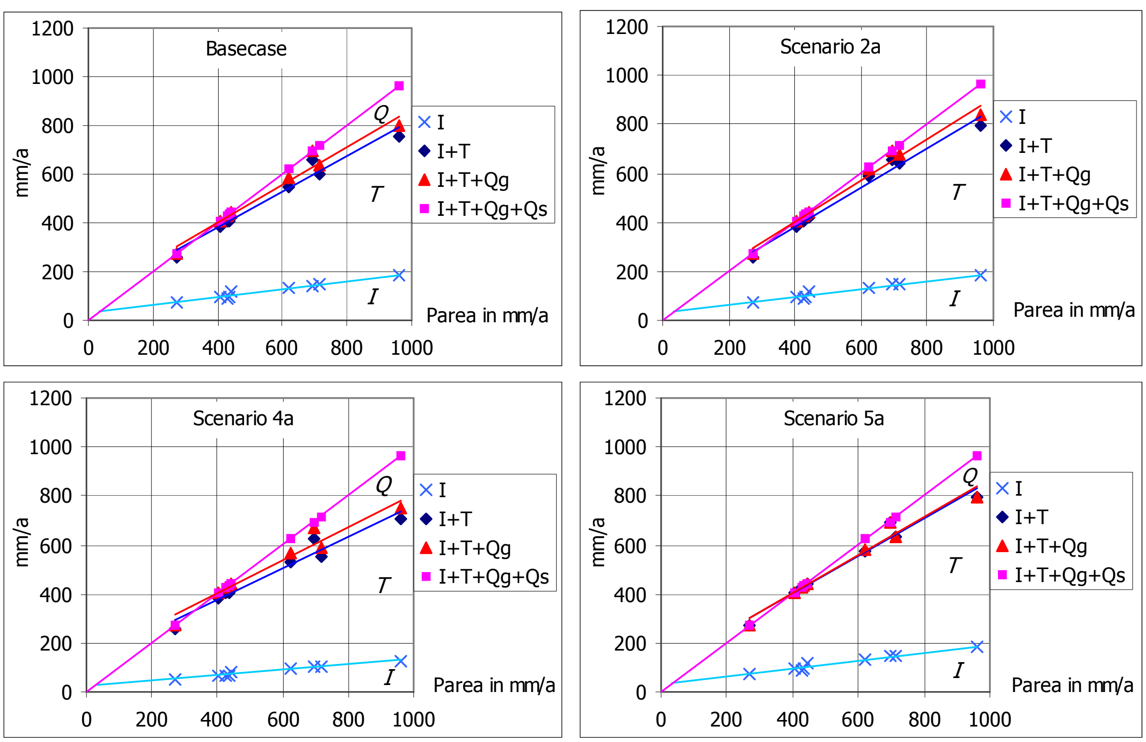

Figure 5.28: Contribution of the terms in the rainfall partitioning to the areal rainfall for different scenarios

Figure 5.28 shows the differences between scenarios 1, 2a, 4a and 5a for the cumulated contributions in the rainfall partitioning. It can be seen that trying to decrease the surface runoff losses gives a small effect on the rainfall partitioning (scenario 2a). Decreasing the interception losses (scenario 4a) provides more water for transpiration and runoff. This enlarges the potential water use by plants and water availability in the river for other purposes and users. When a lot of effort is put in root system optimisation (scenario 5a) the amount of river water that is recharged by groundwater is very small, which is very bad for water availability in the river during dry periods.

5.6 Conclusions

A multiple linear regression model is applied to conceptualise the rainfall runoff relation in the Mzinyathini catchment. Modelling with a weekly time step resulted in an acceptable coefficient of determination (0.7113). The corresponding variables that characterise this catchment are plausible. The daily interception threshold is 3mm/d, and the catchment storage is regarded full at a threshold of 190mm and daily leakage of 2mm/d. Based on the model calculations it should be stated that the memory of the system is two weeks, meaning that the effect of rainfall on river discharge is felt until two weeks after the end of the rain. However, as described in Section 5.3.1 and shown in Appendix C, already after a few days there was no more effect of rainfall peaks observed in the runoff. This discrepancy between the rainfall and calculated and observed runoff can be explained in two ways. First, rainfall events occur every two weeks generating direct runoff, that is attributed to the rainfall event of two weeks earlier. Another reason can be that the cracks in the rocks store water and releases only after sufficient recharge. In this case , the model actually only works properly over a certain threshold value when groundwater outflow can be taken into account.

Now that a mathematical relation between rainfall and runoff is established, a water balance model can be created. The rainfall partitioning on farm scale is linked to the input variables from the multiple linear regression model. The input variables can be adjusted to represent the effects of different farm management implementations on rainfall partitioning. Unfortunately, the water balance applies only on a catchment scale, while the farm management innovations work on farm scale. Besides that, it should be noted that there is no residual term in the water balance which accounts for human activities. The residual has crept in the transpiration term, which also explains the high dominance of this term (68%) in the average annual rainfall partitioning. There is considerable more *Green* water than *Blue* water available in the catchment, so there is a lot of potential for optimising rainfed agriculture. The goal of the farm management practices is to maximize the transpiration. It appeared to be effective to increase the plant available soil moisture (increase *c*), but this reduces the river recharge through base flow. Decreasing the interception losses (scenario 4a) through minimum tillage or mulching provides more water for transpiration and runoff. The water is transformed from interception loss to usable water for plants, besides that, the effects on river water users downstream are minimized.

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6 Conclusions and Recommendations

6.1 Conclusions

From Chapter 3 and 4 it became clear that there are solutions for small scale farmers in Sub-Saharan Africa to improve their yields. The way forward is to apply conservation farming practices that do not have to be very complex or expensive. Several conclusions can be drawn based on the literature review performed on the reasons and solutions for the food deficit in the Sub-Saharan region and, more in particular, the Mzinyathini catchment in Zimbabwe.

- 94% (FAO, 2005) of the cultivated land in Zimbabwe is dependant on rainfall for crop growth. The rainfall in the Mzinyathini catchment is erratic with an average annual around 550mm/a and a standard deviation of 200mm/a.
- Water-related problems in semi-arid areas are often associated with intra-seasonal dry spells during critical stages of crop growth, rather than cumulative rainfall. Dry spells, short periods of 2-4 weeks with no rainfall, are detrimental to crop yields if their occurrence coincides with critical phases of crop development.
- The probability of occurrence of a dry spell longer than 25 days in a growing season (November to March) in Esigodini is 50%.
- The rainfed agriculture experiences a yield gap between what *is* (0.5-1 t/ha) and what *can* (1.5-2 t/ha) be produced by a small scale farmer (Rockström, 2003b).
- Small improvements in farm management on rainfed agricultural fields can already lead to doubling of yields. Technology extension on a large scale can increase the food security in Sub-Saharan Africa.
- Conservation farming contributes to yield stability and dry spell mitigation in drought prone regions through improved soil characteristics, plant growth conditions and farm management. The risk of crop failure as a result of water stress can be decreased significantly, moreover the willingness to invest more in crops in terms of fertilization eventually leads to even higher yields.
- Tillage is an important aspect of conservation farming, because it changes the surface conditions such as pore space and roughness, affecting the potential for infiltration and runoff. Research from several countries show significant improvements in crop yields and reduced soil erosion after the introduction of alternative tillage practices for conventional mouldboard ploughing. Mulching, covering the plot with plant residue, appeared to be very effective by reducing the surface runoff with 90-100% compared to mouldboard ploughing.
- Runoff is the greatest water management problem on rainfed crop lands because not only is it the loss of a potential water resource but it also causes damaging soil erosion
- Weeding improves the infiltration capacity of the soil surface significantly, as the surface crust is temporarily broken up and the roughness of the soil surface is increased.
- Investing in equipment for innovative tillage practices is not enough, knowledge transfer with an eye for existing local conditions is at least as important.
- Adoption of conservation practices is still very low due to lack of adequate labour, insecure land tenure systems, limited access to credit and markets, and failing technology transfer.

To enable estimation of the influence of on-farm conservation practices on the water balance a model is applied on the Mzinyathini catchment.

- The multiple linear regression model applied for the Mupfure catchment by Savenije (1997) is elaborated and conceptualises the rainfall runoff relation in the Mzinyathini catchment.
- Modelling with a weekly time step results in an acceptable coefficient of determination (0.7113). The corresponding model variables that characterise this catchment are plausible. The daily interception threshold is 3mm/d, and the

catchment storage is regarded full at a threshold of 190mm and daily leakage of 2mm/day.

- The time lapse between a rainfall event and the resulting effect on runoff in the river is seldom longer than a week. However, according to the model the effect of rainfall on river discharge is felt until two weeks after the end of the rain. This can be attributed to the statistical character of the model. The model is actually only applicable over a certain threshold value for sub-surface storage, because of cracks and in the underlain rocks.
- Hydrological processes appear to be more regular on a monthly than on a weekly time scale. On larger time scales variability's are evened out due to lumping of the hydrological response over a time step.
- The model is limited to say something about the rainfall partitioning on a catchment scale, rather than on farm scale.
- Q_s=0 does not mean 'no erosion or surface runoff in the catchment', but it means that there is no surface runoff recorded at the outlet of the catchment. On the farms in the catchment a lot of surface runoff could have occurred, it is just not recorded, because it is either infiltrated again, or stored in local depressions.
- Interception and transpiration constitute on average respectively, 22% and 68% of the annual rainfall. Research on the Mupfure catchment by Savenije (2003) showed an opposite image. Interception constituted 62% and transpiration 23%. Rockström (2001) proposed that on a farm interception ranges between 30-50%, and transpiration around 15-30% of annual rainfall in semi-arid regions.
- The high dominance of transpiration (68%) in the average annual rainfall partitioning can be attributed to the absence of a residual term accounting for human activities. This residual has crept in the transpiration term.
- Transpiration can be optimised by increasing the plant available soil moisture (increase c), but this reduces the river recharge through base flow.
- Putting a lot of effort in reducing the surface runoff for the entire catchment with 40% through ridging, results in only a 3% increase in available water for transpiration and base flow.
- Decreasing the interception losses through minimum tillage or mulching provides more water for transpiration and runoff. The water is transformed from interception loss to usable water for plants, besides that, the effects on river water users downstream are minimized.

6.2 Recommendations

At the end of this research several recommendations can be made.

- Research the downstream consequences of an increase or decrease in base flow.
- Research the break-even point where most gains can be obtained at higher roughness (retains surface runoff) or lower roughness (minimal evaporative area). Similar for high canopy cover (minimal soil evaporation through better micro climatic conditions for air above the top soil) or low canopy cover (minimal leaf interception evaporation).
- A more extensive gauging network in the catchment can remove some of the uncertainties concerning the data quality. The catchment can be split up in smaller sub-catchments, the smaller the drainage area the better processes on farm scale can be approached.
- Abstraction data from the reservoir make the runoff data of the weir downstream of the Mzingwane dam also useful for data checking.
- The water balance model is a simple model that can distinguish interception, transpiration and runoff fluxes in a catchment over a year on a monthly or weekly basis.
- This model can be used for many catchments in the region to obtain a first estimate of important processes. However different combinations of the model variables D, L and D_s all give a high coefficient of determination. This is a equifinality problem.

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Appendix A: Dry spell occurrence

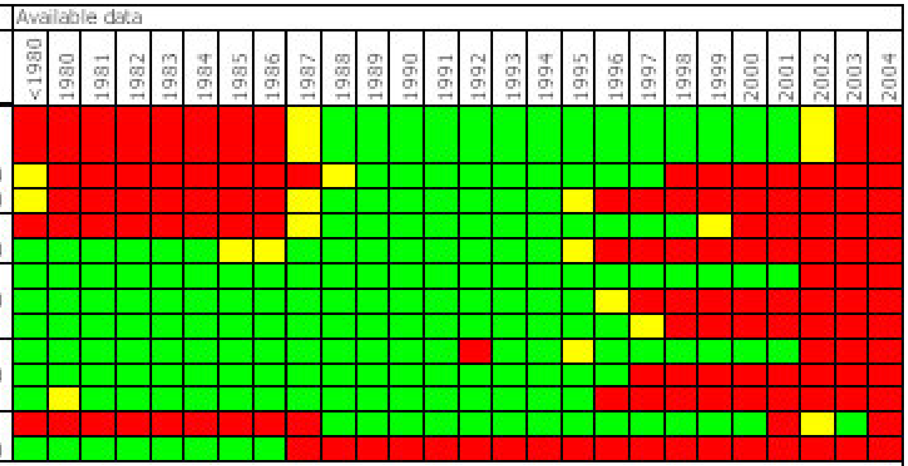
Calculation of the probability *P* that a dry spell of a duration longer than *t* does occur at least once in a growing season in Esigodini (1988-2001). The growing season is assumed to run between the 1st of November and the 31st of March and lasts 151 days.

t =spell duration
m =number of spells of duration *t* in growing seasons
I =accumulated number of spells
n =possible number of start days per season
N =total number of start days over 13 seasons (1988-2001)
P =probability that a dry spell longer than t occurs at least once in a growing season

					I/N	**1-p**	**1-q^n**
t	**m**	**I**	**n**	**N**	**p**	**q**	**P**
1	38	217	151	1963	0,111	0,889	1,000
2	29	179	150	1950	0,092	0,908	1,000
3	19	150	149	1937	0,077	0,923	1,000
4	18	131	148	1924	0,068	0,932	1,000
5	12	113	147	1911	0,059	0,941	1,000
6	19	101	146	1898	0,053	0,947	1,000
7	8	82	145	1885	0,044	0,956	0,998
8	6	74	144	1872	0,040	0,960	0,997
9	14	68	143	1859	0,037	0,963	0,995
10	6	54	142	1846	0,029	0,971	0,985
11	6	48	141	1833	0,026	0,974	0,976
12	3	42	140	1820	0,023	0,977	0,962
13	4	39	139	1807	0,022	0,978	0,952
14	5	35	138	1794	0,020	0,980	0,934
15	5	30	137	1781	0,017	0,983	0,902
16	5	25	136	1768	0,014	0,986	0,856
17	2	20	135	1755	0,011	0,989	0,787
18	5	18	134	1742	0,010	0,990	0,751
19	2	13	133	1729	0,008	0,992	0,634
20	0	11	132	1716	0,006	0,994	0,572
21	1	11	131	1703	0,006	0,994	0,572
22	0	10	130	1690	0,006	0,994	0,538
23	1	10	129	1677	0,006	0,994	0,538
24	0	9	128	1664	0,005	0,995	0,501
25	0	9	127	1651	0,005	0,995	0,501
26	2	9	126	1638	0,005	0,995	0,501
27	0	7	125	1625	0,004	0,996	0,417
28	0	7	124	1612	0,004	0,996	0,417
29	0	7	123	1599	0,004	0,996	0,417
30	0	7	122	1586	0,004	0,996	0,417
31	1	7	121	1573	0,004	0,996	0,417
32	0	6	120	1560	0,004	0,996	0,370
33	1	6	119	1547	0,004	0,996	0,370
34	0	5	118	1534	0,003	0,997	0,320
35	1	5	117	1521	0,003	0,997	0,320
36	0	4	116	1508	0,003	0,997	0,265
37	0	4	115	1495	0,003	0,997	0,265
38	1	4	114	1482	0,003	0,997	0,265
39	1	3	113	1469	0,002	0,998	0,206
40	0	2	112	1456	0,001	0,999	0,143
41	0	2	111	1443	0,001	0,999	0,143
42	0	2	110	1430	0,001	0,999	0,143
43	0	2	109	1417	0,001	0,999	0,143
44	0	2	108	1404	0,001	0,999	0,143
45	0	2	107	1391	0,001	0,999	0,143
46	0	2	106	1378	0,001	0,999	0,143
47	0	2	105	1365	0,001	0,999	0,143
48	0	2	104	1352	0,001	0,999	0,143
49	0	2	103	1339	0,001	0,999	0,143
50	1	2	102	1326	0,002	0,998	0,143
51	0	1	101	1313	0,001	0,999	0,074
52	1	1	100	1300	0,001	0,999	0,074
53	0	0	99	1287	0,000	1,000	0,000

Appendix B: Rainfall data availability

Station	Name	Zone	Sub	Alt	Lat	Lon
Esigodini	METEO DEP DA			1160	20-17-30	28-56-30
	Agricul Inst	B	UZ4	1180	20-20-00	28-56-30
Mbalabala	METEO DEP Rail	B	UZ3	1100	20-26-30	29-02-30
Bulawayo	METEO DEP Goetz *Waterworks*	A		1340	20-9-2000	28-37-00
Matopos	METEO DEP Research St. *Park*	B	T4	1400	20-23-00	28-30-00
Umzinqwane	METEO DEP Dam	B		1110	20-23-30	28-58-20

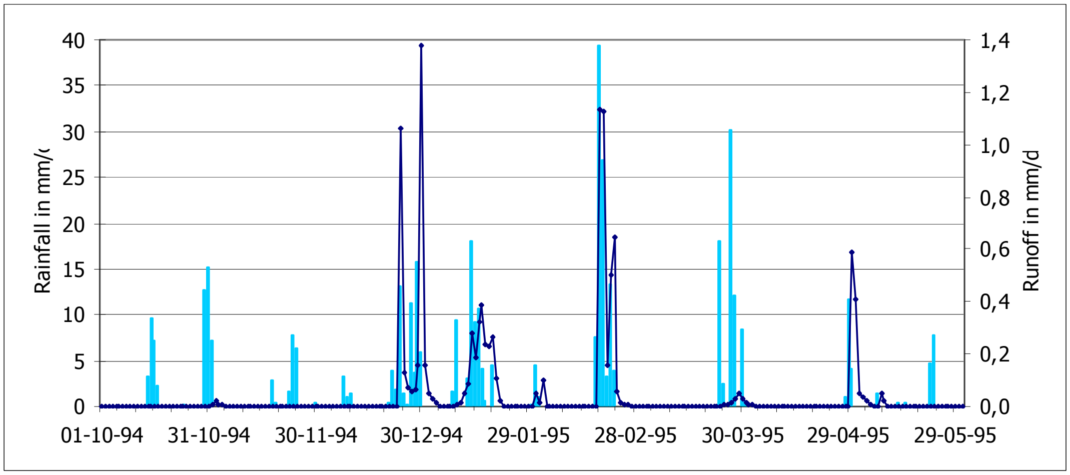


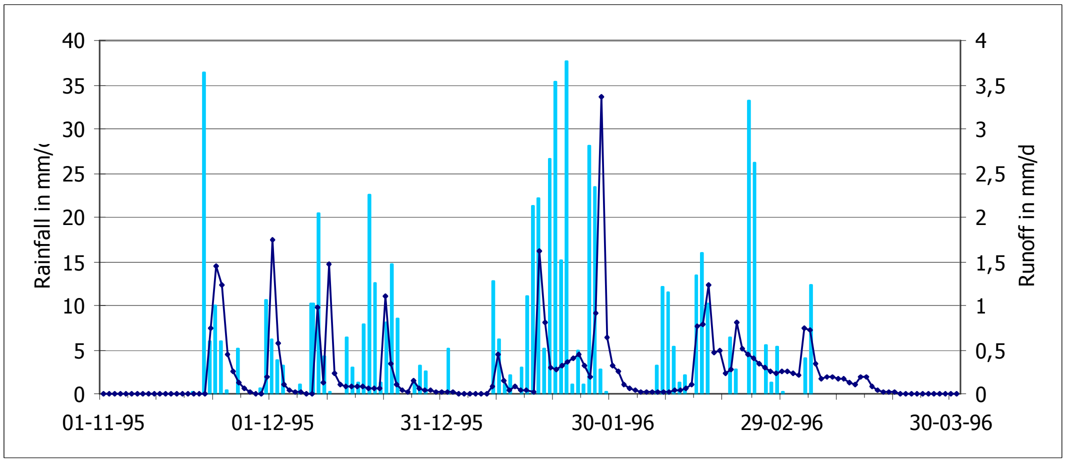
Alt. = Height in meters above Mean Sea Level
Lat. = Lattitude in degrees - minutes - seconds
Lon.= Longitude in degrees - minutes - seconds

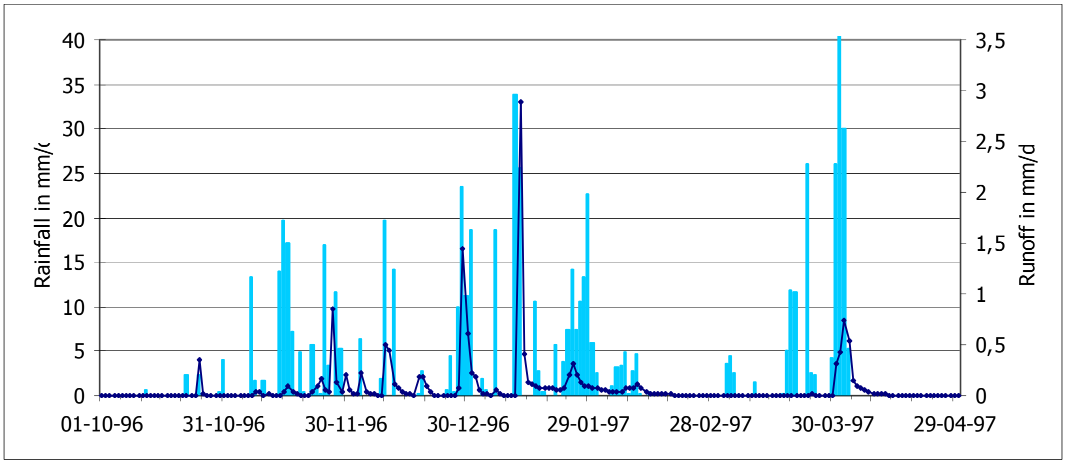
No data available
Few months of data available
Data Available

Appendix C: Hydrographs

Daily observed areal rainfall and runoff recorded at weir B30 for hydrological years 1994-95, 1995-96, 1996-97. It can be seen that normally the runoff peak is recorded one day later or on the same day the rainfall peak occurs, but never more than two days later. Besides that it can be observed that normally there is no more runoff recorded after one day after the last rainfall day in the cluster of rainy days. This entails too that the effect of the rainfall peak can not be recognised in the river after a maximum of about seven days.







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Appendix D: Calculation Results MLR model

The value for *D* is fixed after which the Solution-application in Excel is used to iterate *L* and D_s. Moisture threshold values in red indicate that the threshold is not exceeded in order to get maximum r^2.

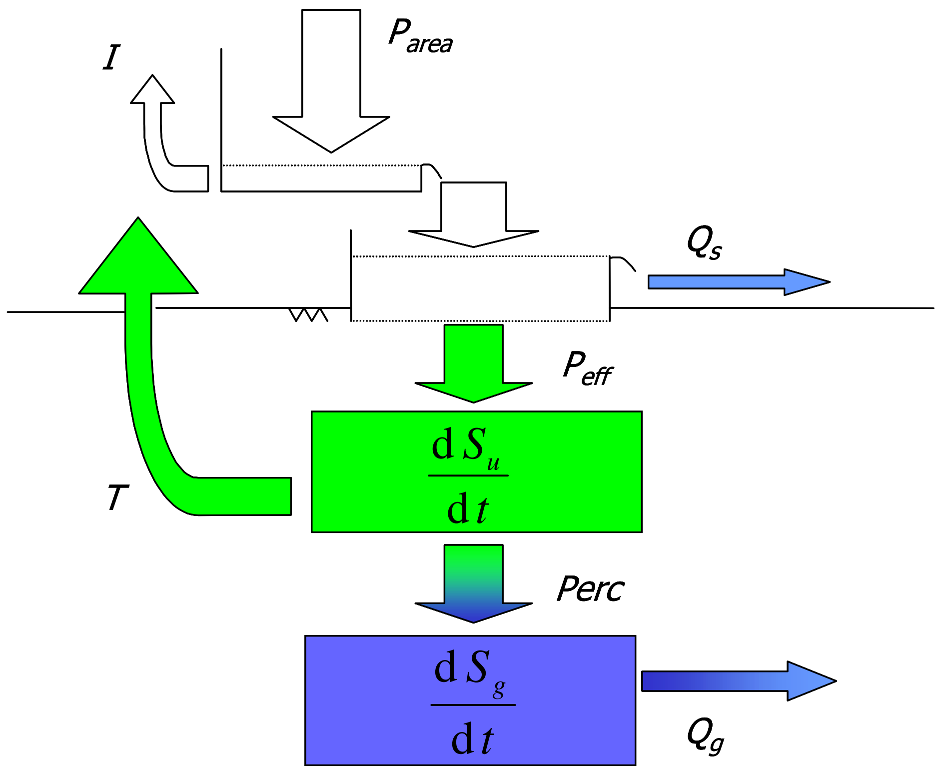
Used data	Monthly						Weekly				
88-01	*D*	5	4	3	2		*D*	5	4	3	2
	L	2	3	3	3		*L*	2	3	3	3
	Ds	180	200	220	230		*Ds*	125	90	140	90
	m=1	0,2261	0,239	0,2441	0,2431	*r2*	m=3	0,1095	0,0982	0,1023	0,0951
91-99	*D*	5	4	3	2		*D*	5	4	3	2
	L	3	4	4	8		*L*	5	7	*8**	*10**
	Ds	120	130	130	90		*Ds*	100	90	*100**	*80**
	m=1	0,5791	0,6252	0,5635	0,5755	*r2*	m=3	0,4271	0,4917	0,4521	0,4551
91-01	*D*	5	4	3	2		*D*	5	4	3	2
	L	3	4	2	3		*L*	1	2	2	3
	Ds	140	140	190	240		*Ds*	210	150	190	140
	m=1	0,8855	0,8345	0,8527	0,9142	*r2*	m=2	0,6922	0,6739	0,7113	0,6328

Used data columns: 88-89, 89-90, 90-91, 91-92, 92-93, 93-94, 94-95, 95-96, 96-97, 97-98, 98-99, 99-00, 00-01

*100** No exceedence of Ds

Appendix E: Catchment Water Balance

Conceptualised catchment water balance, with applied equations and reference to equations in document.



	Definition	Applied Equation	Eq.
P_{area}	Areal Rainfall	$P_{area,t} = 0.35 * P_{Esigodini} + 0.29 * P_{Bulawayo} + 0.33 * P_{Matopos}$	5.1
I	Interception	$I_t = P_{area,t}\left(1 - \exp\left(\frac{-D * n_r}{P_{area,t}}\right)\right)$	5.7
Q_s	Surface Runoff	$Q_{s,t} = \max(S_t - D_s, 0)$	5.11
$Peff$	Effective Rainfall (Infiltration)	$P_{eff,t} = P_{area,t} - I_t - Q_{s,t}$	5.12
dS_u/dt	Change in Storage in Unsaturated zone	$\frac{dS_u}{dt} = (1-c) * P_{eff,t} - Min(a * S_{u,t-1} * T_p, T_p)$	5.30
T	Transpiration	$T_t = Min(a * S_{u,t-1} * T_{p,t}, T_{p,t})$	5.29
$Perc$	Percolation	$Perc_t = c * P_{eff,t}$	5.21
dQ_g/dt	Change in sub-surface storage	$\frac{dS_g}{dt} = c * P_{eff} - Q_g$	5.21
Q_g	Sub-surface flow	$Q_{g,t} = b_1 * P_{eff,t} + b_2 * P_{eff,t-1} + b_3 * P_{eff,t-2}$	5.22