ALTERRA
WAGENINGEN UR

Impact of farm dams on river flows

A case study in the Limpopo River basin, Southern Africa

Alterra report 2394
ISSN 1566-7197

Esther Meijer, Erik Querner and Harm Boesveld

WAGENINGEN UR
For quality of life

Impact of farm dams on river flows

This study has been carried out with support from the Dutch Ministry of Economic Affairs, Agriculture and Innovation and was also supported by the EAU4FOOD project, EC Priority Area 'Environment (including Climate Change)', contract number 265471.
Project code [5237655-01] and [5238573-01]

Impact of farm dams on river flows

A case study in the Limpopo River basin, Southern Africa

Esther Meijer[1], Erik Querner[2] and Harm Boesveld[1]

1 Wageningen University
2 Alterra Wageningen UR

Alterra report 2394

Alterra Wageningen UR
Wageningen, 2013

Abstract

Meijer, E.C., E.P. Querner and H. Boesveld, 2013. *Impact of farm dams on river flows; A case study in the Limpopo River basin, Southern Africa.* Wageningen, Alterra, Alterra report 2394. 62 pp.; 26 fig.; 13 tab.; 40 ref.

The study analysed the impact of a farm dam on the river flow in the Limpopo River basin. Two methods are used to calculate the water inflow: one uses the runoff component from the catchment water balance; the other uses the drainage output of the SIMFLOW model. The impact on the flow in a sub-catchment with and without the presence of a farm dam, has been analysed. Different farm dam storage capacities and infiltration rates of the soil were considered. In general, the change in natural flow is decreasing when the farm dam capacity becomes higher. On the other hand, the Remaining Natural Flow is increasing when the catchment area becomes larger. The Crop Water Availability was expressed as the relative difference between the crop water requirements and the amount of water supplied by precipitation and irrigation from the farm dam. For a given storage capacity of the farm dam the change in natural flow is calculated when the farm dam covers 90% of the potential evapotranspiration of maize.

Keywords: Limpopo River basin, farm dam, water harvesting, irrigation requirements, SIMFLOW, river flow

ISSN 1566-7197

The pdf file is free of charge and can be downloaded via the website www.wageningenUR.nl/en/alterra (go to Alterra reports). Alterra does not deliver printed versions of the Alterra reports. Printed versions can be ordered via the external distributor. For ordering have a look at www.rapportbestellen.nl.

© 2013 Alterra (an institute under the auspices of the Stichting Dienst Landbouwkundig Onderzoek)
P.O. Box 47; 6700 AA Wageningen; The Netherlands, info.alterra@wur.nl

– Acquisition, duplication and transmission of this publication is permitted with clear acknowledgement of the source.
– Acquisition, duplication and transmission is not permitted for commercial purposes and/or monetary gain.
– Acquisition, duplication and transmission is not permitted of any parts of this publication for which the copyrights clearly rest with other parties and/or are reserved.

Alterra assumes no liability for any losses resulting from the use of the research results or recommendations in this report.

Alterra report 2394
Wageningen, 2013

Contents

Summary

The Limpopo River basin is an area where the livelihood of the rural population is mainly based on rain-fed agriculture. Also in the river basin there are problems with water scarcity and therefore an unreliable food production, especially in dryer areas like the northwest part of the basin. Water harvesting could be a method to cope with these problems. On the other hand, water harvesting methods can cause unplanned impacts. Reported impacts vary considerably between different water harvesting techniques, locations, climatic regimes, seasons, and socio-economic contexts (Andersson et al., 2011). In the study carried out, the focus was on the impact of a farm dam as water harvesting method in a small catchment in the Limpopo River basin.

Farm dams generally capture water before it reaches the waterway. As farm dams are the first to capture the water, they reduce the flow in the smaller streams and rivers. In such a way it impacts on the amount of water available for downstream water users and environmental deterioration. The greatest impact of a farm dam occurs immediately downstream of the impoundment, and this impact progressively reduces as the intervening catchment area downstream of the dam increases. In most cases, the impact of one individual dam is relatively small, the cumulative impact of farm dams on stream flows can be significant. The larger the volume of the farm dams in a catchment the greater the impact might be.

The study analysed the impact of a farm dam in a small catchment situated in the Limpopo River basin on river flows downstream of such a dam. Further output is the amount of irrigation water used from the dam. The analysis might lead to more insight in the effects of a farm dam on small catchment scale and might contribute to future studies on basin scale. It was beyond the scope of the study to examine socio-economic factors.

To analyse the impact of a farm dam on the river flow downstream in the Limpopo River basin (Southern Africa), two methods were proposed and some scenarios were formulated. The method differs in the calculation procedure of the water inflow into the farm dam and the scenario's considered different infiltration capacities of the soil. Method A makes use of the runoff component, as a very simple approach, from the catchment water balance to calculate the water inflow. Method B uses the drainage output of the SIMFLOW model (Querner et al., 2000). The entire calculation procedure was carried out in an Excel sheet in such a way that farm dam capacities could be changed and different meteorological data can be used.

Two parameters were defined to express the change in river flow caused by the storage dam and the available water for the crop by precipitation and irrigation. The Remaining Natural Flow (RNF) is the relative difference between the flow entering the storage dam and the downstream river. This parameter expresses the impact of a farm in the study area. The Crop Water Availability (CWA) is the relative difference between the crop water requirements and the amount of water supplied by precipitation and irrigation from the farm dam. The impact on the RNF is analysed for different farm dam capacities and infiltration capacities of the soil. In general, the RNF is decreasing when the farm dam capacity becomes higher. This is also the case when the infiltration rate becomes higher. As an example Figure 19 shows the modelling results for a catchment of 10 ha. On the other hand, the RNF is increasing when the upstream catchment area of the farm dam becomes larger. The Crop Water Availability (CWA) is used to determine the farm dam capacity where the RNF covers 90% of the water needs of the crop (potential evapotranspiration).

The impact of a farm dam on the river flow downstream strongly depends on the local situation, e.g. the size of the catchment area, farm dam capacity (volume), soil type, infiltration rate of the soil, meteorological conditions, land use and crop water requirements. The study analysed a catchment area of 10 and 20 ha in the Shashe sub-basin with natural vegetation and deciduous forest, the soil is fine textured (clay). The farm dam is used to irrigate a maize field of one ha and the dam capacities range from 0 to 10.000 m^3.

1 Introduction

1.1 Background of the research

The Food and Agriculture Organization (FAO) estimates that the food production has to increase with 70% by 2050 in order to meet the growing global demand for food. Particular in sub-Saharan Africa (SSA) it is necessary to increase food production due to high levels of undernourishment, rapid population growth and a considerable degree of water stress (FAO, 2009). The increased food demand could be met by increasing the production level of the low-yield farmers up to 80% of that which high-yield farmers obtain from equivalent fields. The biggest potential to increase yields are in rain-fed areas where a lot of the poorest rural people of the world live. A key to increase these yields is water management (CAWMA, 2007), because there is no hydrological limitation in SSA to double the staple crop production of the smallholder rain-fed agriculture through better soil and water management techniques (Rockström et al., 2002).

Since the 1970s and 1980s, water harvesting (WH) has received great attention in SSA as a possibility to increase food production. The semi-arid climate with long periods of droughts and rainfall that is spatially and temporally variable, leads to scarce water resources and subsequently to low agricultural yields which threaten a reliable food production in the majority of SSA (Pachpute et al., 2009).

Most rainfall events occur as a storm with high rainfall intensity. These storm events cause a lot of runoff, which can be harvested using a farm dam. The excess water can be stored and used in dryer periods, leading to more water available (Kahinda et al., 2007). The harvested water can be used for irrigation, livestock, and domestic water use and can be applied to groundwater. Field scale studies generally indicate that WH has substantial potential to increase crop yields (Vohland and Barry, 2009). A more reliable food production could be a result. However, a number of WH projects in the SSA do not succeed in combining the technical efficiency with low cost and acceptability to the local farmers. This is partly due to the lack of technical knowledge and to an inappropriate approach with regard to the socio-economic conditions (FAO, 1991).

1.2 Problem description

The Limpopo River basin (LRb) is an area in the SSA where the livelihoods of the rural population are mainly based on rain-fed agriculture. However, the basin faces problems with water scarcity and an unreliable food production, especially is very dry areas like the north-west part of the LRb (LBPTC, 2010).
WH could be a method to cope with these problems.

On the other hand, WH methods can cause unplanned impacts. Reported impacts vary considerably between different WH techniques, locations, climatic regimes, seasons and socio-economic contexts (Andersson et al., 2011). In this study, the focus will be on the impact of a farm dam as WH method in a small catchment in the north-west part of the LRb. Examples of the impact of a farm dam are inequitable water sharing between upstream and downstream users (Batchelor, 2002) and alterations in river flow regimes (Andersson et al., 2011).
Farm dams generally capture water before it reaches the waterway. As farm dams are the first to capture the water, they reduce the flow in creeks and rivers and impacts on the amount of water available for downstream water users and the environment. The greatest impact of a farm dam occurs immediately downstream of the

impoundment, and this impact progressively reduces as the intervening catchment area below the dam increases (Nathan and Lowe, 2012).

In most cases, the impact of one individual dam is relatively small, the cumulative impact of farm dams on stream flows can be significant. The larger the volume of the farm dams in a catchment the greater the impact might be. This study will analyse the impact of a farm dam on the river flow downstream in a small catchment of the LRb. The analysis might lead to more insight in the effects of a farm dam on small catchment scale and might contribute to future studies on basin scale.

Socio-economic factors, like the attitude of the farmers towards new agricultural practices, the farming system of the community, the financial capabilities of the farmers, the cultural behaviour, religious believes, land tenure and property rights of the communities can also influence the impact and effectiveness of a farm dam (Prinz and Singh, 2000). It is beyond the scope of this study to examine the socio-economic factors.

1.3 Goal of the research

The goal of the research is to analyse the impact of a farm dam on the river flow downstream in a small catchment in the LRb, South Africa. This goal will be reached by the following objectives:

1. Use an existing hydrological model and an Excel-tool to model the impact of a farm dam in a sub-basin in the LRb.
2. Evaluate the impact of a farm dam on the river flow in a sub-basin, using the output of the model.

The acquired knowledge in the research can be used in regional studies that make use of hydrological models, like SIMGRO.

1.4 Research questions

In order to reach the goal of the research, research questions are formulated that need to be answered during the research project. Answers on these questions will ensure that the goal will be reached.

The following main research question is derived from the goal of the research:
What is the impact of a farm dam on the river flow downstream in a sub-basin in the LRb, South Africa?

To answer the main research question the following sub-questions are created:

1. How can the impact of a farm dam on the river flow downstream be analysed?
2. Which methods can be used to calculate the runoff in the catchment?
3. What is the effect of the infiltration rate of the soil on the runoff?
4. What will be the impact of a farm dam on the river flow downstream?
5. What is the difference between the results of both calculation methods for the water inflow parameter?
6. What is the influence of the farm dam capacity on the impact of a farm dam?
7. At which farm capacity are the crop water needs covered?

1.5 Outline of the report

The content of this report is structured in seven chapters. Chapter 1 gives an introduction of the study area and address the water challenge they face in the Limpopo River basin. WH has been proposed as a possible way of increasing water productivity and availability. The goal of the research, quantifying the impact of WH on the river flow and water availability for agriculture in a sub-basin in the LRb, is presented and the underlying research questions to achieve this goal are discussed. Chapter 2 includes the literature review and gives background information of the LRb. WH definitions and the classifications are briefly discussed. The next chapter discusses the site selection approach of the study area and includes a description of the study area. The materials and methods are discussed in Chapter 4. First, the farm dam dimensions are presented followed by a description of the farm dam water balance equation and the derivation of its components. The approach of the research analysis is discussed in the last part. Chapter 5 gives an overview of the results of the analysis, with the catchment areas of 10 and 20 ha separately discussed. Chapter 6 and 7 includes the discussion and conclusion, respectively.

2 Literature review

2.1 Background of the Limpopo River basin

2.1.1 Geography

The Limpopo River basin is located on the Southern Africa continent, covering portions of Mozambique (20%), Zimbabwe (15%), Botswana (20%) and South Africa (45%) (Figure 1). The population is estimated at 14 million people (CGIAR, 15-3-2012). The LRb has an area of about 413,000 km^2 and is divided in 27 sub-basins. The Limpopo River consists of 24 individual tributaries, with the Elephants River as main tributary. Plateaus, interspersed and interrupted by medium gradient mountains, deeply incised valleys and low-gradient hills are dominant landforms of the basin (FAO, 2004). The distribution of high elevation land has big effect on the precipitation patterns in the LRb (RAK, 2012). The main land use in the basin is grassland, savannah and shrub land (68%); cropland covers about 26%, of which only 1% is irrigated. Wetlands cover 3% and the remaining area is forest and urban areas (LBPTC, 2010).

Figure 1
The Limpopo River basin, is situated partly in Mozambique, South Africa, Zimbabwe and Botswana.

2.1.2 Climate and weather

Large parts of the LRb are semi-arid or arid. The average rainfall of the basin is 530 mm per year, ranging from 200 to 1200 mm/y. The mountainous areas in South Africa receive highest rainfall, while along the Limpopo River between Zimbabwe and South Africa the lowest rainfall can be found. Rainfall is seasonal and occurs mainly (95%) in the summer months, from October to March with peaks in January. The temperature in the LRb shows a seasonal cycle as well, with highest temperatures during the summer months and lowest temperatures during the winter months. The mean maximum temperature generally varies from 30 to 34 °C during summer to 22 to 26 °C in winter. Droughts are frequent, but floods also occur because of the short and intense rainfall in the rainy season (LBPTC, 2010). Evapotranspiration is relatively high compared to the rainfall, varying from 1000 mm/y in the southern part of the basin to 2000 mm/y in the north (RAK, 2012). There is an overall net moisture loss across the basin (FAO, 2004).

2.1.3 Hydrology

The LRb is located in a region where water resources are under huge pressure from the environment, and water is seen as a limiting factor in development in the region (CGIAR, 2003). The water resources of the basin are shared by the four countries and supports economic activities.

Extensive rain-fed agriculture with low input levels is perhaps one of the most important economic activities, because a large portion of the rural population depends on it for their livelihoods (RAK, 2012). The largest water source for development schemes in the LRb is surface water (LBPTC, 2010). More than 50% of the total water use in the basin is used for irrigated agriculture, followed by urban water supply with 30%. Irrigation is mostly found in South Africa, but Zimbabwe and Mozambique also have large irrigated areas. Irrigation mainly relies on stored water in numerous dams across the basin (RAK, 2012).

Groundwater is used extensively supplying a large percentage of water for irrigation and rural water supply schemes (FAO, 2004). It is especially used in rural areas that have no access to surface water and by the mining industry (CGIAR, 2003).

2.2 Water harvesting definition and classification

WH is a low-cost method which alters the partitioning of precipitation into less surface runoff and more soil moisture; and utilizing more of the soil moisture into crop transpiration and less to soil evaporation (Andersson et al., 2011). WH may be defined as 'the process of concentrating precipitation through runoff and storing it for beneficial use' (Oweis and Hachum, 2006).

WH techniques are grouped under two terms: WH techniques which harvest runoff from roofs or ground surfaces fall under the term rainwater harvesting (RWH), while all systems which collect discharges from watercourses are grouped under the term floodwater harvesting (FAO, 1991). RWH includes three components: a watershed area to produce runoff, a storage facility (soil profile, surface reservoirs or groundwater aquifers), and a target area for beneficial use of the water (agriculture, domestic or industry) (Rockström et al., 2007).

Water harvesting can be classified in several ways; most are based on the runoff generation process, size of the catchment and storage type (Figure 2). In-situ WH aims at conserving the rainfall where it falls in the cropped area or pasture (Ngigi, 2003), while external WH refers to systems that concentrate runoff from uncultivated areas onto the fields (Rockström, 2000). WH practices are further defined by storage strategies: direct runoff concentration in the soil profile and collection and storage of water in storage structures (Fox and Rockström, 2000), like check dams, farm ponds and harvesting bunds (Singh et al., 2008). Size of the catchment includes two categories, the macro and micro catchments. Macro catchments WH use a long-slope technique, whereas micro catchments WH use a short-slope catchment technique (FAO, 1991). A practical classification of a number of WH techniques and their characteristics is shown in Figure 3.

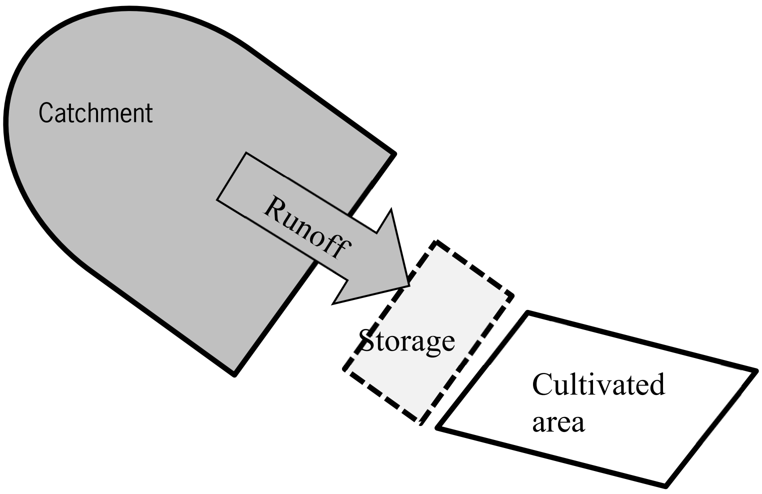


Figure 2
Three components of a rain water harvesting solution.

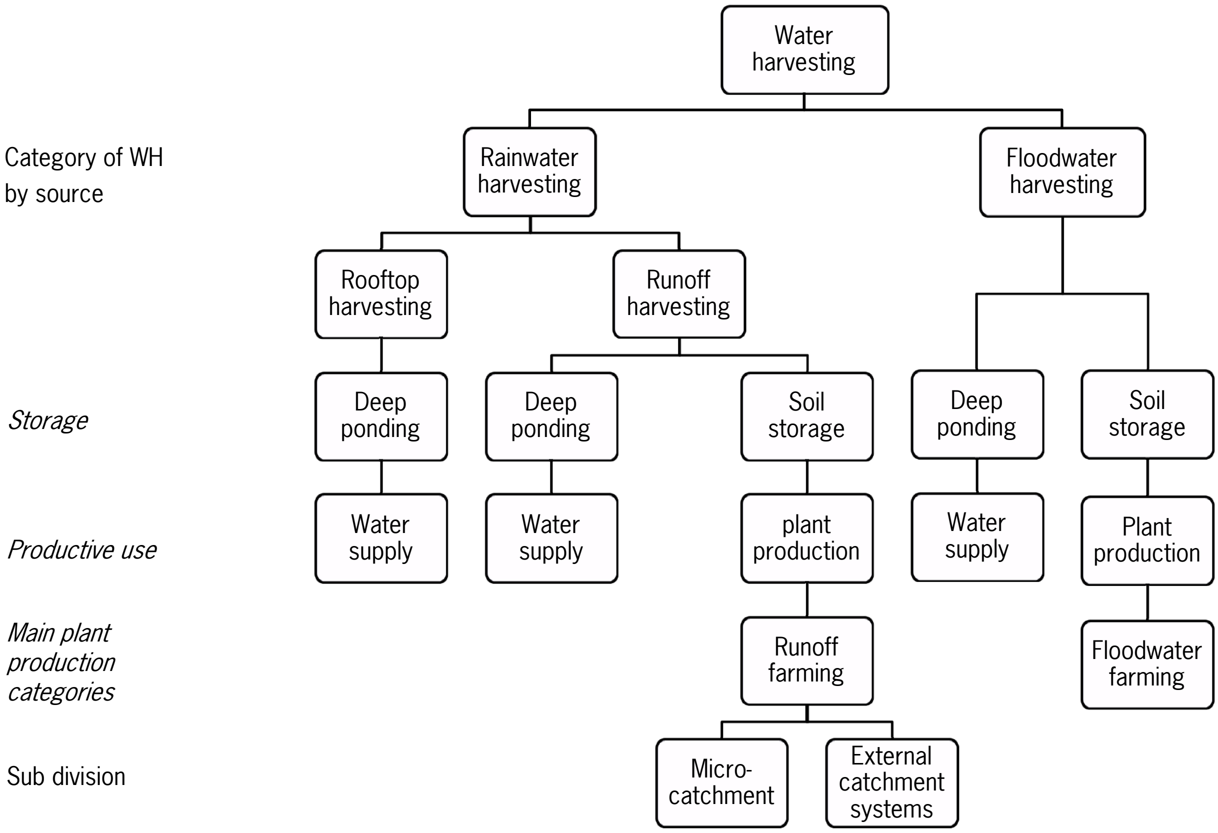


Figure 3
Classification of water harvesting techniques (FAO, 1991).

The analysis focuses on the impact of a farm dam on the river flow in a small catchment in the north-west part of the LRb. The word dam in this report refers to the reservoir itself, rather than just the water-retaining wall. It is a small dam; the wall is made from earth. On suitable sites, these dams are effective and economical and are probably the most common man-made storage type (Hudson, 1987).

3 Study area

This section describes the selection procedure of the study area and gives a short description of the study area and its main characteristics.

3.1 Site selection

The site selection approach is mainly based on two criteria. One is the indication of northwest part of the LRB as a very dry area with water scarce resources (LBPTC, 2010). The soil textural class is also used as selection criterion for the study area, being an important factor in the selection of a suitable site for a farm dam. Clay soils are the best soils for water storage reservoirs because they have high water holding capacity, high water retention capacity and they allow relatively low seepage and percolation rates (Mbilinyi et al., 2005). Soils with high infiltration rates are not suitable. Therefore, areas with the soil textural class clay are the most suitable for farm dams.

The study area is selected with the help of the geographic information system ArcGIS10 and a SOTER-database with soil textural class information. The hydrological map of the sub basins from the LRb is used to identify the borders of the basins and the north-west part of the LRb. The hydrological map is obtained from HydroSHEDS data (Hydrological data and maps based on Shuttle Elevation Derivatives and multiple Scales). HydroSHEDS is a mapping product that provides hydrographic information for regional and global-scale applications in a consistent format. It is based on high-resolution elevation data obtained during a Space Shuttle flight for NASA's Shuttle Radar Topography Mission (SRTM) (USGS, 2011). HydroSHEDS vector and raster datasets include: stream networks, watershed boundaries, drainage directions, and ancillary data layers such as flow accumulations, distances, and river topology information (Samuels and Amstutz, 2009). The stream networks and sub basins of the LRb are delineated (Figure 4) using the Digital Elevation Model (DEM) of the Limpopo.

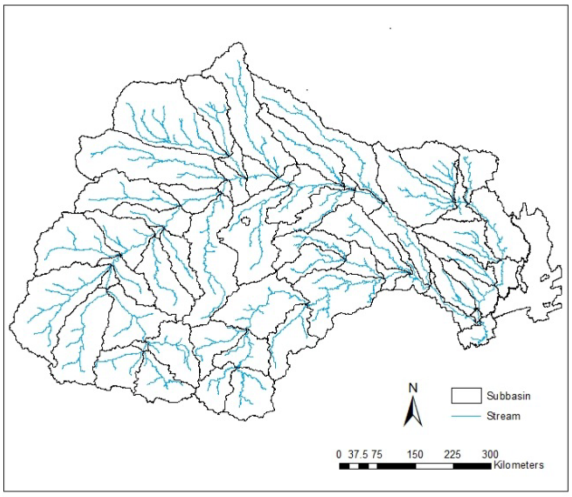


Figure 4
The Limpopo basin with its streams and sub basins as derived from the DEM (USGS, 2011).

A World Soils and Terrain Digital Database (SOTER) provided the soil data of the study area. SOTERSAF is used, the SOTER database for Southern Africa (FAO and ISRIC, 2003). The SOTERSAF database uses the textural classes following the criteria of FAO (1988) and CEC (1985). PSCL in the table of the SOTER-database includes the soil textural classes. The abbreviations that are used are in Table 1. For a more detailed description of the database, see Batjes (2004).

Table 1
Abbreviations soil textural classes of the SOTER-database.

Abbreviation	Textural class (PSCL)
C	coarse
M	medium
Z	medium fine
F	fine
V	very fine
#	Class not unique (two or more of the above classes are present)

The soil textural classes are based on the relative proportions of clay, sand and silt. The original soil texture triangle and the soil texture triangle with the classes of the SOTER-database can be found in Figure 5 and Figure 6 respectively.

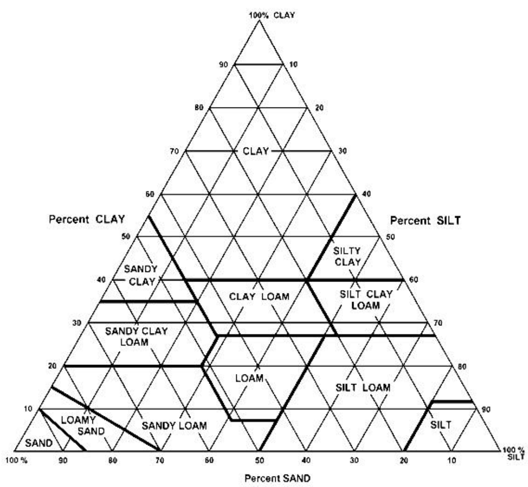


Figure 5
Soil texture triangle.

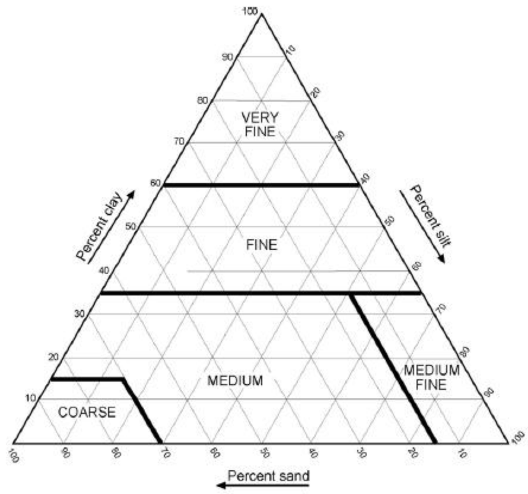


Figure 6
Soil texture triangle with classes from SOTER-database.

The textural class clay is most suitable for the selection of the study area (Mbilinyi et al., 2005). This corresponds with the soil textural classes fine and very fine (F and V). Using ArcMap of the LRb with its streams, sub basins and the dataset of SOTER with the soil textural classes, a study site is selected. All polygons in the LRb that have a F or V for PSCL in the SOTER-database are shown in Figure 7.

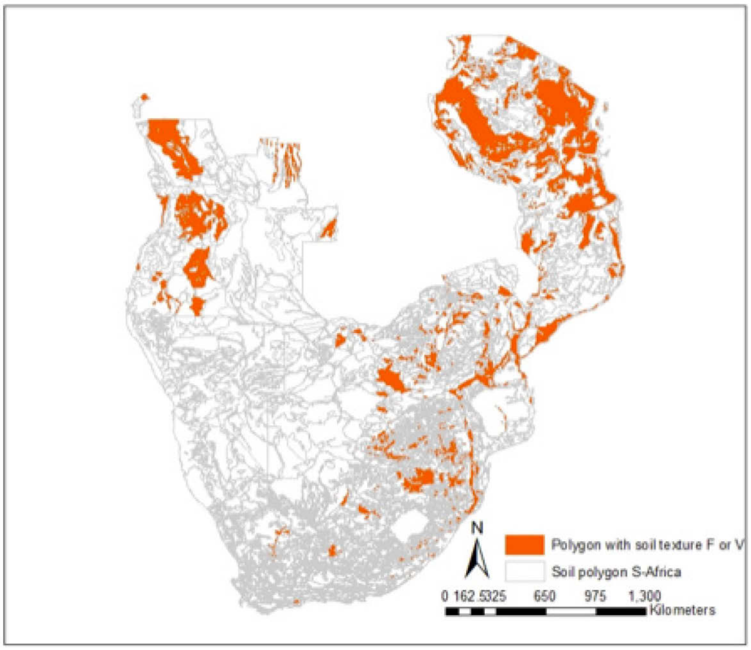


Figure 7
Selected polygons with suitable soil texture fine or very fine (FAO and ISRIC, 2003).

Next step was to add the layer from LRb with its streams and sub basins and determine suitable sites in the northwest part. The selected region is marked with a yellow arrow in Figure 8.

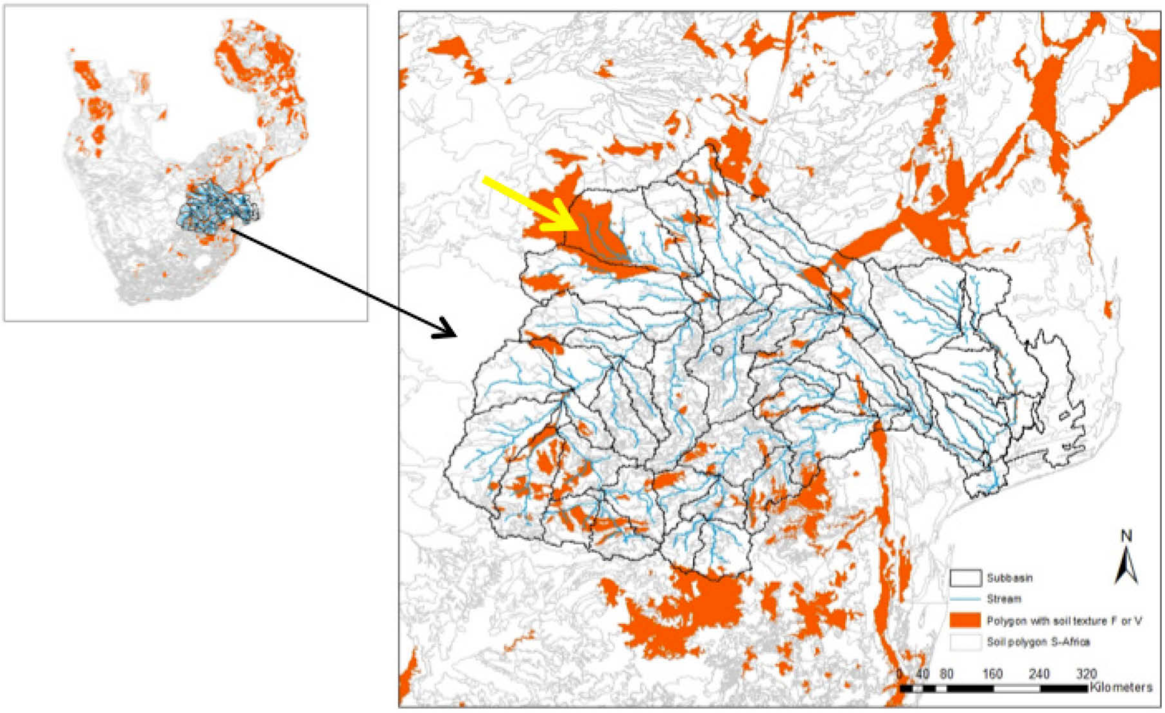


Figure 8
Selected suitable region in the north west part of the Limpopo River basin

The meteorological data (precipitation, evaporation etc.) required for the analysis of farm dams is provided by the EU WATCH project (Weedon et al., 2010; Wanders et al., 2010). The meteorological data from 1981 to 2001 has a resolution of 45 x 45 km and covers the entire LRb, as shown in Figure 9. From the meteorological regions, one is chosen which lies in the selected region of Figure 8.

It resulted in the selection of meteorological region 211, with the soil textural class fine. The selected number 211 is outlined in a red rectangle in Figure 9.

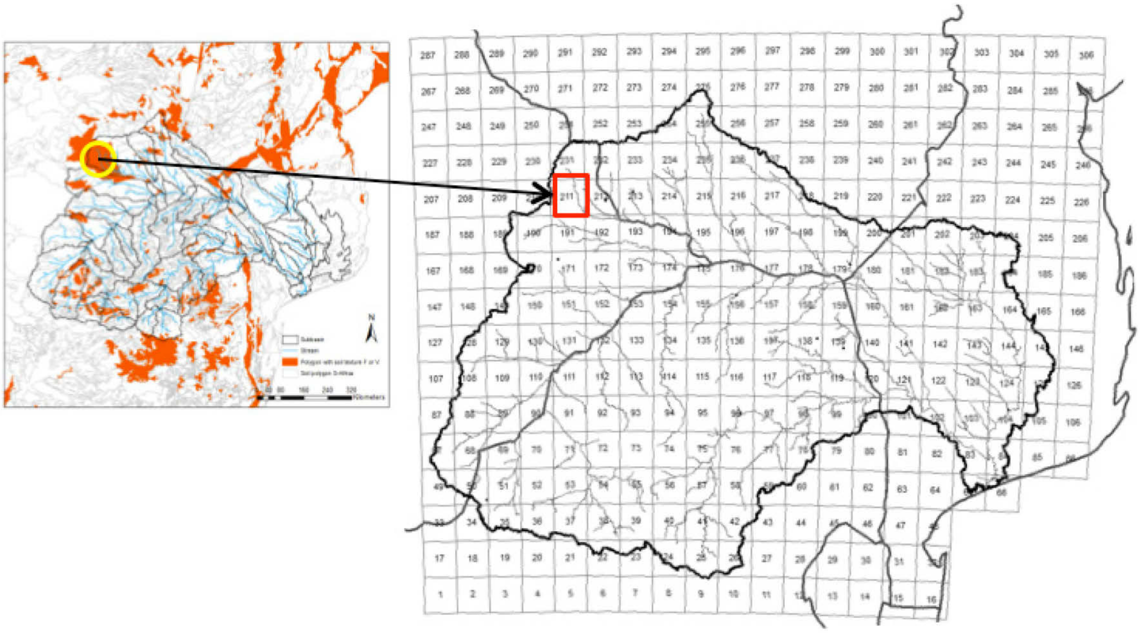


Figure 9
Selected study area: meteorological region 211.

3.2 Description of the meteorology

The selected study area is situated in the Shashe sub basin in Botswana as shown in Figure 10.

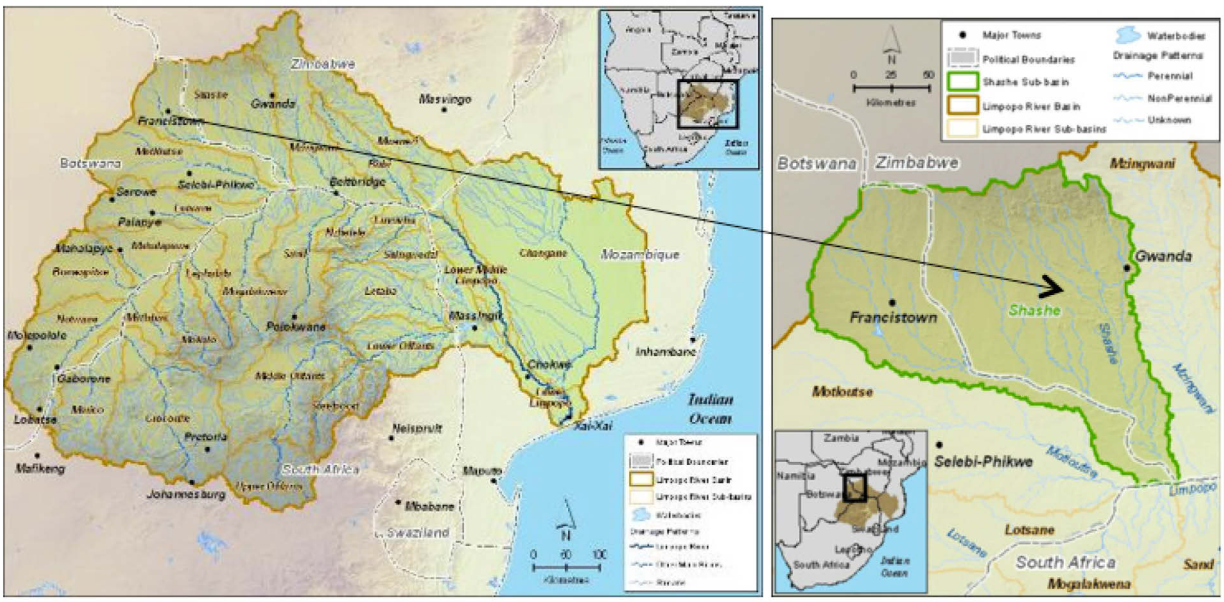


Figure 10
Location of Shashe sub basin in the Limpopo River basin.

Over a period of 20 years from 1981 to 2001, the average annual precipitation is 741 mm, while the average amount of the reference evapotranspiration is 1515 mm/y.
Figure 11 shows the seasonal variation in the amount of precipitation and reference evapotranspiration ETo, with the rainy period from October to March. The distribution of the annual precipitation is shown in Figure 12, the meteorological data indicate that the precipitation falls within a couple of months, making the area suitable for WH. The average annual temperature over period 1981-2001 is 21.8 °C (Figure 13).

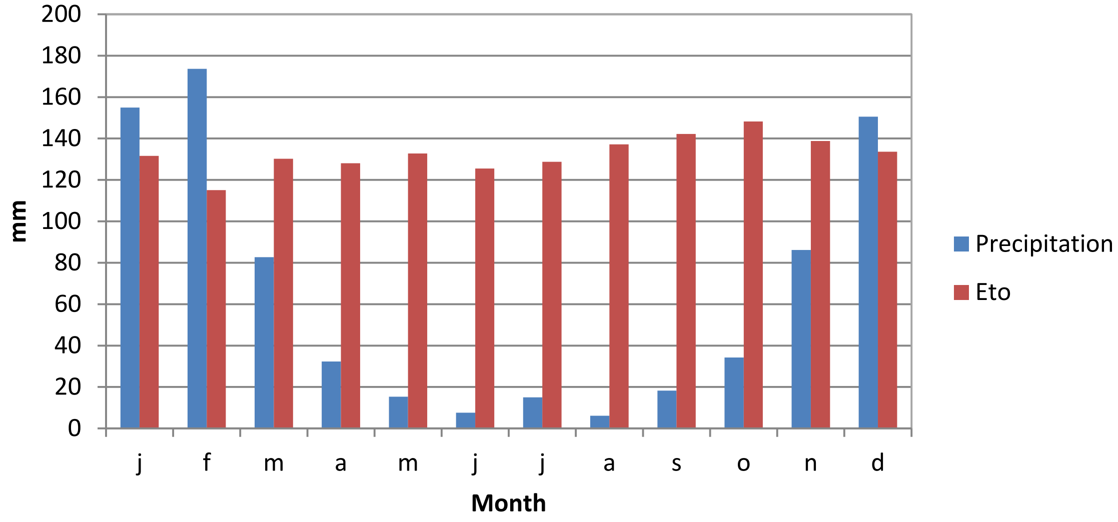


Figure 11
Distribution of the mean monthly precipitation and reference evapotranspiration (ETo) (1981-2001).

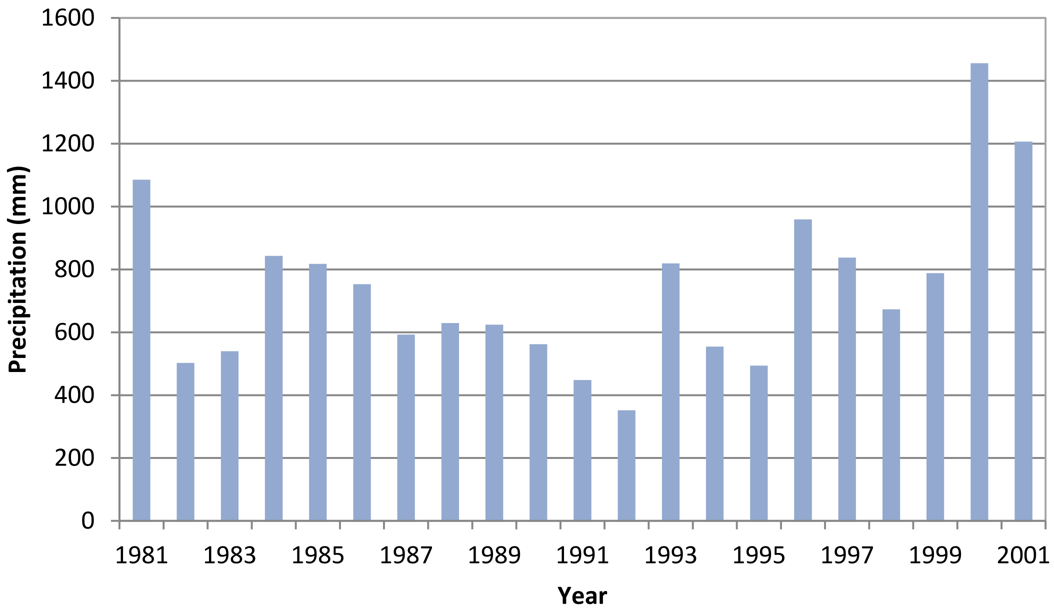


Figure 12
Distribution of the annual precipitation (1981-2001).

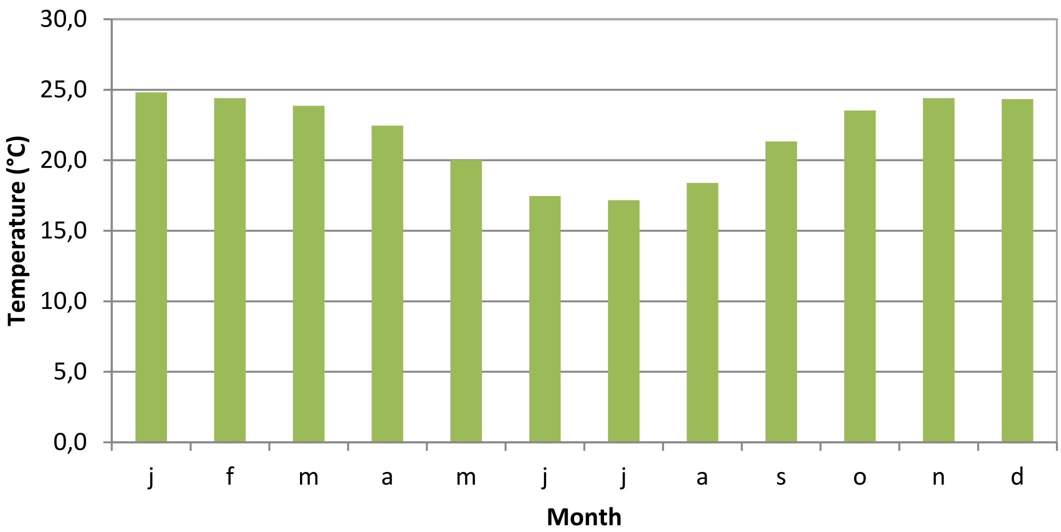


Figure 13
Distribution of the mean monthly temperature (1981-2001).

The elevation of the study area varies between 1000 and 1100 m. The study area is primarily covered with cultivated land, grassland and savanna (RAK, 2012). Luvisols (soils with a clay-enriched subsoil) are dominant in the study area (FAO, 2004).

4 Materials and methods

With input data from different sources and a number of assumptions, four scenarios of a farm dam water balance in a small catchment area of the Shashe sub basin in Botswana are created. The assumptions where the scenarios are based on, are listed in Appendix 10. The water balances are developed with a monthly time step, from January 1997 up to and including December 2001. This is the most recent period of five years out of the 20-year available data.

Four different scenarios will be considered, they differentiate in the method to calculate the hydrology and in the levels for the infiltration rate. Table 2 gives an overview of the different scenarios.

Scenario A makes use of a catchment water balance equation (Equation 10) to calculate the water inflow. This scenario is based on a simple approach using excel to calculate the water inflow. Scenario B, C and D use the SIMFLOW model (described in 4.3.3) and Equation 15 to calculate the water inflow. These scenarios are based on a more elaborated approach, because they are based on the hydrological model SIMFLOW. The difference between scenario B, C and D is the infiltration rate of the soil, being 40, 50 and 60 mm/d respectively, giving different amounts of surface runoff. A detailed description of both calculation methods is given in paragraph 4.3.2.

Table 2
Overview of the four scenarios defined to estimate the inflow of the storage dam and the variable infiltration rate of the soil.

Scenario	**Method to calculate inflow parameter**		**Infiltration rate soil**
	Catchment water balance; equation 11	**SIMFLOW;** equation 15	**(mm/d)**
A	X		-
B		X	40
C		X	50
D		X	60

Two surface areas of the upstream catchment are compared for every scenario: 10 and 20 ha. These values are chosen because a small catchment generally has a surface area between 10 and 40 ha (AgriInfo, 2011).

First, a description of the farm dam dimensions used in the analysis is given. The farm dam water balance equation is discussed in the next paragraph and the adjustments in the equation for both calculation methods of the water inflow parameter are explained. The derivation of the components of the farm dam water balance equation follows and the approach of the data analysis is clarified in the last paragraph of this chapter.

4.1 Farm dam dimensions

The farm dam dimensions are not fixed and can be altered to analyse different scenarios. The dead storage of the farm dam is the capacity of the dam that is below the minimum operating level and cannot be supplied

(under normal circumstances) (AWR, 2005). In this case, the volume of the farm dam is completely available for users and does not include the dead storage.
Small dams are typically between the 1,000 and 10,000 m^3 in size and are rarely larger than this (Meigh, 1995). Six different capacities of the farm dam are chosen to analyse the impact of a farm dam on the river flow downstream. The storage capacities are 0 (no dam), 1,125, 3,200, 5,625 and 9,900 m^3 and lie between the typical ranges. The depth of each of these farm dams is chosen in such a way, that the depth is realistic for its corresponding capacity.
The surface area of the farm dam is calculated using Equation 1:

$$A = C/D * 1.3 \qquad (1)$$

Where,

Ad surface area of the dam (m^2)
C storage capacity of the dam (m^3)
D depth of the dam (m)

In Equation (1) the value 1.3 is a correction factor. The farm dam is not a rectangular container with straight sides, but has more sloping sides. There is a need for a correction factor to take this into account when calculating the surface area of the farm dam. In this case, the value of 1.3 is used to correct for the slopes of the farm dam. The capacity, depth and corresponding surface area of each farm dam are shown in Table 3.

Table 3
Farm dam dimensions used in the analysis of scenarios A-D.

Capacity (m^3)	Depth (m)	Surface area (m^2)
0	-	-
1125	1.5	975
3200	2.0	2080
5625	2.5	2925
9900	3.0	4290

The initial water volume of the farm dam at the beginning of the calculation period is assumed at full capacity. The reason for this is that in January generally high rainfall events occur (Figure 15), which results in a dam at full capacity.

4.2 Farm dam water balance equation

The computation of the farm dam water balance is made on the basis of the water accounting principle, which considers all water inflows, outflows and storage in the reservoir. As shown schematically in Figure 14, the inflow components are water inflow from the upstream catchment area (WI), precipitation on the farm dam surface (Pd) and groundwater inflow to the farm dam (Gin). The outflow components are evaporation from the farm dam (Ed), groundwater outflow (Gout) and water extraction for irrigation (IRR). The storage of the farm dam (S) is a result of the difference between all inflow and outflow from the farm dam. When the storage of the farm dam exceeds its maximum capacity (C), the excess water will flow directly to the downstream sub-catchment. This excess water is defined as the overflow of the farm dam (O).

The general equation of the farm dam water balance is read as:

$$S = Pd + WI + Gin - Ed - Gout - IRR - O \qquad (2)$$

Where,

S	Farm dam water storage
Pd	Precipitation falling directly on the dam surface
WI	Water inflow from the upstream area
Gin	Groundwater inflow
Ed	Evaporation from the farm dam surface
Gout	Groundwater outflow
IRR	Extraction for irrigation
O	Overflow of the farm dam

All parameters have the unit m^3/month.

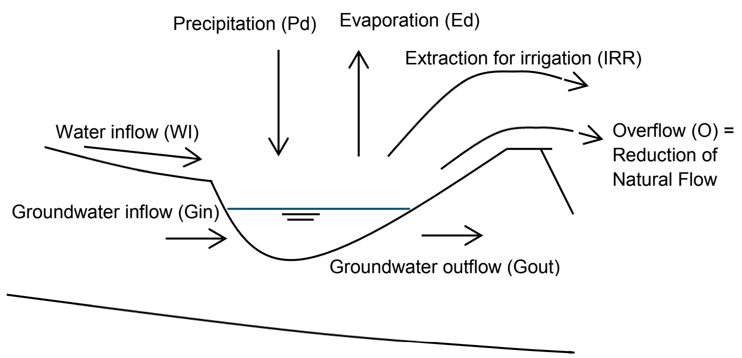


Figure 14
Components of the farm dam water balance.

The water balance of the farm dam computes the volume of water in the dam at the end of each time step. It also computes the volume of overflow that will flow directly to the downstream sub-catchment.
The overflow that will flow directly to the downstream sub-catchment is calculated with Equation 3.

$$O = Pd + WI + Gin - Ed - Gout - IRR - S \qquad (3)$$

Where, the definitions of the parameters are as given in Equation 2.

4.2.1 Farm dam water balance equation of scenario A

Scenario A is based on the assumption that the farm dam is located on a clayey soil, with low seepage rates. Owing to this fact the groundwater inflow and groundwater outflow components were considered negligible and taken out from the farm dam water balance equation. Equation 2 is rearranged to:

$$S = Pd + WI - Ed - IRR - O \qquad (4)$$

Where, the definitions of the parameters are as given in 2.

The water inflow from the upstream area (WI) is calculated with the catchment water balance equation (see for a detailed description paragraph 4.3.2. The catchment water balance equation calculates the runoff in the catchment upstream of the farm dam (R), representing WI of the farm dam water balance equation. The farm dam water balance equation for scenario A is read as:

$$S = Pd + R - Ed - IRR - O \quad (5)$$

Where, the definitions of the parameters are as given in 2 and R is the runoff in the upstream catchment (m^3/month).
Equation 3 in case of scenario A becomes:

$$O = Pd + R - Ed - IRR - S \quad (6)$$

4.2.2 Farm dam water balance equation of scenario B, C and D

Scenario B, C and D are based on the SIMFLOW model (see Paragraph 4.3.3 for a description). SIMFLOW calculates the interaction between the groundwater and surface water. The output of the model is the removal of surface and sub-surface water in the upstream catchment of the farm dam and is called drainage (Dc). This drainage represents WI in the farm dam water balance equation. The groundwater inflow and groundwater outflow components are covered by the drainage component and taken out from the farm dam water balance equation. Equation 2 is rearranged to:

$$S = Pd + Dc - Ed - IRR - O \quad (7)$$

Where, the definitions of the parameters are as given in equation 2 and Dc is the drainage in the upstream catchment (m^3/month). Equation 3 in case of scenario B, C and D becomes:

$$O = Pd + Dc - Ed - IRR - S \quad (8)$$

4.3 Derivation of the farm dam water balance components

4.3.1 Precipitation component

The meteorological data are derived from the WATCH forcing data (Weedon et al., 2010 and Wanders et al., 2010). The data covers a period of 20 years from 1981 to 2001. Precipitation is given in mm/d for 306 meteorological stations. The analysis only uses precipitation data from station 211 from a period of five years: 1 January 1997 up to and including 31 December 2001. Figure 15 indicates the difference between the mean monthly precipitation from the period of 20 year (1981-2001) and the period of five years (1997-2001).

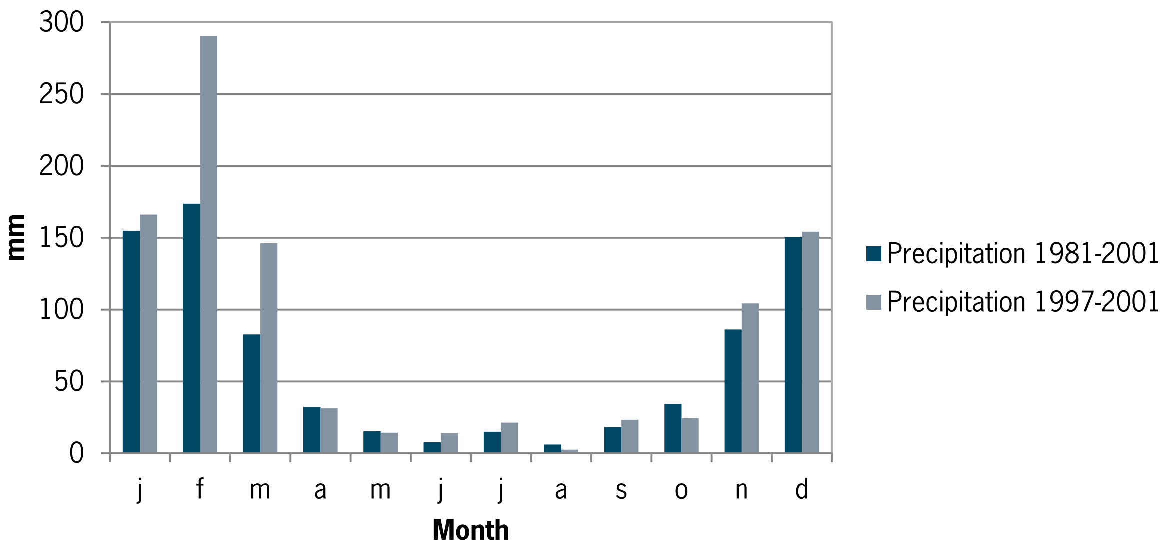


Figure 15
Comparison mean monthly precipitation: 1981-2001 with 1997-2001.

The rainfall pattern in both periods is similar, with the rainy period from October to March. However, the study period is relatively wet compared to the whole data range/period. The mean annual precipitation from the 5-year period is 28% higher compared to the mean annual precipitation from the 20-year period.

To calculate the precipitation falling directly on the dam surface in m^3/month, the daily values of the precipitation are summed per month to obtain the total precipitation per month for the period of five years. Then, these values are divided by 1,000 to obtain the unit m/month. The following equation is used to calculate the precipitation falling directly on the dam surface:

$$Pd = \frac{P}{1000} * Ad \qquad (9)$$

Where,

Pd Precipitation falling directly on the dam surface (m^3/month)
P Precipitation (m/month)
Ad area of the dam surface (m^2)

The area of the dam surface is variable and discussed in Paragraph 4.1.
With Equation 9 the precipitation falling directly on the variable dam surface in m3 for each month in the study period of five years are calculated for every scenario.

4.3.2 Water inflow component for scenario A: runoff

Catchment water balance equation
Scenario A is based on the catchment water balance to calculate the water inflow component of the farm dam water balance. The catchment water balance allows to study hydrological processes taking place in a catchment area and to determine unknown parameters, based on known ones. The catchment water balance is based on water accounting principles in which water flows into the catchment, leaving the catchment and change in storage (as groundwater and as water in soil, ponds, dams and vegetation) for the period considered are taken into account.

Assuming that the boundary of the surface water catchment coincide with that of the groundwater, the catchment water balance is formulated as:

$$\Delta S = Pc - ETa - R \quad (10)$$

Where,

ΔS Change in groundwater and soil moisture storage for the time considered
Pc Precipitation falling on the catchment
Eta Actual evapotranspiration from the catchment
R Runoff in the catchment

The change in water storage on water balance includes e.g. infiltration and percolation and drainage components. The change in water storage depends on the period of time over which the water balance is computed. It can be significant when considered for a period of a day, a week or a month, but on annual basis it is likely to be small in relation to the total water balance components and assumed to be zero. The equation of the upstream catchment water balance on annual basis is therefore reduced to:

$$R = Pc - ETa \quad (11)$$

Where, the definitions of the parameters are as given in Equation 10.

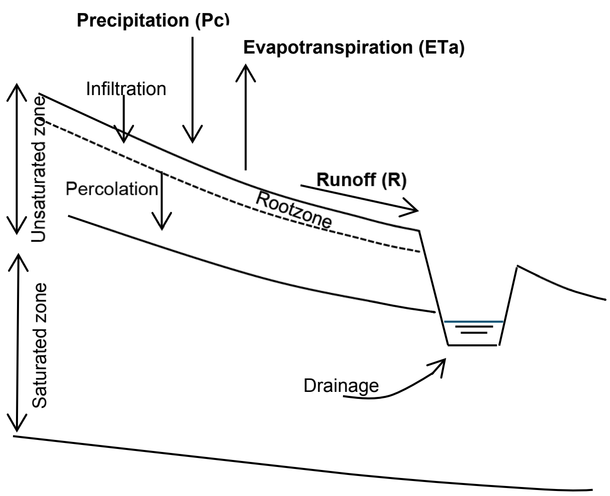


Figure 16
Components of the catchment water balance

Precipitation component
The precipitation data described in Paragraph 4.3.1 is used to calculate Pc of Equation 12.
To calculate the precipitation for the upstream catchment area in m3/month, the daily values of the precipitation are summed per month to obtain the total precipitation per month for the period of five years. Then, these values are divided by 1,000 to obtain the unit m/month. The following equation is used to calculate the precipitation on the upstream catchment:

$$Pc = \frac{P}{1000} * Ac \quad (12)$$

Where,

Pc	Precipitation on the catchment (m^3/month)
P	Precipitation (m/month)
c	area of the catchment (m^2)

With this equation the precipitation in the upstream catchment in m^3 for each month in the study period of five years is calculated.

Evapotranspiration component
Besides the precipitation on the catchment, the evapotranspiration from the catchment is needed to calculate the runoff. The evapotranspiration depends on the vegetation growing in the catchment.
The upstream catchment of the farm dam is not for agricultural use, but is a natural area.
The land use of the catchment area in percentage of the total catchment area is defined as shown in Table 4.

Table 4
Land use in percentage of the total study area

Land use	% of total area
Natural area	85
Agriculture	0
Deciduous forest	15
Pine forest	0

Besides the evapotranspiration of grassland (ETo), that of deciduous forest (ETdeci) is needed to calculate the evapotranspiration in the catchment area. The evapotranspiration is calculated using the evapotranspiration data described in Paragraph 4.3.4. The daily values of ETo are summed per month to obtain the total ETo per month in the study period of five years. Then, these values are divided by 1,000 to obtain the unit m/month. From the WATCH forcing data the evapotranspiration of deciduous forest (ETdeci) has been calculated. These values are also summed per month for the study period and divided by 1,000 to obtain the unit m/month.
The total evapotranspiration in the catchment per month (ETcatchment) is calculated with Equation 13:

$$ETcatchment = (ETo * 0.85) + ETdeci * 0.15) \tag{13}$$

To calculate the total evapotranspiration in the upstream catchment area in m^3/month, the following equation is used:

$$ETcatchment, tot = ETcatchment * Ac \tag{14}$$

Where,

ETcatchment,tot	total evapotranspiration in the catchment (m^3/month)
ETcatchment	evapotranspiration in the catchment (m/month)
Ac	area of the catchment (m^2)

With Equation 14, the total evapotranspiration rates of the upstream catchment in m^3 for each month in the study period of five years is calculated. The calculated precipitation and evapotranspiration in m^3/month can be used as input for Equation 11 to calculate the water inflow parameter of the farm dam water balance equation.

4.3.3 Scenario B, C and D: Drainage component

The SIMFLOW model is used to calculate the drainage to the farm dam, representing the water inflow (WI) parameter of Equation 2. The goal is to get an estimation of the amount of water that flows into the farm dam from the upstream catchment and compare this with the results of the method using the catchment water balance. This paragraph contains a brief description of the model, followed up by a delineation of the input data and the drainage component of the farm dam water balance.

Description of SIMFLOW

SIMFLOW is a one-dimensional model that covers the component of the unsaturated zone in the SIMGRO model (Querner and Van Bakel, 1989). In SIMFLOW, the interaction between groundwater and surface water is of interest, as shown in Figure 17. The time step of the model is one day.
Two reservoirs represent the unsaturated zone, one for the root zone and one for the underlying subsoil. The subsoil is the soil profile between the root zone and the water table. The depth and the soil moisture characteristics of the soil determine the moisture storage of the root zone. Precipitation, irrigation, evapotranspiration, capillary rise and percolation cause replenishment or subtraction out of this system. When the equilibrium moisture storage for the root zone is exceeded, the excess water will percolate to the subsoil. This is groundwater recharge to the saturated zone. If the moisture storage in the root zone is less than the equilibrium soil moisture storage, capillary rise will occur: the water will flow upwards from the saturated zone. The water flow in the unsaturated zone is pseudo stationary, that is to say, by a sequence of stationary situations.
The height of the phreatic surface is calculated from the water balance of the subsoil below the root zone, using a storage coefficient that is dependent on the depth to the groundwater.
The unsaturated zone is modelled one-dimensionally per sub region and land use type. Evapotranspiration is a function of the crop and moisture content in the root zone. The measured values for net precipitation and potential evapotranspiration for a reference crop and woodland are used as input. The potential evapotranspiration for other crops or vegetation types are derived in the model from the values for the reference crop by converting with known crop factors.

The saturated zone has interactions with the unsaturated zone and the surface water, while there may be leakage or seepage over the lower boundary. Watercourses affect the interaction between the surface water and groundwater. There are three types of drainage systems to calculate the interaction between the groundwater and surface water: trenches/furrows, ditches/drains (tertiary system) and larger watercourses (secondary system). It is assumed that these subsystems are distributed evenly over a sub region. The surface water within the area of interest is modelled with one surface water level. The surface water level can differ in time, like during wet and dry periods. The model takes into account the absence of water supply from the surface water towards the groundwater system (meaning no infiltration is possible).
The interaction between surface and groundwater is calculated for each drainage system, using a drainage resistance and the difference in level between groundwater and surface water (Ernst, 1978).

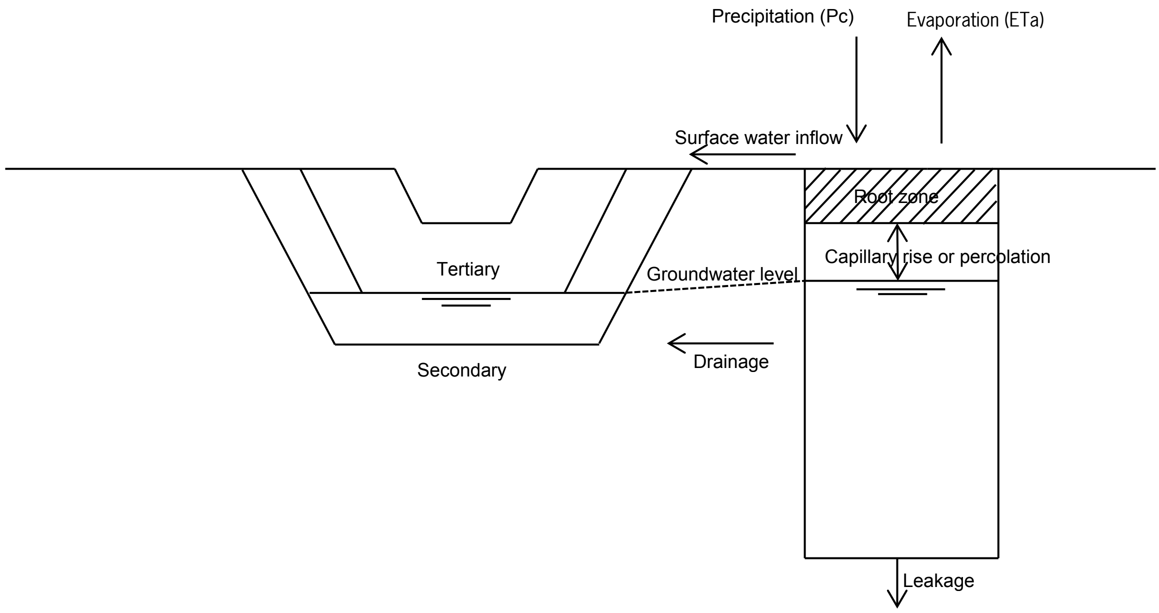


Figure 17
One-dimensional model SIMFLOW (unsaturated and saturated zone with drainage systems)

Input data
The SIMFLOW model is from origin developed for Dutch hydrological conditions. The calculations of the model are based on the growing seasons of the Netherlands.
The meteorological data used in this analysis is shifted in such a way that the season on the southern hemisphere coincide with the one in the Netherlands. Therefore meteorological data is shifted half a year in order to correspond with the growing season of the model.
The meteorological data are derived from the WATCH forcing data (Weedon et al., 2010 and Wanders et al., 2010) (see Paragraph 4.3.1).
Using SIMFLOW, calculations are being performed for three scenarios with different infiltration capacities. The input data for the model are summarized in Table 5. The ground level is set at 0.00 m and there is no infiltration from the surface water towards the groundwater system. The soil type is defined as clay on sand. The seepage is assumed as a function of the groundwater level, and given in Table 6, based on expert judgement.

Table 5
Data used in calculations with the SIMFLOW model.

Description		
Land use	**% of total area**	**Rooting depth (m)**
Natural area	85	0.4
Agriculture	0	0.35
Deciduous forest	15	1.0
Pine forest	0	1.0
Summer level (m -GL)	4,0	
Winter level (m -GL)	4,0	
Drainage resistance (d)		
Secondary	3000	
Tertiary	9999	
Depth ditches (m)		
Secondary	4.0	
Tertiary	0.5	

Table 6
Seepage as function of the groundwater level (upward flow/seepage is positive, downward flow is negative).

H* (m -GL)	**0.0**	**0.5**	**1.0**	**1.5**	**2.0**	**3.0**	**4.0**	**5.0**
Flux (mm)	-1.5	-1.3	-1.2	-1.0	-0.8	-0.3	0.0	0.5

Three scenarios make use of SIMFLOW to calculate the drainage in the catchment in which the infiltration rate of the soil is ranging from 40 to 60 mm/d. Table 7 gives an overview of the scenarios and their infiltration capacities.

Table 7
Infiltration rate soil per scenario.

Scenario	**Infiltration rate (mm/d)**
B	40
C	50
D	60

Drainage component

The output of SIMFLOW is the drainage in mm/d from a catchment of one ha for the defined calculation period. Because the study area covers an area of 10 or 20 ha, the output of SIMFLOW will be multiplied with 10 or 20. The drainage represents the removal of surface and sub-surface water in the catchment.
This drainage corresponds with the water inflow (WI) parameter of the farm dam water balance equation.
The daily values of the drainage are summed per month to obtain the total drainage per month for the study period of five years. Then, these values are divided by 1,000 to obtain the unit m/month. The following equation is used to calculate the drainage in m^3/month:

$$Dc = \frac{D}{1000} * Ac \qquad (15)$$

Where,

Dc Drainage in the catchment (m^3/month)

D Drainage (m/month)

Ac Surface area of the catchment (m^2)

With Equation 15 the drainage in the upstream catchment in m^3 for each month in the study period of five years is calculated for the three scenarios. The drainage in the catchment is used to calculate the water inflow (WI) parameter of the farm dam water balance equation.

4.3.4 Evaporation

The evaporation data are derived from the same database (WATCH forcing data (Weedon et al., 2010 and Wanders et al., 2010)) as the precipitation data and it includes the reference evapotranspiration in mm/d in the 20-year period. The reference evapotranspiration is the evapotranspiration of the reference surface and is denoted as ETo. The reference surface is a hypothetical grass reference crop with specific characteristics (Allen et al., 1998). Figure 18 indicates the difference between the mean monthly ETo in the period of 20 year (1981-2001) and the period of five years (1997-2001).

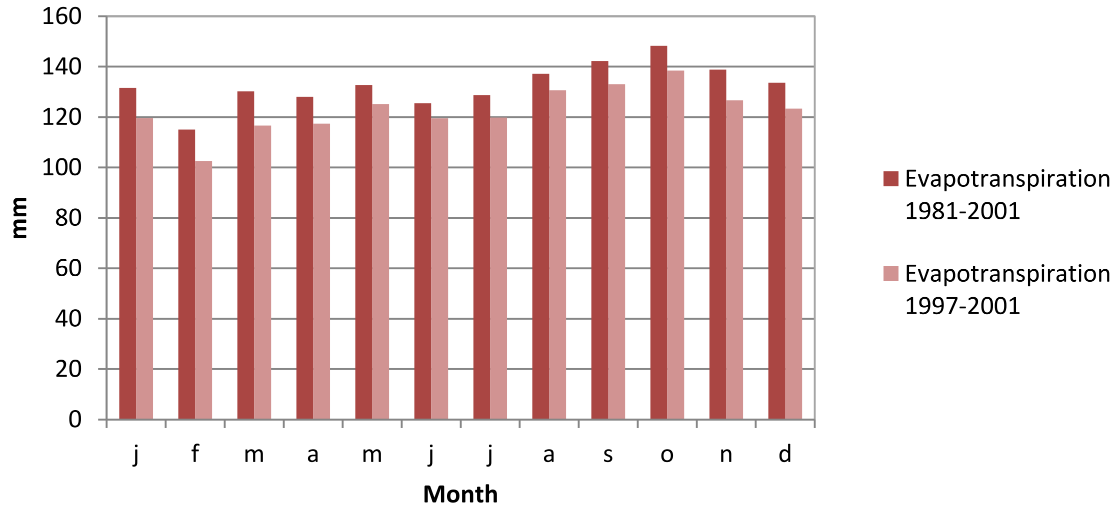


Figure 18
Comparison mean monthly ETo: 1981-2001 with 1997-2001.

The pattern in the mean monthly evapotranspiration in both periods is similar. The mean annual ETo in the five-year period is 7.5% lower compared to the mean annual ETo in the 20-year period.

Evaporation rates will influence how full the dam is and consequently the available water. The volume of evaporation from the farm dam will depend on the rate of evaporation in the region and the surface area of the farm dam. First, the daily values of ETo are summed per month to obtain the total ETo per month in the study period of five years. Then, these values are divided by 1000 to obtain the unit m/month. The evaporation rate of the reference grass crop is now calculated. The conversion factor of 1.25 is used to calculate the evaporation rate of open water (Allen et al., 1998), see Equation 16.

$$ETp, open\ water = ETo * 1.25 \tag{16}$$

Where,
ETp,open water evaporation rate of open water (m/month)
ETo reference evapotranspiration (m/month)
1,25 conversion factor (-)

To obtain the evaporation rate of the dam surface, the following equation is used:

$$Ed = ETp, open\ water * Ad \tag{17}$$

Where,
Ed evaporation of the dam surface (m^3/month)
ETp, open water evaporation rate of open water (m/month)
Ad surface area of the farm dam (m^2)

With Equation 17 the evaporation rates of the variable dam surfaces in m^3 for each month in the study period of five years is calculated for every scenario and are used as input for the farm dam water balance equation.

4.3.5 Extraction for irrigation

In Botswana**,** the main subsistence crops are sorghum, maize, millet, beans, other pulses and oilseeds. These crops form an important source of food and income for many people (FAO, 2004). Maize is selected as agricultural crop to calculate the irrigation water needs and are calculated following the guidelines for irrigation water needs (FAO, 1986). The surface area of the maize field is set at 1 ha.

First, the potential crop evapotranspiration is calculated. The relationship between the ETo and the crop actually grown is given by the crop factor Kc, as shown in Equation 18:

$$ETcrop = ETo * Kc \tag{18}$$

Where,
ETcrop potential crop evapotranspiration (mm/month)
ETo reference evapotranspiration (mm/month)
Kc crop factor

To determine the crop factor Kc for maize, it is necessary to know the total length of the growing season and the lengths of the various growth stages.
The total growing period for maize is assumed as 180 days and the sowing date is 1 October. The duration of the various growth stages and their corresponding Kc values are shown in Table 8 (FAO, 1986).

Table 8
Number of days and crop factor (Kc) per crop development stage of maize.

Crop dev. Stage	**Number of days per stage**	**Kc per stage**
Initial stage	30	0.4
Crop dev. Stage	50	0.8
Mid-season stage	60	1.15
Late season stage	40	0.7

Using Table 8, the Kc factor for each month that maize is growing is calculated (all months assumed to have 30 days). The result is shown in Table 9.

Table 9
Calculated crop factors (Kc) of maize per month in growing period.

Month	**Kc**
Oct.	0.40
Nov.	0.80
Dec.	0.92
Jan.	1.15
Feb.	1.33
March	0.70

With these crop factors, the potential crop evaporation for each month of the five year period can be calculated with Equation 18.

Next step is to determine the irrigation water needs. Part of the crop water need is supplied by precipitation and the remaining part will be supplied by irrigation from water out of the farm dam. In such cases, the irrigation water need (IN) is the difference between the potential crop water need (ETcrop) and part of the precipitation that is effectively used by the plants (Pe) divided by the Water Use Efficiency (WUE, in %). In formula:

$$IN = \frac{ETcrop - Pe}{WUE/100} \quad (19)$$

The effective precipitation (Pe) is the total amount of rainwater useful for meeting the water need of the crops. The manual uses two equations to estimate the fraction of the total precipitation that is used effectively:

$$Pe = 0.8 * P - 25 \quad (if\ P > 75\ mm/month) \quad (20)$$
$$Pe = 0.6 * p - 10 \quad (if\ P < 75\ mm/month) \quad (20)$$

Where,
Pe effective precipitation (mm/month)
P precipitation (mm/month)

The effective precipitation for each month of the five year study period is calculated using these formulae.

The Water Use Efficiency (WUE) is the part of the diverted water into the field effectively used by the plants. The value of the WUE depends on the local situation, and water losses are in the order of 20-40% (based on Wolters, 1992). In this situation, the assumption is that the water losses are 30% and the WUE is 70%.
The irrigation water needs (IRR) can now be calculated. To obtain the IRR in m^3/month, Equation 21 is used.

$$IRR = \frac{IN}{1000} * Am \quad (21)$$

Where,
IRR Irrigation water needs (m^3/month)
IN irrigation water need (mm/month)
Am surface area of the maize field (m^2)

With this equation the irrigation water needs in m^3 for each month in the study period of five year is calculated for every scenario, representing the extraction for irrigation of the farm dam water balance equation.

4.4 Description of the analysis

The goal of the research is to analyse the impact of farm dams on the river flow downstream. This paragraph describes which method is used to analyse this impact.

4.4.1 Analysis

The impact of a farm dam with capacities ranging from 0 (no farm dam) to 9900 m^3 will be compared for catchments with a surface area of 10 and 20 ha. For each scenario, the RNF (the overflow from the farm dam) and CWA are calculated for the study period and plotted in a graph.

An Crop Water Availability (CWA) of 90% is defined as sufficient for maize crops. The point where the CWA is 90% and the corresponding capacity of the farm dam will be determined by reading from the graphs (e.g. see Figure 19). The Remaining Natural Flow (RNF) at this capacity will also be determined and compared for the different scenarios. The farm dam capacity at this point represents the capacity at which the dam can meet the irrigation water needs of maize. A larger farm dam capacity could lead to more water storage (which would not be used for irrigation), but a lower, resulting in less water available downstream. Because of the inaccuracy, the RNF at the point where the CWA is 90% is rounded to the nearest 5 per cent and the farm dam capacity at this point to the nearest 200 m^3.

The three scenarios based on SIMFLOW will also be compared, looking to the effect of the infiltration rate of the soil on the RNF and CWA.
These three scenarios will also be compared with Scenario A, which makes use of Equation 11 to calculate the Water Inflow in the catchment. The influence of the calculation method on the RNF and CWA will be analysed.

4.4.2 Remaining Natural Flow

The RNF is used to calculate the impact of a farm dam on the amount of water that will flow directly to the downstream sub-catchment. It represents the overflow of the farm dam in percentage of the flow to the downstream sub-catchment when no dam would be present.

Overflow of a farm dam will occur when the storage of the farm dam exceeds its capacity and the excess water will flow to the downstream sub-catchment. The capacity of the farm dam determines the amount of overflow.

The flow to the downstream catchment when no farm dam would be present is the reference situation.
The total runoff (in case of scenario A, using equation 11) or the total drainage (in case of scenario B,C and D, using equation 15) of the study area represents this reference flow.

The following equation is used to calculate the RNF in case of Scenario A:

$$Remaining\ Natural\ Flow = \frac{O}{R} * 100\% \qquad (22)$$

Where,
O Overflow of the farm dam (m^3/month)
R Runoff in the catchment (m^3/month)

To calculate the RNF in case of scenario B, C and D, Equation 22 is rearranged to:

$$Remaining\ Natural\ Flow = \frac{O}{Dc} * 100\% \qquad (23)$$

Where,
O Overflow of the farm dam (m^3/month)
Dc Drainage in the catchment (m^3/month)

Percentages of RNF are calculated per month and averaged over the study period of five years for the different farm dam capacities and surface areas of the catchment.

4.4.3 Crop Water Availability

To analyse whether the irrigation farm dam can meet the irrigation water needs of the crops, the relative difference between the crop water requirements and the amount of water supplied by precipitation and irrigation from the farm dam. This relationship is called the CWA; calculated using equation 29. The CWA shows the extent to which the farm dam in combination with the precipitation can meet the crop water requirements.

The potential evapotranspiration of the maize crop is the amount of evapotranspiration that would occur when sufficient water sources are available. In this study, the actual water supply is the actual amount of water delivered to the atmosphere by evaporation (interception included) and transpiration. The actual water supply of the crop is determined by the amount of water supplied to the crop by precipitation and irrigation. The actual water supply in this analysis is the sum of the water supplied by precipitation and irrigation to the maize field of 1 ha. The CWA of the maize crop is calculated for the two catchment area surfaces and a farm dam with different capacities, ranging from 0 (no dam) to 9,900 m^3.

To calculate the CWA, the crop evapotranspiration of Equation 18 is first converted to obtain the potential crop evapotranspiration in m^3/month. Based on a surface area of 1 hectare of maize, the potential crop evapotranspiration in m^3/month is calculated with Equation 24:

$$ETp = \frac{ETcrop}{1000} * Am \qquad (24)$$

Where,
ETp Potential evapotranspiration maize (m^3/month)
ETcrop Crop evapotranspiration (mm/month)
Am Surface area of the maize field (m^2)

The amount of water supplied by precipitation is called 'Rainfed'. It is the potential evapotranspiration (ETp) minus the irrigation water need (IRR):

$$Rainfed = ETp - IRR \ (if \ ETp > 0) \tag{25}$$

Where,
ETp Potential evapotranspiration maize (m^3/month)
IRR Irrigation water need (m^3/month)

The amount of water available in the farm dam and which can be supplied for irrigation, is called 'Irrigation':

$$Irrigation = IRR \ (if \ S > IRR \ and \ ETp > 0)$$
$$Irrigation = S \ (if \ S < IRR \ and \ ETp > 0) \tag{26}$$

Where,
IRR Irrigation water need (m^3/month)
S Farm dam storage (m^3/month)
ETp Potential evapotranspiration maize (m^3/month)

This leads to the equation for the actual water supply (AWS):

$$AWS = Rainfed + Irrigation \tag{27}$$

This can be written as:

$$AWS = ETp - IRR + IRR \ (if \ S > IRR \ and \ ETp > 0)$$
$$AWS = ETp - IRR + S \ (if \ S < IRR \ and \ ETp > 0) \tag{28}$$

Where,
AWS Actual water supply of maize (m^3/month)
ETp Potential evapotranspiration maize (m^3/month)
IRR Irrigation water need (m^3/month)
S Farm dam storage (m^3/month)

The relation between the actual water supply and the potential evapotranspiration of maize is used to analyse the CWA.
The following equation is used to calculate the CWA:

$$Crop \ Water \ Availibility = \frac{AWS}{ETp} * 100\% \tag{29}$$

Where, the definitions of the parameters are as given in Equation 27 and 28.

The CWA when no dam would be present (0 m^3), is the amount of water only supplied by precipitation in percentage of the potential crop evapotranspiration, and calculated with equation 30:

$$Crop \ Water \ Availibility, no \ dam = \frac{Rainfed}{ETp} * 100\% \tag{30}$$

The CWA is calculated per month and averaged over the study period of five years for the different farm dam capacities and surface areas of the catchment.

On the basis of Equation 23 and 29, the different components of the water balance are estimated. The entire calculation procedure was carried out in an Excel sheet in such a way that farm dam capacities could be changed and different meteorological data can be used. In Chapter 5 the results of the analysis are shown.

5 Results

This chapter describes the results of the analysis. The CWA and the RNF are calculated for the four different farm dam capacities of each scenario, using the approach described in Paragraph 4.4. First, an overview of the CWA and the RNF for a catchment area of 10 ha, followed by an overview for a catchment area of 20 ha.

5.1 Catchment area 10 ha

Table 10 gives an overview of the calculated CWA and RNF for the different storage capacities of one farm dam and for each of the four scenarios. The catchment upstream of the dam has an area of 10 ha.

Table 10
The CWA and RNF for different farm dam capacities and for each of the scenarios. The upstream catchment is 10 ha (Scenario A uses equation (11) and Scenario B-D uses results from the SIMFLOW model).

Farm dam capacity (m^3)	**CWA (%) for scenario**				**RNF (%) for scenario**			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
0	53	53	53	53	100	100	100	100
1050	67	89	88	88	84	79	78	78
3200	71	99	97	97	81	75	73	72
5625	80	100	100	100	77	72	70	69
9900	90	100	100	100	72	67	65	64

The CWA gives the percentage of the potential evapotranspiration of the maize field, in this case 53% (point where CWA crosses y-axes). When water is used from the farm dam, the CWA increases as shown in Figure 19: the value increases to 90% for a farm dam of 9900 m^3 (Table 10). For a farm dam capacity is 0 m^3 (no dam), the RNF Is 100%, meaning no change in river flow. For an increasing capacity of the farm dam the river flow is reduced to 72% (Table 10). The results are plotted in graphs for each scenario and shown in Figure 19 - 22.

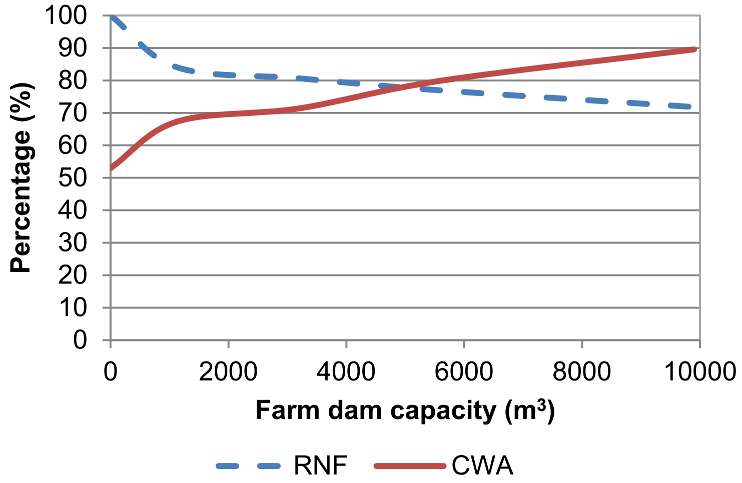


Figure 19
RNF and CWA for different farm dam capacities in case of Scenario A: catchment area = 10 ha.

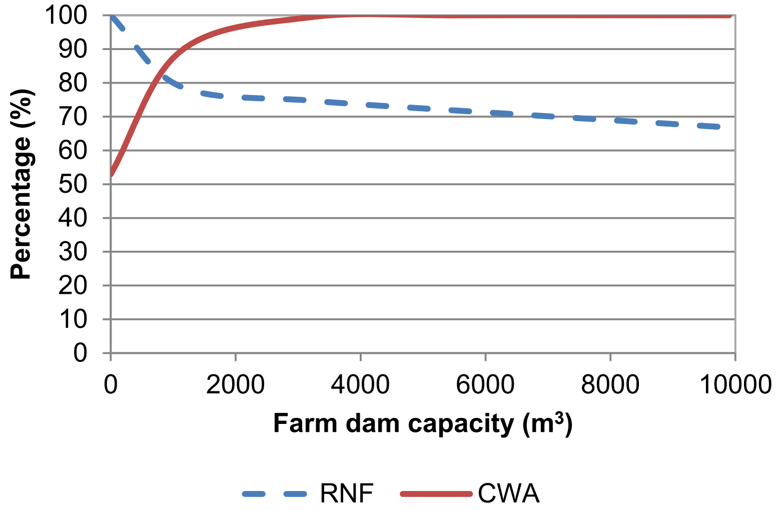


Figure 20
RNF and CWA for different farm dam capacities in case of Scenario B: catchment area = 10 ha, infiltration rate = 40 mm/d.

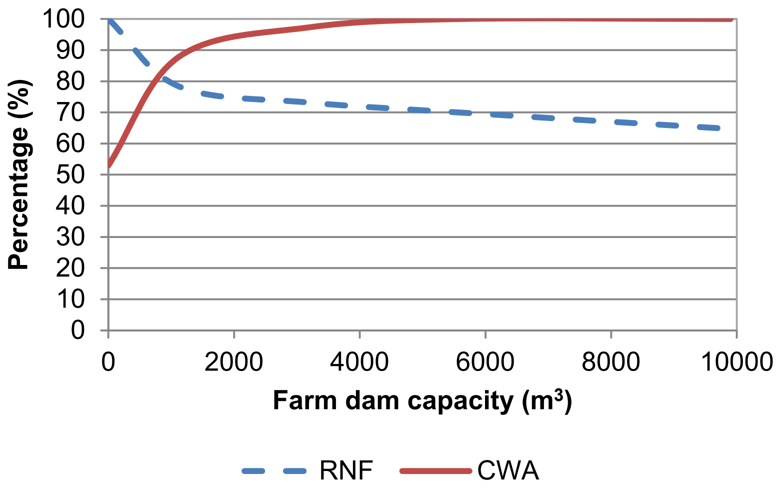


Figure 21
RNF and CWA for different farm dam capacities in case of Scenario C: catchment area = 10 ha, infiltration rate = 50 mm/d.

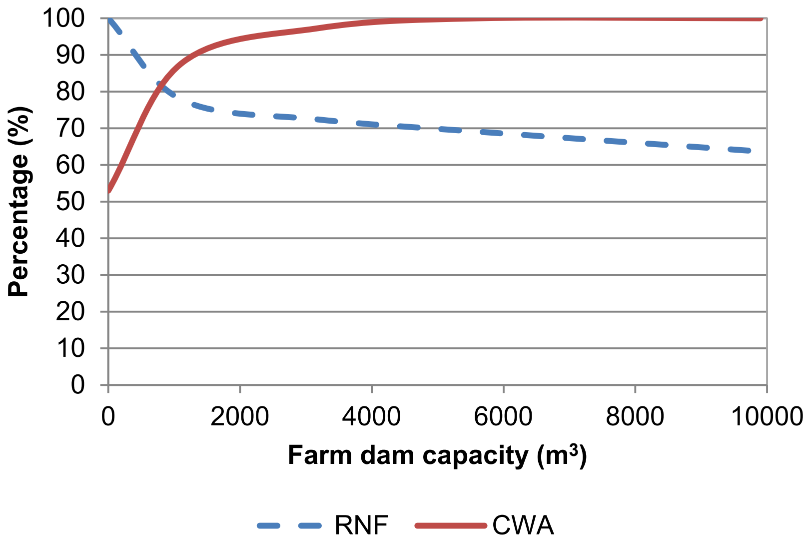


Figure 22
RNF and CWA for different farm dam capacities in case of scenario D: catchment area = 10 ha, infiltration rate = 60 mm/d.

The general trend in the graphs of Figure 19 up to 22 is that the RNF becomes lower with an increasing farm dam capacity. On the other hand, the CWA becomes higher with an increasing farm dam capacity.
The CWA at the point where the capacity of the farm dams is 0 m^3 (no dam present) is the percentage of the potential evapotranspiration of the maize field only supplied by precipitation. This point is for all scenarios the same and calculated at 53% using Equation 30. This is the point in all graphs where the CWA crosses the y-axes.

The RNF at the point where the capacity of the farm dam is 0 m^3 (no dam present) is 100%. There is no overflow from the dam and all the runoff (scenario A) or drainage (scenario B, C and D) from the catchment flows to the downstream sub catchment.

The calculated RNF values of scenario A are at every point higher than the RNF of the other scenarios. The RNF values from scenario D are lower than that of Scenario C and the RNF value of Scenario B is the highest. The CWA values of scenario A are at every point lower than the CWA values of the other scenarios. The CWA values of scenario B are highest and that of scenario C and D are about the same. Table 11 gives information on the farm dam capacity and the RNF at the point where the CWA is 90% for a catchment area of 10 ha.

Table 11
Farm dam capacity and RNF when the CWA is 90% (catchment area is 10 ha).

Scenario	**Farm dam capacity (m^3)***	**RNF (%)****
A	9900	70
B	1200	80
C	1400	75
D	1400	75

*Farm dam capacity (m^3) is rounded to nearest 200 m^3

**RNF (%) is rounded to nearest 5 per cent

The farm dam capacity at the point where the CWA is rounded off at 9,900 m^3. The RNF at this point is rounded off at 70 per cent. In case of scenario B, the farm dam capacity when the CWA is 90% is rounded off at 1,200 m^3. The corresponding RNF becomes 80%. The farm dam capacity for both of scenario C and D is rounded off at 1,400 m^3 for an CWA of 90%. Both RNF values are rounded off at 75%.

5.2 Catchment area 20 ha

Table 12 gives an overview of the calculated CWA and RNF for the different farm dam capacities for a catchment area of 20 ha.

Table 12
CWA and RNF for different farm dam capacities (catchment area is 20 ha).

Farm dam capacity (m^3)	**CWA (%) for scenario**				**RNF (%) for scenario**			
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
0	53	53	53	53	100	100	100	100
1050	68	98	98	98	86	89	89	88
3200	72	100	100	100	84	87	87	86
5625	81	100	100	100	82	86	85	85
9900	90	100	100	100	80	83	82	82

The results are plotted in graphs for each scenario and shown below (Figure 23 - 26).

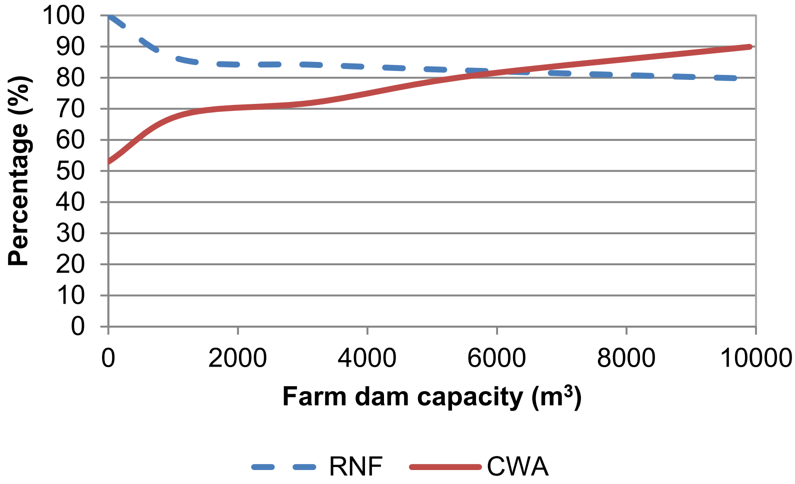


Figure 23
RNF and CWA for different farm dam capacities in case of Scenario A: catchment area = 20 ha.

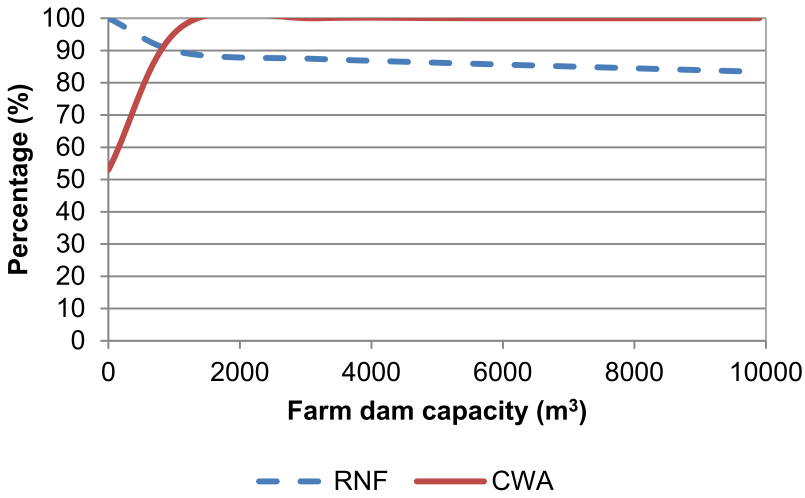


Figure 24
RNF and CWA for different farm dam capacities in case of Scenario B: catchment area = 20 ha, infiltration rate = 40 mm/d.

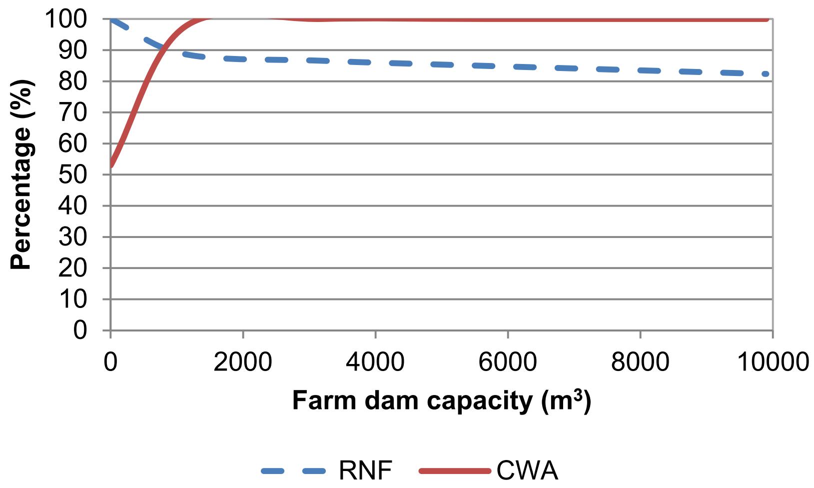


Figure 25
RNF and CWA for different farm dam capacities in case of Scenario C: catchment area = 20 ha, infiltration rate = 50 mm/d.

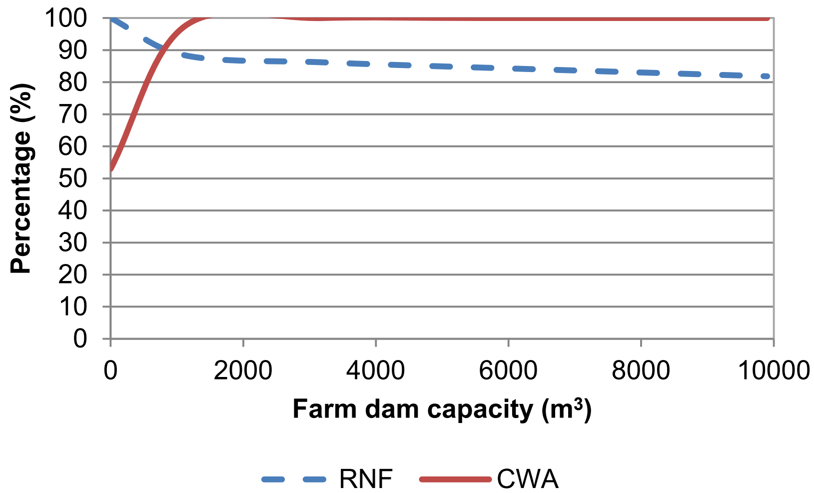


Figure 26
RNF and CWA for different farm dam capacities in case of Scenario D: catchment area = 20 ha, infiltration rate = 60 mm/d.

The general trend in Figures 23-26 is that the RNF becomes lower with an increasing farm dam capacity. On the other hand, the CWA becomes higher with an increasing farm dam capacity. In the situation of rain fed irrigation (no dam present) the CWA gives the percentage of the potential evapotranspiration of the maize field. This point is for all scenarios the same and calculated at 53% using Equation 30. This is the point in all graphs where the CWA crosses the y-axes.

No reduction in the natural flow takes place when no dam is present, and thus the RNF is then considered to be 100%. All the runoff from the catchment flows to the downstream sub catchment.

The calculated RNF values of Scenario A are at every point lower than the RNF of the other scenarios. The RNF values from Scenario B are highest, than that of scenario C and D. The CWA values of Scenario A are at every point lower than the CWA values of the other scenarios. The CWA values of Scenario B, C and D are the same. Table 13 gives information on the farm dam capacity and the RNF when the CWA is 90% (catchment area is 20 ha).

Table 13
Farm dam capacity and RNF when the CWA is 90% (catchment area is 20 ha).

Scenario	Capacity farm dam (m^3)	RNF (%) **
A	9900	80
B	800	90
C	800	90
D	800	90

*Farm dam capacity (m^3) is rounded off to nearest 200 m^3

**RNF (%) is rounded off to nearest 5%

The farm dam capacity at the point where the CWA is 90% in case of Scenario A is the maximum farm dam capacity analysed: 9,900 m^3. The RNF at this point is rounded off at 80%. The farm dam capacity for all scenarios B, C and D are rounded off at 800 m^3 at the point where the CWA is 90%. All RNF values at this point are rounded off at 90%.

6 Discussion

The goal of the study is to analyse the impact of farm dams on the river flow downstream in the LRb. The impact of a farm dam with capacities ranging from 0 (no farm dam) to 9,900 m^3 were compared for catchments with an area of 10 and 20 ha. Four different scenarios for the LRb were considered. They differentiate in the calculation method of the hydrology and in the infiltration rate of the soil. One scenario makes use of the catchment water balance, the other three scenarios make use of the SIMFLOW model to calculate the water inflow component of the farm dam. The scenarios using SIMFLOW differ in the value for the infiltration rate of the soil.

This Chapter first discusses the results related to the RNF. Then results related to the CWA and the point where the CWA is 90% are given. The last paragraph discusses the possible influence of the assumptions made on the results. Important to note is that the results of the analysis are really dependent on the local situation and cannot be generalized.

6.1 Results Remaining Natural Flow

The RNF is used to analyse the impact of a farm dam on the river flow downstream. The reference situation considers a catchment area with no farm dam present. The other situation considers a catchment area (10 or 20 ha) including a farm dam with different capacities used for irrigation of a maize field of 1 ha.

The relative difference between the flow to the downstream sub-catchment with and without the presence of a farm dam for all scenarios is calculated for the different farm dam capacities and is called the RNF. The general trend in the RNF that it becomes lower with increasing farm dam capacities, is due to more water storage in a farm dam larger in size. This results in a reduced overflow to the downstream sub-catchment. This effect is up to the point where the amount of water inflow (runoff and precipitation) is lower than the maximum capacity of the farm dam. At this point, the RNF reaches its minimum and will be a straight line at larger capacities. None of the scenarios reach this point that is larger than the maximum analysed capacity of 9,900 m^3. The point will (probably) be reached at much larger farm dam capacities.

Scenario A that uses the runoff in the catchment to calculate the water inflow of the farm dam has higher RNF values than the other scenarios. This means that the overflow from the farm dam in scenario A is lower than the overflow of the farm dam in the other scenarios. A reason for this could be that the runoff is calculated using the catchment water balance equation (simple approach) and is mainly based on the amount of precipitation and evaporation. When the precipitation is 0 in one month, there is also no runoff in that month resulting in no additional water flow to the dam and a no overflow to the downstream sub-catchment. Using SIMFLOW, in the same month, there is drainage to the farm dam and more overflow to the downstream sub-catchment, even if there is no precipitation. This is probably because SIMFLOW does take into account the storage in the groundwater system.

Scenario B, C and D use SIMFLOW to calculate the drainage in the catchment that represents the water inflow parameter of the farm dam. Scenario B had the lowest infiltration rate: 40 mm/d. Scenario B and C use an infiltration rate of 50 and 60 mm/d respectively.
The calculated RNF is lower when the infiltration rate of the soil is higher. This is caused by the fact that there will be less runoff with a higher infiltration rate, because more water can infiltrate into the soil. It results in a

smaller amount of drainage to the farm dam, leading to a smaller volume of water in the farm dam and a lower amount of overflow to the downstream sub-catchment.

The size of the catchment area has a positive effect on the RNF in all scenarios. A larger catchment area leads to more runoff and drainage to the farm dam, resulting in a higher volume of water in the farm dam and a higher amount of overflow to the downstream sub-catchment (and a higher RNF).

6.2 Results Crop Water Availability

The CWA is used to analyse at which capacity the farm dam meet the crop water requirements. The CWA is defined as relative difference between the crop water requirements and the amount of water supplied by precipitation and irrigation from the farm dam with different capacities.
The CWA at the point where the farm dam capacity is 0 m^3, is calculated at 53%. The crop will only be supplied by precipitation and this covers 53% of the potential evapotranspiration of maize. This is the point in all graphs where the CWA crosses the y-axes.

The general trend in the CWA is that it becomes higher with increasing farm dam capacities. This is due to more water storage in a farm dam with larger capacities, resulting in more water available for irrigation. This effect is up to the point where the water storage in the farm dam is higher than the irrigation water needs of the crop. A larger farm dam capacity will no longer increase the CWA. The CWA will be a straight line at 100% at higher farm dam capacities.
The scenarios using SIMFLOW to calculate the water inflow component of the farm dam all reach this point of 100% for the CWA. Scenario A does reach this point with the maximum analysed capacity of 9,900 m^3. This point will (probably) be reached at higher farm dam capacities.

Scenario A that uses the runoff in the catchment to calculate the water inflow parameter of the farm dam has lower CWA values than the other scenarios. This means that the water availability in the farm dam for irrigation is lower than in the other scenarios. A reason for this could be the calculation method of the water inflow parameter and is already described in Paragraph 6.1.

Scenario B, C and D use SIMFLOW to calculate the drainage in the catchment that represents the water inflow parameter of the farm dam. Scenario B had the lowest infiltration rate: 40 mm/d. Scenario B and C use an infiltration rate of 50 and 60 mm/d respectively. The calculated CWA is lower when the infiltration rate of the soil is higher. The difference between the scenarios is rather small. The effect of a higher infiltration rate is that there will be less runoff, because more water can infiltrate into the soil. It results in a smaller amount of drainage to the farm dam, leading to a smaller volume of water in the farm dam and less water available for irrigation.

The size of the catchment area has a positive effect on the CWA in all scenarios. A larger catchment area leads to more runoff and drainage to the farm dam, resulting in a higher volume of water in the farm dam and a higher amount of water available for irrigation (and a higher CWA). A CWA of 90% is defined as sufficient for maize. The RNF and farm dam capacity at this point are determined for each scenario. The determined farm dam capacity at this point is sufficient to meet most of the crop water requirements.
A larger capacity than at this point could result in a higher CWA, but also in a lower RNF. The higher CWA is assumed to have no impact on the crop growth and yield. In this case, a larger capacity is considered negative on the flow to the downstream sub-catchment.

The farm dam capacities and RNF values are determined from the graphs and therefore rounded to the nearest 200 m^3 and 5 per cent, respectively. Therefore, the farm dam capacities and RNF values for an CWA of 90% are estimations, and cannot be considered as hard figures.
In case of a catchment area of 10 ha and scenario A, the farm dam capacity must be at least 9900 m^3 to meet the crop water requirements. The corresponding RNF is 70%, meaning 70% of the water that will flow to the downstream sub-catchment in case of the absence of a farm dam (reference situation) flows to the downstream sub-catchment in this situation. In case of a catchment area of 10 ha and Scenario B, the farm dam capacity must be at least 1200 m^3 to meet the crop water requirements. The corresponding RNF is 80%. In case of scenario C and D, the farm dam capacities must be at least 1400 m^3, the corresponding RNF is 75%.

In case of a catchment area of 20 ha and scenario A, the farm dam capacity must be at least 9,900 m^3 to meet the crop water requirements, the corresponding RNF is 80%.
In case of a catchment area of 20 ha and Scenario B, C and D, the farm dam capacity must be at least 800 m^3 to meet the crop water requirements, the corresponding RNF is 90%.

The influence of the catchment area on the RNF values of the scenarios is already explained in Paragraph 6.1. The reason why the Farm dam capacities in case of a catchment area of 10 ha must be higher than with a catchment area of 20 ha is that the water inflow parameter of the farm dam is higher when the catchment area is larger. A larger catchment area results in more runoff or drainage to the farm dam, reaching with lower farm dam capacities the point where the CWA is 90%. The RNF is also higher in a larger catchment area, because of the same reason.

6.3 Possible influence of assumptions on the results

The possible influence of the assumptions made in the analysis on the results is shortly discussed for each assumption. The assumption will be stated, followed by the description of the possible influence.

- The site selection procedure of the study area is based on the geographical location and the soil textural class.

The geographical location of the study area is the north-west part of the LRB. The north-west part of the LRb is identified as a region that is in need of water harvesting methods. The soil textural class fine is used to select a region within this north-west part, because these soils are most suitable for farm dams.
Using this selection procedure, there were several potential meteorological regions to be selected. One of these is randomly selected. When another meteorological region would be chosen, the specific values of the RNF and CWA would be different, but the general trend in both, using the different scenarios, would be the same.

- The study area is a small catchment of 10 or 20 ha, there is 1 ha of irrigated maize field and the remaining area is natural. The land use of the upstream catchment is assumed to consist of natural area (85%), and deciduous forest (15%).

The influence of the size of the catchment area is already discussed in Paragraph 6.1 and 6.2.
In this study, maize is chosen as crop to be irrigated. Another crop choice would lead to different values for the extraction for irrigation parameter of the farm dam water balance and to different results. It depends on the crop type what will be the influence. The land use of the upstream catchment of the farm dam has influence on the evaporation parameter of the farm dam water balance and consequently on the results.
It depends on the land use what would be the effect.

- The groundwater inflow and groundwater outflow components from the farm dam water balance of scenario A are considered negligible.

These components are considered negligible in scenario A, because there is no information available on these components for the study area. Besides this, literature also considers these components as negligible. The influence of these components on the results is unknown and must be investigated when needed.

- The change in groundwater storage is likely to be small in relation to the total catchment water balance components and assumed to be zero.

This assumption is made in scenario A and is based on literature. There is no information available for the study area on the change in groundwater storage and must be investigated when needed.

- The drainage component of the SIMFLOW model represents the inflow parameter of the farm dam water balance equation in case of scenario B, C and D.

Scenario B, C and D make use of the drainage output of the SIMFLOW model to calculate the water inflow parameter of the farm dam water balance equation. The drainage in the upstream catchment of the farm dam is calculated with SIMFLOW. SIMFLOW calculates the interaction between the groundwater and surface water. It is a more elaborated method to calculate the water inflow parameter, compared to scenario A. The SIMFLOW model is originally developed for the hydrological situation in the Netherlands. Whether the output of the model is representative for the study area is not analysed. Field measurements in the study area are needed to validate the model for the study area.

- The groundwater level considered in SIMFLOW is estimated at initial condition 4 m below ground level. The drainage resistance of the secondary system and tertiary system is assumed to be 3,000 days and 9,999 days respectively, the depth of the ditches is 4.0 m and 0.5 m respectively

The groundwater level will influence the interaction between groundwater and surface water as calculated with SIMFLOW. The initial groundwater level is assumed to be 4 m below ground level based on expert judgement. The effect of the groundwater level on the results is not analysed and need to be investigated when needed. The drainage resistances are standard for the model. The depth of the ditches is related to the groundwater level and based on expert judgement. The effect of the drainage resistance and depth of the ditches is not analysed and need to be investigated when needed.

- The farm dam capacities are assumed between 1,000 and 10,000 m^3 and at 0 (no dam), 1125, 3,200, 5,625 and 9,900 m^3. The depth of the farm dam is representative for the capacity.

The range in farm dam capacities is based on literature. The five farm dam capacities are chosen within the range. The corresponding depths are based on expert judgement. For each of these capacities, the RNF and CWA are calculated. The values of the RNF and CWA for intermediate capacities are interpolated.
The depth of the farm dam is of real importance for the results. It has influence on the evaporation from the dam surface: a lower depth with the same capacity will result in higher evaporation rates from the farm dam. The exact effect of the depth is not analysed and further research is required when needing this information.

- The Water Use Efficiency (WUE) is assumed to be 70%.

Based on literature, the WUE used in the analysis is 70%. The amount of water losses depends on the local situation and is between the 20 and 40%. 30% is chosen as intermediate value. A lower WUE (more losses) would lead to higher values of the extraction for irrigation parameter of the farm dam water balance. The RNF and the CWA will be lower.

Conclusion

The goal of the research is to quantify the impact of a farm dam on the river flow downstream in a small catchment in the Limpopo River basin, South Africa. A scenario analysis was carried out to determine farm dam capacities in relation to rainfall data and crop water requirements. The entire calculation procedure was carried out in an Excel sheet in such a way that farm dam capacities could be changed and different meteorological data can be used.

Four scenarios of the farm dam water balance are considered using meteorological data of the Shashe sub-basin in the LRb for a period of five years from January 1997 to December 2001. The catchment areas that are analysed are 10 and 20 ha and the farm dam capacities range from 0 to 9,900 m^3. The scenarios differentiate in the method to calculate the water inflow parameter of the farm dam water balance and the levels for the infiltration rate. Scenario A makes use of the catchment water balance to calculate the runoff parameter that represents the water inflow parameter. Scenario B, C and D make use of the SIMFLOW model to calculate the drainage that represents the water inflow parameter. The difference between scenario B, C and D is the infiltration rate of the soil, being 40, 50 and 60 mm/d respectively.

To give answer on the general research question, the RNF used to analyse the impact of a farm dam on the river flow downstream. The river flow downstream will decrease as a result of the farm dam, but the exact amount of reduction strongly depends on the local situation. The impact of a farm dam depends on, among other, the size of the catchment area, farm dam capacity and depth, soil type, infiltration rate of the soil, meteorology, land use and crop water requirements. An increase in the size of the catchment area results in a higher river flow downstream than with smaller catchment sizes. The storage capacity of a farm dam has a negative effect on the river flow downstream, as it will decrease with increasing storage capacities.
The same applies for the infiltration rate of the soil. With higher infiltration capacities, the RNF and river flow downstream will decrease. Using the runoff from the catchment water balance equation instead of, ceteris paribus, the drainage output of the SIMFLOW model, it will result in a lower RNF.
The CWA is used to determine the farm dam capacity and RNF at the point where the farm dam covers 90% of the potential evapotranspiration of maize. The farm dam capacity of scenario A must be at least 9,900 m^3 for both catchment areas. The RNF for catchment areas of 10 and 20 ha are 70% and 80%, respectively. The farm dam capacity of scenario B must be at least 1200 m^3 with a RNF of 80% to reach the 90% in case of a catchment area of 10 ha. The farm dam capacities of scenario C and D are 1400 m^3 with a RNF of 75%. In case of 20 ha, all three scenarios have the same value for the farm dam capacity: 800 m^3. The corresponding RNF is 90%.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation Drainage Paper no. 56, FAO, Rome, Italy, 300 pp.

Andersson, J.C.M, A.J.B. Zehnder, J. Rockström and H. Yang, 2011. Potential impacts of water harvesting and ecological sanitation on crop yield, evaporation and river flow regimes in the Thukela River basin, South Africa. Agricultural Water Management 98 (7), pp. 1113-1124.

AgriInfo, 2011. Website: http://agriinfo.in/default.aspx?page=topic&superid=8&topicid=76, Accessed July 2012.

AWR, 2005. Website: http://www.water.gov.au/Glossary.aspx, accessed 24 April 2012.
Batjes, N.H., 2004. SOTER-based soil parameter estimates for Southern Africa. Report 2004/04. ISRIC - World Soil Information, Wageningen.

Batchelor, C., Singh, A., Mohan Rao, R., Butterworth, J., 2002. Mitigating the potential unintended impacts of water harvesting. In: IWRA International Regional Symposium "Water For Human Survival", Hotel Taj Palace, New Delhi, India.

CEC, 1985. Soil Map of the European Communities (1:1,000,000). Report EUR 8982, Office for Official Publications of the European Communities, Luxembourg.

CAWMA, 2007. Water for food, Water for life: Comprehensive Assessment of Water Management in Agriculture. Earthscan, London.

Durga, R.K.H.V. and M.K. Bhaumik, 2003. Spatial Expert Support System in Selecting Suitable Sites for Water Harvesting Structures - A Case Study of Song Watershed, Uttaranchal, India. Geocarto International 18, pp. 43 - 50.

Ernst, L.F., 1978. Drainage of undulating sandy soils with high groundwater tables. Journal of Hydrology, Vol 39, pp. 1-50.

FAO, 1986. Irrigation Water Management: Irrigation water needs by C. Brouwer and H. Heibloem. Training manual no. 3.

FAO (Food and Agriculture Organization), 1991. A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production by Will Critchley - Conservation Agronomist Centre for Development Cooperation Services Free University, Amsterdam and Klaus Siegert - Water Resources Engineer Land and Water Development Division FAO, Rome with contributions from: C. Chapman, FAO Project Manager M. Finkel, Agricultural Engineer, Yoqneam, Israel; Food and agriculture organization of the United Nations, Rome, 1991.

FAO, 2004. Drought impact mitigation and prevention in the Limpopo River Basin: A Situational Analysis. Land and Water Discussion Paper Vol.4. Food and Agriculture Orgnisation of the United Nations, Rome, Italy.

FAO, 2009. How to feed the world in 2050? Policy brief of the High-level expert forum in Rome Global agriculture toward 2050. Rome, 12-13 October 2009. Rome: FAO.

FAO and ISRIC, 2003. Soil and Terrain database for Southern Africa (1:2 million scale). FAO Land and Water Digital Media Series 25, ISRIC and FAO, Rome.

Fox, P. and J. Rockström, 2000. Water Harvesting for Supplemental Irrigation of Cereal Crops to Overcome Intraseasonal Dry-spells in the Sahel. Physics and Chemistry of the Earth, Part B Hydrology, Oceans and Atmosphere 25 (3), pp. 289-96.

Hudson, N.W., 1987. Soil and water conservation in semi-arid area. FAO Soils Bulletin 57.

Kahinda, J.M., J. Rockström, A.E. Taigbenu and J. Dimes, 2007. Rainwater harvesting to enhance water productivity of rainfed agriculture in semi-arid Zimbabwe. Physics and Chemistry of the Earth 32 (2007) pp. 1068 - 1073.

Limpopo Basin Permanent Technical Committee (LBPTC), 2010. Joint Limpopo River basin Study Scoping Phase. Final Report. BIGCON Consortium.

Mbilinyi, B.P., S.D. Tumbo, H.F. Mahoo, E.M. Senkondo and N. Hatibu, 2005. Indigenous knowledge as decision support tool in rainwater harvesting. Physics and Chemistry of the Earth 30, pp. 792-798.

Meigh, J., 1995. The impact of small farm reservoirs on urban water supplies in Botswana. Natural Resources Forum. Vol. 19 No. 1, pp. 71-83.

Nathan, R. and L. Lowe, 2012. The hydrologic impacts of farm dams. Australian Journal of Water Resources, Vol. 16, No. 1, pp. 75-83

Ngigi, S.N., 2003. Rain water harvesting for Improved Food Security. Promoting Technologies in the Greater Horn of Africa. Greater Horn of Africa Rainwater Partnership (GHARP). Kenya Rainwater Association (KRA).

Oweis, T. and A. Hachum, 2006. Water-harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agric. Water Manage., 80, 7-73.

Pachpute, J.S., D. Tumbo Siza, H. Sally and M.L. Mul,2009. Sustainability of Rainwater Harvesting Systems in Rural Catchment of Sub-Saharan. Afr. Water Resource Management, 23.

Prinz, D. and A.K. Singh, 2000. Technological Potential for Improvements of Water Harvesting Study for the World Commission on Dams, Cape Town, South Africa. Report: Dams and Development.

RAK, 2012. Website: http://www.limpoporak.com/, Accessed May 2012

Rockström, J., 2000. Water resources management in smallholder farms in Eastern and Southern Africa: an overview. Phys. Chem. Earth Part: B 25 (3), 275-283.

Rockström, J., J. Barron and P. Fox, 2002. Rainwater management for increased productivity among smallholder farmers in drought prone environments. Phys. Chem. Earth 27, pp. 949-959.

Rockström, J., J. Barron and P. Fox, 2003. Water productivity in rainfed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agro-ecosystems. In: Kijne, W.J., R. Barker and

D. Molden, (Eds.). Water Productivity in Agriculture: Limits and Opportunities for Improvement, Comprehensive Assessment of Water Management in Agriculture, No. 1. CABI Publishing, Wallingford, UK, pp. 145 - 163.

Rockström, J., N. Hatibu, T.Y. Oweis, S. Wani, J. Barron, A. Bruggeman, J. Farahani, L. Karlberg and Z. Qiang, 2007. Managing water in rainfed agriculture. In Molden, David (Ed.). Water for food, water for life: A Comprehensive Assessment of Water Management in Agriculture. London,UK: Earthscan; Colombo, Sri Lanka: IWMI. pp. 315-352.

Querner, E.P., J.B.M. van Acker and R.P. Moens, 2000. Analysis of catchment response for regional water systems in the Netherlands. In: River Flood Defence, Int. Symposium on River Flood Defence (ed. F. Toensmann and M. Koch), Kassel. Sept 2000: pp. C-51 - C-58.

Querner, E.P. and P.J.T. van Bakel, 1989. Description of the regional groundwater flow model SIMGRO*;* Rapport 7. DLO-Staring Centrum, Wageningen.

Samuels, W.B. and D.E. Amstutz, 2009. Using HydroSHEDS and GeoSFM to Calculate River Discharge, Proceedings. International Perspective on Environmental and Water Resources, January 5-7, 2009, Bangkok, Thailand.

SRTM, 2011. Website: http://www2.jpl.nasa.gov/srtm, Accessed 15 Oct 2011.

USGS, 2011. Website: http://hydrosheds.cr.usgs.gov, Accessed 15 Oct 2011.

Vohland, K. and B. Barry, 2009. A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. Agric. Ecosyst. Environ. 131 (3-4), pp. 119-127.

Wanders, N., H.A.J. van Lanen en A.F. van Loon, 2010. Indicators for drought characterization on a global scale. Tech. rept. 24. EU WATCH (Water and global Change) project.

Weedon, G.P., S. Gomes, P. Viterbo, H. Osterle, J.C. Adam, N. Bellouin, O. Boucher and M. Best, 2010. The WATCH Forcing Data 1958-2001: A Meteorological forcing dataset for land surface- and hydrological mo*dels.* Tech. rept. 22. EU WATCH (Water and global Change) project.

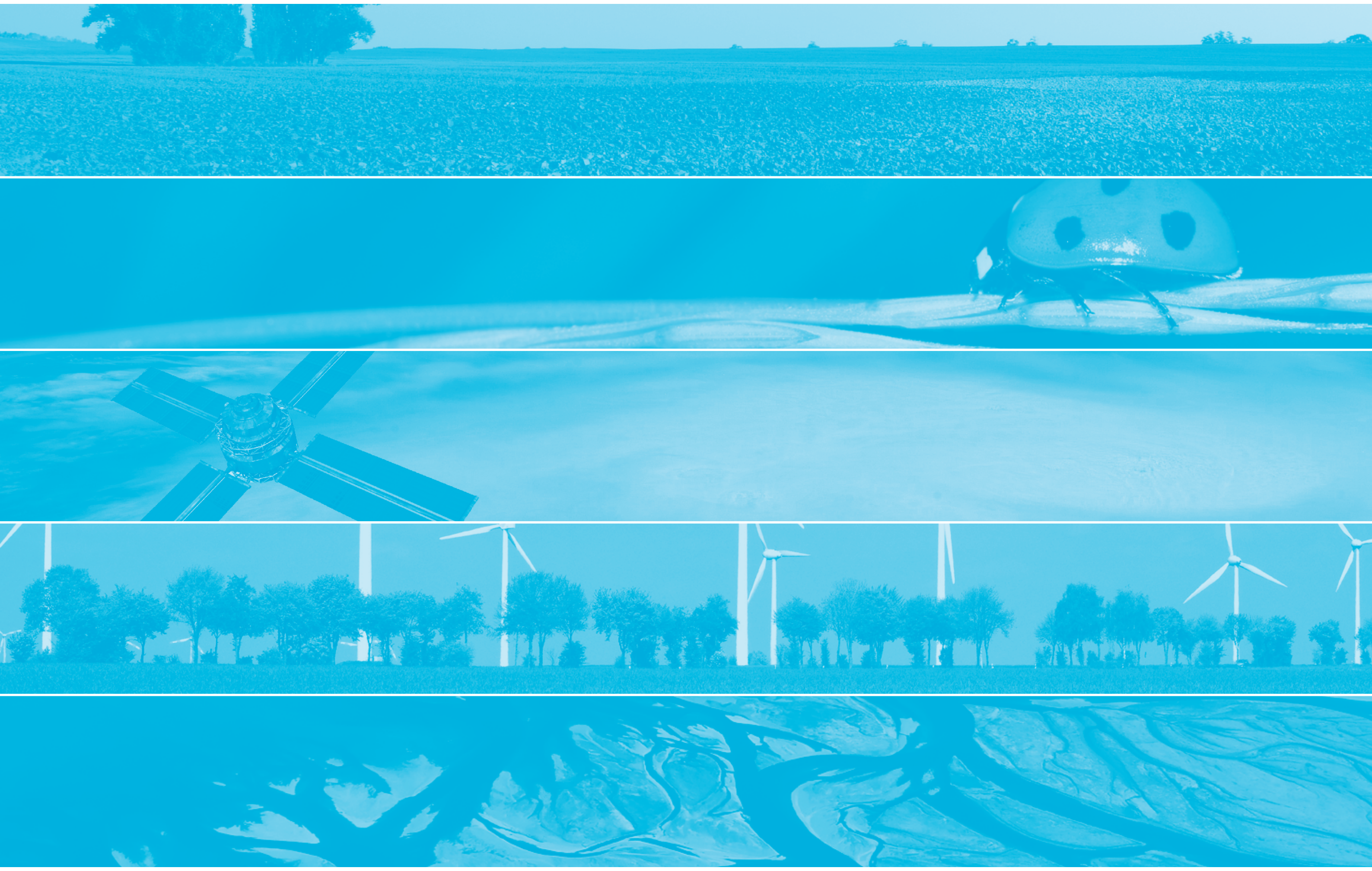
Wolters, W.,1992. Influences on the efficiency of irrigation water use. International Institute for Land Reclamation and Improvement. Publication 51, Wageningen, The Netherlands

Appendix 1 Assumptions made in the analysis

Below a list is given a list of the assumptions made in this study.

- The site selection procedure of the study area is based on the geographical location and the soil textural class.
- The meteorological data used from region 211 is representative for dry areas in the LRb.
- There is no farm dam present in the upstream catchment.
- The farm dam capacities with corresponding depths and the correction factor of 1.3 from equation 1 are determined based on expert judgement.
- The study area is a small catchment of 10 or 20 ha, there is 1 ha of irrigated maize field and the remaining area is nature. The land use of the upstream catchment is assumed to consist of grassland (75%), maize (not irrigated, 10%) and deciduous forest (15%) .
- The groundwater inflow and groundwater outflow components from the farm dam water balance of scenario A are considered negligible.
- The change in water storage is likely to be small in relation to the total catchment water balance components and assumed to be zero.
- The runoff component from the catchment water balance equation represents the inflow parameter of the farm dam water balance equation in case of scenario A.
- The drainage component represents the inflow parameter of the farm dam water balance equation in case of scenario B, C and D.
- The soil type of the catchment used in SIMFLOW is defined as clay on sand.
- The groundwater level considered in SIMFLOW is estimated at 4 m below ground level.
- The seepage rates as function of the groundwater were based on expert judgement.
- The drainage resistance of the secondary system and tertiary system is assumed to be 3,000 days and 9,999 days respectively, the depth of the ditches is 4.0 m and 0.5 m respectively
- The infiltration capacities are variable and defined at 40, 50 and 60 mm/d.
- The farm dam capacities are assumed between 1,000 and 10,000 m^3 and are chosen at 0 (no dam), 1,125, 3,200, 5,625 and 9,900 m^3.
- The depth of the farm dam is representative for the capacity.
- The main crop is maize and the extraction for irrigation is calculated using the Kc factors, crop development stages, sowing date and calculation method according to the guidelines for irrigation water needs (FAO, 1986).
- The Water Use Efficiency (WUE) is assumed to be 70%.
- The RNF is used to analyse the impact of the farm dam on the river flow in the downstream sub-catchment.

The CWA is used to analyse at which farm dam capacity the dam can meet the irrigation water needs of maiz



Alterra is part of the international expertise organisation Wageningen UR (University & Research centre). Our mission is ‘To explore the potential of nature to improve the quality of life’. Within Wageningen UR, nine research institutes – both specialised and applied – have joined forces with Wageningen University and Van Hall Larenstein University of Applied Sciences to help answer the most important questions in the domain of healthy food and living environment. With approximately 40 locations (in the Netherlands, Brazil and China), 6,500 members of staff and 10,000 students, Wageningen UR is one of the leading organisations in its domain worldwide. The integral approach to problems and the cooperation between the exact sciences and the technological and social disciplines are at the heart of the Wageningen Approach.

Alterra is the research institute for our green living environment. We offer a combination of practical and scientific research in a multitude of disciplines related to the green world around us and the sustainable use of our living environment, such as flora and fauna, soil, water, the environment, geo-information and remote sensing, landscape and spatial planning, man and society.

More information: www.wageningenUR.nl/en/alterra