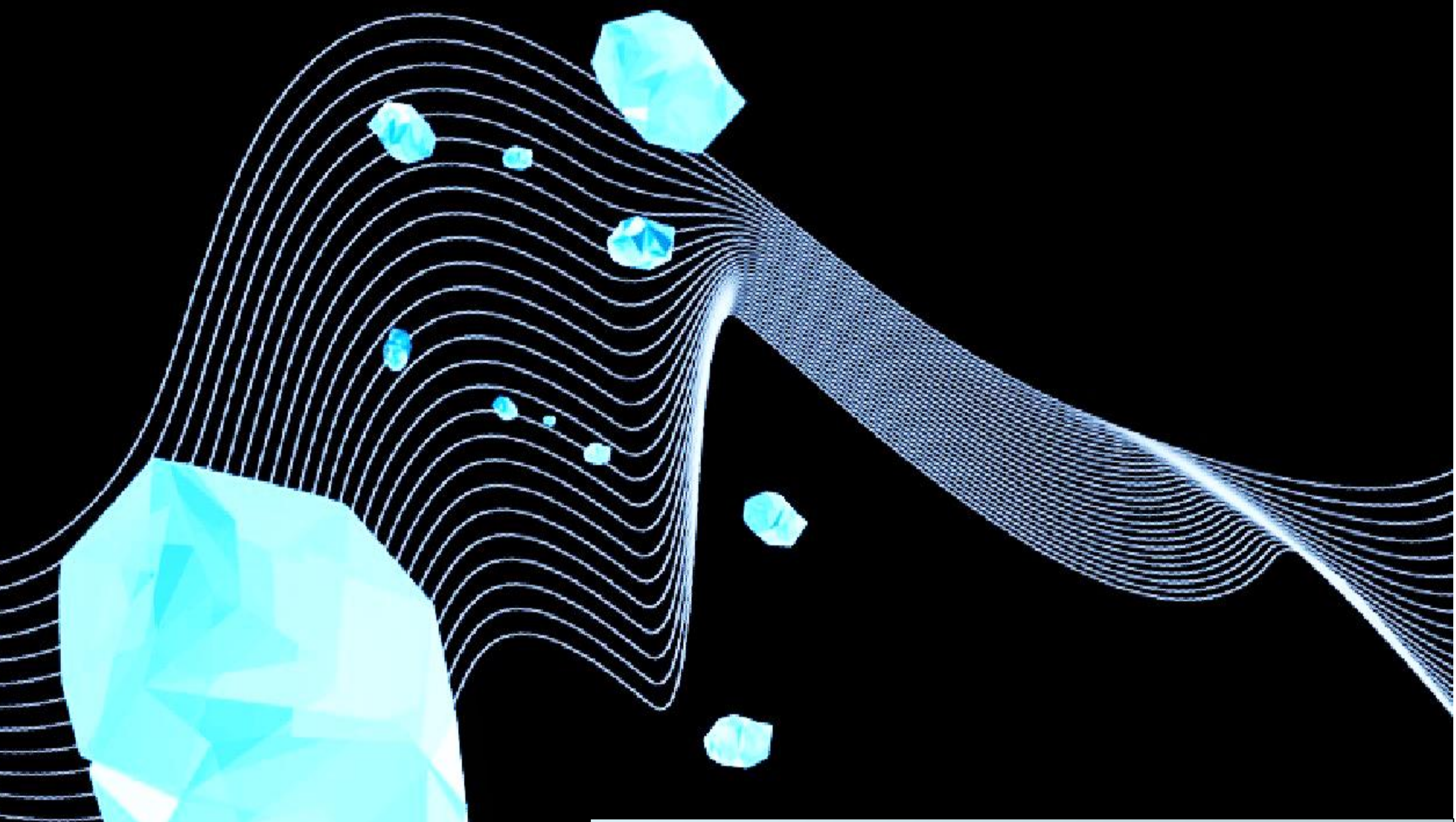

MASTER THESIS

THE BLUE WATER FOOTPRINT AND LAND FOOTPRINT OF WATER STORAGE SYSTEMS

An analysis of the evaporation losses from differently sized water storages within a semi-arid catchment

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April 2018

UNIVERSITY OF TWENTE.

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Master thesis in Civil Engineering and Management

Faculty of Engineering and Technology
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University of Twente

April 2018

Version 1.0

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I LIST OF ABBREVIATIONS

Abbreviation	Initial word, name or phrase
BREB	Bowen ratio energy balance
CRU	Climatic Research Unit
ECA&D	European Climate Assessment & Dataset
ECMWF	European Centre for Medium-Range Weather Forecasts
FAO	Food and Agriculture Organization
GIS	Georeferenced Information Systems
GLWD	Global lakes and wetlands database
GPCC	Global Precipitation Climatology Centre
GRanD	Global Reservoir and Dams
ICOLD	International commission of large dams
IRR	Irrigational purposed storage
IWMI	International Water Management Institute
MP	Multi-purposed storage
WRD	World register of dams

II LIST OF SYMBOLS

Symbol	Meaning	Unit
$A_{(res)}$	Surface area of a storage	m^2 or ha
$A_{catchment}$	Catchment area of a storage	m^2 or ha
$A_{res,max}$	Maximum surface area of a storage	m^2 or ha
BWF	Blue water footprint	m^3 / m^3
CN	Water demand for cultivating crops	m
c_s	Volumetric heat capacity of the soil	MJ / m^3 / K
D	Depth	m
$d_{irrigation}$	Country's distribution percentage of irrigational water use	%
d_{other}	Country's distribution percentage of non-irrigational water use	%
dpt	dew point temperature	K or °C
E	Evaporation	m
e_a	Actual vapour pressure	kPa
e_s	Mean saturation vapour pressure	kPa
ET	Evapotranspiration	m
f(w)	Wind function	m/s
G	Heat flux	MJ / m^2
h	Storage height	
IRR land use	Land use distribution directed to irrigation	%
l	Storage length	m
LF	Land footprint	m^2 / m^3
LWR	Long wave radiation	W / m^2
n	Time at time step n	$hours^{-1}$ or day^{-1}
P	Precipitation	m
Qin	Inflow volume into a water storage	m^3
Qout	Outflow out of a water storage	m^3
$Q_{s(eepage)}$	Seepage flow out of a water storage	m
R^2	Goodness of fit / explained variance	(-) or %
R_n	Net radiation	KJ / m^2
S	Storage	m^3
SWR	Short wave radiation	W / m^2
T_a	Air temperature	K or °C
T_{max}	Maximum temperature	K or °C
T_{mean}	Mean temperature	K or °C
T_{min}	Minimum temperature	K or °C
u	Amount of storage within a system	(-)
V	Volume	m^3
w	Storage width	m
w_n	Resultant of the U and V wind	m/s
WA	Water abstraction	m^3
z	Water depth	m
γ	Psychrometric constant	kPa / °C
δ	Slope of the temperature saturation water vapour curve at T_a	kPa / °C
λ	Latent heat of vaporization	MJ / kg

III PREFACE

This thesis has been written to complete my master study in Civil Engineering and Management at the University of Twente. The idea that this study could make a small contribution to the world, had me excited from the start. Despite the expected, frequent struggles I had to face during the graduation process, I enjoyed the challenge of putting the pieces together. Looking back on the master and the graduation project I took pleasure in gaining a great deal of knowledge. Learning about the magnitude of the influence of water scarcity and the difficulties in regulating the division of water, is what inspired and motivated me to work more in the field of climate change adaptation.

What also motivated me was the help of my supervisors from the University of Twente. I would like to thank Abebe Chukalla and Arjen Hoekstra for their time, feedback, suggestions and inspiration. Furthermore, I would like to thank my office colleagues, friends and family, whom I very much appreciate and, who helped me throughout the graduation process. Finally, I would like to thank Rosalyn, for her love and support.

After working long and hard on this thesis, the final report is here. I hope you enjoy your reading!

Alex Bos

Enschede, April 2018

IV SUMMARY

Water scarcity is a global challenge, affecting billions of people around the world. At the global level, enough freshwater is available to meet a rising demand, however, spatial and temporal variations are large, resulting in a lack of water availability. By capturing water in times of excess and releasing water in times of deficit, implementing water storages is a promising part of the solution. On the contrary, stored water is exposed to evaporation, leading to losses of the available water resources. Therefore, more knowledge is required about the quantities of the water losses occurring with different systems of storing water. The aim of this study is to estimate the differences in blue water footprints and land footprints between water storage systems consisting of multiple decentralized small-sized water storages and centralized large-sized reservoirs used for water supply.

The blue water footprint is expressed as the ratio between the evaporative water losses and the total available withdrawable water in m^3/m^3 over a period of time. The land footprint is expressed as the area required for the available withdrawn water to be stored in m^2/m^3. The evaporation calculation is based on the method of Finch (2001). The blue water footprint and land footprint calculations were performed using a storage water level fluctuation model with multiple in- and outflows from the storages within four systems. Moreover, the calculations were performed for six scenarios. Three scenarios consisting of irrigational purposed storages and three scenarios consisting of multi-purposed storages were analysed, differing in amount of precipitation during the year from a dry to a wet year. From the irrigational purposed storage systems water is only abstracted during the 100-day cropping season. For the multi-purposed storage systems water abstraction occur year-round. The total yearly water abstractions are kept equal for all scenarios.

The systems are based on the Challawa reservoir (Global Water System Project, 2017), located in Nigeria and multiple small-scale water harvesting storages (Hagos, 2005; Rämi, 2003). The climatological data of Challawa reservoir from 1997 to 2016 were retrieved from the ERA-Interim database (ECMWF, 2017). System 1 has the largest inflow volume and maximum surface area, water depth and water volume per storage unit, followed by system 2, system 3 and, respectively, system 4. The total maximum volume and inflow volumes are however equal for all four systems. System 1 is assumed to have one large storage. The second system is designed to have 64 medium-large storages, the third system consists of 3,950 medium-small storages and the fourth system consists of 252,000 small-sized storages.

The storage water level fluctuation was similar for all four storage systems. Even though the systems have different dimensions, resulting in lower volumes and depths, the systems followed almost the same pattern throughout the year. More decentralized systems consisting of smaller storages were more often empty within the year than centralized systems consisting of larger storages. The differently purposed scenarios showed different storage water level fluctuations throughout the year, however both scenarios were empty during part of the cropping season under normal precipitation conditions. The multi-purposed storage systems also showed empty storages just before the raining season. The dry, normal and wet year showed yearly precipitations of 268 mm, 386 mm respectively 464 mm. As a result, the storages were more often empty during the dry year than during the wet year.

Under normal precipitation conditions, for irrigational purposed water storage systems 15% to 30% of the total seasonal water abstractions is lost through evaporation. For multi-purposed water storage systems 12% to 24% of the total annual water abstractions is lost through evaporation. For both the irrigational purposed and multi-purposed water storage systems, under normal precipitation conditions, 0.12 to 0.39 square meter is required to abstract one cubic meter of water.

It can be concluded that the, seasonal and yearly, blue water footprint and land footprint are positively correlated with the amount of storages within a storage system. This correlation happens for three reasons. Firstly, with aggregated water capacities being equal for all four systems, the probability of water supply, and thus the amount of abstracted water, is lower for systems consisting of many smaller storages than for systems consisting of fewer large reservoirs. Additionally, this correlation becomes stronger due to the occurrence of water partly not being captured from the land by the storages. This occurs more often in systems consisting of many smaller storages. Thirdly, the systems differ in flatness of the storages. The flatter (depth / surface area) the storages are, the more evaporation relatively occurs, resulting in higher blue water footprints and land footprints for water storage systems consisting of smaller, decentralized storages than systems consisting of larger, centralized storages. The blue water footprint and land footprint of a storage system consisting of one large-sized reservoir is about twice as low as the blue water footprint and land footprint of a storage system consisting of many small-sized storages.

Furthermore, it can be concluded that the be the blue water footprints are higher for irrigational purposed storages than for multi-purposed storages. Moreover, the blue water footprint and land footprint are positively correlated with yearly precipitation. These correlations occur due to differences in probability of water supply. The probability of water supply is strongly correlated with yearly precipitation.

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1 INTRODUCTION

Water scarcity is a global challenge, affecting every continent around the world. Water scarcity is defined as a situation in which water demand approaches (or exceeds) the available water supply. It is estimated by the International Water Management Institute (IWMI) (2000) that 1.2 billion people live in areas of physical water scarcity. In addition, there is a group of 500 million people whom live in areas approaching physical water scarcity. Another 1.6 million people are coping with with economic water scarcity on a daily basis, where water is available, but human capacity or financial resources limit access (Cooley, et al., 2014). Hoekstra and Mekonnen (2016) took seasonal fluctuations in water consumption and availability into account and stated that 66% of the global population (4.0 billion people), living from 1996-2005, lived under conditions of severe water scarcity at least one month of the year.

Much research has been conducted on assessing and reducing water scarcity. Research of the past sixty years has drawn attention to the development of large-scale physical infrastructure, such as dams and reservoirs. In the 1990's it became increasingly recognized that technology and infrastructure were not sufficient solutions by themselves, therefore aiming towards governing water more effectively became more urgent (Cooley, et al., 2014; van der Zaag & Gupta, 2008). Since the beginning of the twenty-first century acknowledgment has grown on the scope of water-related challenges to be spatially extending further than national and regional boundaries. Water is shared and exchanged by people around the world directly and indirectly through natural hydrologic systems and global trade (Hoekstra A. , 2006; Cooley, et al., 2014).

At the global level and on an annual basis, enough freshwater is available to meet a rising demand, but spatial and temporal variations of water demand and availability are large, leading to water scarcity in several parts of the world during specific times of the year. A solution to level availability of water is to make use of water storages. Water storages, such as reservoirs, ponds, tanks and aquifers, capture water in times of excess and store it until the water is used in times of deficit. Thereby water storages increase the availability of water throughout the year. Yet, when water is stored, approximately up to half of it may be lost due to evaporation leading to a huge waste of the water resources (Maestre-Valero, Martinez-Granados, Martinez-Alvarez, & Calatrava, 2013). Until this day, different opinions exist on strategies of using water storages effectively.

1.1 Problem definition

Stored water is exposed to evaporation, leading to losses of the available water resources (FAO, 2016). Multiple studies have shown that manmade water storages are water consumers (Knook, Hoekstra, & Hogeboom, 2016). However, these studies only focus on large water storages, or reservoirs. Other, often smaller, forms of water storages, such as ponds, earth dams, tanks, rain water harvesting systems and aquifers, exist, but their water losses have not been quantitatively compared to the water losses of reservoirs. As a result, it is still unknown how much the water footprint and land footprint between different forms of water storage differ.

1.2 Objective and research questions

The objective of this research is to estimate the differences in the blue water footprints and in land footprints between water storage systems consisting of multiple decentralized small-scale water storages and centralized large-scale reservoirs used for water supply.

In consequence, the following research question will be discussed in this thesis:
"What are the differences in blue water footprints and land footprints between multiple water storage systems with differently sized water storages used for water supply?"

The main research question has been divided in three sub questions:

1. What are the dimensions of water storages of different water storage systems?
2. How large are the **seasonal** blue water footprints, measured in evaporation per water abstraction, and land footprints, measured in the required storage area per water abstraction, differences between the different systems with irrigational purposes only?
3. How large are the **yearly** blue water footprints, measured in evaporation per water abstraction, and land footprints, measured in the required storage area per water abstraction, differences between the different systems with irrigational, domestic and industrial water abstraction?

1.3 Defining the blue water footprint and land footprint

A method to estimate water demands, or water consumption, is called the water footprint analysis. The water footprint analysis measures the amount of water used to produce each of the goods and services we use. The water footprint can also tell how much water is being consumed by a particular country – or globally – in a specific river basin or from an aquifer. The water footprint looks at both direct and indirect water use of a process, company or sector and includes water consumption throughout the full production cycle from the supply chain to the end-user. The water footprint has three components: green, blue and grey water footprint. Green water footprint is water from precipitation that is stored in the root zone of the soil and is evaporated, transpired or incorporated by plants. Blue water footprint is water that has been sourced from surface or groundwater resources and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time. Grey water footprint is the amount of fresh water required to assimilate pollutants to meet specific water quality standards (Water Footprint Network, sd).

Another scarce resource in land. Competition for land is expected to enlarge during the coming decades due to multiple drivers similar to water scarcity drivers. Food production, for which a large percentage of land is reserved, is expected to be needing to double to keep up with the increasing demand (De Ruiter, et al., 2017). The land footprint is an indicator used to measure the amount of land used to produce the goods and services consumed by a country or region (Schutter & Lutter, 2016).

In this research the blue water footprint and land footprint of different water storages used for water supply are quantified. The blue water footprint is expressed as the ratio between the evaporative water losses and the total available withdrawable water in m^3/m^3 over a period of time. The land footprint is expressed as the area required for the available withdrawn water to be stored in m^2/m^3.

1.4 Theoretical background

Although water footprint and land footprint are far broader concepts, this research focusses on assessing the blue water footprint and land footprint of different water storage systems. This paragraph gives an overview of the share of water storages within the water cycle and their different forms. Furthermore, this paragraph describes different evaporation calculation methods and climatological databases that are required to support the evaporation calculations.

1.4.1 The water cycle

Water scarcity is caused by (and growing due to) multiple water demand and supply factors. One of the causes of water scarcity is evaporation, a process that is at the head of the water cycle. Water evaporates at one location and comes back in the form of precipitation at another location at a different time. The net precipitation, the precipitation minus the evaporation, becomes runoff. The runoff partly flows through surface water channels and partly through the ground water channels (subterranean flow). Between the water channels, water storages are located. Within a water storage system, the change in storage is determined by the difference between the in- and outflows. Inflow comes from direct precipitation above the storage and inflow from upstream runoff (through subterranean and surface water channels). Flows leaving the water storage can be categorized into evaporation, seepage, discharge through the outlet point and water abstractions by organisms. All in- and outflows of a water system together form the water balance of the system (Hoekstra A. , 2011). The water balance of a water storage system is given in Figure (Austin, 2017).

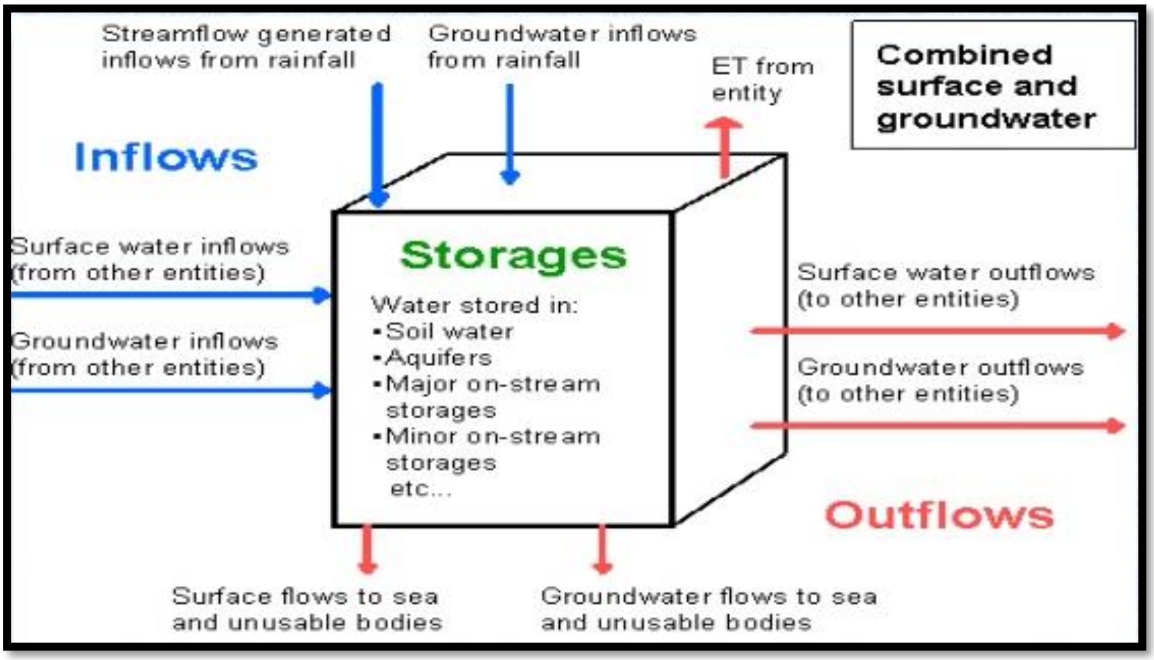


FIGURE 1 WATER BALANCE OF A STORAGE SYSTEM (AUSTIN, 2017)

1.4.2 Overview of different forms of storing water

The IWMI (2000) suggests that a mixture between small and large reservoirs, along with effective aquifer management, can provide efficient solutions for conserving water and increasing its productivity. Cosgrove & Rijsberman (2000) have a similar viewpoint and discuss traditional small-scale water storage techniques, rainwater harvesting and water storage in wetlands as additional options. On the contrary, Van der Zaag & Gupta (2008) argue that it is unclear whether “storage capacity should be centralized in the form of conventional large reservoirs and large interbasin water transfer schemes, or decentralized and distributed in the farmers’ field and at the level of the microwatershed and village or whether a combination of these two extremes is most suitable”.

Water is stored for water harvesting. For water harvesting different systems exist that differ in scale of storage and usage of stored water. Van der Zaag & Gupta (2008) make a distinction between systems of water harvesting based on the source of the water and the medium in which the water is stored (see Table 1).

Small and large are relative measurement terms. IWMI (2000) distinguishes small storages from large storages by looking at the structure heights of dams and the storage volumes. They considered reservoirs small if the structure height is less than 15 meters and the volume is less than 0.75 million cubic meters. If one or more of these components of a reservoir is larger, the reservoir is considered large.

TABLE 1 DIFFERENT FORMS OF WATER STORAGE (VAN DER ZAAG & GUPTA, 2008)

	Water source	
Storage Medium	Rainfall	Surface Water
Saturated Zone	• Aquifer storage of seepage "losses" from impoundments.	• Aquifer storage from artificial recharge; sand dams.
Unsaturated Zone	• Rainwater harvesting through plant spacing, ploughing along the contour, ridges and bunds, and terracing.	• Runoff harvesting from adjacent uncultivated plots, compound areas, roofs and roads directly onto cropped fields.
Container	• Runoff harvesting from adjacent uncultivated plots, compound areas, roofs, and roads into a pond, tank or reservoir.	• Impounding river flow in small, medium and large reservoirs, both in stream and off channel.

Van der Zaag & Gupta (2008) make a distinction between two systems (centralized and decentralized) that are comparable in number of beneficiaries in the arid and semi-arid regions. The decentralized system is using 2000 on-farm tanks with a capacity to store 500 m^3 of water each. The centralized system is using one (centralized) reservoir with a capacity to store 50 million m^3 of water. In Table 2 multiple existing small-scale water harvesting storages are given.

TABLE 2 MULTIPLE EXISTING SMALL-SCALE WATER STORAGE FORMS

Name	**Location**	**Catchment area (ha)**	**Surface area (ha)**	**Depth (m)**	**Volume (m^3)**	**Source**
Water for food movement	South Africa	0.5 - 2	-	-	50-500	(van der Zaag & Gupta, 2008)
War on hunger	Kenya	0.5 - 2	-	-	50-500	(van der Zaag & Gupta, 2008)
On-farm storages	Queensland, Australia	(125,000)	-	-	(2.5 * 10^9)	(Martinez-Granados, 2011)
AWRs	Segura basin	-	0.1 – 3 mean = 0.32	5 – 10	42,700	(Martinez-Granados, 2011)
Earth dams	Ethiopia	950	17.6	9.0 – 24.0	50.7 * 10^6	(Hagos, 2005)
Farm ponds	Ethiopia	-	0.014	3	180	(Rämi, 2003)
Percolation ponds	-	4-5	-	-	10,000 – 15,000	(Sivanappan, 2017)
System tanks	Peninsular India	-	1,05 - 60	1.5 – 2.7	112,000	(Gunnell & Krishnamurthy, 2003)
Indian tanks (totals)	South India	(1,131,000)	(85,500) mean = 34.3	0.5 – 1.5 mean = 0.88	(486*10^6) mean = 194,867.7	(Mialhe, Gunnell, & Mering, 2008)
Small reservoirs	South India		0.05	2	1000	(Mialhe, Gunnell, & Mering, 2008)
RWH systems	Sub-Saharan Africa	1-2ha		0.5 – 1.5	50-1000	(Ngigi, 2003)

Information on large-scale water harvesting storages and their hydrological variables are collected by multiple databases. The most common reservoir databases are:

- the world register of dams (WRD), provided by the international commission of large dams (ICOLD, 2017);
- the global dams and reservoirs (GRanD) database, provided by Lehner et al. (2011);

- the global lakes and wetlands database (GLWD), provided by Lehner and Döll (2004), based on the GRanD database;
- the dam database provided by AQUASTAT (FAO, 2015).

The number of dams and reservoirs available (37,500+) is largest in the WRD database. However, the reservoirs in the WRD database are not georeferenced, which is required to determine the evaporation. Reservoir locations are available in the AQUASTAT database (Kohli & Frenken, 2015) and the GRanD database (Lehner, et al., 2011) (Knook, 2016). The AQUASTAT database consists of 58,600+ dams. However, many of these dams are small dams and 5,759 are Wikipedia sourced. Version 1.1 of the GRanD database contains 6,862 spatially explicit records of dams with their respected 6,824 reservoirs (38 dams do not have an associated reservoir, incl. some diversion barrages and planned dams) and gives information on their storage volume (Global Water System Project, 2017). The locations of the available reservoirs and dams in the GRanD database are given in Figure 2.

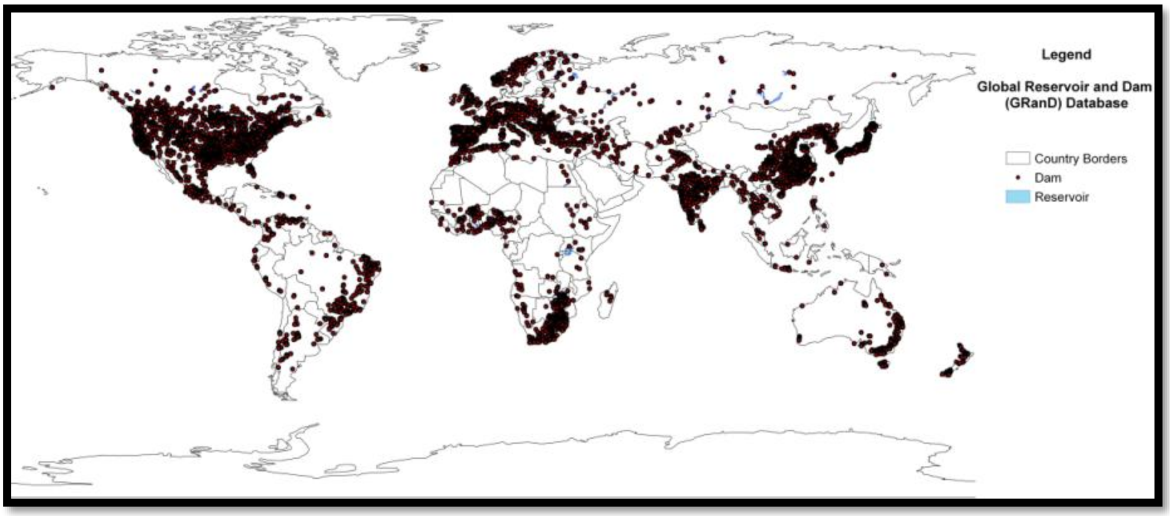


FIGURE 2 LOCATIONS OF THE AVAILABLE RESERVOIRS AND DAMS IN THE GRAND DATABASE (GLOBAL WATER SYSTEM PROJECT, 2017)

Another form of using stored water is groundwater extraction. Groundwater extraction is a commonly used method, however, in some areas people have become overly dependent on this method, such that the rate of groundwater extraction now consistently exceeds natural recharge rates, causing depletion and declining groundwater levels, sometimes causing land subsidence (Cooley, et al., 2014).

Reservoirs have different dimensions. Multiple studies were conducted to derive shapes of reservoirs. Using the area-volume and depth-volume relations, the shapes of the reservoirs are determined. Table 3 gives an overview of the area-depth-volume (A-d-V) relations of multiple reservoirs for different regions (Grin, 2014).

Table 3 shows that the reservoirs are shaped based on power relations between area and volume and depth and volume. The goodness of fit (R^2) is a measure of how well data points fit a statistic model, line or curve. It provides a measure of how well observed outcomes are replicated by the model, as the proportion of total variation of outcomes explained by the model (Steel & Torrie, 1960). In general, the higher the R-squared, the better the model fits the data. Equation 1 gives the calculation of the goodness of fit by linear regression.

$$R^2 = 1 - \frac{\text{SEresidual}}{SEtotal} = \frac{\sum_i^i (y_i - f_i)^2}{\sum_i^i (y_i - \bar{y})^2} \qquad eq. 1)$$

TABLE 3 AREA-DEPTH-VOLUME RELATIONS (GRIN, 2014)

Region	A-V relation	d-V relation	R^2
Upper east Ghana	$V=0.0088*A^{1.44}$	(-)	0.98
Upper east Ghana	$V=0.0088*A^{1.44}$	(-)	0.98
Limpopo Basin Zimbabwe	$V=0.0230*A^{1.33}$	(-)	0.95
Preto River Basin Brazil	$V=0.45*A^{1.11}$	(-)	0.83
Madalena Basin Brazil	$V=0.0036*A^{1.49}$	$V=4980*D^{2.83}$	0.99 (for both)

When implementing water storages, dimensioning the storages is of great importance. A storage must not be too large, to avoid unnecessary land use and evaporation losses, and not be too small, to avoid water supply losses. Dimensioning the storage maximum capacity can be done using the residual mass curve. A residual mass curve is found by plotting the cumulative of the net reservoir inflow against time and then measuring the difference between the maximum and minimum value of this curve from the normal. The outcome of this difference gives the storage maximum required capacity (Bharali, 2015).

1.4.3 Evaporation calculation methods

There is a significant amount of methodologies for estimating the evaporation from surface water. They can be categorized into: (1) mass-transfer, (2) pan coefficient, (3) energy budget (4) temperature and radiation and (5) a combination of methods.

Dalton (1802) and Penman (1948) are one of the first researchers to describe the method mass-transfer method. Later on, Harbeck (1962) developed a similar equation for estimating evaporation from reservoirs (Finch & Calver, 2008). The equation takes into account the wind speed, vapour pressures and an empirical constant of C that is known. Attempts have been made to produce a generally applicable value of C (Finch & Calver, 2008).

The pan coefficient method is well known to have significant uncertainties. Although its extensive use, because of its simplicity, for adequate operations/development and water accounting strategies for managing drinking water in arid and semi-arid conditions, more accurate evaporation estimates are required (Majidi, Alizadeh, Farid, & Vazifedoust, 2015).

The energy budget method tries to find the change in energy storage in a water body. It consists of two components: the energy required to convert liquid water into water vapour and the energy of the water vapour molecules carried from the water body (Finch & Calver, 2008). It is often difficult to determine the sensible heat term. Therefore, different methods have been suggested. The Bowen Ratio Energy Balance (BREB) Method is such a method and takes into account a ratio between the sensible and latent heat fluxes. For the accuracy of the BREB method it is of importance that a suitable timescale and size of the water body are found. The larger the water body, the longer the time interval between measurements of the temperature profile needs to be (Majidi, Alizadeh, Farid, & Vazifedoust, 2015).

In addition, more simplified, less accurate, methods exist, i.e.: Jensen and Haise (1963) developed an empirical temperature-radiation method for calculating daily evaporation. Stephens and Stewart (1963) adjusted the radiation method for monthly mean temperatures, however, the method is still very similar to the method of Jensen and Haise (1963). Both methods only take into account the incoming solar radiation (R_s) and the air temperature (T_a). Other methods only require air temperature and hours of daylight (Blaney-Criddle, 1959; Hamon, 1963).

The Penman Method combines mass transfer and energy budget approaches and eliminates the need for surface temperature data to find the evaporation from open waters. De Bruin and Keijman (1979) derived a model based on Penman's method, however, they considered correction factors for the energy component. Their equation coincides with the energy balance (BREB) method (Majidi, Alizadeh, Farid, & Vazifedoust, 2015).

Most of the above methods do not take heat storage within an open water body into account, therefore these methods tend to underestimate the evaporation in winter and overestimate the evaporation in summer. Finch (2001) and Finch & Calver (2008) state that “the heat transferred into a lake by inflows and outflows of water may be a significant factor in the energy budget of the lake and thus the evaporation rate. They give methods for calculating the yearly evaporation of open water including the heat storage and changing water levels. One is the energy budget method, discussed above. This is an accurate method, but many parameters are required for the calculation. The other method is the equilibrium temperature method (Finch & Calver, 2008). The advantage of this method in comparison to the energy budget method is that this method assumes the water bodies to be thermally stratified and therefore only needs one temperature for the whole water body. The disadvantage is that in reality the temperature of a water body is likely to decrease with depth increase.

The energy-budget method is often considered the most accurate method for open-water evaporation estimation. Estimates of evaporation using the energy-budget method are recognized as a standard by which other estimates are compared. Complex equations to estimate evaporation, such as the Penman, DeBruin-Keijman, and Priestley-Taylor, have performed well when compared with energy-budget method estimates when all of the important energy terms, such as net radiation, change in the amount of stored energy, and advected energy, are included and ideal data are collected. However, these terms require appreciable effort and expense to collect and include in the equations. Given these difficulties in collecting ideal data, sometimes non-ideal data are collected and important energy terms are not included in the equations. When this is done, the corresponding errors in evaporation estimates are not quantifiable. The simple empirical equations, such as the Hamon, Makkink, Jensen-Haise, Thornthwaite, and Papadakis equations, have been shown to provide reasonable estimates of evaporation when compared to energy-budget method estimates. Yet, when applying these equations to various water bodies, their performance remains questionable without accurate energy-budget or water-budget estimates to compare against because of the empirical origin of their coefficients (Harwell, 2012).

Majidi, et al. (2015) compared the accuracy of 18 different methods with the Bowen Ratio Energy Balance (BREB) method. On a daily basis, the Jensen-Haise, Makkink, Penman and Hamon methods had relatively reasonable performance in comparison with the BREB method. On a monthly basis, the accuracy of these four methods was even slightly higher.

For the calculation of the evaporation estimates multiple climatological variables need to be valued. Data on climatological variables are collected by multiple databases. The European Centre for Medium-Range Weather Forecasts (ECMWF) periodically uses its forecast models and data assimilation systems to reanalysed archived observations, creating global data sets describing the recent history of the atmosphere, land surface, and oceans parameters. ERA-Interim is a global atmospheric reanalysis from 1979, continuously updated in real time. The system includes a 4-dimensional variational analysis (4D-Var) with a 12-hour analysis window. The spatial resolution of the data set is approximately 80 km. ERA-Interim products are updated once per month (ECMWF, 2017).

The Climatic Research Unit (CRU) delivers grids of monthly climate observations from meteorological stations comprising nine climate variables. The Global Precipitation Climatology Centre (GPCC) provides monthly precipitation data sets covering the global land areas excluding Greenland and Antarctica (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006). The monthly mean maximum and minimum temperature can be obtained from the Global Historical Climatology Network.

The ECA dataset contains series of daily observations at meteorological stations throughout Europe and the Mediterranean. A gridded version with daily temperature, precipitation and pressure fields is available (ECA&D, 2017).

1.5 Scope

The scope of this research will be on the blue water footprint and land footprint of the process of storing water in multiple storage systems. The grey and green water footprint will not be taken into account in this particular thesis. The land footprint in this research is an indicator used to measure the area of land required for the water storage area only. The area required for connecting water bodies to distribute the water and maintaining the water storages are not included in this research. Nor will the water footprint and land footprint of constructing the water storages be included.

The focus of the mediums of water storages will be on the unsaturated zone and the container medium given in Table 1. The saturated zone medium is left out of the scope.

Only four water storage systems will be used for this research. The most decentralized water storage system focusses on small-scale on farm water ponds and the most centralized system on a medium-large reservoir storage. The small-scale water storage system consists of multiple small water storages based on the South African “water for food movement” (van der Zaag & Gupta, 2008), Ethiopian farm ponds (Rämi, 2003), small reservoirs in South India (Mialhe, Gunnell, & Mering, 2008) and rain water harvesting systems in sub-Saharan Africa (Ngigi, 2003) given in Table 2. The medium-large reservoir storage will be selected from the GRanD-database. The other two systems consist of water storages with dimensions that are interpolated between the small-scale on farm ponds and medium large reservoir. The methodology for the selection of reservoirs, the methodology for a detailed description of the small-scale water storages, as well as the interpolation method for the two other systems, is given in Chapter 2.

1.6 Justification

Water scarcity is becoming more and more severe throughout the world. The growing severity is partly caused by water losses through evaporation from water storages. In order to reduce the water scarcity, more knowledge about evaporation from water storages and the systems around them is required. According to Finch (2001), the heat storage within water storages and the total surface area can have a significant impact on the amount of evaporated water from open water bodies. However, the extent of the difference in evaporated water per system of calculating the evaporation has not been calculated often. Furthermore, current research has mainly focused on artificial lakes and reservoir, while other systems of water harvesting are being used as well.

In order to reduce water scarcity, this research will focus on the differences in blue water footprint and land footprint between small-scale water harvesting systems and large-scale water storage systems, taking heat storage capacities into account. Thereby, water losses could be reduced and storage systems could be implemented more effectively.

1.7 Reading guide

This thesis describes the differences in blue water footprint and land footprint between multiple small-scale water storages and large reservoirs. Chapter 2 describes the methods used to determine the footprints for hypothetical water systems. Chapter 3 outlines the results of each sub question. Chapter 4 discusses the assumptions made in the used methodology and goes into the interpretation of the results. The conclusions and recommendations for further research are described in chapter 5.

2 METHODOLOGY AND DATA

This chapter describes the methods and data used to determine the difference in the blue water footprints and land footprints between four systems with differently sized water storages. The chapter starts with an overview picture of the methodology of the thesis (Figure 3) and then gives a detailed description of the methodologies used to answer the sub questions of this research.

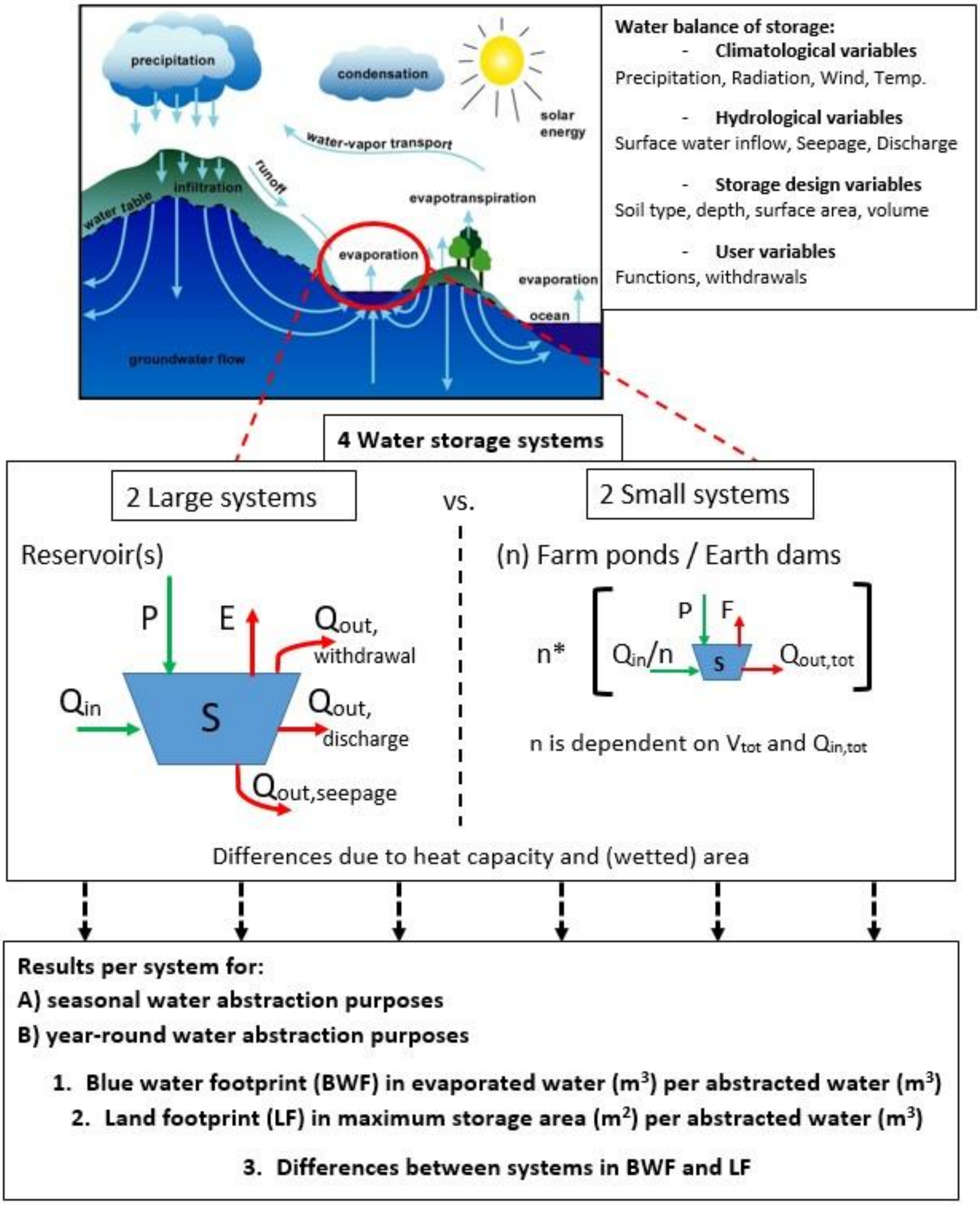


FIGURE 3 OVERVIEW OF THE METHODOLOGY

2.1 Data

In order to calculate the differences in blue water footprint and land footprint between multiple water storage systems, data need to be collected on multiple variables. This paragraph describes the variables and their sources.

2.1.1 Climatological data

For the climatological variables the European Centre for Medium-Range Weather Forecasts (ECMWF) provides measured and forecasted data. The ECMWF provides a global atmospheric reanalysis from 1979 to present day, called the ERA-Interim reanalysis (ECMWF, 2017). Data are measured for every 12-hour window, with forecasted values for every 3 hours and analysed values for every 6 hours. Forecasted values are produced from forecasts beginning every 12 hours. The following data are extracted from the ERA-Interim reanalysis over the period of 20 years from 1997 to 2016:

- Forecasted 3 hourly precipitation (m);
- Forecasted 3 hourly long wave radiation (MJ/m^2/day);
- Forecasted 3 hourly short wave radiation (MJ/m^2/day);
- Forecasted 3 hourly maximum temperatures (K);
- Forecasted 3 hourly minimum temperatures (K);

- Analysed 6 hourly 2-meter dew point temperature (K);
- Analysed 6 hourly 10 metre U and V wind components (m/s).

2.1.2 Hydrological data

For the hydrological variables most of the data are found in the Global Reservoir and Dam (GRanD) database and on the website of the Food and Agriculture Organization of the United Nations (FAO). The FAO-website provides guidelines for computing crop water requirements, which can also be used for open water bodies. The following variables are extracted from the GRanD database (Global Water System Project, 2017):

- Altitude of the reservoir (m);
- Data quality (-);
- Longitude and latitude of dam location (°);
- Maximum reservoir depth (m);
- Purposes of usage (-);
- Reservoir dam heights (m);
- Reservoir maximum area (km^2);
- Reservoir volume (MCM);
- Reservoir's catchment area (km^2).

From the FAO website the following variables data are extracted (Allen, Pereira, Raes, & Smith, 1998):

- Daily evapotranspiration rate (mm/d).
- Density of water (kg/m^3);
- Latent heat of vaporization (MJ/kg);
- Maximum hours of daylight (hr/day);
- Psychometric constant (dependent on the altitude) (kPa/°C);
- Seepage losses per soil type for large reservoirs (mm/d);
- Volumetric heat capacity of soil (MJ/kg/K).

2.1.3 Other data

Other variables were extracted from different sources:

• Crop season (Odekunle, 2004)	(d);
• Crop water needs (Brouwer & Heibloem, 1986)	(m^3/d/ha);
• Water abstraction distribution (FAO, 2016)	(%);
• Land use distribution (FAO, 2016)	(%);
• Main soil type (dependent on the location)	(-);
• Seepage losses per soil type for small storages (Khetkratok, 2010)	(mm/d);
• Soil's angle of repose (Verruijt, 2007)	(°);
• Water abstraction distribution (FAO, 2016)	(%).

2.1.4 Editing data

In order to use the data properly, the above data are edited:

- The data from the databases are rewritten such that 12 hourly data points are available for calculations.

- Leap days are taken out of the data, for simplification of the calculations.

- The wind data are rewritten as the resultant of the U wind and V wind components.

- The data are rewritten such that units correspond with each other and no confusion occurs from multiples or fractions of the units.

- If the data consists of climatological trends, these trends are eliminated. This elimination is based on the differentiation between the driest, the average and the wettest hydrological year and rainy season. The hydrological year starts directly after the rainy season. The differentiation in precipitation is based on ranking the years and rainy seasons from dry to wet.

  The four years with the lowest ranks (driest four years) are classified as dry. From these four years, the year with the lowest sum of ranks (one rank from yearly mean precipitation and one rank from the mean precipitation during the rainy season) is taken as the driest year. The same is done for the four wettest years, but in this case the year with the highest sum of ranks is chosen to be the wettest year. For the year with average amount of precipitation, the years within the four middle ranks are considered as average years. From these four years, the year with the sum of ranks closest to the average of the total sum of ranks (rank 10,5) is chosen as the average year.

  If no year falls within the four ranks for driest, normal or wettest of years, the amount of ranks will be extended until such a year is found. If the sum of ranks of multiple driest, wettest or average years is equal, the year with the lowest, closest respectively highest mean yearly precipitation is chosen to use for the calculation of the blue water footprint and land footprint.

2.2 Method to determine the dimension of the water storages

As mentioned in paragraph "1.4.2 Overview of different forms of storing water" differently sized storages exist. In this thesis, differently sized storages will be compared on the basis of a water storage system for a catchment area, based on evaporation losses with equal water withdrawals for each system. Four differently sized storage systems will be analysed, ranging from a storage system with one large reservoir to a system consisting of many small on-farm water storage ponds. When more than one storage is present in a storage system, the storage sizes are the same for all storages and the storages are assumed to be orientated parallel to each other.

Below, the methodology for determining the dimensions of the large reservoir and small on-farm water storage ponds is given. The determination of the other two systems, of which the dimensions of the storages are in between the dimensions of the two aforementioned storages, is based on the maximum values of the dimensions of the aforementioned storages, see Table 4. From the calculation of the dimensions the A-d-V (surface area – water depth – water volume) relationships can be determined, which will be used in a Matlab-model for calculating the blue water footprint and land footprint differences between the four different systems.

TABLE 4 THE FOUR DIFFERNTLY SIZED WATER STORAGE TYPES

Storage system	**Name**	**Shape**	**Based on:**
1 (largest)	Large reservoir	From source (Knook, 2016). See figure 4.	(Global Water System Project, 2017)
2 (mid-large)	Mid-large reservoirs	From source (Knook, 2016). See figure 4.	Storage types 1 and 4 and (Global Water System Project, 2017).
3 (mid-small)	Earth dams	Upside down cut-off pyramid. See figure 5.	Storage types 1 and 4 and (Hagos, 2005).
4 (smallest)	On-farm ponds	Upside down cut-off pyramid. See figure 5.	(Rämi, 2003) and other sources from Table 2.

2.2.1 Determination of large storage dimensions

The first step in determining the dimensions of the storages is to appoint one reservoir from the GRanD database as an average reservoir. For appointing an average reservoir, a selection within the 6824 reservoirs, collected in the GRanD database, is made. The first step in this selection is the deletion of unsuitable reservoirs. Reservoirs are seen as unsuitable when no data on reservoir area, capacity and / or average depth is available. Reservoirs are also deleted from the selection when they have a data quality categorized in the database as “poor” or “unrealistic” and when the comments of the database say the reservoir is rather a barrage than a reservoir.

From the remaining selection the average reservoir area, the average reservoirs average depth and the average reservoir capacity are calculated. Ranges of 10% above and below these averages are calculated. Reservoirs that fall within the combination of the average capacity range and the average depth range or within the combination of the average capacity range and the average area range, are within the last selection of reservoirs.

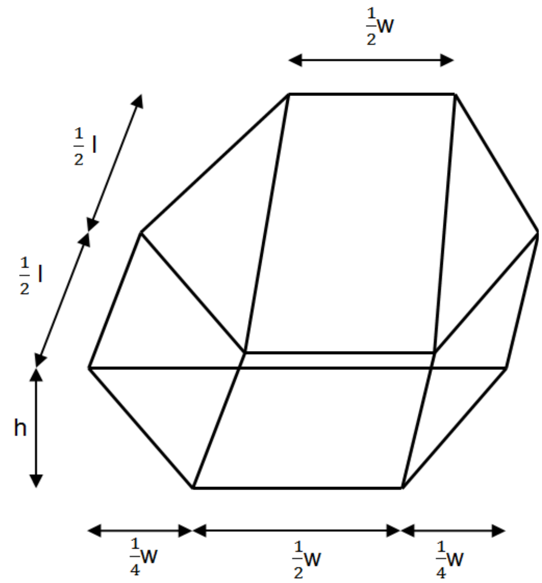


FIGURE 4 ASSUMED RESERVOIR SHAPE (KNOOK, 2016)

From this last selection of reservoirs, the final step in selecting a hypothetical reservoir is to further analyse the data availability of these reservoirs. Within this, subjective, analysis the quality of the data is checked to be at least “fair” according the GRanD dams database (2017), the area of the reservoir is checked for its shape and sources are searched for validated information on the reservoir. The remaining reservoir serves as a hypothetical reservoir to gather climatological and hydrological data from.

Although reservoirs have different shapes, a simplified, assumed shape of the reservoir is used in this research. This shape is assumed by Knook (2016) for calculating the A-d-V (surface area – water depth – water volume) relationships of reservoirs and is given in Figure 4Table 4.

According to multiple sources power trendlines must be present for the A-d-V relationships (Grin, 2014). Using Microsoft Excel (2016) and the assumed shape of the reservoirs (Knook, 2016), the polynomial and power equations for the A-d-V relationships of the reservoirs are found. If the polynomial and power equations explain at least the variance of 95% (R^2>0.95), they are used for the calculation of the fluctuating water levels within the reservoirs. The forms of the polynomial and power equations are given by equations 1 and 2:

$$Polynomial\ eq.: \quad y = ax^2 + bx + c \qquad eq. 1$$

$$Power\ eq.: \quad y = Ax^B \qquad eq. 2$$

In which:
- y = the output variable: surface area, water depth or water volume;
- x = the input variable: surface area, water depth or water volume;
- a, b, c, A and B = constants dependent on the ratios of the input and output variable.

N.B. c equals zero for the d-V and V-d relationships, because the storage is empty at zero volume or zero water depth. For the A-d, d-A, A-V and V-A relationships c equals non-zero, because, the area is non-zero when the depth or volume is zero, due to the flat bottom of the reservoir's shape.

The next step in determining the A-d-V relationships is to use the residual mass curve method to find the new maximum water volume within the average reservoir based on the inflow. The normal precipitation year (method given in paragraph 2.1) is used for the calculation of the yearly inflow. The new maximum water volume is used, together with the A-d-V relationships of the old polynomial equations, to calculate the new maximum depth and new maximum surface area. With the new maximum dimensions and the A-d-V ratio's, the new absolute A-d-V relationships are calculated. These absolute relationships will be used in a Matlab-model, to measure the fluctuating water levels in the reservoir.

2.2.2 Determination of small-scale storage dimensions

The determination of the small-scale water storage dimensions is similar to the determination of large-scale storage dimensions. The differences between the types of storage are found within the shape and the maximum values of the surface area, water depth and water volume of the storages.

The assumed shape of the small-scale storages is different from the assumed reservoir storage shape. The shape of the small-scale storages is an upside down pyramid with a flat base and slopes that correspond with the angle of repose of the main soil type at the location of the reservoir, see figure 5. The angles of repose for different soil types are given in Appendix A "Soil characteristics".

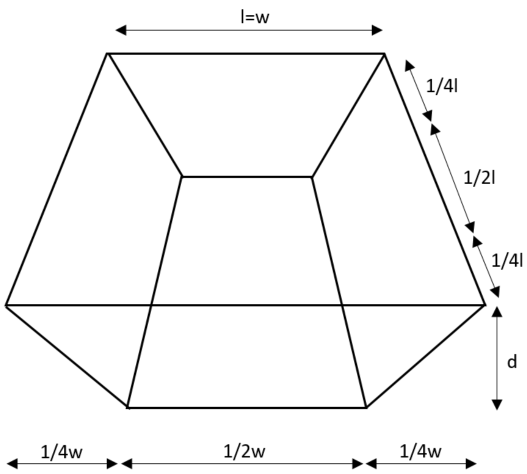


FIGURE 5 ASSUMED SMALL SCALE STORAGE SHAPE

The maximum values of the small-scale water storages are based on the South African "water for food movement" (van der Zaag & Gupta, 2008), Ethiopian farm ponds (Rämi, 2003), small reservoirs in South India (Mialhe, Gunnell, & Mering, 2008) and rain water harvesting systems in sub-Saharan Africa (Ngigi, 2003) given in Table 2. Given these sources and the aforementioned shape, the starting values (before the calculation given in paragraph 2.2.1) of each small-scale water storage are:

- maximum water volume: 432 m^3;
- maximum surface area: 256 m^2;
- maximum depth: 3 m.

2.2.3 Determination of mid-large and mid-small storage dimensions

As mentioned above the determination of the dimensions of the other two water storages is based on the dimensions of the large and small-scale water storages, determined above. For this determination, it is useful to number the storage types from large to small, storage type 1 to 4, see Table 4.

The shape of storage type 2 is assumed to equal the shape of storage type 1 and the shape of storage type 3 is assumed to equal the shape of storage type 4, however, the absolute values of the maximum surface area, water depth and water volume differ between the storage types. The A-d-V relationships storage types 2 and 3 are determined by determining the maximum surface area, water depth and water volumes of these storages types in the same way as for storage types 1 and 4. The difference between the determination of these maxima is that the maxima of storage types 1 and 4 are determined based on the GRanD dam database and multiple small water storage sources respectively, whereas the maxima of storage types 2 and 3 are based on the interpolation of the maxima of storage types 1 and 4 in Excel (Microsoft, 2016).

Different interpolation equations are applied: exponential, linear, logarithmic and power equations are fitted to the maximum surface area, water depth and water volume of storage types 1 and 4. The outcomes of the interpolations for the maxima of storage type 2 need to meet the criteria of IWMI (2000) for large storages to have a larger water depth than 15 meters or a larger water volume than 0.75 million cubic meters and must have comparable values to the GRanD database. The outcomes of the interpolations for the maxima of storages type 3 need to be comparable to the earth dams of Hagos (2005).

Based on the interpolated maxima for surface area, water depth and volume, the polynomial and power equations of the first A-d-V relationships are determined. These equations are also tested on the goodness of fit (R^2 >0,95). If they are tested positively, the residual mass curve method is used to determine the new A-d-V relationships using the same method as used for storages types 1 and 4.

2.2.4 Determination of the amount of storages and inflow per system

The amount of storages per system is based on the surface area of storage type 1. System 1 consists of one large reservoir of which the surface area is determined from the GRanD database (Global Water System Project, 2017). The amount of water storages in systems 2 and 3 are interpolated from systems 1 and 4. The amount of storages in system 4 is based on the maximum surface area of the large reservoir of system 1 divided by the starting value of the surface area of the water storage of system 4, see equation 3.

$$u_4 = \frac{A_{res}\,system\ 1}{A_{res}\,system\ 4} \qquad eq.3$$

The amount of storages mentioned above are starting values. Once the dimensions of the storages are known, the amount of storages are iteratively determined further by optimizing the probability of water supply, also called reliability, towards at least 90 percent. This probability determines how many times per year the storages are not empty. During times that a storage is not empty, water can be abstracted from the storage. It is assumed that the probability of water supply must be at least 90% for all systems. More information on this optimization is found in paragraph 2.3.2.

The amount of water storages determines the quantity of the inflow into each storage based on equations 4:

$$Q_{in,n}(m^3) = \frac{((P_n\ - ET_n) * (A_{catchment} - A_{res,max} * u))}{u} \qquad eq.4$$

In which:

- $Q_{in,n}$ = inflow volume from the catchment into the storages at time step n (m^3);
- P_n = precipitation from time step n-1 to n (m) (ECMWF, 2017);
- ET_n = evapotranspiration from time step n-1 to n (m) (ECMWF, 2017);
- $A_{catchment}$ = total catchment area of the reservoir (m^2) (Global Water System Project, 2017);
- $A_{res,max}$ = maximum surface area of the reservoir (m^2);
- u = amount of storages in systems 1, 2, 3 or 4;
- n = time step of 12 hours.

N.B. The dimensions and amount of storages are kept constant in the calculation of the blue water footprints and land footprints in dry, normal and wet years. The inflow volumes of each storage are not constant, due to a different amount of storages per system. Furthermore, the net precipitation (P-E) above the storages is not taken into account as inflow volume; it is added to the water volume of the reservoir separately. The calculation of fluctuating water volume is given in the next paragraph.

2.3 Blue water footprint and land footprint for irrigational water abstractions

To determine the differences in blue water footprints (BWF) and land footprints (LF) between a large water storage system and a small water storage system, four hypothetical storage systems are compared based on the same amount of abstracted water. Table 4 explains the differences between the four storage systems. The calculations are based on water abstractions for irrigational purposes only. The method of the calculations of the fluctuating water levels with water abstractions for multiple purposes are found in paragraph 2.4.

The BWF of all four systems is calculated as the amount of evaporated water (E) divided by the total amount of water that is abstracted from the reservoirs (WA) (see eq. 5). These calculations are made for three different hydrological years; a dry, normal and wet year.

$$BWF\left(\frac{m^3}{m^3}\right) = \frac{E\ (m^3)}{WA\ (m^3)} \qquad eq.5$$

To make a more realistic estimation of the blue water footprint, the evaporation, which is dependent on the shape of the storages, is calculated under fluctuating water level conditions using 12 hourly data points. A fluctuating water level means a fluctuating water volume. The water volume of the storage(s) is dependent on equation 6:

$$V_n = V_{n-1} + A_{res,n} * E_n + P_n * A_{res,max} * u + Q_{in,n} * u - WA_n - Q_{seepage} \qquad eq.6$$

In which:

- V_n = water volume at time step n (m^3);
- $A_{res,n}$ = surface area of the storage(s) at time step n (m^2);
- E_n = evaporation above the storage(s) from time step n-1 to n (m);
- P_n = precipitation above the storage(s) from time step n-1 to n (m);
- $A_{res,max}$ = maximum surface area of the storage(s) (m^3);
- u = amount of storages in systems 1, 2, 3 or 4;
- $Q_{in,n}$ = inflow volume from the catchment(s) into the storage(s) (m^3);
- WA_n = water abstraction from the storage(s) at time step n (m^3);
- $Q_{seepage}$ = seepage flowing out of the storage(s) (m);
- n = time step of 12 hours.

The surface area of the storage(s) at time step n is determined by the d-A relationship (determined in paragraph 2.2) of the system's storage(s). The depth at each time step is determined by the V-d relationship of the system's storage(s). To complete this loop, the water volume of each time step is determined by equation 6. This results in a fluctuating water level of the storage(s). The loop described, is schematized in Figure 6. An explanation of all variables within the calculation of the fluctuating water level is given below.

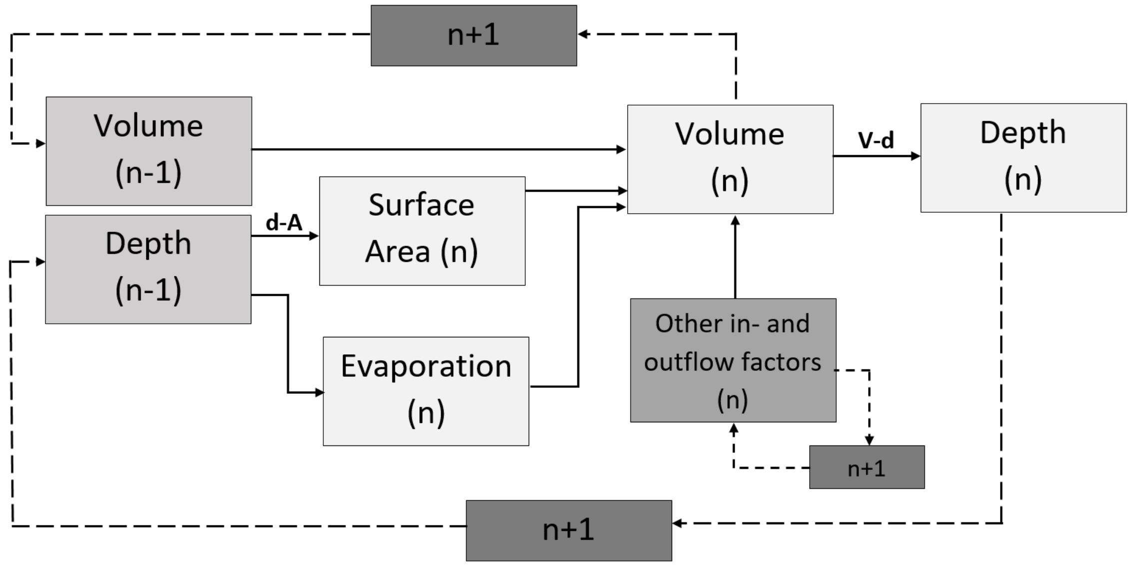


FIGURE 6 A-D-V RELATIONSHIPS

<u>Evaporation calculation</u>

As given in Figure 6, the evaporation and other in- and outflow factors influence the water volume and depth in the storage(s). The method of Finch (2001) is used for the calculation of the evaporation. The method uses multiple variables, given in equations 7 to 13.

$$E_{Finch,n} = (\delta_n * (R_{n,n} - G_n + \gamma * \lambda * f(u)_n * (e_{s,n} - e_{a,n})) \;/\; (\delta_n \; + \gamma)) \;/\; \lambda \;/ 1000 \qquad eq.7$$

In which:

- $E_{Finch,n}$ = Evaporation by Finch' method from time step n-1 to n (m).
- γ = psychometric constant (kPa / °C) = 0.064 kPa / °C.
- λ = latent heat of vaporization (MJ / kg) = 2.45 MJ / kg.
- δ_n = slope of the temperature saturation water vapour curve at air temperature at time step n (kPa / °C). Calculated by equation 8.
- $R_{n,n}$ = net radiation from time step n-1 to n (KJ / m^2). Given by equation 9.
- G_n = heat flux from time step n-1 to n (MJ / m^2). Given by equation 10. Assuming stratified water temperature throughout the whole storage's water volume.
- $f(w)_n$ = wind function of Sweers (1976) at time step n. Given by equation 11.
- $e_{s,n}$ = mean saturation vapour pressure from time step n -1 to n (kPa). Given by equation 12.
- $e_{a,n}$ = actual vapour pressure at time step n (kPa). Given by equation 13.

$$\delta_n = \frac{\left(4098 * \left(0.610 * \exp\left(\frac{17.27 * T_{mean,n}}{T_{mean,n} + 237.3}\right)\right)\right)}{\left(T_{mean,n} + 273.3\right)^2} \qquad eq.8$$

In which:

- $T_{mean,n}$ = mean temperature at time step n (°C).

$$R_n = \; SWR_{mean} + LWR_{mean} \qquad eq.9$$

In which:

- SWR_{mean} = mean short wave radiation at time step n (W / m^2).
- LWR_{mean} = mean long wave radiation at time step n (W / m^2).

$$G_n = c_s * (T_{mean,n} - T_{mean,n-1}) * z_{n-1} \qquad eq. 10$$

In which:

- c_s = volumetric heat capacity of the soil (MJ / m^3 / K).
- $T_{mean,n}$ = mean temperature at time step n (°C).
- $T_{mean,n-1}$ = mean temperature at the previous time step n-1 (°C).
- z_{n-1} = water depth at the previous time step n-1 (m).

$$f(w)_n = \frac{(0.864 * (4.4 + 1.82 * w_n))}{\lambda} \qquad eq. 11$$

In which:

- w_n = resultant of the U and V wind data at time step n (m/s).
- λ = latent heat of vaporization (MJ / kg) = 2.45 MJ / kg.

$$e_{s,n} = 0.6108 * \exp\left(\frac{17.27 * T_{mean,n}}{273.3 + T_{mean,n}}\right) \qquad eq. 12$$

In which:

- $T_{mean,n}$ = mean temperature at time step n (°C).

$$e_{a,n} = 0.6108 * \exp\left(\frac{17.27 * dpt_n}{273.3 + dpt_n}\right) \qquad eq. 13$$

In which:

dpt_n = dew point temperature at time step n (°C).

<u>Inflow, precipitation, water abstractions and seepage</u>

Other factors that flow in or out of the storage(s) are the precipitation above the storage(s) (P), the inflow from precipitation from areas upstream of the storage(s) that falls onto the catchment area (Q_{in}) and the water abstractions (WA) and seepage (Q_s) from the storage(s). The precipitation above the storage(s) is derived from the ECMWF-website (2017) and calculation of the inflow (Q_{in}) is given in paragraph 2.2.4. The calculation of the water abstractions from the storage(s) is given below.

The seepage is subtracted from the depth in meters per 12 hours and dependent on the soil type. In Appendix A "Soil characteristics", the seepage water losses are given per soil type. The soil type of the storage is assumed to be the main soil type found at the location of the storage (Brouwer & Heibloem, 1986). According to Kumar, et al. (2005) the seepage losses are 1.4 mm/day for small-sized water storages. According to Brouwer and Heibloem (1986) the seepage losses for larger reservoirs are 5 mm/day for average soils.

The water abstractions from the storages are calculated for the dry, normal and wet precipitation years for irrigational purposes only. Depending on the location of the hypothetical reservoir, the precipitation data will be analysed on what period is suitable and common for irrigation. This period is called the crop season. During the crop season the irrigation takes place. The amount of irrigation in cubic meters is dependent on the available water and the water demand. The available water is equal to the net precipitation. The water demand for irrigational purposes is dependent on the cultivated crops. Crops have a water demand that is dependent on climatological conditions, such as radiation, humidity, temperature and wind speeds. Brouwer and Heibloem (1986) calculated the crop water needs (mm/day) per climate. The crop water needs corresponding to the climate of the found hypothetical reservoir are used in the calculation of the water demand. The water abstractions from the storage(s) during the crop season per time step of 12 hours are given by equation 14:

$$WA_n = (P_n - E_n) * A_{catchment} * IRR\ land\ use - CN_n * A_{catchment} * IRR\ land\ use \qquad eq. 14$$

In which:

- WA_n = water abstraction at time step n (m^3).
- P_n = precipitation from time step n-1 to n (m) (ECMWF, 2017);
- E_n = evaporation from time step n-1 to n (m) (ECMWF, 2017);
- $A_{catchment}$ = total catchment area of the reservoir (m^2) (Global Water System Project, 2017);
- IRR land use = land use distribution directed to irrigation (%) (FAO, 2016);
- CN_n = water demand for cultivating crops per time step n (m) (Brouwer & Heibloem, 1986).

The water abstractions of each storage of systems 2, 3 and 4 is equal to the water abstractions of system 1 divided by the amount of storages of system 2, 3 and 4 respectively, see equation 15.

$$WA_{system2,3,4} = \frac{WA_{system1}}{u_{sys2,3,4}} \qquad eq. 15$$

If the crop needs become larger than the net precipitation, the water abstraction is higher than zero. If the crop needs are met by the net precipitation, the water abstraction from the storage stays zero for the given time step. If the net precipitation becomes less than zero, the net precipitation equals zero, because water can only evaporate when it is present.

Land footprint

The land footprint is the required amount of area reserved for water storages per seasonal water abstractions. Equation 16 gives the mathematical definition:

$$LF_{season} = \frac{A_{res,max} * u}{WA_{season}} \qquad eq. 16$$

In which:

- LF_{season} = seasonal land footprint (m^2 / m^3);
- $A_{res,max}$ = maximum surface area per storage (m^2);
- u = amount of storages per storage system (-);
- WA_{season} = seasonal water abstractions used for irrigation per system (m^3).

System optimization

From the first calculations, differences may appear in the percentage of water abstractions that can be met by the system without having empty storages, the reliability. When storages are empty, water cannot be abstracted. If differences exist between the systems they need to be accounted for, because the comparison is only fair, if the water abstractions of all four systems are equal. To compensate for these possibly occurring differences, the 90% probability of water supply is introduced.

The 90% probability of water supply means that all systems, under normal hydrological conditions, can be empty maximally 10% of the crop season. During the rest of the crop season irrigation from the storage(s) onto the crop fields must be possible.

Given the 90% probability rule, and given the assumption that the water abstractions must be equal for all storage systems and as high as possible to fulfill the water demand for crop cultivation, it is possible to optimize the systems.

Two methods are used for optimization: 1) maximizing the water abstractions and 2) compensating for system reliability differences. The first method maximizes the water abstractions, while keeping the probability of water supply for all systems above 90%. After that, the amount of storages per system is changed (apart from system 1), to further maximize the water abstractions, while keeping the probability of the water supply for all systems above 90%. Once the optimization is complete, the blue water footprint and land footprint are calculated.

The second method is similar to the first method, apart from the last step. After optimizing the amount of storages per system, the second optimization method compensates for the differences in reliability. The differences are compensated for by dividing the blue water footprints and land footprints by the reliability, this results in compensated blue water footprints and land footprints.

N.B. the 90% probability rule only accounts for the normal hydrological year. Differences in probability of water supply during the dry and wet hydrological years are also accounted for, these might however be different.

2.4 Blue water footprint and land footprint for multi-purpose water abstractions

To answer the third sub question of this research, the yearly blue water footprints and land footprints are calculated. These calculations are similar to the calculations of the seasonal blue water footprints and land footprints for irrigational purposes, given in the paragraph 2.3. The difference with these calculations are found in the purposes of the water abstractions. As a result, the methodologies are the same, apart from the quantity of the water abstractions and the period in which water is abstracted from the storages, leading to different reliabilities, blue water footprints and land footprints for multi purposed water storages compared to storages used for irrigational purposes only.

The amount of water abstractions during the year is divided into multiple purposes: the agricultural, domestic and industrial purposes. Agricultural purposes are split up into aquacultural, irrigational and livestock purposes. The method for calculating amount of water abstraction for irrigational purposes was already given in paragraph 2.3. The other purposes of water abstraction from storages are determined by using the water use distribution of AQUASTAT's country profiles section (FAO, 2016). This database can be used to find the country's average water use distribution corresponding to the location of the found hypothetical reservoir.

In addition, it is assumed that the water abstractions of irrigational purposes occur during the cropping season only and the water abstractions of all other purposes happen during the whole year. As a result, equation 17 needs to be used to find the amount of water abstractions for other purposes than the irrigational purpose.

$$WA_{other,year} = WA_{irrigation,season} * \frac{d_{other}}{d_{irrigation}} \qquad eq. 17$$

In which:

- $WA_{other,year}$ = total non-irrigational purposed water abstractions per year (m^3);
- $WA_{irrigation,season}$ = total irrigational purposed water abstraction per season (m^3);
- d_{other} = country's distribution percentage of non-irrigational water use (%);
- $d_{irrigation}$ = country's distribution percentage of irrigational water use (%).

In order to find the water abstractions per time step of 12 hours, the totals are divided by the amount of time steps per year for all non-irrigational purposes.

The water abstractions for all purposes are found for the dry, normal and wet hydrological years. When these abstractions are known, the model is run to find the blue water footprints and land footprints of the four storage systems. In these calculations, the amount of storages and the total water abstractions are kept the equal to the amount of storages and the total water abstractions found for water storages with irrigational purposes only. The differences in probability of water supply, or reliability of the systems, are compensated only for by dividing the blue water footprints and land footprints by the reliability, this results in compensated blue water footprints and land footprints.

3 RESULTS

This chapter describes the results found by using the methodologies given in chapter 2. Firstly, the data and editing the data are discussed. Secondly, the dimensions of the storages are described together with the A-d-V relationships. Thirdly, the results of the seasonal blue water footprints and land footprints of the irrigational purposed storages are presented, followed by the results of the yearly blue water footprints and land footprints of multi-purposed storages. This chapter concludes with presenting the differences in the blue water footprints and land footprints between the different water storage systems. In total, 6 scenarios are presented: for both the irrigational and multiple purposed storages systems analyses i made for a dry, normal and wet hydrological year.

3.1 Data

The first step in finding the data that is required for the calculation of the blue water footprints and land footprints is finding the location of the hypothetical reservoir on which the data is based. The reservoir found to be appropriate as the hypothetical reservoir is the Challawa reservoir in Nigeria at 8,025417° longitude and 11,724583° latitude. The coordinates were used to find the climatological data above the Challawa reservoir from the ERA-Interim database (ECMWF, 2017).

The climatological data retrieved from the ECMWF-website (2017) is edited towards time step of 12 hours. The precipitation data are given in Figure 7. The data from 1997 to 2016 for long and short wave radiation, maximum and minimum temperatures, 2-meter dew point temperatures and 10 meter wind components are given in Appendix B: climatological data.

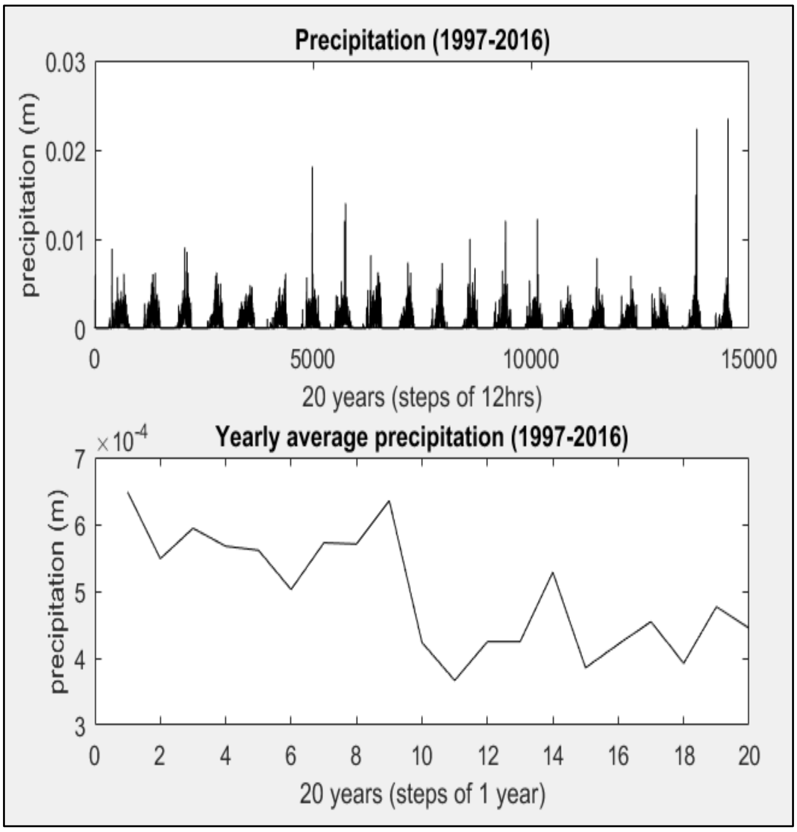


FIGURE 7 PRECIPITATION ABOVE CHALLAWA RESERVOIR (M) (ECMWF, 2017)

Figure 7 shows the precipitation data over the period 1997 to 2016. The upper graph shows 20 peaks corresponding to the rainy season which occurs every year between June and October and lasts about 100 days (Odekunle, 2004).

Figure 7 also shows a climatological trend is present in the precipitation data. Although this is difficult to see from the precipitation data per time step of 12 hours, the yearly average precipitation shows a decline in precipitation over the period 1997 to 2016. The climatological downward trend can also be shown by dividing the lower graph into three parts of seven, seven and six years and showing their averages:

- Average of hydrological years 1997 to 2003: 11.40e-04 mm/day = 416.6 mm/year;
- Average of hydrological years 2004 to 2010: 9.64e-04 mm/day = 351.8 mm/year;
- Average of hydrological years 2011 to 2016: 8.58e-04 mm/day = 313.3 mm/year.

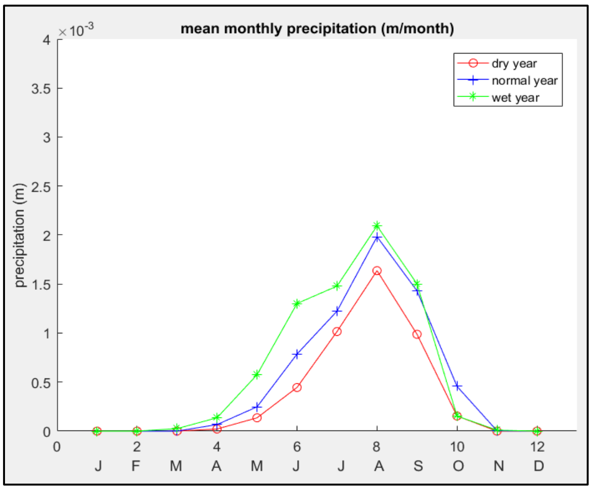
The difference in yearly average precipitation between the first seven years and the last six years equals 33%. These averages are based on the hydrological years, which start in October and end in September. The hydrological year of year 1 is thus from October 1996 to September 1997.

Due to the climatological downward trend in the precipitation data, the precipitation data is analyzed further and split into a dry, normal and wet hydrological year, which are analyzed separately such that the effect of the amount of precipitation can be analyzed. Table 5 gives an overview of these years:

TABLE 5 OVERVIEW OF PRECIPITATION IN DRIEST, NORMAL AND WETTEST HYDROLOGICAL YEARS

	Hydrological year	**Numbered year**	**Yearly precipitation (mm/year)**	**Seasonal precipitation (mm/season)**	**Ratio seasonal / yearly precipitation (%)**
Driest year	2006 / 2007	11	267.7	225.7	84.3
Normal year	2009 / 2010	14	385.8	297.5	77.1
Wettest year	2004 / 2005	9	463.8	337.8	72.9

Table 5 Overview of precipitation in driest, normal and wettest hydrological yearsshows that in the driest year, proportionally, the most precipitation occurs during the cropping season followed by the normal year and lastly the wettest hydrological year. Furthermore, the most precipitation occurs during the cropping season. Figures 8 and 9 also illustrate this using the monthly averages of each extreme year and the 10 day periods within the 100 day during cropping season. From the data and Figure 8 the cropping season was determined to be 100 days starting at the end of June and finishing at the beginning of October. The period of the rainy season of 100 days is similar to the period found by Odekunle (2004) for the Kano region in which the Challawa reservoir is situated. Odekunle (2004) proved the rainy season for the Kano region to start at the beginning of June and end in the middle of September. When shifting from the rainy season to the cropping season the period of the rainy season is shifted about one month to be able to fill the storages before starting the irrigation from the storages.



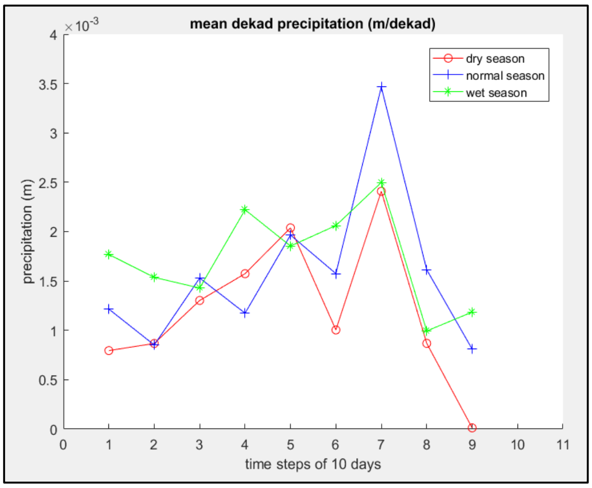


FIGURE 8 MEAN MONTHLY PRECIPITATION

FIGURE 9 MEAN DEKAD (10 DAY) PRECIPITATION DURING THE CROPPING SEASON

The hydrological data of the Challawa reservoir of system 1 is given in Table 6. Table 7 gives extra information on other variables. The dimensions of the storage systems are later on adapted to the inflow of the storages.

TABLE 6 HYDROLOGICAL VARIABLES CHALLAWA RESERVOIR (GLOBAL WATER SYSTEM PROJECT, 2017)

Variable	Unit	Quantity
Dam height	m	42
Surface area	km^2	65.2
Capacity	MCM	930
Average depth	m	14.3
Elevation above sea level	m	521
Catchment area	km^2	3844
Irrigational usage	(-)	Main usage
Water supply usage	(-)	Secondary usage
Data quality	(1-5)	3) Fairly good
Climate	(-)	Semi-arid
Longitude	(°)	8.02542
Latitude	(°)	11.7246

TABLE 7 OTHER VARIABLES FOR CHALLAWA RESERVOIR

Variable	Unit	Quantity	Source
Evaporation driest year	mm/yr	1935.7	(ECMWF, 2017)
Evaporation normal year	mm/yr	1852.2	(ECMWF, 2017)
Evaporation wettest year	mm/yr	1839.4	(ECMWF, 2017)
Main soil type	(%)	85% sand	(Sonneveld, 2005)
Angle of repose (water- filled sand)	(°)	30	(Verruijt, 2007)
Seepage losses (large storages)	mm/day	5.0	(Allen, Pereira, Raes, & Smith, 1998)
Latent heat of vaporization	MJ/kg	2.45	(Allen, Pereira, Raes, & Smith, 1998)
Density of water	kg/m^3	1000	(Allen, Pereira, Raes, & Smith, 1998)
Volumetric heat capacity of a soil	MJ/kg/K	0.0042	(Allen, Pereira, Raes, & Smith, 1998)
Psychrometric constant	kPa/°C	0.064	(Allen, Pereira, Raes, & Smith, 1998)
Crop water needs	m^3/day/ha	85.0	(Brouwer & Heibloem, 1986)
Irrigational land use	(%)	44.0	(FAO, 2016)

3.2 Dimensions of the water storages

3.2.1 Hypothetical reservoir selection

The first step in finding the dimensions of the four differently sized storages is determining which reservoir is suitable to function as the hypothetical large reservoir from the GRanD database. In the GRanD database, consisting of 6,824 reservoirs located across the world, a selection is made based on missing data and low-quality data. 6312 reservoirs made it through the first selection. From these reservoirs the average depth, surface area and capacity are determined. Table 8 gives an overview of these averages and the amount of reservoirs that fall within different ranges from the averages. In total, 17 reservoir meet the criteria of falling within 10% range from the average capacity and the 10% range from either the average depth or the average surface area.

The last selection is based on data availability of the remaining reservoirs. The reservoir that was subjectively chosen from this selection to serve as a hypothetical reservoir to gather climatological and hydrological data from is the Challawa reservoir, situated in the Hadedja-catchment in the semi-arid Kano region in Nigeria. The climatological data and hydrological data of Challawa reservoir are already given in paragraph 3.1 and Appendix B.

TABLE 8 AVERAGES AND THE AMOUNT OF RESERVOIRS FALLING WITHIN THE RANGES FROM THE AVERAGES

	Depth (d) (m)		**Surface Area (A) (km^2)**		**Capacity (V) (MCM)**		**Amount of reservoirs within separate ranges**
Averages	23.6		69.0		927.2		6312
Ranges	Lower	Upper	Lower	Upper	Lower	Upper	d / A / V
5 %	22.4	24.8	65.6	72.5	880.8	973.5	280 / 52 / 33
10%	21.2	25.9	62.1	75.9	834.4	1019.9	597 / 75 / 93
15%	20.0	27.1	58.7	79.4	788.1	1066.2	848 / 109 / 132
Combinations							
Ranges	Depth and Surface Area		**Depth and Capacity**		**Surface Area and Capacity**		Depth, Surface Area and Capacity
5%	1		1		1		0
10%	9		**13**		**4**		0
15%	18		26		13		0

3.2.2 A-d-V relationships

The starting values of the dimensions of the storages of systems 1 and 4 are known and given in paragraphs 3.1 and 2.2.2. Table 9 gives the d-V and A-V relationships of the starting values of systems 1 and 4.

TABLE 9 STARTING D-V AND A-V RELATIONSHIPS FOR THE STORAGES OF SYSTEMS 1 AND 4

System	Relationship	Function	R^2
1	d-V power	V=6.51E+06*d^1.3095	0.9972
1	d-V polynomial	V=2.9351E+05*d^2 + 9.8153E+06*d	1.0
1	A-V power	V=1.68E-12*A^2.66	0.973
1	A-V polynomial	V=1.4333E-07*A^2 + 8.2559*A – 2.1465E+08	0.99994
4	d-V power	V=96.188*d^1.3019	0.9967
4	d-V polynomial	V=26.813*d^2+63.501*d	1.0
4	A-V power	V=1.12E-03*A^2.35	0.99993
4	A-V polynomial	V=2424.6*A^2+1.5052*A-110.9	0.970

The goodness of fit (R^2) of the power trendline are above 0.95 and therefore these storages are used for the interpolation of systems 2 and 3. Figure 10 gives the interpolation of the maximum volumes (capacities) of the storages of systems 1 and 4 is given.

As shown in Figure 10, the linear and logarithmic trendlines (orange and red lines) find very high values for the maxima of system 3. The same occurs when interpolating the maximum surface areas of the storages of systems 1 and 4. The function of the exponential trendline shows higher values for the maxima of systems 2 and 3 than the function of the power trendline. The exponential function shows higher values for the maxima of system 2 and 3 than the power function. Looking at the values of system 2, only the exponential value falls within the criteria of IWMI (V>0,75 MCM) (2000), and system 3 does not.

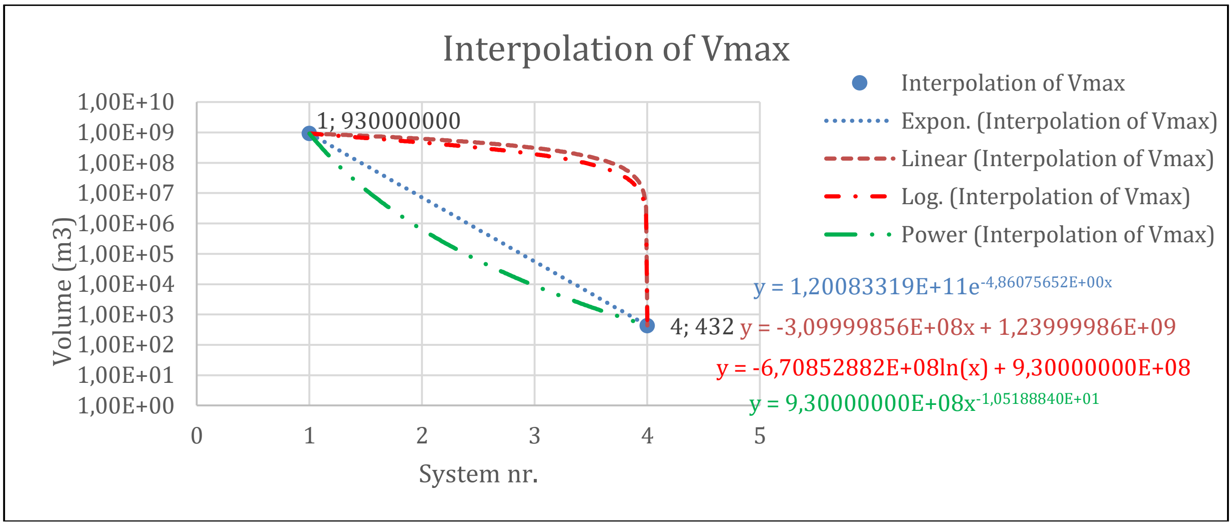


FIGURE 10 INTERPOLATION OF THE MAXIMUM VOLUMES OF THE STORAGES OF SYSTEMS 1 AND 4

Looking at the values of system 3, both, the exponential and power function, values are comparable to values in Table 2 about small reservoirs, such as the earth dams of Hagos, (2005) and multiple small storages, such as in India (Mialhe, Gunnell, & Mering, 2008) and sub-Saharan Africa (Ngigi, 2003) & (Suwanyama, Senzanje, & Mhizha, 2005). Again, the same applies when interpolating the maximum surface areas of the storages of systems 1 and 4. Interpolating the depths of the storages of systems 1 and 4 exponentially also gives results that are comparable to literature. Because the power function values fall short on the maximum volume of system 3 to be greater than a small reservoir, the exponential function values for the maximum volume of systems 2 and 3 is used for the calculation of the depth, surface area and volume within the reservoirs of these systems. From the exponential function the starting values of the storage dimensions arise, given in Table 10.

TABLE 10 STARTING VALUES OF THE MAXIMUM DIMENSIONS OF THE STORAGES

System	Max. surface area (m^2)	Max. depth (m)	Max. volume (m^3)
1	6.52E+07	42.0	9.30E+08
2	1.29E+06	17.4	7.20E+06
3	1.62E+04	7.2	5.58E+04
4	2.56E+02	3.0	4.32E+02

From these starting values also the starting d-V and A-V relationships of the storages of systems 2 and 3 can be determined. The functions of the trendlines are given in Table 11. Due to using equal shapes for systems 1 and 2 ánd for systems 3 and 4, the goodness of fit of all relationships are equal, and thus above 0.95.

TABLE 11 STARTING D-V AND A-V RELATIONSHIPS FOR THE STORAGES OF SYSTEMS 2 AND 3

System	Relationship	Function	R^2
2	d-V power	V=1.59934E+05*d^1.3095	0.9972
2	d-V polynomial	V=1.3244E+04*d^2+1.8349E+05*d	1.0
2	A-V power	V=8.21E-10*A^2.66	0.973
2	A-V polynomial	V=4.4600E-06*A^2 + 4.0529*A – 1.6624E+06	0.99994
3	d-V power	V=3973*d^1.3019	0.9967
3	d-V polynomial	V=601.06*d^2+3416.4*d	1.0
3	A-V power	V=8.42E-06*A^2.35	0.99993
3	A-V polynomial	V=7.7921E-05*A^2+3.0662*A-1.4320E+04	0.970

The next step is to find the amount of storages per system. System 1 is assumed to have only 1 large storage. The amount of storages of systems 2, 3 and 4 are based on the ratio between the maximum surface area of system 1 and their own surface area.

In order to prevent unnecessary land use for storages and unnecessary water losses through spillage of water the dimensions of the storages are checked to be rightly sized. The residual mass curve method is used. The inflow volumes are calculated based on the normal precipitation year. Based on these inflow volumes the new maximum water volumes per storage type are found. Once the optimized maximum water volumes are found, the polynomial A-d-V relationships are used to calculate the new maximum surface areas and depths. Table 12 gives the new values of the maximum dimensions, the amount of storages and the inflow volumes per system. Appendix C gives the mass curve and residual mass curve of system 1 as an example.

TABLE 12 INFLOW VOLUME, AMOUNT OF STORAGES AND OPTIMIZED MAXIMUM DIMENSIONS OF STORAGES PER SYSTEM

System	Amount of storages (-)	Inflow volume (m^3 / year)	Max. surface area (m^2)	Max. depth (m)	Max. volume (m^3)	Max. Total volume (m^3)
1	1	2.38E+08	2.75E+07	8.95	1.19E+08	1.19E+08
2	63	3.56E+06	5.37E+05	7.00	1.83E+06	1.19E+08
3	4,000	5.96E+04	1.12E+04	5.35	2.97E+04	1.19E+08
4	255,000	9.45E+02	3.44E+02	3.30	4.75E+02	1.21E+08

Table 12 shows that the total maximum volume is similar for all systems, while the maximum values of the storages are different for all systems.

With these new dimensional values and with the starting A-d-V relationships, the new A-d-V relationships are determined. The new d-V and A-V relationships are given in Table 13.

TABLE 13 NEW D-V AND A-V RELATIONSHIPS

System	Relationship	Function	R^2
1	d-V power	V=7E+06*d^1.3095	0.9972
1	d-V polynomial	V=9.9835E+05*d^2 + 6.4705E+06*d	1.0
1	A-V power	V=2.13E-12*A^2.66	0.973
1	A-V polynomial	V=1.0262E-07*A^2 + 2.4970*A – 2.7424E+07	0.99994
2	d-V power	V=1.51623E+05*d^1.3095	0.9972
2	d-V polynomial	V=2.5158E+04*d^2 + 1.2740E+05*d	1.0
2	A-V power	V=1.18E-09*A^2.66	0.973
2	A-V polynomial	V=4.1571E-06*A^2 + 1.9712*A – 4.2189E+05	0.99994
3	d-V power	V=3.5292E+03*d^1.3019	0.9967
3	d-V polynomial	V=7.0249E+02*d^2 + 2.6952E+03*d	1.0
3	A-V power	V=1.08E-05*A^2.35	0.99993
3	A-V polynomial	V=8.7304E-05*A^2 + 2.3684*A - 7625,3	0.970
4	d-V power	V=105.76*d^1.3019	0.9967
4	d-V polynomial	V=29.482*d^2+ 69.821*d	1.0
4	A-V power	V=1.09E-03*A^2.35	0.99993
4	A-V polynomial	V=2.3967E-03*A^2 + 1.5692*A – 121.94	0.970

With these new A-d-V relationships, the calculations for the fluctuating water levels within the storages and the calculations of the blue water footprints and land footprints of the storage systems can start.

3.3 Blue water footprint and land footprint for irrigational water abstractions

The blue water footprints and land footprints of the storage systems used for irrigational water abstractions only are dependent on the fluctuating water levels within the storages. These water levels are based on a seasonal water abstraction with a water supply probability / reliability during the 100 days cropping season of 90%, meaning at least 90% of the time during the cropping season the storage is not empty and water demands are fulfilled.

3.3.1 Optimizing the amount of storages

After running the model for the first time, the amount of storages is iteratively changed to maximize the (probability of) water supply and minimize the total surface area. The optimized amounts of storages per system are found in Table 14. These amounts are also taken into account for the calculation of the driest and wettest conditions and for the calculation of the yearly multi-purpose water abstractions in paragraph 3.4.

TABLE 14 CHANGE IN THE AMOUNT OF STORAGES AND PROBABILITY OF WATER SUPPLY PER SYSTEM

System	Old amount of storages	Old probability of water supply (%)	New amount of storages	New probability of water supply (%)
1	1	96.0	1	96.0
2	63	93.5	64	94.0
3	4,000	92.0	3,950	92.0
4	255,000	90.0	252,000	90.0

Table 14 shows that the amount of storages in system 1 is kept constant. The amount of storages in system 2 has become slightly larger, resulting in a larger (probability of) water supply throughout the season. The amounts of storages for systems 3 and 4 are slightly smaller, because the probability of water supply was already maximized, but lowering the amount of storages, results in a lower total surface area, which results in a lower total evaporation, which results in a lower blue water footprint if the seasonal water abstraction, or water supply, is equal. Lowering the amount of storages even further, results in a lower probability of water supply, this means the amounts of storages given in Table 14 are optimized.

3.3.2 Fluctuating water levels

Running the model also shows the fluctuating water level over the year within each storage type. In Figures 11 and 12 the fluctuating water levels of the four storage systems under normal precipitation conditions in one year are given.

Figures 11 and 12 show that the water level for each storage type follows almost the same pattern, caused by the equal amount of total inflow (2.4885E+08 m^3) and water abstractions (2.2341E+08 m^3 / season). The differences in probability of water supply are caused by the differences in yearly evaporation and differences in seepage.

The yearly evaporation is dependent on the surface area times the evaporation per square meter. Table 15 shows amount of storages, average surface area, the average evaporation per square meter, the yearly evaporation in cubic meters and the actual met seasonal water supply per system.

Table 15 illustrates that the average surface area per storage system differs the most between the systems, showing a negative correlation between the average surface area and the seasonal water supply. In addition, the average surface area is negatively correlated to the amount of storages. The same applies for the correlation between the evaporation and the amount of storages and the evaporation and the seasonal water supply, but the differences in evaporation per square meters between the systems are smaller. As a result, the reliability of the water storage system decreases with increasing amount of storages and decreasing capacity per storage.

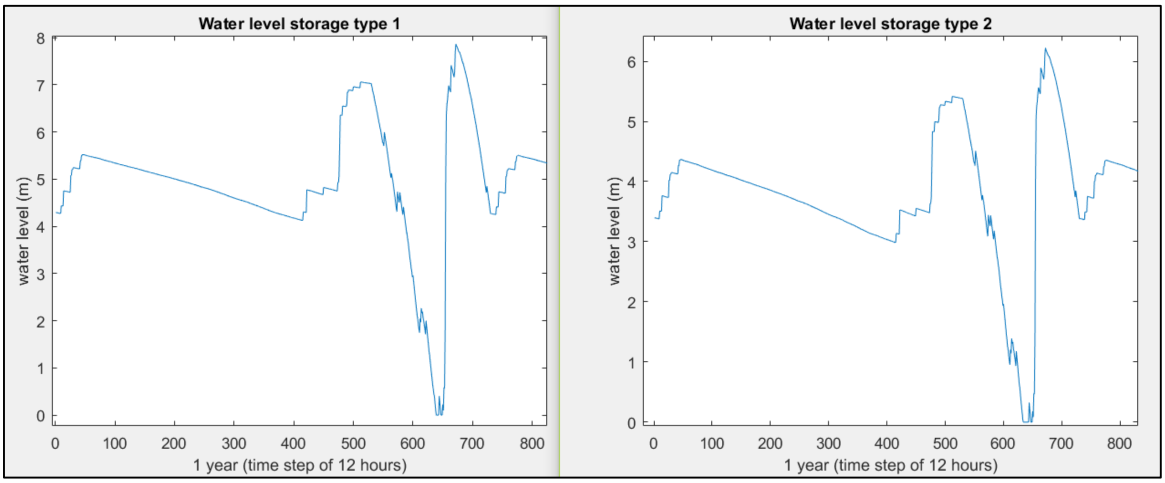


FIGURE 11 YEARLY WATER LEVEL FLUCTUATIONS FOR STORAGES OF SYSTEMS 1 AND 2 UNDER NORMAL PRECIPITATION CONDITIONS

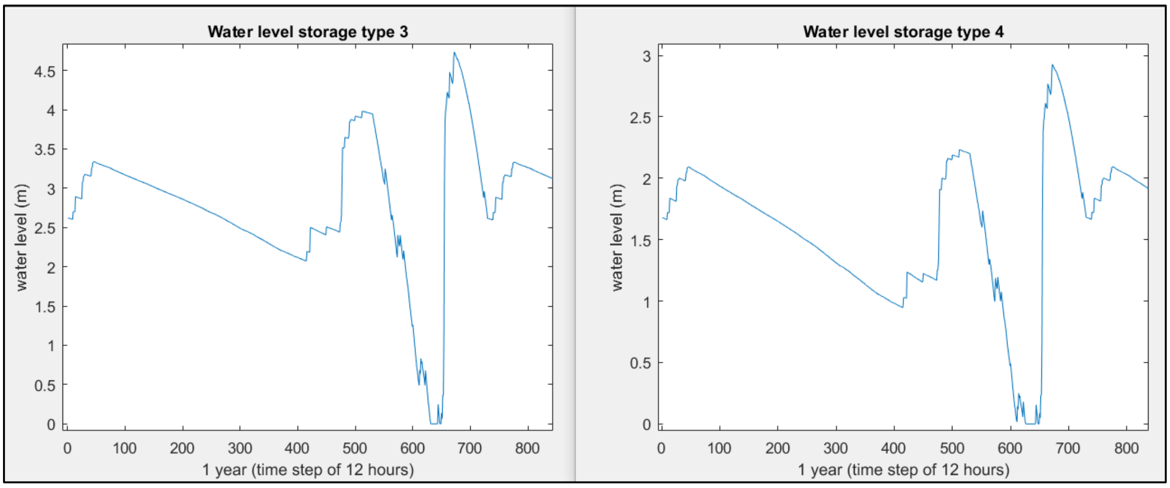


FIGURE 12 YEARLY WATER LEVEL FLUCTUATIONS FOR STORAGES OF SYSTEMS 3 AND 4 UNDER NORMAL PRECIPITATION CONDITIONS

TABLE 15 AMOUNT, SURFACE AREA, EVAPORATION AND WATER SUPPLY PER SYSTEM

System	Amount of storages	Average total surface area (m^2)	Average total evaporation (mm / m^2)	Yearly total evaporation (m^3)	Seasonal water supply actually met (m^3)
1	1	1.8825e+07	2.3964	3.3004e+07	2.1448e+08 (96.0%)
2	64	2.2972e+07	2.3978	4.0292e+07	2.1001e+08 (94.0%)
3	3,950	2.7169e+07	2.3990	4.7562e+07	2.0554e+08 (92.0%)
4	252,000	3.9183e+07	2.4004	6.8224e+07	2.0107e+08 (90.0%)

3.3.3 Blue water footprints and land footprints

If the blue water footprints (BWF) and land footprints (LF) would now be calculated, it could be said that the comparison between the systems is unequal. For this reason, the difference in probability of water supply is compensated for. The compensated BWF and LF arise from the division of the BWF and LF by the reliability of the system. The BWF and LF of each system are given in non-compensated forms as well as the compensated forms in Table 16 and Figure 13 and Figure 14. The seasonal blue water footprint (BWF) is given as seasonal evaporation (m^3) per seasonal water abstraction (m^3), also called water supply. The land footprint (LF) is defined as the ratio between the land used for storages (m^2) and the water abstracted (m^3).

TABLE 16 BLUE WATER FOOTPRINTS AND LAND FOOTPRINTS PER SYSTEM UNDER NORMAL PRECIPITATION CONDITIONS

System	Amount of storages	BWF (m^3/m^3)	BWF (comp.) (m^3/m^3)	LF (m^2/m^3)	LF (comp.) (m^2/m^3)
1	1	0.1474	0.1536	0.1233	0.1284
2	64	0.1802	0.1917	0.1538	0.1636
3	3,950	0.2126	0.2311	0.1978	0.2150
4	252,000	0.3055	0.3394	0.3880	0.4311

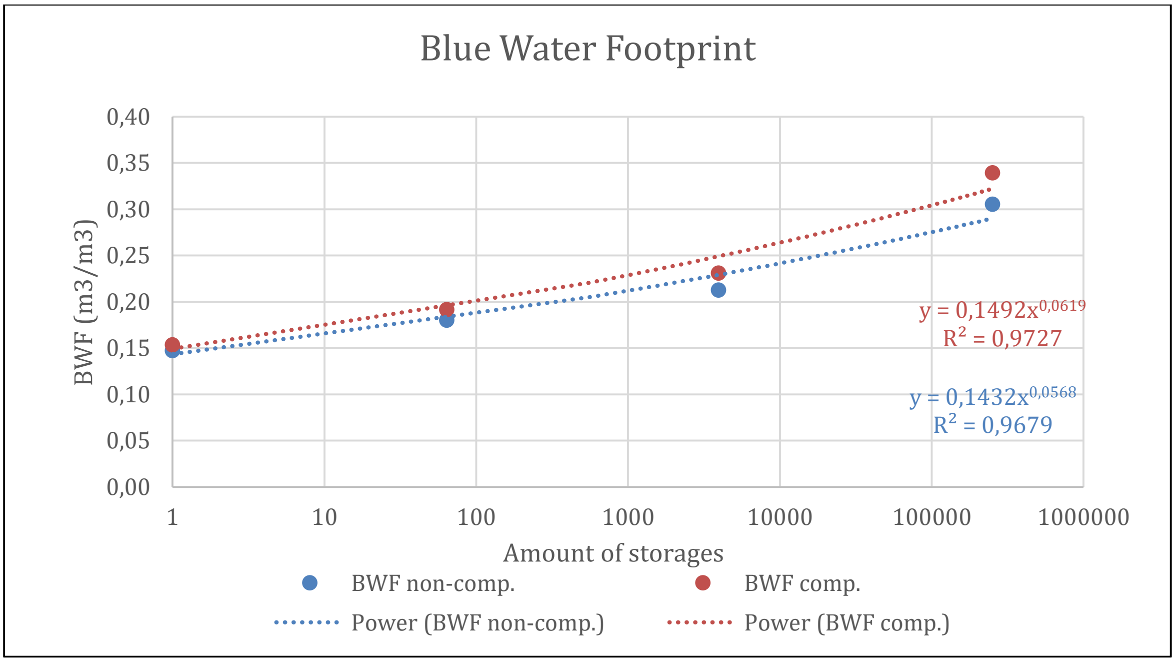


FIGURE 13 NON-COMPENSATED (BLUE) AND COMPENSATED (RED) BLUE WATER FOOTPRINT PER AMOUNT OF STORAGES

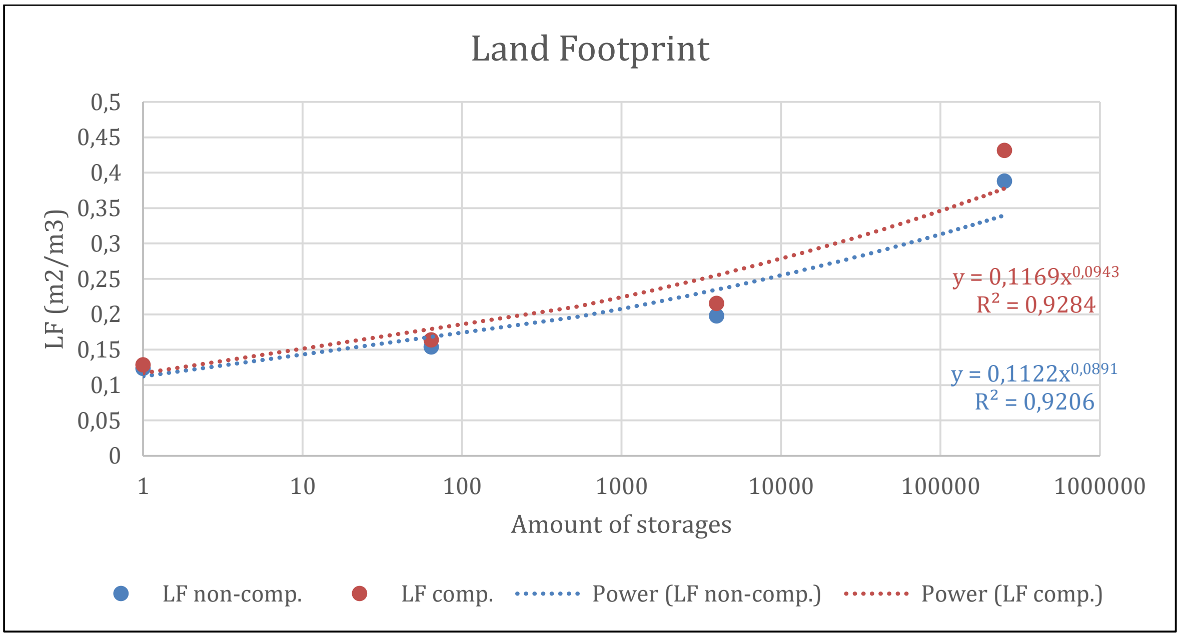


FIGURE 14 NON-COMPENSATED (BLUE) AND COMPENSATED (RED) LAND FOOTPRINT PER AMOUNT OF STORAGES

From Table 15 and Figures 13 and 14 it follows that the BWF and LF rise with a rising amount of storages. Fitting trendlines to Figures 13 and 14 results in power functions with high scores for the goodness of fit. The blue water footprint and land footprint of system 3 deviates the most from these trendlines. The deviation could be caused by the differences in shapes between the storages of systems 1 and 2 and the storages of systems 3 and 4.

Furthermore, the values of the blue water footprints and land footprints of all systems rise when compensating for the differences in water supply. This elevation is larger for systems with lower water supply probabilities.

3.3.4 Driest and wettest hydrological years

The results mentioned in paragraphs 1.3.1, 1.3.2 and 1.3.3. are based on inflow volumes that are based on the normal hydrological year. This paragraph also shows the results for the driest and wettest hydrological years. For these years, only the incoming precipitation and the water abstractions are changed in the model. Table 17 shows the differences in precipitation, inflow volumes and seasonal water abstractions between the different hydrological years. A difference in water abstraction occurs as a result of the differences in the part of met crop water needs. These differences in turn are a result of differences in direct precipitation onto the cultivation plots (see Figures 8 and 9).

TABLE 17 DIFFERENCES IN INPUT BETWEEN HYDROLOGICAL YEARS

Hydrological year	Driest	Normal	Wettest
Yearly Precipitation (mm)	267.7	385.8	463.8
Yearly Precipitation (% of normal)	69.4	100	120.2
Yearly Inflow volume (m^3)	1.5080e+08	2.3822e+08	3.2568e+08
Yearly Inflow volume (% of normal)	63.3	100	136.7
Seasonal water abstractions (m^3)	2.3583e+08	2.2341e+08	2.1579e+08
Seasonal water abstractions (% of normal)	105.6	100	96.6

As a result of the difference precipitation, the water abstractions for drier hydrological year are slightly higher than for wetter hydrological years. These differences result in different total surface areas, total evaporations, probabilities of water supply, blue water footprints and land footprints. Tables 18 and 19 give an overview of the differences in these variables between the different hydrological years.

TABLE 18 SURFACE AREA, TOTAL EVAPORATION AND WATER SUPPLY PROBABILITY REACHED PER SYSTEM PER HYDROLOGICAL YEAR

System	Hydrological year	Amount of storages	Average total surface area (m^2)	Total evaporation (m^3)	Seasonal water abstractions met (m^3)
1	Driest	1	5.6024e+06	9.4760e+06	1.4975e+08 (63.5%)
	Normal	1	1.8825e+07	3.3004e+07	2.1448e+08 (96.0%)
	Wet	1	2.1468e+07	3.6378e+07	2.1579e+08 (100%)
2	Driest	64	6.5261e+06	1.0812e+07	1.5093e+08 (64.0%)
	Normal	64	2.2972e+07	4.0292e+07	2.1001e+08 (94.0%)
	Wet	64	2.6181e+07	4.4193e+07	2.1579e+08 (100%)
3	Driest	3,950	7.1324e+06	1.1635e+07	1.5211e+08 (64.5%)
	Normal	3,950	2.7169e+07	4.7562e+07	2.0554e+08 (92.0%)
	Wet	3,950	3.1820e+07	5.3259e+07	2.1579e+08 (100%)
4	Driest	252,000	9.8835e+06	1.5919e+07	1.5918e+08 (67.5%)
	Normal	252,000	3.9183e+07	6.8224e+07	2.0107e+08 (90.0%)
	Wet	252,000	4.7208e+07	7.8093e+07	2.1579e+08 (100%)

TABLE 19 BLUE WATER FOOTPRINTS AND LAND FOOTPRINTS PER SYSTEM PER HYDROLOGICAL YEAR

System	Hydrological year	Amount of storages	BWF (non-comp.) (m^3/m^3)	BWF (comp.) (m^3/m^3)	LF (non-comp.) (m^2/m^3)	LF (comp.) (m^2/m^3)
1	Driest	1	0.0401	0.0631	0.1168	0.1839
	Normal	1	0.1474	0.1536	0.1233	0.1284
	Wet	1	0.1683	0.1683	0.1276	0.1276
2	Driest	64	0.0452	0.0706	0.1447	0.2276
	Normal	64	0.1802	0.1917	0.1538	0.1636
	Wet	64	0.2047	0.2047	0.1592	0.1592
3	Driest	3,950	0.0495	0.0767	0.1874	0.2905
	Normal	3,950	0.2126	0.2311	0.1978	0.2150
	Wet	3,950	0.2465	0.2465	0.2048	0.2048
4	Driest	252,000	0.0675	0.1000	0.3676	0.5446
	Normal	252,000	0.3055	0.3394	0.3880	0.4311
	Wet	252,000	0.3619	0.3619	0.4017	0.4017

Table 17, 18 and 19 show that when the precipitation is decreased (30.6%) and the total seasonal water abstractions are increased (5.6%) (dry hydrological year), the average total surface areas are lowered (± 75% lower), leading to lower total evaporations (± 75% lower). The water abstractions met decrease relatively less (± 30% lower) than the total evaporations decrease, leading to lower, non-compensated (± 75% lower) and compensated (% lower), BWF. Also the water abstractions met decrease relatively more than the areas covered by storages decrease, which is kept constant, leading to higher, compensated LF (26% to 43% higher) for the dry hydrological year compared to the normal hydrological year. The non-compensated LF show a small decrease (± 6% lower) as a result of a small increase in water abstractions from normal to dry hydrological year.

In a wet hydrological year, when the total yearly precipitation is increased (20.2%) and the total seasonal water abstractions decreased (4.4%), the same pattern as for the difference between dry and normal hydrological years is followed, nevertheless, the differences are smaller. The average total surface areas are higher for the wettest hydrological year than the normal hydrological year (± 16% higher). As a result, the total evaporations become higher (± 11% higher). The water abstractions met increase relatively less (± 7% higher) than the total evaporations increase. As a result, the, non-compensated (± 16% higher) and compensated (± 7% higher), BWF increases from a normal to a wet hydrological year. The non-compensated LF increases slightly (3.5%) as a result of slightly increased water abstractions (±5%). The compensated LF decreases (1% to 7% lower) as a consequence of the difference in reliability between the normal and wet conditions.

Furthermore, Table 19 shows the BWF increases with increasing amount of storages and increasing average total storage surface area for the dry, normal and wet hydrological years. The increase in compensated BWF is highest for the wettest year (2.15 times higher), followed by the normal year (2.07 times higher and is lowest for the driest year (1.68 times higher for system 1 compared to system 4). The LF also increases with increasing amount of storages and increasing average total storage surface area for the dry, normal and wet hydrological years. The increase in LF from system 1 to system 4 is highest for normal years (± 3.25 times higher), followed by the wettest year (3.15 times higher) and the increase in LF is lowest in dry years (3.05 times higher).

3.4 Blue water footprint and land footprint for multi-purpose water abstractions

In the same way as for paragraph 3.3, the blue water footprints and land footprints of the storage systems used for yearly multi-purpose water abstractions are determined. The amount of storages and their dimensions per system are similar to those in paragraph 3.3. However, where paragraph 3.3 gives the results for water abstractions for irrigational purposes only, which happen only during the cropping season, this paragraph gives the results for water abstractions for multiple purposes, which happen during the whole year. This paragraph first describes the different water abstractions, followed by the effect on the water levels in the storages and the effects on the blue water footprints (BWF) and land footprints (LF) per system per hydrological year.

3.4.1 Water abstractions

The amount of water abstraction during the year is divided into multiple purposes: the agricultural, domestic and industrial purposes. Agricultural purposes are split up into aquacultural, irrigational and livestock purposes. Table 20 and Figure 15 give the amount of water abstraction per purpose and the periods in which they occur during the year. The values are based on the normal hydrological year. The proportional water abstraction are based on the mean water use values of Nigeria (FAO, 2016). The period of the cropping season was determined to be 100 days, see paragraph 3.1 and the work of Odekunle (2004).

TABLE 20 WATER ABSTRACTIONS PER PURPOSE

Purpose	Yearly water abstraction (m^3)	Yearly water abstraction (%)	Period of the year
Agriculture	9.7835e+07	44	(-)
- Aquaculture	4.4471e+06	2	Year-round
- Irrigation	8.0047e+07	36	Cropping season
- Livestock	1.3341e+07	6	Year-round
Domestic	8.8941e+07	40	Year-round
Industry	3.5576e+07	16	Year-round
TOTAL	2.2235e+08	100	(-)

The water abstractions for irrigational purposes is more than one-third of the total water abstractions and this amount is extracted only during the cropping season, resulting in a much higher water abstraction during the cropping season (53.5% of the total yearly water abstractions) than during the rest of the year (46.5%). The total water abstracted from the storages over the year (2.3583e+08, 2.2341e+08 and 2.1579e+08 m^3 for dry, normal respectively wet hydrological years) is equal to the water abstracted when irrigation is the only purpose.

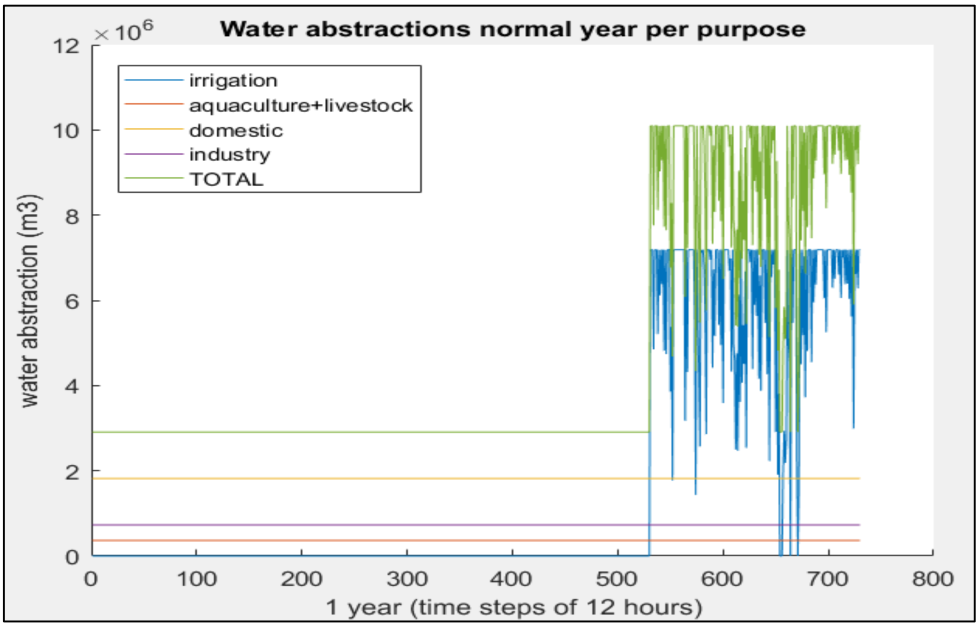


FIGURE 15 WATER ABSTRACTIONS PER PURPOSE

3.4.2 Fluctuating water levels

Running the model shows the fluctuating water levels over the year within each storage. In Figure 16 and Figure 17 and the fluctuating water levels of the four systems' storages under normal precipitation conditions in one year are given (one year equals 730 time steps of 12 hours).

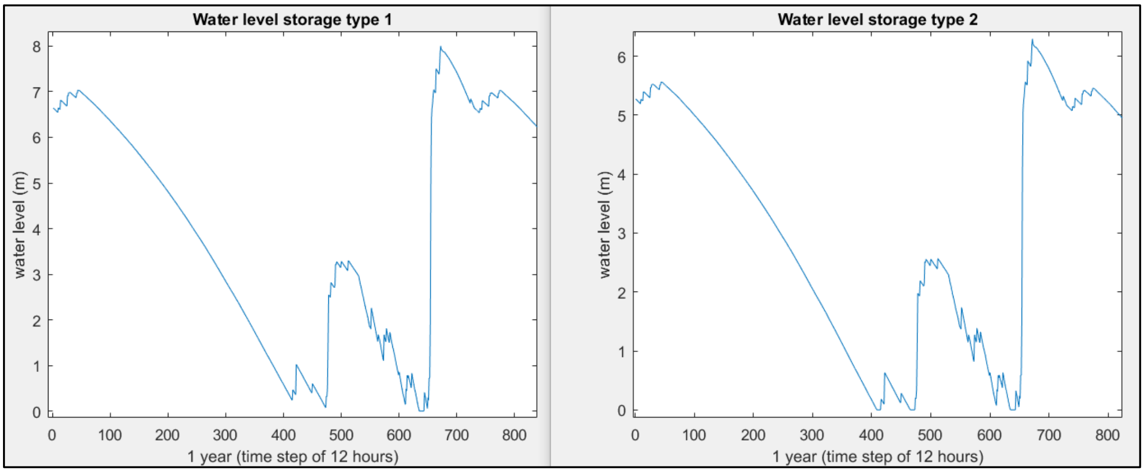


FIGURE 16 YEARLY WATER LEVEL FLUCTUATIONS FOR SYSTEMS 1 AND 2 UNDER NORMAL PRECIPITATION CONDITIONS

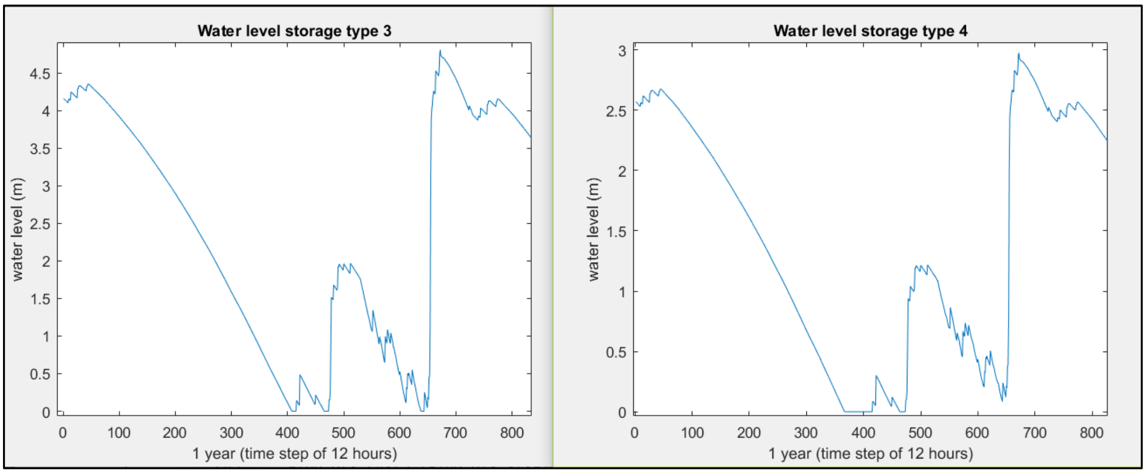


FIGURE 17 YEARLY WATER LEVEL FLUCTUATIONS FOR SYSTEMS 3 AND 4 UNDER NORMAL PRECIPITATION CONDITIONS

Figure 16 and Figure 17 show that the water level for each storage type follows almost the same pattern, caused by the equal amount of total inflow and yearly water abstractions. The differences in probability of water supply are caused by the differences in yearly evaporation. Furthermore, the same correlations between variables exist for systems purposed for irrigation only and systems with multiple purposes. The differences in water abstraction distribution over the year does, however, result in a different shape of the graph of the water level fluctuation over the year. The graphs of the irrigational purposed storages show a fast decline in water level during the cropping season, whereas the graphs of the multi-purposed storages show a fast decline in water level during the dry season (non-rainy season) and during the cropping season. Both types show an increase in water storage about 30 days before the cropping season.

3.4.3 Blue water footprints and land footprints

Similarly, as calculated for the irrigational purposed storage systems, the blue water footprints and land footprints of the multi-purposed storage systems are determined. The results of the calculations are given in Table 21 and Table 22 for the driest, normal and wettest hydrological years.

TABLE 21 SURFACE AREA, TOTAL EVAPORATION AND WATER SUPPLY PROBABILITY REACHED PER SYSTEM PER HYDROLOGICAL YEAR

System	Hydrological year	Amount of storages	Average total surface area (m^2)	Total evaporation (m^3)	Water supply met (m^3)
1	Driest	1	3.4850e+06	4.9079e+06	8.0940e+07 (34.3%)
	Normal	1	1.6073e+07	2.7612e+07	2.2066e+08 (98.7%)
	Wet	1	1.9075e+07	3.1539e+07	2.1579e+08 (100%)
2	Driest	64	4.5518e+06	6.4839e+06	8.1409e+07 (34.5%)
	Normal	64	1.9638e+07	3.3576e+07	2.1316e+08 (95.4%)
	Wet	64	2.3001e+07	3.7925e+07	2.1462e+08 (99.5%)
3	Driest	3,950	5.1617e+06	7.2954e+06	8.2556e+07 (35.0%)
	Normal	3,950	2.4050e+07	4.0898e+07	2.0941e+08 (93.7%)
	Wet	3,950	2.7405e+07	4.4521e+07	2.0927e+08 (96.8%)
4	Driest	252,000	8.9361e+06	1.3090e+07	8.7531e+07 (37.1%)
	Normal	252,000	3.4950e+07	5.8130e+07	2.0012e+08 (89.6%)
	Wet	252,000	4.0117e+07	6.3581e+07	1.9860e+08 (92.0%)

TABLE 22 BLUE WATER FOOTPRINTS AND LAND FOOTPRINTS PER SYSTEM PER HYDROLOGICAL YEAR

System	Hydrological year	Amount of storages	BWF (non-comp.) (m^3/m^3)	BWF (comp.) (m^3/m^3)	LF (non-comp.) (m^2/m^3)	LF (comp.) (m^2/m^3)
1	Driest	1	0.0218	0.0634	0.1168	0.3403
	Normal	1	0.1234	0.1250	0.1233	0.1248
	Wet	1	0.1462	0.1462	0.1276	0.1276
2	Driest	64	0.0275	0.0796	0.1457	0.4219
	Normal	64	0.1461	0.1531	0.1548	0.1611
	Wet	64	0.1752	0.1762	0.1592	0.1601
3	Driest	3,950	0.0324	0.0925	0.1874	0.5353
	Normal	3,950	0.1703	0.1817	0.1978	0.2110
	Wet	3,950	0.2066	0.2130	0.2048	0.2112
4	Driest	252,000	0.0557	0.1501	0.3676	0.9904
	Normal	252,000	0.2444	0.2729	0.3880	0.4332
	Wet	252,000	0.2974	0.3232	0.4017	0.4365

Again, the results show that the BWF and LF rise with a rising amount of storages. Furthermore, it applies for the multi-purpose storage systems that the average total surface area and the yearly total evaporation become smaller when the yearly precipitation becomes less. The non-compensated LF becomes larger with increasing yearly precipitation, while mostly the opposite applies for the compensated LF. The BWF of the driest years are smallest, followed by the normal years and the wettest hydrological years results in the largest BWF. These differences are largely explained by the differences in met water supply, or reliability of the storage systems. Especially during the driest year, the reliabilities of the storage systems are low (34% to 37% of the total water demand).

A deviating value given in Table 22 is the compensated LF of the wet hydrological year. For systems 1, 3 and 4 the compensated LF is higher for the wet hydrological year than for the normal hydrological year. The small difference can be explained by the slightly lower total yearly water abstractions for wet years compared to normal years (4.4% lower) and by the higher total yearly evaporation (8% to 14% higher) for wet years compared to normal hydrological years, as a result of fuller storages throughout the year.

3.4.4 Comparison multi-purposed and irrigational storages

Differences in blue water footprint, land footprint and reliability occurred between systems and hydrological years. In addition, differences are present between the usage of storages. Although the reliability of the multi-purposed (MP) and irrigational (IRR) purposed storages under normal and wettest precipitation conditions are quite similar, the reliability differs for the driest precipitation conditions. The reliabilities for irrigational purposed storages are almost twice as large as for multi-purposed storages in the driest hydrological year. The differences in reliabilities are explained by the differences in water abstractions, which happen only during the rainy season for irrigational purposed storages and during the whole year for multi-purposed storages. As a result, the non-compensated BWF of the multi-purposed storages are significantly lower than for irrigational purposed storages. For the same reason, the compensated LF is significantly lower for irrigational purposed storages than for multi-purposed storages under the driest precipitation conditions.

Figures 18 to 21 give an overview the BWF and LF of all six scenarios, three irrigational purposed scenarios (IRR) and three multi-purposed scenarios (MP) for all four storage systems per hydrological year in the non-compensated and compensated form.

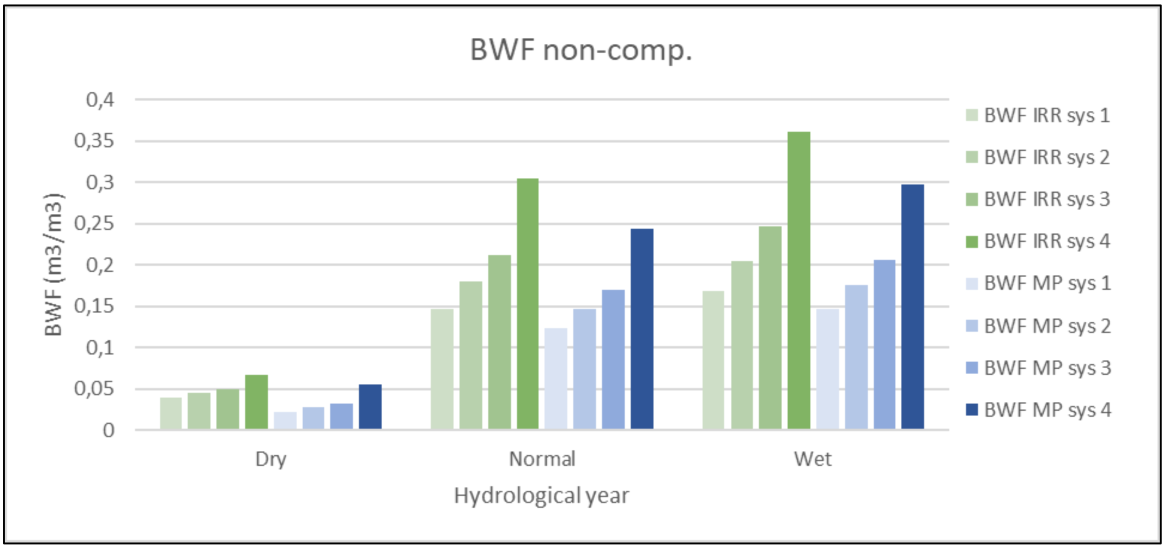


FIGURE 18 NON-COMPENSATED BLUE WATER FOOTPRINT PER SYSTEM PER HYDROLOGICAL YEAR

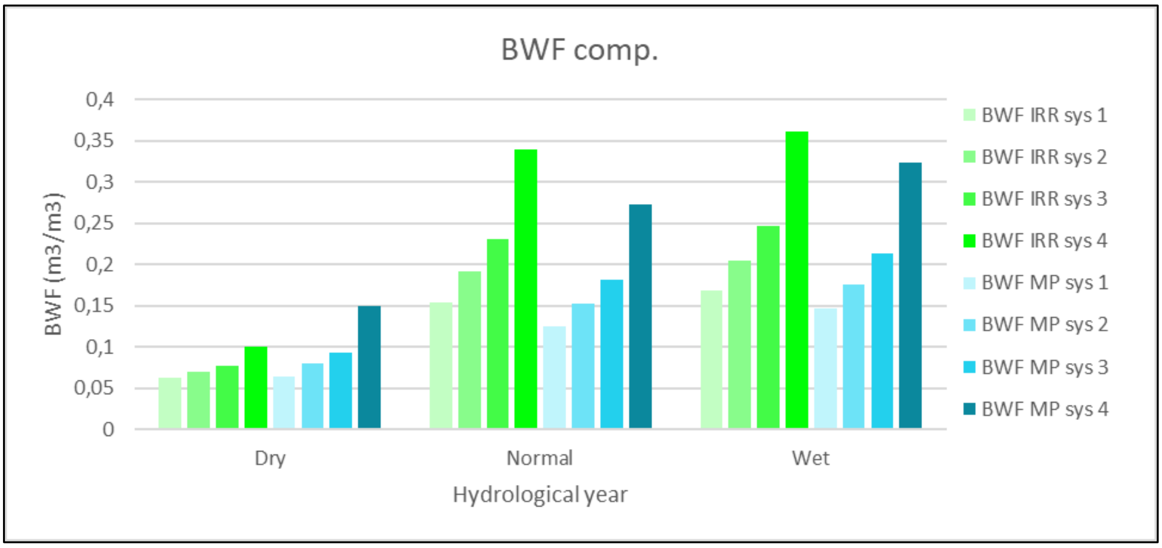


FIGURE 19 COMPENSATED BLUE WATER FOOTPRINT PER SYSTEM PER HYDROLOGICAL YEAR

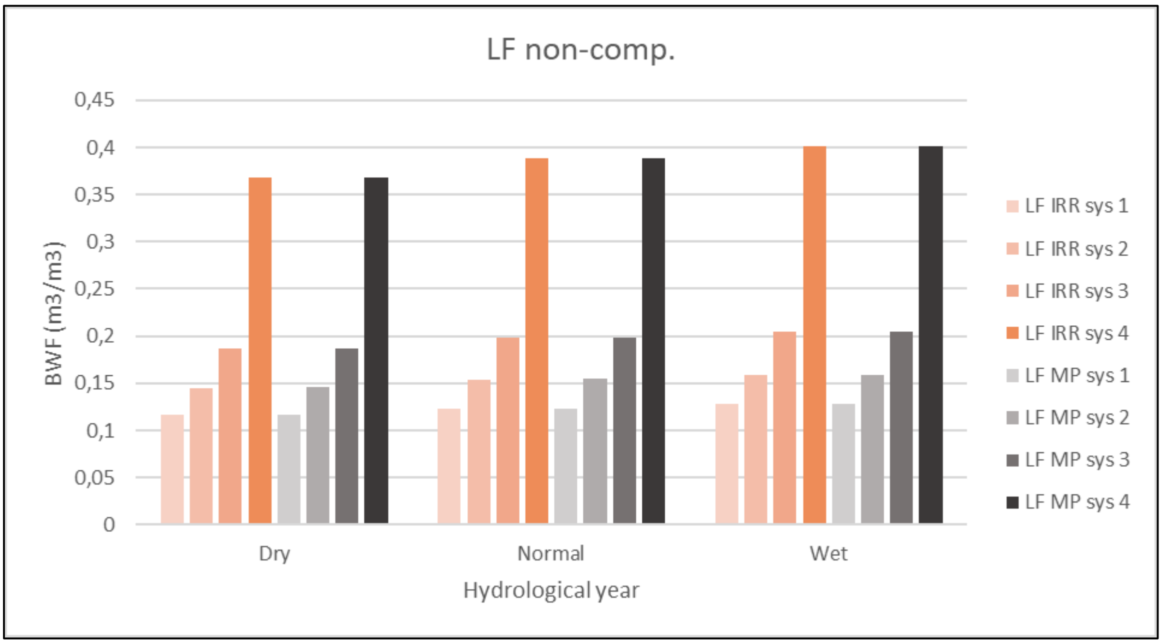


FIGURE 20 NON-COMPENSATED LAND FOOTPRINT PER SYSTEM PER HYDROLOGICAL YEAR

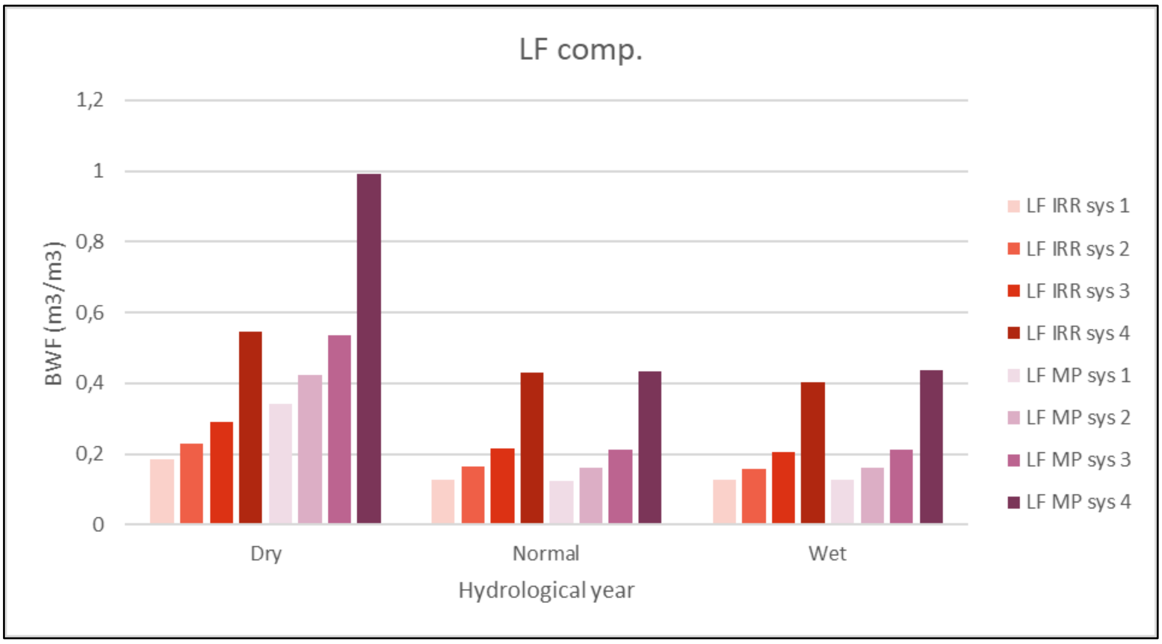


FIGURE 21 COMPENSATED LAND FOOTPRINT PER SYSTEM PER HYDROLOGICAL

Figures 18 and 19 show that the BWF is mostly higher for irrigational purposed storages than for multi-purposed storages. The difference is caused by the higher total yearly evaporation for irrigational purposed storages than for multi-purposed storages. Furthermore, Figures 20 and 21 show little differences between the irrigational and multi-purposed storages. For the non-compensated LF, no differences are present. However, for the compensated LF, the multi-purposed storages show higher results than the irrigational purposed storages. The difference is mainly caused by the differences in reliability, which are higher for the irrigational purposed storages than for the multi-purposed storages.

4 DISCUSSION

The research described in the previous chapters is a detailed analysis of the blue water footprints and land footprints of different storage systems. Such a detailed analysis is inevitably subject to assumptions and is therefore up for discussion to improve further research on the topic. In order to make this research applicable for further research, this chapter discusses several remarks concerning the methodology and the obtained results.

The assumption with the largest effect on the results made in this study is the assumption of choosing a hypothetical reservoir. Using the hypothetical reservoir made this study to some extent, even though the choice is based on average hydrological values, a case study for the Challawa reservoir, located in Nigeria. Many values of the variables are based on the values of the Challawa reservoir, having a semi-arid climatological character. Thereby, great care has to be taken when applying the results of this research for further research. When applying the results for further research extra care has to be taken in comparing the climatological data and storage dimensions.

In paragraph 2.2 the assumptions are made on the shapes of the storages. Even though these shape are based on literature (Knook, 2016; Hagos, 2005), the shapes might differ in reality. Furthermore, according to Sawunyama, et al. (2005), siltation occurs in storages. In small storages siltation can add up to 30% storage capacity loss in 40 years. Changing the shape has effect on the A-d-V relationships, leading to changes in, among other things, the storage surface area. Eventually, this leads to changes in blue water footprint and land footprint.

By using the A-d-V relationships and the residual mass curve method, the storage dimensions have been determined in this research. The residual mass curve method involves using the total inflow volume of the sum of storages within a system. The inflow volume used for the calculation of the new maximum volume, in paragraph 3.2, is based on the precipitation fallen in the normal hydrological year. The reason for choosing this year is based on reducing the required space for storages. It could be argued that the wettest hydrological year needs to be used in designing the storages, because then the storages would will not overflow, leading to safer water management and lesser spillage over the dam, however, it would also lead to more required space.

For this study climatological data are retrieved from the ERA-Interim database (ECMWF, 2017). The smallest, and used, resolution of these data has a grid size of 0.125x0.125 degrees' longitude x latitude. For Nigeria this grid size is equal to about 80 x 80 kilometres. Due to the coarse resolution all climatological data is equal for the whole catchment area. In reality, climatological data will be variable over the catchment area; there might even be multiple climates within one catchment area. Using equal climatological data over the whole catchment might results in unfair blue water footprints and land footprints and is therefore up for discussion. Still, the ERA-Interim database is chosen to use over other climatological databases, because it provides many atmospheric variables for the whole globe, based on model information as well as observation of many different sorts combined.

Additionally, it is debatable to further detail the water fluctuation model of this study, by using it in combination with georeferenced data programs, i.e. GIS (Georeferenced Information Systems). GIS could, for example, be used to follow the exact flowing patterns or elevations in the landscape in order to make a more detailed system in which storages are more adjusted to each other and assumptions on the catchment area per storage can be eliminated. Moreover, this study did not take into account groundwater flows. Georeferenced data programs could help implementing groundwater flows too.

The evaporation is calculated using the method of Finch. The method of Finch takes into account the depth of storages to account for differences in heat storage capacities. The heat storage capacities are calculated assuming stratified water temperatures throughout the whole storage depth. In reality, the water temperatures are not stratified. Moreover, the stratified water temperatures are determined by the 2m height air temperatures. The air temperature is far more sensitive to changes than the water temperature. Therefore, applying the method of Finch results in more fluctuations in water temperatures. More fluctuations in water temperatures can result in an overestimation of the evaporation (Finch, 2001).

In the calculation of the inflow volumes coming from upstream channels this study takes into account evaporation losses occurring during the transport of the water towards the storages. Even though the catchment areas become smaller for smaller storage types, often leading to shorter transport times of the water and shallower water, thus leading to more evaporation, the evaporation taken into account for the inflow volumes is kept equal for all storage systems. Furthermore, the inflow volumes are determined by the precipitation falling onto the catchment areas, but some precipitation also falls in between different catchment areas of storages and is runoff by the river. The more storages, the more precipitation becomes runoff through river that does not reach any storage. Additionally, the conveyance efficiency is not taken into account. The conveyance efficiency is a measure of the ratio of water supplied to the irrigated field to the quantity withdrawn from the water source, determining the quantity of water lost during transport (Rohwer, Gerten, & Lucht, 2007). In order to compensate for the more water losses when implementing more small storages, the runoff coverage factor is implemented into the model of this research. The results in chapter 3 of this study are based on a runoff coverage factor of 1.0 for all storage systems. In reality, this factor might be lower, due to aspects described in this subsection. When changing the runoff coverage factor to 0.9 in equation 18 the inflow volume become smaller for systems with smaller storages. This results in lower possible water abstractions, leading to higher blue water footprints and land footprints or resulting in lower probabilities of water supply. Thereby, this research underestimates the blue water footprints and land footprints of systems consisting of smaller storages.

$$Qin_{system\ number} = \frac{Qin\ system1}{u_{system\ number}} * runoff\ coverage\ factor^{system\ number} \qquad eq.18$$

In which:
$Qin_{system\ number}$ = the inflow volume per system (1, 2, 3 or 4) (m^3);
$u_{system\ number}$ = the amount of storage within the system;
runoff coverage factor = compensation factor for the more water losses with more small storages;
system number = the number of the system from 1 to 4 from large to small storages.

Table 23 shows the differences in inflow volumes from upstream channels into the total amount of storages per system and the differences in probabilities of water supply per system for a runoff coverage factor of 1.0 and 0.9. The differences are based on the calculations for irrigational purposed water storages under normal precipitation conditions.

TABLE 23 EFFECT OF THE RUNOFF COVERAGE FACTOR ON THE INFLOW VOLUME AND PROBABILITY OF WATER SUPPLY

Runoff coverage factor	**System**	**1**	**2**	**3**	**4**
1.0	Inflow volume (m^3 / year)	2.3822e+08	2.3822e+08	2.3822e+08	2.3822e+08
0.9	Inflow volume (m^3 / year)	2.3822e+08	2.1440e+08	1.9296e+08	1.7366e+08
1.0	Probability of water supply per season (%)	96.000	94.000	92.000	90.000
0.9	Probability of water supply per season (%)	96.000	85.225	77.800	71.375

The probability of water supply is assumed to be at least 90% for all storage systems when calculating with the irrigational purposed storages. The probability of water supply could also be chosen to be different. The actual probability is likely to be decided on by governmental organizations. For example, in paragraph 3.4, the probability of water supply comes below 90% for system 4 when calculating with multi-purposed storages. This probability is too low according to the earlier made pre-condition. In this case decision-makers have to consider whether the pre-condition has to be revalued or whether to change the total amount of water supply.

Moreover, the total water abstractions in this research are equal for all six scenarios. As a consequence, the actual met water supplies differ between the scenarios. In reality, one might argue that if more water is available (wet conditions), more water will be used and if less water is available (dry conditions), less water will be used. Maximizing the water abstractions, with a pre-condition of 90% water reliability, results in higher total water abstractions for wet conditions and lower total water abstractions for dry conditions.

The volumes of the water storages are determined by different in- and outflow factors. The outflow factor seepage can be calculated in different ways (Verruijt, 2007). This study uses a simplified method, which determines the effect of seepage on the water level in a constant water level difference per day (Khetkratok, 2010; Brouwer & Heibloem, 1986). Seepage losses from one storage are assumed not to flow into another storage. Other, more detailed, ways of calculating the seepage losses through the walls of the storages might result in more differences between the results of the different systems.

Other storage and outflow factors, such as the passive storage and the discharge, or environmental flow, are not taken into account separately. Although the model can be changed such that the water abstraction is differently distributed, they are not included in this study. Including these factors means that the storages total water abstractions increase, leading to lower probabilities of water supply. The model excludes these factors by dimensioning the storages such that no runoff occurs from the storages. The reality can be different. Including runoff from the storages would mean that storages in systems with multiple storages, if assumed that they are dependent on each other, could profit from each other.

This research is conducted for different hydrological years; the driest, normal and wettest year between 1997 and 2016. The reason for this is that a climatological trend is found in the precipitation data. The climatological trend has effect on the inflow volume, leading to large differences in the probability of water supply between separate years. Realistically, even without climatological trends, the total precipitation and its distribution differ per year (ECMWF, 2017).

The blue water footprint is measured to be between 15% and 31% for irrigational purposed, or 12% and 24% for multi-purposed, storage systems. These proportions are comparable with values from literature: In the Rio Grande basin (USA), evaporation from a mid-sized reservoir (Elephant Butte) accounts for 15%–25% of the Rio Grande (New Mexico) water consumption each year (Martinez-Granados, Francisco Maestre-Valero, Calatrava, & Martinez-Alvarez, 2011). Furthermore, it is estimated that the annual evaporation from on-farm storages in the Segura basin (Spain) is at around 58.3×10^6 m^3, which is more than 8% of irrigational water use in the basin. Moreover, Knook (2016) calculated the evaporation from irrigational purposed storages worldwide to be 515 m^3 per hectare of irrigated land per year. This study shows an evaporation from irrigational purposed storages in a semi-arid region to be 1014 m^3 / ha. Even though, the evaporation per hectare is almost doubled, this can be explained by the climatological conditions, which involve higher evaporations for semi-arid region than the worldwide average.

5 CONCLUSION AND RECOMMENDATIONS

The research question of this study was: What are the differences in blue water footprints and land footprints between multiple water storage systems with differently sized water storages used for water supply? The research question was split up for irrigational purposed storage systems and multi-purposed storage systems and answered using a hydrological model. This chapter gives a description of the answers of the research question.

5.1 Designing storage systems

In order to find the blue water footprints and land footprints, four storage systems were designed and ranked by storage size and centralization. The systems were based on the Challawa reservoir (Global Water System Project, 2017), located in Nigeria and multiple small-scale water harvesting storages (Hagos, 2005; Rämi, 2003). The climatological data of Challawa reservoir from 1997 to 2016 were retrieved from the ERA-Interim database (ECMWF, 2017). The data showed a downward climatological trendline in annual average precipitation. Therefore, the data was split up into three different hydrological years, given in Table 5; driest, normal and wettest year. Furthermore, by analyzing the data and finding literature, the cropping period was determined to be 100 days, starting in the end of June and ending in the beginning of October (Odekunle, 2004). For dimensioning the storages, the precipitation data of the normal hydrological year was used, leading to more efficient water harvesting.

Using A-d-V relationships (R^2>0.95) and the residual mass curve method, the dimensions of the storages have been determined, see Table 12. The dimensions are based on normal precipitation conditions above Challawa reservoir for storages that are used for irrigational purposes only and having a probability of water supply of a least 90% during the cropping season. In conclusion system 1 has the largest inflow volume and maximum surface area, water depth and water volume per storage unit, followed by system 2, system 3 and, respectively, system 4. The total maximum volume and inflow volumes are however equal for all four systems.

The amounts of storages were determined per storage system. System 1 is assumed to have one large storage. The amount of storages of systems 2, 3 and 4 are based on the ratio between the maximum surface area of system 1 and their own surface area. As a result, the second system is designed to have 64 medium-large storages, the third system consists of 3,950 medium-small storages and the fourth system consists of 252,000 small-sized storages. Consequently, under normal precipitation conditions, system 4 has the largest total mean surface area (1.8825e+07 m^2), followed by system 3, then system 2 and system 1 has the smallest total mean surface area (3.9183e+07 m^2). As a result, the most centralized storage system's total yearly evaporation is twice as large as the most decentralized storage system's total yearly evaporation.

5.2 Blue water footprint and land footprint

The blue water footprint and land footprint calculations were performed using a storage water level fluctuation model with multiple in- and outflows from the storages within the four systems. The main inflows are upstream-runoff and direct precipitation. The main outflows were seepage, evaporation and water abstractions. The model was used for six scenarios, using the dimensions and climatological data mentioned in paragraph 5.1. The scenarios differ in climatological input, in the form of dry, normal and wet hydrological years, and hydrological output, in the form of purpose of abstracted water; abstractions for irrigational purposes or multi-purposed water abstractions. The blue water footprints and land footprints of each scenario are given per system in Table 19 and 22 and Figure 18 to 21.

The blue water footprint under normal precipitation conditions, was found to be seasonally 0.15 to 0.30 evaporated m^3 per abstracted m^3 of water for irrigational purposed storages, and yearly 0.12 to 0.24 evaporated m^3 per abstracted m^3 of water for multi-purposed storages. This means that for irrigational purposed water storage systems 15% to 30% of the total seasonal water abstractions is lost through evaporation. For multi-purposed water storage systems 12% to 24% of the total annual water abstractions is lost through evaporation. The (seasonal and annual) blue water footprint is positively correlated to the amount of storages within a storage system.

The land footprint, defined as the total square meters required area for water storages within a system per cubic meters of water abstracted from the storage system, was found to be 0.12 to 0.39 m^2/m^3 for irrigational purposed as well as multi-purposed storages, under normal precipitation conditions. This means that 0.12 to 0.39 square meter is required to abstract one cubic meter of water. The (seasonal and annual) land footprint is positively correlated to the amount of storages within a storage system.

The positive correlations are caused by the increasing total surface area for more decentralized systems with smaller-sized storages. In conclusion the shape, or flatness (depth/surface area ratio), of the storage highly determines the amount of evaporated water and therefor also the water abstractions and thus the blue water footprints and land footprints. The blue water footprint and land footprint are positively correlated with flatness of the storages. In order to lower the blue water footprint and land footprint the flatness needs to be reduced.

Furthermore, the systems are designed to have equal total water capacities. Having also the same inflows could mean, that the water losses are equal. However, this study shows that the probabilities of water supply between the systems already differ with equal total water capacities. Compensating for these differences shows that the differences in blue water footprint and land footprint become even larger.

Moreover, as mentioned in chapter 4, the inflow volumes are determined by the precipitation falling onto the catchment areas, however some precipitation also falls in between different catchment areas of storages and is runoff by the river. The more storages, the more precipitation becomes runoff through rivers that do not reach any storage. As a consequence, the probabilities of water supply for smaller systems decrease, resulting even higher blue water footprints for smaller systems than for systems with large, centralized storages.

The blue water footprints are higher for irrigational purposed storages than for multi-purposed storages. The difference is mainly caused by the differences in probability of water supply. Although the total water abstractions should be the same for all systems, the water demands are not always met and can differ between scenarios. Especially for the driest hydrological conditions the probabilities of water supply differ between purpose of storage. Furthermore, the probability of water supply is positively correlated to the amount of yearly precipitation, resulting in a positive correlation between the blue water footprint and the amount of yearly precipitation, because more evaporation occurs with fuller storages, due to larger surface area with rising water levels.

The land footprint is equal for irrigational purposed storages and multi-purposed storages. This is a consequence of equal total water abstractions for both scenarios and equal total surface areas. Compensating for the differences in actual water abstractions between the purposes, gives a different result: under normal and wet conditions the land footprints of both purposed storage scenarios are similar, however under dry conditions, the multi-purposed storage systems show higher land footprints than irrigational purposed storage systems, caused by the lower reliabilities for multi-purposed storage systems.

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APPENDICES

APPENDIX A. SOIL CHARACTERISTICS

Multiple soil characteristics influence the calculation of the blue water footprint and land footprint. This appendix gives the values of multiple soil characteristics.

Seepage water losses
The horizontal and vertical seepage, Q_S, through the walls and base of a water storage is dependent on the soil type. Below the seepage water losses are given per soil type (Brouwer & Heibloem, 1986).

TABLE 24 SEEPAGE WATER LOSSES (BROUWER & HEIBLOEM, 1986)

Sr. No	Natural soil type	Seepage water losses (mm/day)
1	Heavy clay	2
2	Sandy	8
6	Average	5

Angle of repose
The angle of repose determines the angle of the shape of the small-scale water storages. The angle of repose is dependent on the soil type. Below the angles of repose are given per soil type.

TABLE 25 ANGLES OF REPOSE FOR VARIOUS SOIL TYPES (STRUCT X, 2017; VERRUIJT, 2007)

No.	Natural soil type	Dry	Moist	Wet
1	Peat	15	45	-
2	Sandy clay		15	
3	Loam	40-45		20-25
4	Clay / silt (solid)		40-50	
5	Clay / silt (loose)		20-25	
6	Silt		19	
7	Sand (compact)		35-40	
8	Sand (loose)	30-35		25
9	Sandy gravel (compact)		40-45	
10	Sandy gravel (loose)		35-45	
11	Gravel (medium coarse)	25-30		25-30
12	Shingle (loose)		40	
13	Shale (hard)		19-22	
14	Broken Rock	35		45

APPENDIX B: CLIMATOLOGICAL DATA

This appendix gives the climatological data from 1997 to 2016 retrieved from the ECMWF-website (2017) for 8,025417° longitude and 11,724583° latitude. At these coordinates the Challawa reservoir, Nigeria is found (Global Water System Project, 2017). Each retrieved variables is given in a figure as the variable over the period from 1997 to 2016, followed by the data of the variable for the dry, normal and wet hydrological year, found in paragraph 3.1. The dry hydrological year is based on the year with the lowest precipitation, this was the hydrological year of 2006/2007, starting in October. The normal hydrological year is based on the year with the mean precipitation, this was the hydrological year of 2009/2010, starting in October. The wet hydrological year is based on the year with the highest precipitation, this was the hydrological year of 2004/2005, starting in October.

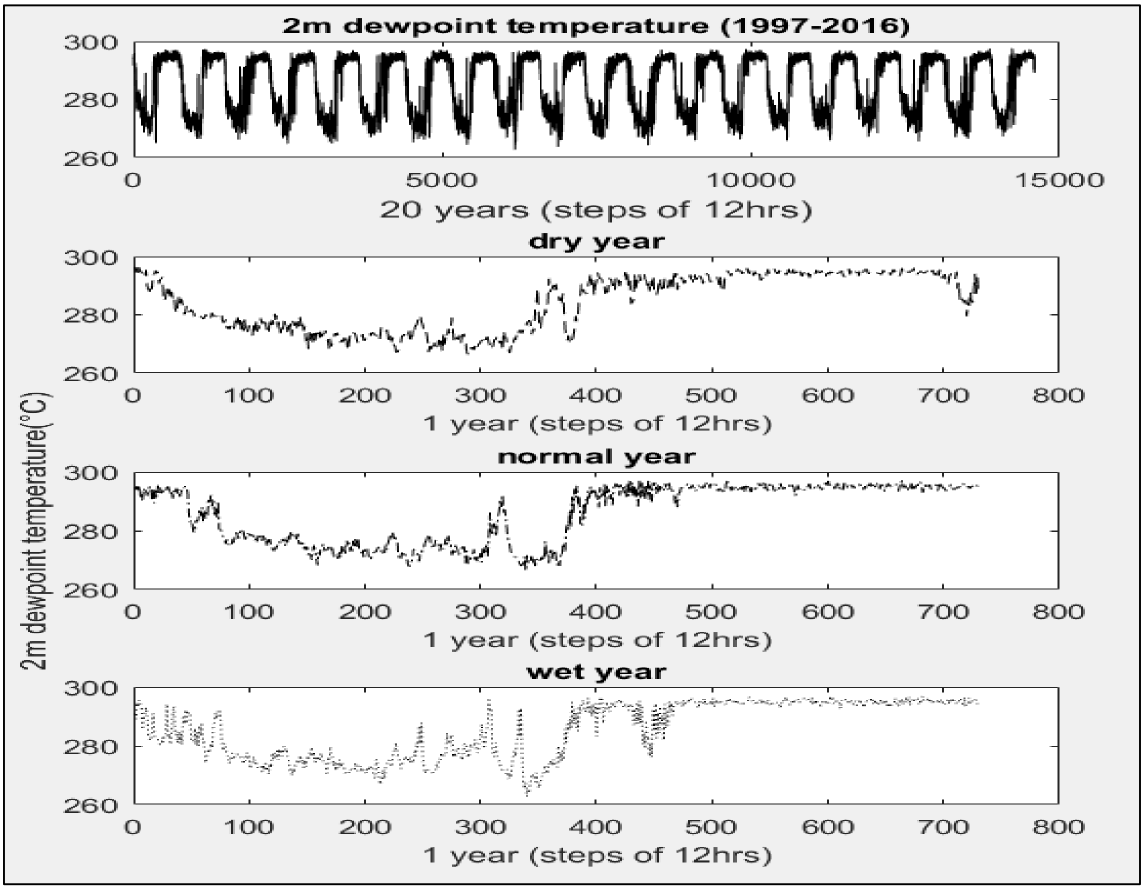

FIGURE 22 2M DEWPOINT TEMPERATURE

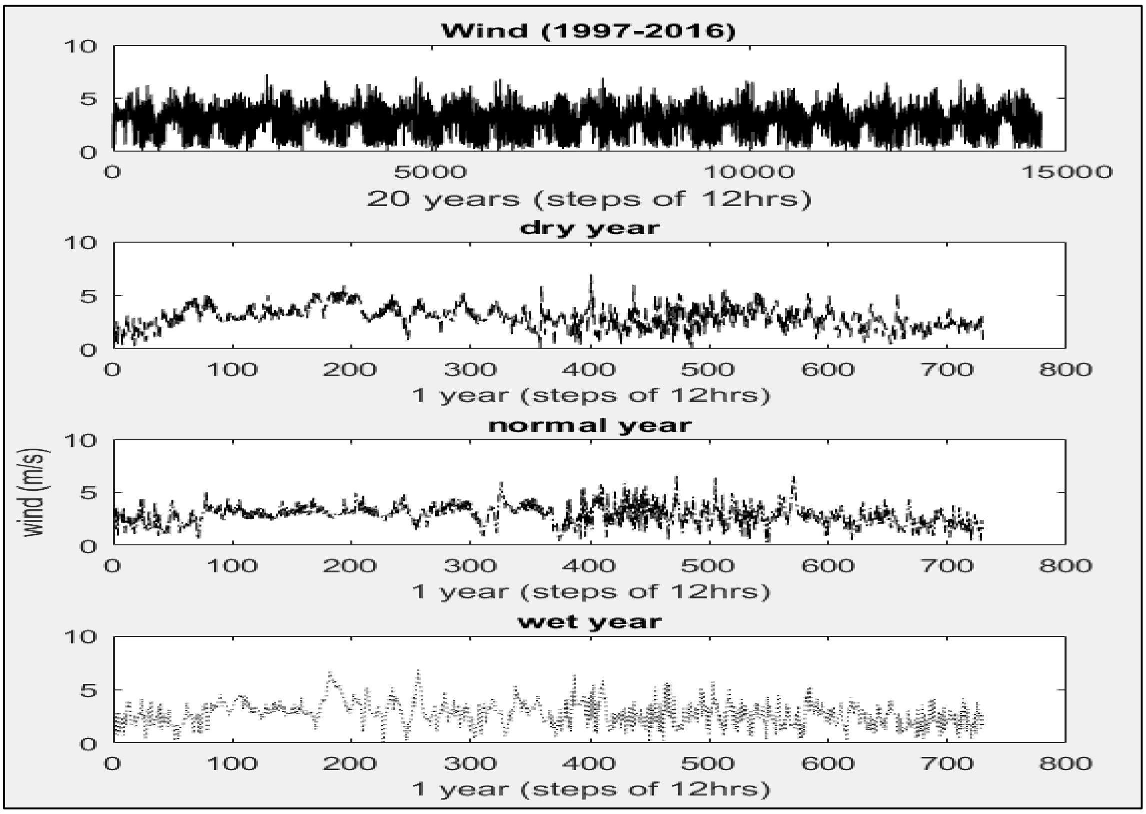

FIGURE 23 WIND

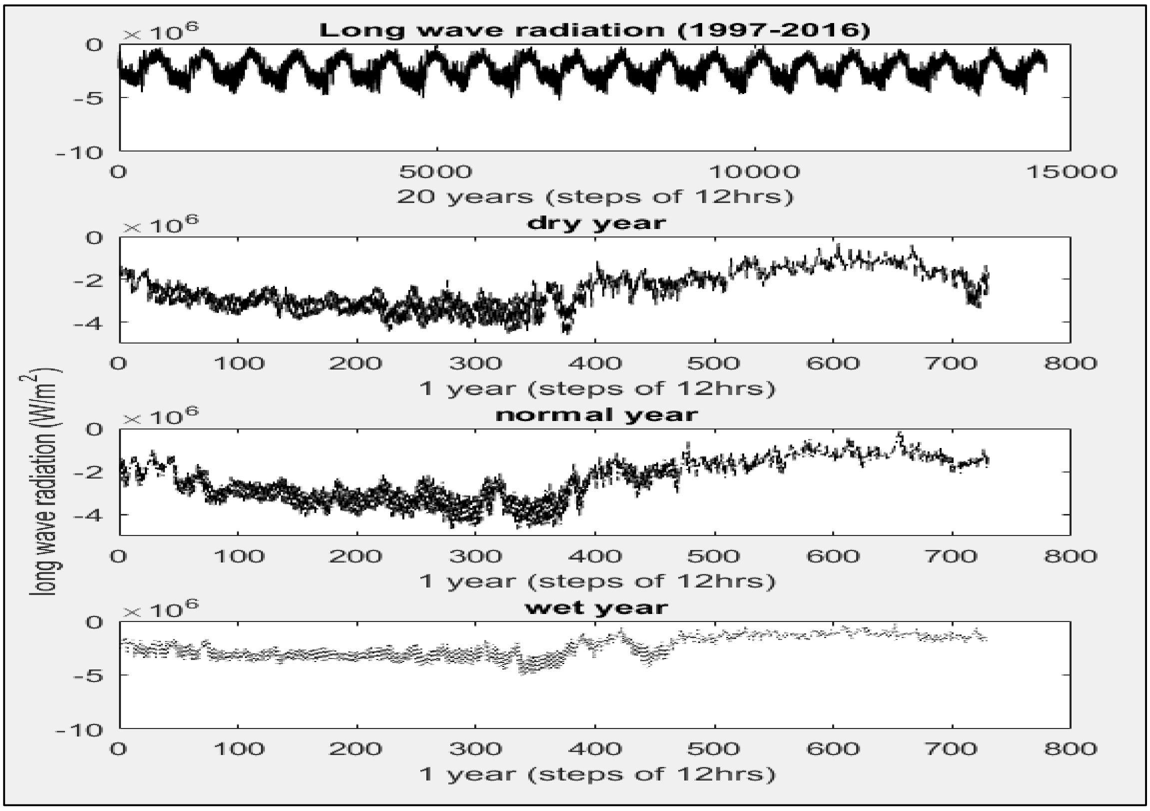

FIGURE 24 LONG WAVE RADIATION

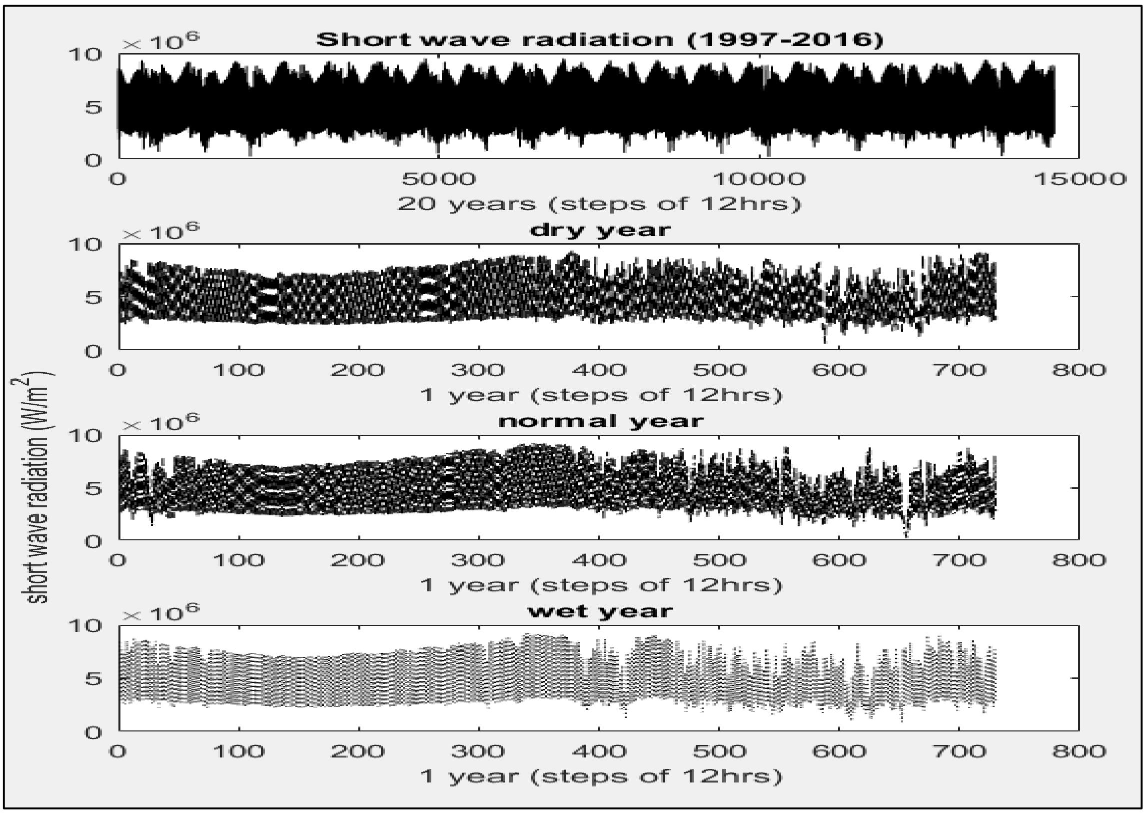

FIGURE 25 SHORT WAVE RADIATION

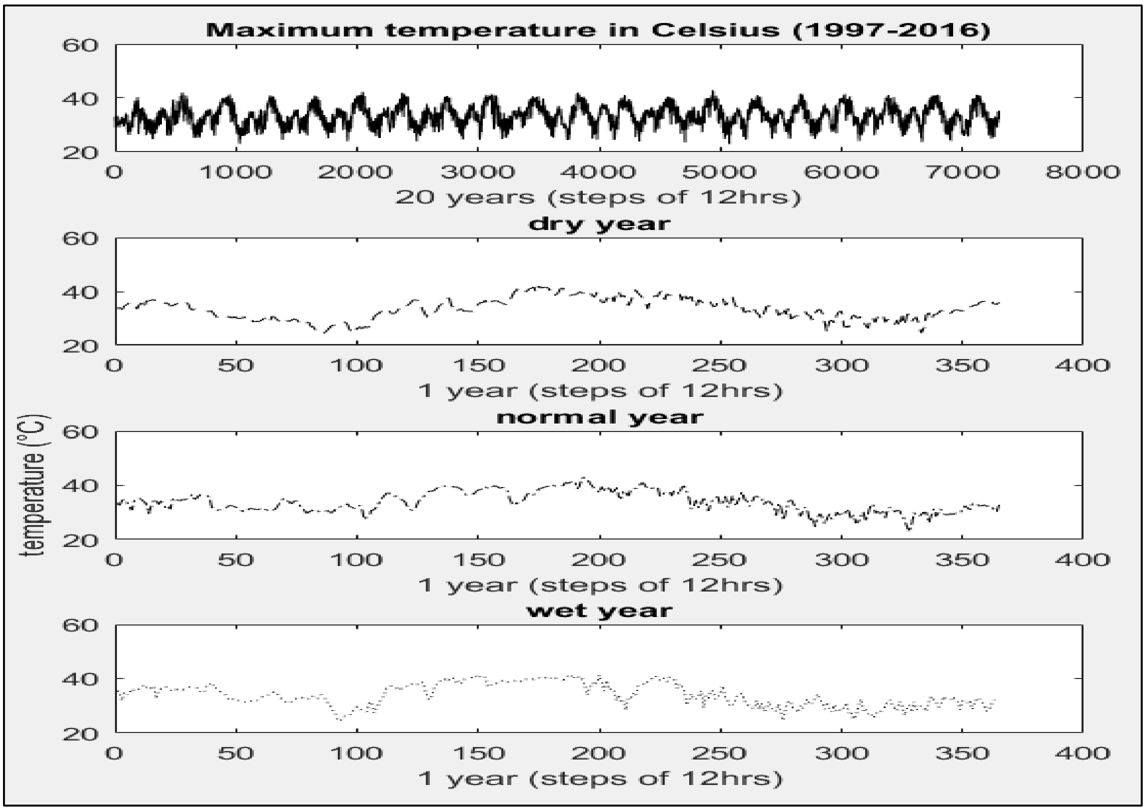

FIGURE 26 MAXIMUM TEMPERATURE

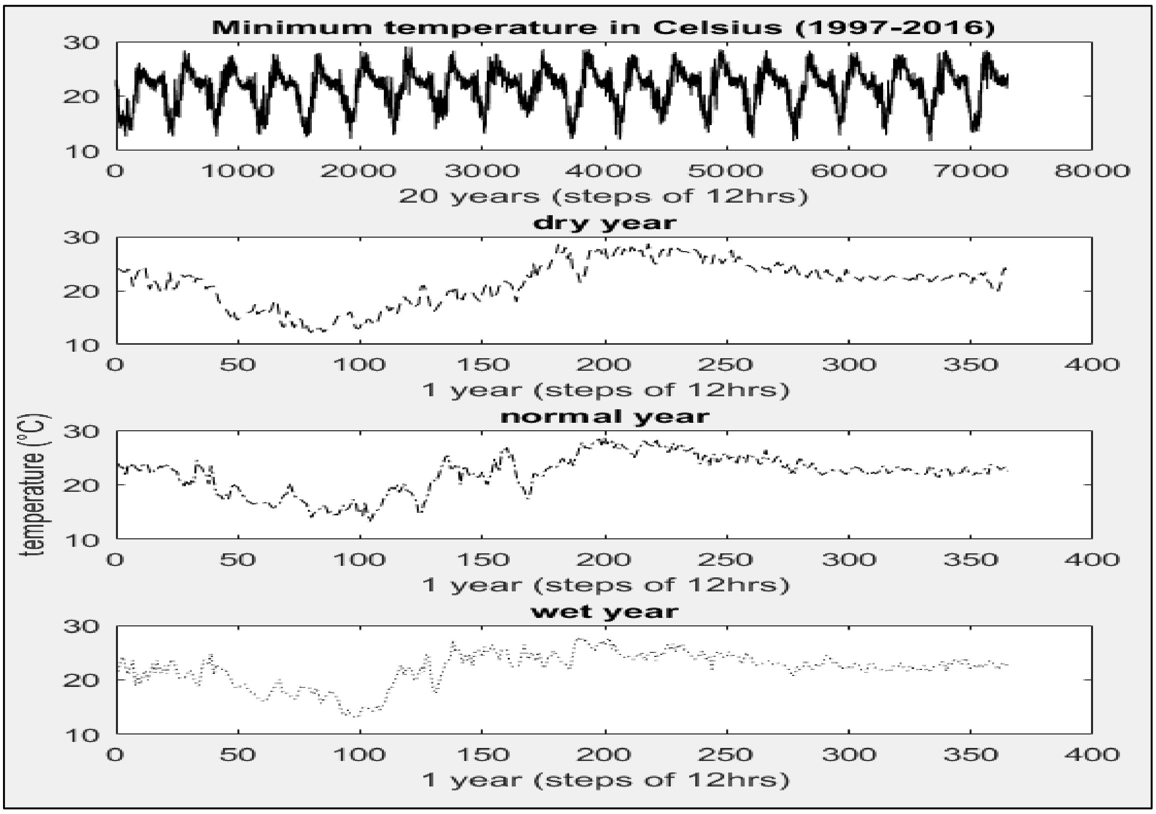

FIGURE 27 MINIMUM TEMPERATURE

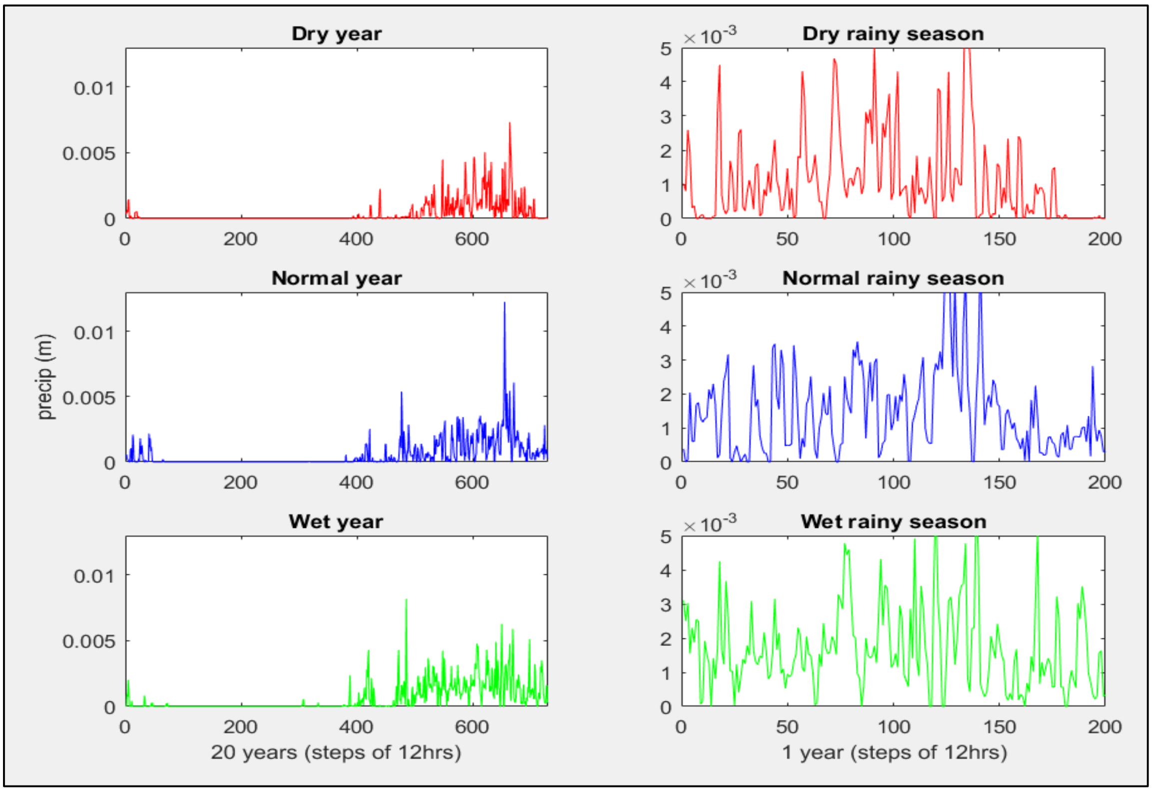

FIGURE 28 YEARLY AND SEASONAL PRECIPITATION

APPENDIX C: RESIDUAL MASS CURVE

The mass curve and residual mass curve of the inflow of system 1, which were used to determine the maximum capacity of the storages of system 1, are given as an example of the residual mass curve method in Figures 29 and 30.

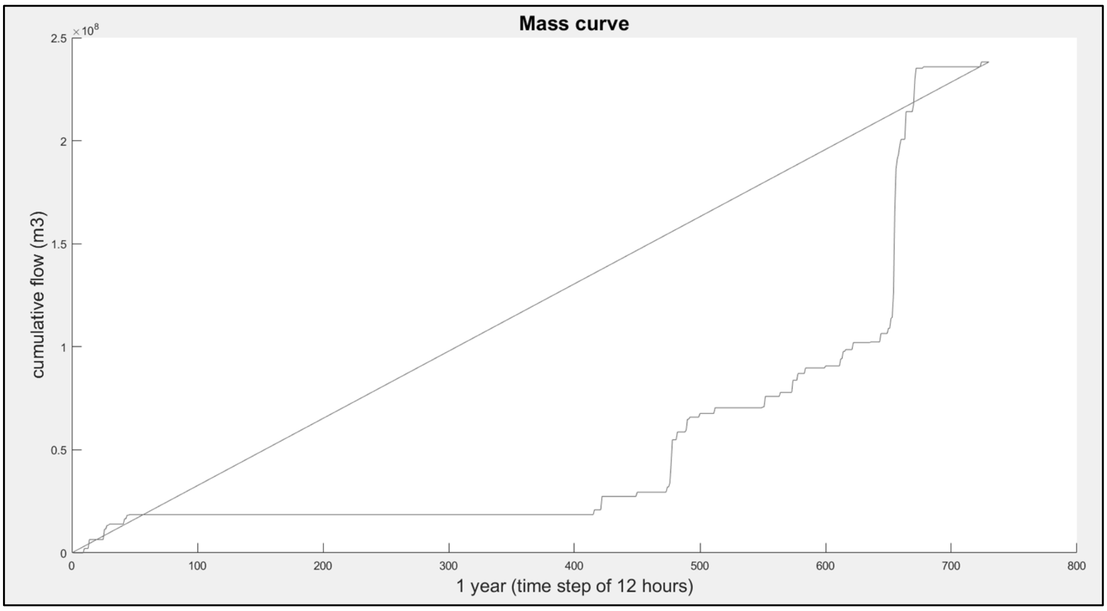

FIGURE 29 MASS CURVE

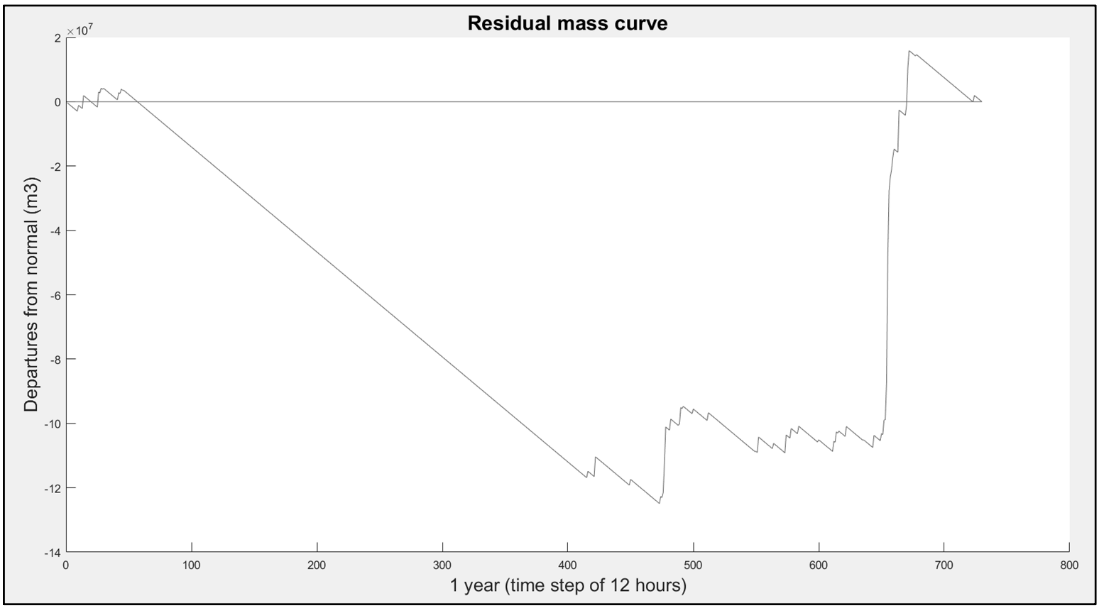

FIGURE 30 RESIDUAL MASS CURVE