MODELLING GROUNDWATER RESOURCES OF TRANSBOUNDARY OKWA BASIN

CHERUIYOT, SAMUEL KIPYEGON February, 2018

SUPERVISORS: Dr. Maciek.W. Lubczynski Ir. Gabriel Parodi

ADVISOR: Moiteela Lekula

MODELLING GROUNDWATER RESOURCES OF TRANSBOUNDARY OKWA BASIN

CHERUIYOT, SAMUEL KIPYEGON Enschede, The Netherlands, February, 2018

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation. Specialization: Water Resources and Environmental Management

SUPERVISORS: Dr. Maciek.W. Lubczynski Ir. Gabriel Parodi

ADVISOR: Moiteela Lekula

THESIS ASSESSMENT BOARD: Dr. ir. C. van der Tol (Chair) Dr. P. Gurwin (External Examiner, University of Wroclaw, Poland)

DISCLAIMER

This document describes work undertaken as part of a programme of study at the Faculty of Geo-Information Science and Earth Observation of the University of Twente. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the Faculty.

ABSTRACT

Transboundary Okwa Basin aquifer is located in the Kalahari Desert, and it is shared between Namibia and Botswana. In this region groundwater is the primary water resource and life and the economy of these two countries depends on it. To better manage the water resources in this area, it is vital to understand and quantify the available groundwater resources and analyse the dynamics water balance components and its interactions with groundwater.

The objective of this study was to evaluate the groundwater resources of Okwa Basin aquifer for management purpose. To achieve this objective, both conceptual and numerical models were developed. A conceptual model was developed to qualitatively describe the groundwater system. A numerical model based the conceptual model was developed to quantify groundwater resources. For that purpose, UZF1 package integrated with MODFLOW–NWT was used to simulate the interactions between the unsaturated and the saturated layers. The model was set up and calibrated in both steady and transient states. Calibration was done using trial and error technique. The modelling period was 12th September 2012 – 11th March 2016.

In the steady state model, the applied precipitation (*P*) was 338.8 mmyear-1, evapotranspiration from the subsurface (ET_{ss}) was 72.7 % of *P*, gross recharge was 85.1 % of *P*, ground water exfiltration (EXf_{gw}) 12.0 % of *P* and net recharge (R_n) was 0.6% of *P*. The spatial distribution of R_n showed that most recharge occurred along river valleys, fault lines and depressions. In decreasing order, the model was most sensitive to: conductance of the drain boundary (C), vertical hydraulic conductivity confining layer (VKCB), horizontal conductivity (HK) and vertical conductivity (VK).

The groundwater fluxes estimated by the transient model showed considerable differences between seasons and between years. Net recharge took place in only a few days during the entire model simulation. Hydrological year period of 12/09/2013 - 11/09/2014 was the wettest with net recharge of 2.1 mm year⁻¹ while 12/09/2012 - 11/09/2013 was the driest with net recharge of -0.6 mm year⁻¹. When tested against both heads and fluxes (R_g , ET_g , $EXF_{gw} \& R_n$), the transient model was most sensitive to initial water content (THT1), UZF saturated water content (THTS), Brooks-Corey exponent (ε) and), ET extinction water content (EXTWC).

This study provides better understanding of the spatial-temporal variability of groundwater fluxes in an arid environment of complex hydrogeology.

<u>Keywords</u>: Integrated hydrologic model, Transboundary Okwa Basin Aquifer, Kalahari, Botswana, Namibia, Groundwater recharge, Water balance.

ACKNOWLEDGEMENT

First, I would like to thank God for the opportunities He has always presented along with my path. Secondly, I will forever be indebted to the NFP for funding my studies.

I would like to thank my first Supervisor, Dr Maciek Lubczynski, for his guidance, patience and encouragement throughout this research and even before we started. To my second supervisor Ir. Gabriel Parodi, who has been of great help when it comes to the preparation of satellite-based input for the model, I am grateful for all you have done. To my advisor, Moiteela Lekula who has always been available for consultations even at odd hours, thank you very much.

During fieldwork, the team at the University of Namibia was of great help. I would like to thank Dr Heike Wanke for hosting me and making arrangement to ensure that my fieldwork was a success. To Albertina, Josefina, Shoopala and Ester, you made me feel at home. My appreciation go to the following organisations for allowing me access and use their data: Hydrological Services of Namibia, Namibia Meteorological Service and SASSCAL.

To all my friends I made during my study at ITC, life would have been dull without you guys. To all who made this possible, you know yourselves, thank you.

TABLE OF CONTENTS

1.	Intro	duction	1
	1.1.	Background	1
	1.2.	Problem statement	2
	1.3.	Research objectives and questions	2
	1.3.1.	Objectives	2
	1.3.2.	Research questions	2
	1.4.	Novelty of the study	2
2.	Study	Area and Materials	3
	2.1.	Location	3
	2.2.	Climate	3
	2.3.	Topography	4
	2.4.	Land use and land cover	4
	2.5.	Soils	5
	2.6.	Geology	6
	2.7.	Hydrology and Hydrogeology	7
	2.8.	Previous Studies	10
3.	Meth	odology	12
	3.1.	Fieldwork	
	3.2.	Conceptual model	
	3.2.1.	Hydro-stratigraphy and Hydrogeological Properties	13
	3.2.2.	Boundaries	14
	3.2.3.	Flow Direction	14
	3.2.4.	Sources, sinks and storages	14
	3.3.	Numerical modelling	15
	3.3.1.	Code selection	15
	3.3.2.	Model setup and model structure analysis	17
	3.3.3.	Driving forces	17
	3.3.4.	State variables	21
	3.3.5.	Model parameters	24
	3.3.6.	Solvers	25
	3.4.	Model Calibration	25
	3.4.1.	Steady-state model calibration	25
	3.4.2.	Transient model Calibration	26
	3.4.3.	Model Performance Evaluation	26
	3.4.4.	Sensitivity analysis.	27
	3.5.	Water Balance and ZONEBUDGET	
4.	Resul	ts and Discussion	29
	4.1.	Data processing results	
	4.1.1.	Precipitation	29
	4.1.2.	Potential Exapotranspiration	32
	413	Interception and infiltration rates	34
	1.1.5.	Evapotranspiration Extinction depth	
	4.2	Hydro-stratioraphic units	35 35
	т.∠. Д 2 1	Kalahari Sand Laver	
	т. <u>2</u> .1. 1 о о	Inter Karoo Aquitard	
	+. <i>L</i> . <i>L</i> .	Ease Assistant	
	4.2.3.	Ecca Aquifer	38

	4.2.4.	Ghanzi Aquifer	
	4.3.	Conceptual Model	
	4.4.	Steady-state model calibration results	41
	4.4.1.	Calibrated parameter sets	41
	4.4.2.	Calibrated heads error assessments	42
	4.4.3.	Water budgets for the steady-state model.	44
	4.4.4.	Spatial distribution of water budget components	46
	4.4.5.	Sensitivity analysis	47
	4.5.	Transient model calibration results.	
	4.5.1.	Calibrated parameter sets	49
	4.5.2.	Calibrated heads error assessments	49
	4.5.3.	Water budgets for the transient model	51
	4.5.4.	Sensitivity analysis	54
5.	Concl	lusion and Recommendation	59
	5.1.	Conclusion	59
	5.2.	Recommendations	
6.	List o	of references	61
7.	Apper	ndixes	64
	7.1.	Rainfall Data obtained	
	7.2.	Data Periods for the weather stations and Piezometer	
	7.3.	Simulated Heads	

LIST OF FIGURES

Figure 1: Study area and modelled area	3
Figure 2: Monthly maximum and minimum temperature and rainfall (WMO (2017))	4
Figure 3: Land cover map (CCI Land Cover team 2017).	5
Figure 4: Soils (Batjes 2004)	6
Figure 5: Geology of modelled area (adapted from (Machacha and Key 1997; Key and Ayres 2000))	7
Figure 6: Previous studies and simulated heads of	11
Figure 7: Methodology flow chart	12
Figure 8: Borehole Logs	. 13
Figure 9: Model boundaries and setup	. 14
Figure 10: Bias decomposition	. 18
Figure 11: Head observations	22
Figure 12: Observed piezometric heads	23
Figure 13: Schematic diagram (adapted from (Berhe 2017))	27
Figure 14: Detection of the SREs at the various stations shown in Figure 44	29
Figure 15: Bias components for CHIRPS and FEWSNET over the study period	. 30
Figure 16: Cumulative precipitation for the entire model	. 31
Figure 17: Average daily precipitation applied to the model	. 31
Figure 18: Daily mean rainfall for the corrected CHIRPS for the period 12/09/2012 to 11/03/2016	. 32
Figure 19: Calculated versus FESNET PET	. 33
Figure 20: FEWSNET PET averages for the period 12th September 2012 to 11th March 2016 (mmday-12) 34
Figure 21: Interception based on land cover (Wet period: Sep-April; Dry Period: April - Oct)	. 34
Figure 22: Extinction depth map	. 35
Figure 23: Hydro-stratigraphic cross-sections of transects in Figure 8	. 36
Figure 24: Kalahari Sand spatial distribution and thicknesses	. 37
Figure 25: Aquitard spatial distribution and thicknesses	. 38
Figure 26: Ecca Aquifer spatial distribution and thicknesses	. 39
Figure 27: Ghanzi Aquifer spatial distribution and thicknesses	39
Figure 28: Conceptual model	. 40
Figure 29: Calibrated hydraulic conductivity (mday-1) for the layers	42
Figure 30: Simulated versus Observed heads	. 43
Figure 31: Residual versus observed heads	. 43
Figure 32: Simulated heads contours for three aquifer layers	. 44
Figure 33: Water fluxes between the layers (mmyear ⁻¹)	. 45
Figure 34: Spatial distribution of water budget components	. 47
Figure 35: Sensitivity analysis for steady-state model	. 48
Figure 36: Simulated and observed heads for BH26674	. 50
Figure 37: Simulated and observed heads for BH9294	. 50
Figure 38: Simulated and observed heads for BH9245	. 51
Figure 39: Water fluxes	. 52
Figure 40: steady-state and transient solutions (Based on table 11)	. 54
Figure 41: Parameters sensitivity against heads.	. 55
Figure 42: Rg , ETg , $EXFgw$ & Rn Sensitivity to Brooks-Corey exponent (ε) and ET extinction water	•
content (EXTWC)	. 56

Figure 43: Rg, ETg, EXFgw & Rn sensitivity to initial water conter	nt (THT1) and saturated water content
(THTS)	
Figure 44: Station locations	

LIST OF TABLES

Table 1: Simplified stratigraphy of Okwa basin (Modified from (Smith 1984; Miller 2008; UNES	CO-IHP
2016))	9
Table 2: Interception loss as a percentage of total rainfall	
Table 3: Average groundwater abstractions.	
Table 4: Rooting Depths	
Table 5: MODFLOW-NWT solver options used	
Table 6: Calibrated parameters for the steady-state model. F indicated that the parameter was fix	ed while
C indicated that it was adjusted during calibration.	41
Table 7: Water Budget components in the different layers.	
Table 8: Water Budget components in the entire model	
Table 9: Transient calibrated parameters	49
Table 10: Error assessment of transient model	
Table 11: Water Balance components (mmyear-1).	53
Table 12: Simulated (Sim) and observed (Obs) heads for Steady state model	66

1. INTRODUCTION

1.1. Background

Water resources are limited in the arid and semi-arid areas of the world and increasingly under pressure from growing population, rising water use per capita and intensified irrigation (Wheater et al. 2008). This is the case in Namibia and Botswana, located in an arid climate. These two countries are amongst the driest countries in the world. Their water resources are both scarce and limited, and surface water resources are mainly intermittent and highly dependent on rainfall pattern. As a result, groundwater is the primary water resource which life and the economy of these two countries depend on it (Mendelsohn et al. 2002).

There are transboundary aquifers along the Botswana-Namibian border (Christelis et al. 2016). These include: Stampriet Aquifer which is shared between Botswana, Namibia and South Africa; Eiseb Graben aquifer shared between Botswana and Namibia; and Okwa Basin aquifer shared between Botswana and Namibia. Comprehensive studies have been done for both, the Stampriet (UNESCO-IHP 2016) and the Eiseb Graben aquifers (Margane et al. 2004; Stadtler et al. 2005) but little on the Okwa Basin aquifer which located in the western tip of the Central Kalahari Basin (CKB) aquifer (Lekula et al. 2017).

Okwa Basin aquifer is characterised by savanna vegetation of semi-arid climate and deep water tables (De Vries et al. 2000). It is a sedimentary basin of complex geology with multiple hydro-stratigraphic units the topmost being a thick aeolian sandy layer. The aquifer is believed to have low to moderate productivity potential (Christelis and Struckmeier 2011).

Evaluation and quantification an aquifers potential is essential for efficient groundwater resource management (Healy and Scanlon 2010). Management of transboundary aquifers is complicated by differences in governance principles and priorities of the involved countries as detailed by Linton and Brooks (2011). This study attempts to provide the knowledge needed for management of such aquifers.

There are numerous new and old methods of water resources assessments and management (Koch and Missimer 2016). These methods range from field observations to modelling and remote sensing which can be applied at field scale to regional scales. A standard tool is numerical groundwater modelling. This because models can predict consequences of various management practices and understand groundwater system dynamics (Anderson et al. 2015).

In this study, evaluation of the hydrogeological condition of the Okwa Basin was done using a numerical model. Three-dimensional (3D) finite-difference computer code -MODFLOW-NWT (Niswonger et al. 2011) and Unsaturated Zone Flow (UZF1) Package (Niswonger et al. 2006) under ModelMuse (Winston 2009) user interface were used.

1.2. Problem statement

Groundwater is the largest available source of freshwater in the world and an essential component of the water cycle. Along the Namibian-Botswana's border, groundwater is the primary water resource available to sustain economic activities. However, the replenishment to these aquifers has been estimated to be limited and highly variable spatiotemporally (Wanke et al. 2013). This brings the concerns that the groundwater resources can be overexploited (Konikow and Kendy 2005) and its quality degraded (Dzhamalov 2006). The hydrogeological knowledge of Okwa Basin aquifer is limited and not consolidated due to its transboundary nature. This makes it prone to mismanagements.

1.3. Research objectives and questions

1.3.1. Objectives

The study aimed to evaluate the water resources of Okwa Basin aquifer with an emphasis on groundwater for management purpose.

The specific objectives are:

- To define hydro-stratigraphy of Okwa Basin aquifer.
- To develop a conceptual model for the Okwa Basin aquifer.
- To develop and calibrate a distributed and a multi-layered numerical model of Okwa Basin aquifer.
- To evaluate groundwater flow patterns and flow interactions between aquifers within the basin.
- To analyse spatiotemporal variability of water balance components with emphasis on net recharge.
- To evaluate water resources of Okwa Basin aquifer and its replenishment

1.3.2. Research questions

Main research question

What is the state of water resources in Okwa Basin aquifer?

Specific research question

- What are the aquifer's extents and boundaries, hydro-stratigraphy, hydrogeological properties and sources and sinks?
- How can the water balance components of the Okwa Basin aquifer be represented in a numerical model?
- What are the flow patterns and directions of the aquifers?
- What is the net recharge and its spatiotemporal distribution?
- What is the spatiotemporal distribution of water balance components in the aquifer?

1.4. Novelty of the study

The research will increase the understanding of the Okwa Basin aquifer and therefore the whole of CKB as it incorporates the following novelties: i) development of a conceptual model; ii) setup and calibration of an integrated numerical hydrological model; and iii) analysis of the spatiotemporal dynamics of water balance components.

2. STUDY AREA AND MATERIALS

2.1. Location

The study area (Figure 1) lies across the Namibian-Botswana border east of Gobabis (Namibia) town. The study area (43,761 km²) is a catchment of the fossil Okwa River and Rietfontein River (Figure 1) and is located in the western part of the Central Kalahari Basin (CKB). The area was delineated based on surface water divides of Okwa River. A portion of that area (29,193 km²) was modelled, and that portion is hereafter referred as *modelled area*. Of the modelled area, 52.2% is located in Botswana, and the rest is in Namibia.



Figure 1: Study area and modelled area.

2.2. Climate

The study area lies in the Kalahari Desert, and it experiences semi-arid conditions. Precipitation is restricted to the hot summer season extending from September to April. The average annual precipitation is approximately 400 mm (Wanke et al. 2008). The dry season is also the cold period, and it extends from May-October, Negligible rainfall is experienced in this period. Figure 2 below shows 30 years (1971-2000) averages of Ghanzi weather station within the study area.



Figure 2: Monthly maximum and minimum temperature and rainfall (WMO (2017)).

2.3. Topography

The study area is generally flat with, a low gradient of <1:1000, gentle slope eastwards towards Botswana (Figure 1). Along the NE of SW transect at the centre of the study area, the gradient is steeper as can be seen in Figure 1 above. It is locally believed to be a fault-line. The elevation ranges from 1001 to 1587 m.a.s.l. The river valleys are wide with fossil river channels mostly not well incised in the valley.

2.4. Land use and land cover

The main land uses in the study area are ranching, game reserve, and settlements. The mainland covers (in decreasing order of area coverage) are shrubland (87.10%), grassland (12.66%), bare land (0.21%), trees (0.02% and built up area (0.01%). A synopsis of the vegetation types in the Kalahari is given by (Scholes et al. 2002). Figure 3 shows the land covers of the study area of 2016.



Figure 3: Land cover map (CCI Land Cover team 2017).

2.5. Soils

The Okwa Basin is mostly covered by arenosol soil type, which is deep and lacks stratification. They are of sandy texture, highly permeable and low in humus content, therefore also low in nutrient content. Physical weathering is the dominant soil-forming process (Christelis and Struckmeier 2011). At the centre of the study area along the NE to SW lie regosols, which are weakly developed, unconsolidated materials (Batjes 2004; Meek et al. 2008). The rivers affected the soil forming processes as shown in Figure 4.



Figure 4: Soils (Batjes 2004)

2.6. Geology

Widely varied and complex geology is found in the area. There are, different nomenclature and survey techniques that are used in the two countries and therefore the geological maps are different. Unlike Namibia, Botswana geology includes an extensive survey of the Pre-Kalahari structures.

For this study, a lookup table was created from the geological descriptions of Botswana. This lookup table was used to extend the structures into Namibian side. Therefore, in this study, Botswanan nomenclature is used.

The main geological groups are the Karoo Basalt, Lebung, Ecca and Ghanzi. The surface cover for the entire study area is the Kalahari Sand. Kalahari lithologies include sand, calcrete and gravel and cover the top of the whole study area (Miller 2008). The Karoo supergroup strata composed of sandstone, shale, siltstone and limestone, underlay the Kalahari Sand mainly to the south of the study area. A combination of Quartzite, conglomerate and schists which belong to Ghanzi group are prominent to the north (Smith 1984; Miller 2008). Figure 5 below shows the spatial distribution of these structures.



	LITHOLOGY	FORMATION	GROUP	SUPERGROUP	SYSTEM/AGE		
Kv	Flood basalt, variably amygdaloidal with minor siliciclastic sedimentary interbeds and lenses		Karoo basalts	Upper Karoo	Jurassic		
KL	Orange, red or white sandstone, locally calcareous with reddish siltstone increasingly common downwards		Lebung	Opper Karoo	Triassic - Jurassic		
KE	Interbedded coal, carbonaceous siltstone and mudstone and white, poorly, cemented arkosic sandstone and rare tonstein		Ecca		Triassic		
KD	Assorted glacial deposits including diamictite, very thinly laminated siltstone (varvite) and sandstone		Dwyka	Lower Karoo	Carboniferous - Early Permian		
Dzu	Weakly Metamorphosed, purple-red to greenish grey,siliciclastic sedimentary rocksarkosic sandstone limestone and siltstone		Undifferentiated Ghanzi		Neoproterozoic		
DZm	Weakly Metamorphosed, purple-red arkosic sandstone limestone and siltstone	Mamuno			Neoproterozoic		
DZd	Weakly Metamorphosed, greenish-grey arkosic sandstone and siltstone, musdtone and rhythmite with Cu-Ag mineralization in basal beds	D'Kar	Ghanzi		Neoproterozoic		
DZn	Weakly Metamorphosed, purple arkosic sandstone	Ngwako Pan			Neoproterozoic		

Figure 5: Geology of modelled area (adapted from (Machacha and Key 1997; Key and Ayres 2000))

2.7. Hydrology and Hydrogeology

Okwa Basin is the catchment of the fossil Okwa river and its tributary Rietfontein River. The transboundary Okwa Basin is part of the broader Central Kalahari Basin (CKB). Okwa basin has limited surface water bodies, but intermittent streams can be found during the wet season. The location of the rivers is shown in Figure 1. Okwa basin has a complex hydrogeological system due to its geology.

In the study area, the hydrogeological structures are four aquifers systems (Kalahari, Lebung, Ecca and Ghanzi) and two aquitards (Stormberg Basalt and Inter-Karoo Mudstone/Siltstone). Lebung aquifer was not incorporated into the study because most of the structure was outside the modelled area domain.

Kalahari Sand layer is the top-most aquifer which has variable thicknesses declining towards west. It is composed of lateral layers of sand, sandstone, marl, conglomerate and gravel (Thomas and Shaw 2009) discontinuously saturated, loosely consolidated sediments and semi-connected (Rahube 2003). Its water strikes occur at 10-40 m below the surface (Petulo 2017).

A combination of two aquitards is found in the southwestern edge of the study area. The two aquitards are Stormberg Basalt and Inter-Karoo Mudstone/Siltstone aquitards (Petulo 2017). The aquitards overlay both overlay Ecca aquitard at different locations as shown in section 4.2.2.

The Ecca Aquifer belongs to the Karoo supergroup from the Palaeozoic era (Triassic Period). The composition varies in the different formation from shale, sandstone, mudstone and siltstones (UNESCO-IHP 2016). Ecca Aquifer is mostly confined except where the overlying layers thin out (Smith 1984; Miller 2008; Petulo 2017). In regions south of the study area, it is overlain by in two different sections by Stormberg Basalt and Inter-Karoo Mudstone/Siltstone Aquitards.

The Ghanzi Aquifer is the most extensive unit in the study area, and it is of pre-Karoo origin (Neoproterozoic Era). In the Mamuno, Ngwako Pan and D'kar formations, the lithologies are sandstones and siltstones. Kamtas Tsumis Doornport formations have quartzite and marble as the dominant lithologies (Smith 1984; Miller 2008).

A summary of the hydrogeology is presented in table 1.

	HYDROGEOLO GY				
Age (Era)	Supergroup	Group	Formation (Member)	Lithology	
Cenozoic	Kalahari	Kalahari		Aeolian Sand, Silcrete,	Unsaturated zone
				Calciele, graver	Kalahari Aquifers
		Karoo basalts		Flood Basalt with siliciclastic interbeds	
Jurassic	Upper Karoo	Inter- Karoo Mudstone / Siltstone		Greenish mudstones with basal conglomerates	Inter Karoo Aquitard
Palaeozoic	Karoo	Ecca	Prince Albert Upper Rietmond Lower Rietmond Auob	Shale, siltstone, mudstone	Ecca Aquifer
Neoproterozoic		Ghanzi	Mamuno, Ngwako Pan, D'kar	Surface covered Weakly metamorphosed, arkosic sandstone, siltstone, mudstone and rhythmite	
	Damara	Nosib Nama	Kamtas Tsumis Doornport	Quartzite, conglomerate, schist, marble	Ghanzi Aquifer

Table 1: Simplified stratigraphy of Okwa basin (Modified from (Smith 1984; Miller 2008; UNESCO-IHP 2016))

2.8. Previous Studies

Due to the limited surface water availability in the Kalahari region, there has been lots of interest in groundwater, and consequentially numerous studies have been done in the Kalahari region over the past years.

Recent studies done in nearby basins have concentrated on recharge assessment and resources evaluation. Külls (2000) in his study on recharge assessment, combined hydro-chemical and isotopic methods in Omatako catchment and found that recharge varies depending on the underlying geology. In that study, it was estimated that fractured hard rock environments received recharge between 0.1 and 2.5 % of mean annual rainfall while the Kalahari Sand recharge was predicted to be even lower, approximately <1% of mean annual rainfall (ref). De Vries et al. (2000) studied recharge in the Botswana side and found comparable results, i.e. that recharge ranges from 1 mm yr⁻¹ - 5 mm yr⁻¹, but suggested that the recharge distribution is affected by annual rainfall. A study by Wanke et al. (2008)in Kalahari catchment north of Okwa basin using a physical soil-water balance model (MODBIL) found that recharge was approximately 2% of the mean annual precipitation. High temporal variability in recharge was found, and that recharge takes place in a few days per year when high rainfall intensity is experienced. Spatially, the main factors influencing the recharge were found to be the distribution of soil and vegetation. Wanke et al.(2013) while using the same MODBIL model but validating the results by chloride mass balance, calculated a highly spatiotemporally variably annual recharge of 0.8-18.98% of annual precipitation and suggested that the factors affecting recharge were variability in soil, vegetation and geomorphology.

Kisendi (2016) using an integrated hydrological model in steady-state approximated the net recharge as 0.03 mmyear⁻¹. However, this was done using limited aquifer data only covering Botswana part. Moreover, the study only used steady-state model solution, so it did not consider temporal variability. Rahube (2003) using a combination of methods found different recharge estimates for the different techniques: hydrochemistry (21.5 mmyear⁻¹), isotope studies (0.68 mm/year), well hydrograph (mmyear⁻¹) and groundwater model (0 - 1.46 mm/year). A steady-state groundwater model obtained comparable recharge estimates of 0.01 mmyear⁻¹ by Petulo (2017).

Water Resources Consultants (2006) carried out resource assessments in Ncojana and Matho-A block, to the south of the study area. They found as per their delineation that Ecca Aquifer has total reserves of 158 million cubic meters while Ntane aquifer has 40 million cubic meters. Lateral outflows to the eastern side have been reported by Rahube (2003), Kisendi (2016) and Petulo (2017) included aspects of groundwater resources evaluation.

Overall, no studies have been done to evaluate the groundwater resources in the area as it is delineated in Figure 6.



Figure 6: Previous studies and simulated heads of Petulo (2017)

3. METHODOLOGY

The methodology followed in this study is outlined in Figure 7. Field data and literature was used to create a conceptual model. This model was then converted into a numerical model calibrated in both steady and transient states to meet the calibration target. Sensitivity analysis was then done on the calibrated models. The results from all the steps were analysed and interpreted.



Figure 7: Methodology flow chart

3.1. Fieldwork

Fieldwork was carried out from 4th -21st September 2017 in Namibia. The fieldwork involved field visits and obtaining data from the relevant offices. The following data were obtained: weather station data from Namibia Meteorological Service; borehole logs and piezometers records from the Hydrological Services of Namibia; and geology was from Geological Survey of Namibia. Field visits were done, and attempts to auger into the Okwa River channel bed were made.

3.2. Conceptual model

As a foundation to every model is a conceptual model. Conceptualization is one of the thorniest problems in modelling (Bredehoeft 2005). A conceptual model can be defined as a qualitative characterisation of the hydrogeological framework and the hydrologic system(Anderson et al. 2015). The resultant conceptual model would include: Model boundary conditions, Hydro-stratigraphy and Hydrogeological Properties and their interrelationships, Flow Direction and Sources and Sinks, Groundwater Budget Components, and other additional information (Maliva and Missimer 2012). The workflow proposed by Anderson et al. (2015) was followed. In this study, the conceptual model was reformulated and updated iteratively with the numerical model as suggested by Bredehoeft (2005).

3.2.1. Hydro-stratigraphy and Hydrogeological Properties

The hydrostratigraphy and hydrogeology of the Botswanan side of the study area have been comprehensively mapped and described by several authors (Kisendi 2016; Lekula et al. 2017; Petulo 2017). This is however not the case on the Namibian side.

Ninety-six borehole completion reports were obtained from the ministry of water in Namibia. Seventy-five usable borehole logs were then extracted from these reports as shown in Figure 8 below. The thicknesses of the hydro-stratigraphic layers from the 75 individual wells at the Namibian side were then modelled in RockWorks17 following the lithologies showed in Table 1. Inverse distance interpolation of the individual wells layer thicknesses was carried out while controlling the results spatial extents with geological maps. The output was then compared with results from Botswana side of Lekula et al. (2017) & Petulo (2017) and then merged to create hydro-stratigraphic layers covering the whole study area. The stratigraphic units modelled in sequence from top to bottom were: Kalahari Sand, Inter-Karoo Aquitard, Ecca Aquifer and Ghanzi Aquifer. The topological boundaries of these units were exported to GIS environment (ArcGIS 10.5) for preparation into ModelMuse compatibility formats. The results are shown in section 4.2.



Figure 8: Borehole Logs

3.2.2. Boundaries.

The study area was defined by surface water divides of Okwa River and piezometric equipotential lines. The delineated river basin was clipped along an equipotential line to the west as shown in Figure 9 below. The equipotential lines were defined by interpolation of the stable piezometric heads obtained from borehole logs. The equipotential lines approached the initially defined boundaries at a right angle, thereby validating that the surface water divides coincide with the groundwater divide.



Figure 9: Model boundaries and setup.

3.2.3. Flow Direction

The modelled area represents a closed basin with diffused recharge percolating through Kalahari Sand downwards to the Ecca and Ghanzi Aquifers. The general groundwater flow originated from that recharge, flows from West to the East, following the general topography of the area (Christelis and Struckmeier 2011). All that groundwater outflows the study area across the eastern artificial boundary. More tests on the flow behaviour and patterns were analysed during calibration and particle tracking.

3.2.4. Sources, sinks and storages

The primary source (inflows) of water into the Okwa Basin is precipitation. A portion of this precipitation is intercepted and evaporated back to the atmosphere. Infiltration (effective precipitation) refers to the remainder of this precipitation that seeps into the top unsaturated layer after subtracting interception loss. Most of the infiltration is lost through evapotranspiration from the unsaturated layer (Kalahari Sand). The portion of the infiltration that reached the saturated layer is then referred to as gross recharge part of which is lost through evapotranspiration from the saturated layer, referred to as groundwater evapotranspiration. The difference between gross recharge and groundwater evapotranspiration is referred to as net recharge.

Ephemeral rivers and seasonal ponds in the area act as flow focussing temporary source recharge areas. The sinks (outflows) in the area include groundwater evapotranspiration, borehole abstractions and lateral outflow across the eastern boundary. Storage changes occur when inflows and outflows are not balanced within specified time frame like for example within a year. This results in loss or gains in groundwater storage followed by rising or falling of groundwater heads.

All these components were quantified during modelling. Quantification of the sources and sinks provides groundwater budget components and in the simplest sense, is represented by Equation 1 as below (Anderson et al. 2015). The individual water balance components are coved extensively is section 3.5.

$$Inflow = Outflow \pm \Delta in Storage$$
(1)

3.3. Numerical modelling

Groundwater flows follow the basic principles of conservation of mass and Darcy's law. Therefore, the groundwater system can be represented mathematically by its governing equation following these principles. These governing equations are bundled into codes that a user can select depending on modelling objectives. The method of solution can either be finite-difference or the finite-element solution methods (Anderson et al. 2015) such as MODFLOW (McDonald et al. 1984) and FEFLOW (Diersch 2014) respectively.

A fundamental limitation of groundwater modelling is the non-uniqueness of the results (Maliva and Missimer 2012). Moreover, models have limited value in the absence of quality data, accurate conceptualisation (Bredehoeft 2005) and incorrect space-time discretisation (Owais et al. 2008). In all instances, modelling results should be considered as approximations of the real aquifer as uncertainties are always present (Anderson et al. 2015).

Hassan et al. (2014) recommend the use of integrated hydrological models, which couples both surface and groundwater resources since they represent the water balance components better than stand-alone groundwater models.

3.3.1. Code selection

MODFLOW-NWT

In this study, MODFLOW-NWT (Niswonger et al. 2011) was used because of its efficient integration of surface, unsaturated and saturated zone fluxes, particularly important for the modelling the hydrogeological system such as the Okwa Basin were recharge is unknown and very difficult to define. In MODFLOW-NWT, in contrast to standard MODFLOW, gross recharge, unsaturated zone evapotranspiration, groundwater evapotranspiration and groundwater exfiltration are calculated internally through the Unsaturated Zone Flow (UZF1) Package, based on unsaturated zone parameterisation and application of external driving forces, i.e. rainfall and potential evapotranspiration as input.

The 3D groundwater movement of constant density throughout a heterogeneous and anisotropic aquifer can be described by a partial differential equation (Equation2) (Anderson et al. 2015).

$$\frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) = S_s \frac{\partial h}{\partial t} - W^*$$
⁽²⁾

Where: $K_{x,} K_{y}$, K_{z} - hydraulic conductivity in the principal directions [mday-1], h - potentiometric head [m], S_{s} - specific storage of the aquifer [m-1], t - time [day-1] and W^{*} - volumetric flux sink/source term [mday-1]. In steady-state, $\partial h/\partial t = 0$.

Unsaturated zone flow (UZF1) package

The study area has a thick unsaturated zone of the Kalahari Sand layer. To simulate the flow in this zone, unsaturated zone flow (UZF1) Package (Niswonger et al. 2006) was used. The UZF1 package partitions infiltration applied into recharge, unsaturated storage, and evapotranspiration. The UZF1 package simulates vertical, one-dimension (1-D) variably-saturated flow between land surface and water table by applying the kinematic-wave approximation of Richard's equation(Equation 3) (Niswonger et al. 2006).

$$\frac{\partial\theta}{\partial t} + \frac{\partial K(\theta)}{\partial z} + i = 0 \tag{3}$$

Where: θ - volumetric water content [m³m⁻³], K(θ) - unsaturated hydraulic conductivity as a function of water content [mday⁻¹], i - ET rate per unit depth [day⁻¹] and t - time [day].

Brooks-Corey exponent function that defines unsaturated hydraulic conductivity $K(\theta)$ in UZF1 is described as Equation 4 (Niswonger et al. 2006).

$$K(\theta) = K_s \left[\frac{\theta - \theta_r}{\theta_s - \theta_r}\right]^{\varepsilon}$$
(4)

where K_s – saturated hydraulic conductivity; θ_r – residual water content; θ_r – saturated water content; and θ_r Brooks-Corey exponent.

The data required by the UZF1 package can be categorised into driving forces and model parameters. The driving forces are infiltration (effective precipitation) and potential evapotranspiration (evapotranspiration demand) while the parameters include: evapotranspiration extinction depth, evapotranspiration extinction water content, saturated water content and residual water content (Winston 2017).

Head observation package

This package is useful in the comparison of simulated heads with the observed heads. The observed heads locations were assigned as point objects, and the simulated heads values are assigned as a function of distance to the nearest cell centre value. A value HOBDRY was set to be assigned to the dry cells.

Well package

Well package was used to simulate the specified fluxes for the cell (Niswonger et al. 2011). It is useful in specifying the rate of groundwater abstraction or injection. In the model domain, six abstraction wells were using this package.

Upstream-Weighting (UPW) Package

UPW is used together with NWT to calculate the intercell conductance. It treats cell drying and rewetting as a continuous function of heads rather than discrete. It uses the hydraulic head of the cell grid upstream (hence the name) to calculate the horizontal conductance between cells. This approach avoids water flows from dry cells which can cause model non-convergence. The parameters assigned were: horizontal hydraulic conductivity (HK), vertical hydraulic conductivity (VK), specific storage (SS) and specific yield(SY) (Niswonger et al. 2011).

3.3.2. Model setup and model structure analysis

The study area was discretised into square grids of 1 km and resulted in 165 rows and 295 columns and 29,193 km² model domain area. Four layers (from top to bottom: Kalahari Aquifer, Inter Karoo Aquitard, Ecca Aquifer and Ghazi aquifer) were defined by hydro-stratigraphy definition as described in section 3.2.1 above. The three aquifers (Kalahari aquifer, Ecca Aquifer and Ghazi aquifer) were simulated as convertible aquifers, i.e. aquifers that can switch from unconfined to confined conditions based on whether the head is above or below the layer top during model simulation. Inter Karoo Aquitard was simulated as a confining layer unit. This confining layer was treated as a quasi-3D layer where vertical flow occurs through the confining layer, but there is no release from storage.

The model was set up, calibrated and simulated in steady-state. Later, it was converted to transient state where further calibration was done. In the transient simulation, 1276 daily stress periods were defined from 12th September 2012 to 11th March 2016. The modelling time units were in days and the length units in meters.

Model Boundaries

The boundaries defined in section 3.2.2 were represented mathematically. The water divide was represented as a Specified flow boundary (no-flow boundary). The fluxes across this boundary were set to zero. The outflow boundary on the western boundary was represented as a Head Dependant Flow boundary (drain boundary). This boundary allows water to leave the groundwater system when the heads in cell rise above the elevation of the drain boundary.

3.3.3. Driving forces

Hydrological models require "driving forces" also known as "hydrologic stresses" or "forcing data" as input data. In this study, the driving forces were: precipitations which were converted to infiltration rates, Potential Evapotranspiration(PET) and groundwater abstraction. The driving forces are described below:

Precipitation.

In-situ precipitation data for seven weather stations were obtained from various sources (Appendix 1). The rain gauge stations are far away from each other, and most of them fall outside the study area (Appendix 1 1). It was therefore not possible to use these stations primarily for the model. To solve this problem, daily satellite rainfall estimates (SRE) were implemented. The SREs were first assessed for their best performance in rainfall detection in Okwa Basin, followed by a bias correction of the best performing SRE using the available in-situ data.

Two SREs were evaluated to determine which product is best suited for the area. These were: Climate Hazards Group Infrared Precipitation with Station (CHIRPS V2.0) and Famine Early Warning Systems Network African Rainfall Estimation Algorithm Version 2 (FEWS NET).

Daily SREs for both products for the period 12th September 2012 to 11th March 2016 were downloaded using ISOD toolbox in ILWIS software. CHIRPS is a high resolution (0.05°) product which incorporates satellites measurements and in-situ data. Details of the products algorithm and validation results are found in Funk et al.(2015). FEWS NET data is obtained from a combination "Meteosat and Global Telecommunication System (GTS) data" (Novella and Thiaw 2012). It is obtained at 0.1° spatial resolution. Details on FEWS NET algorithm are found in (Novella and Thiaw 2012; NOAA 2017).

An inter-comparison of the SRE and the in-situ measurements were done to determine the biases at pixel scale. The different sources of biases were analysed by decomposing the total bias into three components: hit bias, missed rainfall and false rainfall. Hit bias is the difference between gauge and satellite rainfall when both detect rainfall. Missed rain the amount of rainfall recorded by the gauge when the SRE detects nothing. False rain is the amount detected by the SRE when the gauge records nothing (Tian et al. 2009; Habib et al. 2014). These biases are represented Figure 10.



Figure 10: Bias decomposition

The SREs were analysed using hit, missed and False biases using equations 5 - 8 below.

$$Total Bias = \sum_{i=1}^{n} R_s - \sum_{i=1}^{n} R_g$$
(5)

$$Hit \ bias = \Sigma(Rs - Rg)|(Rs > 0\&Rg > 0) \tag{6}$$

$$Missed \ bias = \Sigma Rg | (Rs = 0 \& Rg > 0$$
⁽⁷⁾

$$False \ bias = \Sigma Rs | (Rs > 0 \& Rg = 0)$$
(8)

where: Rs is rain rate from the satellites (mm), and Rg is rain rate from the gauges (mm).

Probability of detection (POD), critical success index (CSI), and false alarm ratio (FAR) were used for assessment. Equations 9 - 11 were used (Montero-Martínez et al. 2012).

$$POD = \frac{hit}{hit + missed} \text{ (best value 1)}$$
(9)

$$FAR = \frac{false}{hit + false}$$
(best value 0 (10)

$$CSI = \frac{hit}{hit + missed + false} (best value 1)$$
(11)

The SREs were corrected using a multiplicative bias factor. The ratio between the gauge measurements to the SREs were calculated then multiplied with the SRE to obtain bias corrected SREs. A time variable space variable (TVSV) scheme with a sequential moving window scheme was used as implemented by Bhatti et al. (2016). A 5-day window was chosen as it allowed for rainfall accumulation since most days were dry. Equation 12 was used.

$$BF_{TVSV} = \frac{\sum_{t=d}^{t=d-m} G(i,t)}{\sum_{t=d}^{t=d-m} S(i,t)}$$
(12)

Where: S is daily satellites estimates (mm), G is daily gauge rainfall estimates (mm), i is gauge location, t is day number, and m is length of time window (5 days in the study)

Conditional application of Equation 12 was applied when the following three conditions were all met: the number of rainy days recorded by the gauge in the time window is more than 3; Sum of rainfall within the time window recorded by the gauge is more than 1 mm and rainfall detected by the satellite in the time window is not null. If any of the conditions were not met, the bias factor was not calculated.

Daily bias correction factors were obtained at rain gauge locations. These bias factors were then interpolated using Inverse Distance Weighted method as recommended by Bhatti et al. (2016). The surface obtained from interpolation was then multiplied with the SRE for a particular day to obtain corrected SREs. The results of the precipitation analysis are shown in section 4.1.1.

Interception and Infiltration rate

UZF1 package accepts *infiltration rate* as the input to the model. Infiltration rate is a measure of the amount of water that enters the soil matrix per unit time. It is calculated as rainfall rate minus interception rate. *Interception* can be defined as the part of the rainfall that clings onto leaves and stems of the canopy cover and subsequently evaporates (Gerrits 2010).

Interception rate depends on rainfall characteristics, ET demand and land cover (Gerrits and Savenije 2011). The study area has various land cover as shown in section 2.4 above. Interception losses values were obtained from literature as shown in Table 2 below for both the dry and wet seasons. The wet season is from September-April while the dry season is from May-October.

Land cover	Interception (Interception in dry season)	Adopted literature
Trees	13% (10%)	Muzylo et al. (2009)
Shrubs	11.7 % (6.9%)	Wang et al. (2005)
Grasslands	5 % (1%)	Beard (1962)
Bare land	0 % (0 %)	

Table 2: Interception loss as a percentage of total rainfall

The interception rate was calculated by using equation 13 (Teketel 2017).

$$I = P(I_f * A_f + I_s * A_s + I_g * A_g + I_b * A_b)$$
(13)

Where:- I is interception per grid cell [m day-1], P – precipitation [m day-1], I_f, and I_S, I_g, I_b - interception rate by trees, shrubs grasslands and bare land, [%] of precipitation, and A_f, A_S A_g, A_b - area ratios coverage per grid for trees, shrubs grasslands and bare land respectively.

The results of interception and infiltration rates are in section 4.1.3.

Potential Evapotranspiration

Penman (1948) and Thornthwaite (1948) first introduced the concept of Potential Evapotranspiration (PET). PET quantifies the amount of evapotranspiration that would occur from uniform vegetation with access to an unlimited supply of water and without heating effects or advection (McMahon et al. 2013). It, therefore, varies spatiotemporally depending on solar radiation, wind and temperature.

Daily PET products (FEWS NET) were obtained from USGS (2017c) at 1-degree resolution then resampled to 1000 m to march the model's spatial resolution. FEWS NET calculates the reference evapotranspiration (ET_o) using Penman-Monteith equation(Equation 14) and incorporates crop coefficients(Kc) from Maidment (1992) to obtain PET.

$$ET_o = \frac{0.408 * \Delta * (R_n - G) + \gamma * \frac{900}{T + 273} \mu_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$
(14)

Where ET_0 is reference evapotranspiration [mm day⁻¹], R_n -net radiation at the crop surface [MJ m⁻² day⁻¹], G - soil heat flux density [MJ m⁻² day⁻¹], T - mean daily air temperature at 2 m height [°C], u_2 -wind speed at 2 m height [m s⁻¹], e_s - saturation vapour pressure [kPa], e_a -actual vapour pressure [kPa], e_s - e_a - saturation vapour pressure deficit [kPa], Δ slope vapour pressure curve [kPa °C⁻¹] and γ - psychrometric constant [kPa °C⁻¹].

$$PET = ET_o * K_c \tag{15}$$

where PET - potential evapotranspiration [mmday-1] and Kc- crop coefficient

To validate the PET product from FEWS NET, the in-situ PET was calculated from microclimatic data in three available stations. The ET_o and PET were calculated using Equations 14 & 15 for Sandveld, Ghanzi

and Tshane stations to validate the FEWSNET PET satellite product at pixel scale. The stations are far from each other therefore suitable to check the spatial variations of PET. The periods chosen for validation depending on the availability of all the microclimate parameters needed in Penman-Monteith equation were: 12th September 2012- 5th February 2014 (Sandveld station),13th February 2014 -30th April 2016 (Ghanzi stations) and 14th February 2014 – 30th April 2016 (Tshane station).

From the land cover map (Figure 3), the stations are located in savanna shrublands. For PET calculation, Kc value of 0.5 for savanna shrublands as reported in Howes et al. (2015) was adopted.

Pearson correlation was performed on the stations calculated PET and FEWSNET PET according to Equation 16 below.

$$r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}}$$
(16)

Where r = Pearson correlation coefficient, x and y are the calculated PET and FEWSNET PET respectively, and \bar{x} and \bar{y} are mean values.

The results of the validation are in section 4.1.2

Groundwater abstraction

Groundwater abstraction records from six boreholes (Figure 9) were available, and these were simulated to the model. All these boreholes were located in the Ghanzi Aquifer. Table 3 below shows the rate of abstraction for six boreholes.

BH No.	Х	Y	Abstractions Averages (m ³ day ⁻¹)
BH7321	20.52417	-22.0792	75.75
BH7322	20.61889	-22.0567	82.26
BH9980	20.62872	-22.0451	76.97
BH9981	20.64981	-22.0364	771.38
BH8949	21.18404	-22.0481	67.91
BH8934	20.03472	-22.3139	348.90

Table 3: Average groundwater abstractions.

3.3.4. State variables

A state variable is a system characteristic that is measurable and can vary in time and space (Rientjes 2015). State variables are used as calibration targets, and a modeller aims to match the simulated values to the observed. In this study, the only state variable was the piezometric head observations.

Head observations and water table

The initial heads of boreholes during drilling were available. These heads were interpolated to obtain the initial water head for the model and used to constrain the steady state model. Time series piezometric levels data for three boreholes were available (Figure 11). One of these, BH26674(Figure 12) monitored the Kalahari Aquifer and were recorded on a daily timestep from 09/12/2012 - 03/11/2016. The two other

boreholes monitored Ecca Aquifer and were recorded on a monthly or bimonthly timesteps. Their records ranged from 5/10/2012 to 9/9/2015 for BH9294 and 2/19/2014 to 9/8/2015 for BH9245 as shown in Figure 12.

During steady-state model calibration, the mean values of the observation records were used as the calibration target. The mean values were 1175.71m, 1105.86m and 1108.22m for BH26674, BH9294 and BH9245 respectively. Also, initial heads measurements recorded during borehole drilling obtained from the boreholes logs were used as a calibration target for the steady-state model. The boreholes used are shown in Figure 11 below.



Figure 11: Head observations



Figure 12: Observed piezometric heads

3.3.5. Model parameters

Model parameters are those characteristics of the hydrological system which remain constant in time. The parameters were categorized into calibrated parameters and non-calibrated parameters. Calibrated parameters were adjusted during calibration as opposed to non-calibration parameters as listed in section 3.4.

UZF1 package Parameters

Various parameters were assigned in the UZF package. These parameters were assigned as follows: Recharge and discharge location option (NUZTOP) - Top layer; Vertical hydraulic conductivity source (IUZFOPT) – Use same vertical conductivity from the flow package; Number of trailing waves (NTRAIL2)-15; Number of wave sets (NSETS2)-20; Simulate evapotranspiration (IETFLG)- Active; Specify residual water content (SPECIFYTHTR)- Active; Specify initial unsaturated water content (SPECIFYTHTR) – Active; and the average height of undulations in the land surface altitude - 1 m.

Extinction Depth and Rooting Depth

Extinction depth is a parameter for UZF1 Package which determines "the depth below land surface below which ET does not occur" (Winston 2017). This depth is depended on the maximum rooting depth of the vegetation. Canadell et al. (1996) summarised maximum rooting depth information at a global scale and reported rooting depths of 5 m, 60 m and 68 m in the Kalahari sand. Stone and Kalisz (1991) lists the maximum rooting depths of 211 species which included some identified from the field such as A*cacia raddiana*. These vegetation types were classified by Mendelsohn et al.(2002) as a shrub. A summary of the rooting depth used is shown in table 4 below. The rooting depth values were assigned to the land cover at 20 m spatial resolution. Equation 17 was used to aggregate to 1000 m spatial resolution to fit the model grids.

Land cover	Maximum rooting depth/Extinction Depth	Reference
Trees	30 m	Canadell et al. (1996)
Shrubs	6	Stone and Kalisz (1991)
Grassland	1.45 m	Shah et al. (2007)
Bare land (sand soil)	0.1	Shah et al. (2007)

Table 4: Rooting Depths

$$E_d = (E_{dt} * A_t) + (E_{ds} * A_s) + (E_{dg} * A_g) + (E_{db} * A_b)$$
(17)

Where E_d is Extinction depth per grid cell [m], E_{dt} , E_{ds} , E_{dg} , E_{db} - Extinction depth of trees, shrubs, grassland and bare land, and A_t , A_s , A_g , A_b are area ratio of trees, shrubs, grassland and bare land areas respectively per grid. The results are shown in section 4.1.4
MODFLOW-NWT parameters

The following properties were used as parameters in the model: Porosity, Specific yield, hydraulic conductivity, Transmissivity, Anisotropy and Storativity. Representative values for the hydrogeological materials were obtained from literature.(Johnson 1963; Domenico and Mifflin 1965; Freeze and Cherry 1979; Heath 1983; Domenico and Schwartz 1998). The calibration parameters were adjusted during calibration. Table 5 below summarises the parameters used.

3.3.6. Solvers

The Newton solver(NWT) was used. Its purpose is to solve the finite difference governing equations in every timestep in MODFLOW-NWT stress periods. The options used are as shown in table 5.

Table 5: MODFLOW-NWT s	solver o	options	used.
------------------------	----------	---------	-------

Name	Parameter value (units)
Head tolerance (HEADTOL)	0.1 [m]
Flux tolerance (FLUXTOL)	$1.0 \ [m^{3}day^{-1}]$
Maximum number of outer iterations (MAXITEROUT)	1000
Portion of cell thickness used for coefficient adjustment (THICKFACT)	0.00001
Matrix solver (LINMETH)	Chi MD
IPRNWT	Active
Correct groundwater heads relative to cell-bottom altitude when cell	Active
surrounded by dry cells (IBOTAV)	
Model complexity	Complex

3.4. Model Calibration

The adjustments of the model parameters to enable the model achieve the required performance was done. This was done until optimal parameter was obtained. For both the steady-state and the transient model, the calibration objective was matching the simulated heads with observed heads. Trial and error calibration was used since it allows the modeller to incorporate site knowledge and it helps in gaining a better understanding of the model behaviour (Hassan et al. 2014). Calibration was first done in steady-state followed by a transient. In both cases, water balance components discrepancies were first reduced followed by heads matching.

3.4.1. Steady-state model calibration

A steady-state model was set up based on the averages of the driving forces described in section 3.3.3 above. The initial head was set up to be the interpolated initial heads of the boreholes described in section 3.3.4.1 above. This model was calibrated by adjusting the following parameters: Horizontal hydraulic conductivity (HK), vertical hydraulic conductivity (VK), the vertical hydraulic conductivity of the confining layer (VKCB) and conductance of the drain boundary.

3.4.2. Transient model Calibration

Transient models are advantageous over steady-state in that they represent how the modelled area respond to changes in forcing factors. The steady-state model was converted into the transient model. The 1st time period was maintained as steady-state. Steady-state simulated heads were set to be the starting heads for the transient model. Parameters imported from the steady-state model were modified during calibration. 1276 daily timesteps were used.

During transient model initialisation, a problem with storages which resulted in non-convergence of the model. The problem was due to dry timesteps after model initialisation. To overcome this problem, 187 timesteps were used in model warmup. The heads at the end of this warm-up period were then imported as initial heads for the model used for calibration.

In addition to the parameter set adjusted during calibration in the steady-state model, these parameters were adjusted: Specific Storage (SS), Specific Yields(SY), UZF1 saturated water content (THTS), UZF1 residual water content (THTR), initial water content, and extinction water content.

3.4.3. Model Performance Evaluation

To measure how good model simulated the observed heads and fluxes, both visual and statistical analysis will be used. The visual tools used were: Observed and simulated water table plot, scatter plots of observed versus simulated heads. The statistical analysis that was used included: Mean Error (ME), Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE), Equations 18-20.

$$ME = \frac{1}{n} \sum_{i=1}^{n} (h_m - h_s)_i$$
(18)

$$MAE = \frac{1}{n} \sum_{1=1}^{n} |(h_m - h_s)|_i$$
(19)

$$RMSE = \left[\frac{1}{n}\sum_{1=1}^{n}(h_m - h_s)_i^2\right]^{0.5}$$
(20)

Where h_m =observed heads; h_s =simulated heads

ME measures the overall/average bias error of the model; it is, however, insufficient on its own since positive and negative errors cancel and may show a falsely low value. Possible values of ME are $-\infty$ to $+\infty$, but a value close to nil is desirable. MAE measures the average magnitude of model errors without considering their direction. (JJ 2017). RMSE like MAE measures the average magnitude of error, but since it squares the errors before being averaged, it is more sensitive to outliers. Possible values of both MAE and RMSE are 0 to $+\infty$, but minimum values are desirable.

3.4.4. Sensitivity analysis.

Groundwater models have uncertainties from different sources. These sources of errors can be categorized into model parameters, errors in observed input data, conceptual model and boundary conditions (Wu and Zeng 2013). Sensitivity analysis was carried out to determine how much these factors affect model output (McCuen 1973; Reilly and Harbaugh 2004). Sensitivity analysis helps during calibration to identify the most important parameters to use in calibration.

Sensitivity analysis was carried out manually by alternatively maintaining all calibrated parameter values except one which was then varied sequentially forward and backwards while observing the effect on the heads.

3.5. Water Balance and ZONEBUDGET

Water balance check was done to account for the sources, sinks and changes in storages in the model domain and helped the modeller in the assessment of model results accuracy (Anderson et al. 2015). To obtain the water balance components of the three different aquifers layers, ZONEBUDGET program was used. The program partitions cell-by-cell flow and assign its zone. This was useful in understanding the flow systems (Harbaugh 1990).





Figure 13: Schematic diagram (adapted from (Berhe 2017))

The water balances were analysed in three steps: Water balance for the entire model, water balance for the UZF1 and water balance for the aquifers.

The water balance for the entire model can be represented as shown in Equation 21 below:

$$P = ET + q_g + Q_w \pm \Delta S \tag{21}$$

Where P - precipitation, *ET* -total evapotranspiration, q_g –groundwater lateral through the drain boundary, Q_w - water abstractions and ΔS – storage change.

The ET is cumulative of processes that occur in different components of the model domain as expressed in Equation 21 below as adapted from Hassan et al. (2014). The total ET is a sum of evapotranspiration as a result of interception by vegetation at the surface (ET_{sf}) and subsurface evapotranspiration (ET_{ss}) . ET_{ss} is a sum of evapotranspiration from the unsaturated zone (ET_{uz}) and groundwater evapotranspiration (ET_a) .

$$ET = ET_{sf} + ET_{ss} = ET_{sf} + ET_{uz} + ET_g$$
(22)

The water balance in the unsaturated zone can be represented as Equation 23 below. Where is actual infiltration (P_a) which is precipitation (P) less interception (ET_{sf}) , R_g - gross recharge, ET_{uz} – unsaturated zone evapotranspiration and ΔS_{uz} - percolation zone storage changes.

$$P_a = R_g + ET_{uz} \pm \Delta S_{uz} \tag{23}$$

However, UZF1 package partitions infiltration (P_a) into gross recharge (R_g) , unsaturated zone evapotranspiration (ET_{uz}) , groundwater evapotranspiration (ET_g) and ground water exfiltration (EXf_{gw}) when the water table rises above the ground level. The groundwater balance can therefore be rewritten as Equation 24.

$$R_g = ET_g + EXf_{gw} + q_g \pm \Delta S_{gw} \tag{24}$$

Where ΔS_{gw} - changes in groundwater storage, Net groundwater recharge (R_n) can be defined as the water that reaches the aquifer and can be represented as Equation 25.

$$R_n = R_g - Exf_{gw} - ET_g \tag{25}$$

4. RESULTS AND DISCUSSION

This chapter describes and discussed the results obtained.

4.1. Data processing results

4.1.1. Precipitation

The results from the inter-comparison of the satellite rainfall estimates of FEWSNET and CHIRPS with in-situ measurements described in section 3.3.3 are shown below. The comparison was made for Sandveld, Gobabis, Tshane and Ghanzi stations as shown in Figure 14 below.



Figure 14: Detection of the SREs at the various stations shown in Figure 44.

From the results in Figure 14 above, it can be seen that the performance of the SREs varies from one station to another and that both CHIRPS and FEWSNET products have detection issues. In Sandveld station, both SREs perform well with higher Probability of detection (POD) values than in the rest of the stations. The detection by the SREs is worst in Tshane station. Overall, FEWSNET has a higher POD than CHIRPS. It also has a higher false alarm ratio (FAR) (low values desirable), and therefore it falsely detects more rainfall. The high FAR values can also be an issue of gauge representation. The critical success index (CSI) values are more comparable for all the stations.

To assess which is the better product, Montero-Martínez et al. (2012) report that CSI is used. From the results represented in Figure 14, both SREs performed were comparable when it comes to CSI. Therefore more analysis was undertaken since CSI does not distinguish the sources of error. The bias decomposition results are shown in Figure 15 below.



Figure 15: Bias components for CHIRPS and FEWSNET over the study period.

It can be seen from Figure 15 that both SREs have positive hit bias at Sandveld station, which translates that they both overestimated the rainfall. At Gobabis and Ghanzi stations, the hit bias was negative, meaning that both SREs under-estimated rainfall in the study period. At Tshane station, FEWSNET underestimated rainfall while CHIRPS overestimated rainfall as shown by their hit biases (Figure 15). About the miss bias, FEWSNET had a lower missed bias in all the stations than CHIRPS. Concerning false bias, FEWSNET had high false biases in all stations except in Tshane. However, the false bias is not a reliable indicator for rainfall detection as it can be an issue of rain gauge representativeness within an SRE pixel. The total bias is also not a reliable indicator for SRE rainfall detection as the miss, and false biases can cancel each other out. Concerning the hit, miss and false bias decomposition, FEWSNET performed better on rainfall detection in the Okwa Basin because its miss component was lower.

In the comparison of the two SREs, it was found out that: about detection (POD, FAR, &CSI), both products performance was comparable. However, FEWSNET outperformed CHIRPS concerning bias decomposition criteria. Other than performance, the other factor taken into consideration in choosing the SRE was the spatial resolution of the product. CHIRPS has a higher spatial resolution at 0.05° as compared to FEWSNET at 0.1°. For this reason, CHIRPS was selected and further used in this study.

CHIRPS was bias corrected by applying methods described in section 3.3.3.1 for the period of 12th September 2012 to 11th March 2016. Figure 16 shows a cumulative curve of averages of the whole model domain. Uncorrected CHIRPS, corrected CHIRPS and the in-situ data were plotted.

From Figure 16, it can be seen that for the entire model time domain, the cumulative underestimation of uncorrected CHIRPS was 230 mm (16% of total rainfall). This is equivalent to an underestimation of 65.8 mm per year. After bias correction, the underestimation was reduced to 38.4 mm per year. This represents a 41 % reduction in the error. This improvement is significant (though not perfect) given that area is arid and underestimation of precipitation results in the underestimation of the water resources as a whole.



Figure 16: Cumulative precipitation for the entire model

The bias-corrected CHIRPS that was applied to the model is shown in Figure 17 below. From both Figures 16 &17, it can be seen that there are four rainy seasons with the fourth being incomplete. The rains follow the rainfall pattern described in section 2.2. The wettest was the second rainy season from September 2013 to April 2014.



Figure 17: Average daily precipitation applied to the model

Figure 18 shows the spatial distribution of precipitation. It can be noted that the eastern and northern regions of the study area receive more precipitation than the rest of the area. This trend is in line with the general spatial distribution of rainfall in the Kalahari desert as described by Dintwe et al. (2015). The mean annual precipitation applied to the model is 338.8 mm. This is equivalent to 0.9 mmday⁻¹.



Figure 18: Daily mean rainfall for the corrected CHIRPS for the period 12/09/2012 to 11/03/2016

4.1.2. Potential Evapotranspiration

Graphical and statistical methods were used to test the correlation between the in-situ calculated PET and FEWSNET PET as described in section 3.3.3.2. The comparison was made for three weather stations whose locations are shown in Appendix 1. Figure 19 shows the comparison between in-situ calculated PET and FEWSNET.

A good correlation was found between the calculated PET and FESNET PET as can be seen from Figure 19. The fluctuations and the trend in all the three stations coincide well, and they follow the two seasons (Section 2.2) experienced in the area: hot-wet season (September-April) and cold-dry season (May-October). High PET cycles coincide with the hot- wet season because the net radiation and air temperature, which influence PET, are high during this period.

The day to day variation of peaks between the calculated PET and FESNET PET was observed. These differences in peaking were minor and of less significance and they tend to cancel each other over time. However, abnormally low values of FEWSNET PET were obtained on 02/04/2015 for both Ghanzi and Tshane stations, 28/03/2015 for Ghanzi Station and on 05/12/2013 for Sandveld station. The probable reason for these low values is an anomaly in the FEWSNET algorithm at the locations on the said days.

The Pearson correlation coefficients were 0.5, 0.83 and 0.86 for Sandveld, Ghanzi and Tshane stations respectively for the calculated PET against FEWSNET PET. Due to the good correlations, FEWNETPET was used as model input without any corrections.



Figure 19: Calculated versus FESNET PET



The spatial variation of PET is shown in Figure 20.

Figure 20: FEWSNET PET averages for the period 12th September 2012 to 11th March 2016 (mmday-1)

Figure 20 above shows the long-term PET averages applied in the steady-state model. It can be noted that PET is higher to the North-East and decreases gradually to the West. The variation spatially is however low. From the results in Figure 19 & 20 above, it is evident that PET is more variable from season to season than spatially.

4.1.3. Interception and infiltration rates

The interception rate calculated and used as model input was spatially and temporary variable as shown in Figure 21 below. The spatial distribution is based on the land cover. The values of the interception differ from those shown in table 2 in section 3.3.3.3. This is because the landcover was resampled from 20 m resolution to 1000 m to match the model scale. The interception rates for the wet seasons are higher than that of the dry season. This is because vegetation is leafier during the wet season and hence intercept more precipitation.



Figure 21: Interception based on land cover (Wet period: Sep-April; Dry Period: April - Oct)

4.1.4. Evapotranspiration Extinction depth

Section 3.3.5.1 describes the methods used to define ET extinction depth (EXTDP) based on vegetation type. The results are shown in Figure 22 below. Low values are observed to the south and to the north where grasslands are prevalent. Most of the modelled area has high extinction depth meaning that evapotranspiration takes place deeper to a depth up to 10.3 m below the surface. Evapotranspiration losses take place in the unsaturated zone above the EXTDP if PET is not met, water is removed from the groundwater when the water level is less than EXTDP.



Figure 22: Extinction depth map

4.2. Hydro-stratigraphic units

Stratigraphic units were modelled in RockWorks17 as described in section 3.2.1. The results are are shown in Figures 23-27 below. Figure 23 shows the transects in sections marked in Figure 8. The transects of Kalahari Sand, Inter-Karoo Aquitard, Ecca Aquifer and Ghanzi Aquifer are drawn to scale. It can be noted that the layers exhibit a complex variability. The only layer that is present in all location of the modelled area is the Kalahari Sand layer. The thickest layer is Ghanzi Aquifer.



Figure 23: Hydro-stratigraphic cross-sections of transects in Figure 8

4.2.1. Kalahari Sand Layer

It was modelled as the topmost layer. It is made up of both unsaturated and saturated parts. The layer was found to have continuous coverage in the whole study area with thicknesses ranging from 12 to 60 m. The aquifer condition in this layer was found to be scattered and loosely connected to each other, similar characteristics were found by UNESCO-IHP (2016) in the same layer but to the south of the study area. The primary composition is unconsolidated sands of eolian origin from the Cenozoic era, but also formations of silcrete, calcrete, gravel and sandstones were found in this layer (Smith 1984). This was found to have higher hydraulic conductivities than the rest of the layers. Figure 24 below shows the spatial distribution of the thicknesses of this layer. This layer was simulated as an unconfined layer.



Figure 24: Kalahari Sand spatial distribution and thicknesses

4.2.2. Inter-Karoo Aquitard

The aquitard was found out to be of Upper Karoo supergroup. It was found exclusively in the south-eastern edge of the model domain. It is composed of two members: Karoo Basalt to the north and the inter Karoo mudstone/siltstone formation to the south. The Karoo basalts are thinner than the inter Karoo mudstone/siltstones.

These two members were found to be made up of different lithologies. The Karoo basalts are sedimentary beds of flood basalts with siliciclastic interbeds while the inter Karoo mudstone/siltstone is made up of redorange sandstones, siltstones, mudstones and basal conglomerate(Smith 1984). Previous studies, i.e. Petulo (2017) have separated the two aquitards into different hydro-stratigraphic units. For this study, the two were considered as one layer since they both overlay the Ecca but at different locations. The aquitard is shown in Figure 25 below. This layer was simulated as a confining layer of 2 to 60 m thickness below the Kalahari layer.



Figure 25: Aquitard spatial distribution and thicknesses

4.2.3. Ecca Aquifer

This aquifer was found below the Inter-Karoo layer. It was prominently in the southwestern section of the study area and thins out northwards. Its thickness ranges from 4 to 120 m as shown in Figure 26. It is predominantly composed of sandstones, mudstones and siltstones (Petulo 2017). This layer was simulated as a convertible layer able to switch between confined and unconfined conditions.



Figure 26: Ecca Aquifer spatial distribution and thicknesses

4.2.4. Ghanzi Aquifer

This layer was found at the base of the majority of the study area except for the southern region. The layer thins out southwards. Its thicknesses varied from 24 to 226 m as shown in Figure 27. This is in agreement with previous studies done in the area by Lekula et al. (2017) and the geology as shown in Section 2.6. This layer is predominantly composed of Quartzite.



Figure 27: Ghanzi Aquifer spatial distribution and thicknesses

4.3. Conceptual Model

Based on the hydro-stratigraphy obtained from the borehole logs, literature and local knowledge, the groundwater flow system in the study area was conceptualised into four layers as shown in Figure 28 below. The outer boundaries are topographical divides all-round the study area except to the east as shown in Figure 9. These boundaries were translated as a no-flow boundary and drain boundaries respectively. The four hydro-stratigraphic units used are described in Section 4.2.

During calibration, the conceptual model was revised several times. The different conceptual models tested and discarded were, these were:

- i. Use of General Head Boundary (GHB) as an outflow boundary. During numerical modelling, this boundary, in some cells, allowed water into the model domain instead of going out, this was caused by uncertainties in the elevation of the GHB.
- ii. Omitting the Inter-Karoo Aquitard over Ecca Aquifer. Its numerical implementation resulted in unrealistic high heads of Ecca Aquifer; this necessitated the introduction of aquitards as per the hydro-stratigraphy.
- iii. Introducing faults as per the geology of the area (Section 2.6). These faults were non-responsive and did not show any effect on the fluxes of the numerical model.

The final conceptual translated to numerical model is schematised in Figure 28 below.



Figure 28: Conceptual model

Kalahari sand layer aquifer (1), Ecca Aquifer (2) and Ghanzi (3) were represented numerically as convertible layers. Inter-Karoo Aquitard (3) was simulated as a quasi-3D confining layer which allows for vertical leakage but has no storage. The drains were implemented in Ecca Aquifer and Ghanzi Aquifer.

Pitchouts in spatially discontinuous layers of Inter-Karoo Aquitard, Ecca Aquifer and Ghanzi Aquifer were represented as an arbitrary thin layer of 1 m thickness and assigned properties of the adjacent overlying layer. i.e. Inter-Karoo aquitard and Ecca aquifer arbitrary layers were assigned properties

representative of the Kalahari Sand layer; while Ghanzi aquifer arbitrary layer was assigned properties representative of Ecca aquifer.

4.4. Steady-state model calibration results.

The steady-state model was calibrated as described in section 3.4.1 above. The results are presented in three sections which are: the calibrated parameter sets, calibrated heads with error assessment, water budgets for the steady-state model and sensitivity analysis.

4.4.1. Calibrated parameter sets

Zones were used for the calibration parameters to represent the heterogeneity of the study area. Each of the three aquifers was assigned zones of horizontal hydraulic conductivity (HK) and vertical hydraulic conductivity (VK). The HK and VK zones overlapped each other. The vertical hydraulic conductivity the quasi-3D Inter-Karoo confining layer(VKCB) was assigned as a value of 1×10⁻⁶ mday⁻¹. Conductance (C) was assigned to the drain boundary in Ecca aquifer and Ghanzi aquifer.

Table 6 includes the following unsaturated zone parameters: ET extinction depth (EXTDP), ET extinction water content (EXTWC), initial water content (THT1), saturated water content (THTS), residual water content (THTR), and maximum unsaturated vertical hydraulic conductivity of (KV).

Zone	Parameter	Minimum value	Maximum Value	Unit	Comment
Unsaturated zone	EXTDP	1.9	10.3	m	F
	EXTWC	0.1	0.1	m ³ m ⁻³	F
	THT1	0.1	0.1	mday-1	С
	THTS	0.39	0.39	m ³ m ⁻³	С
	THTR	0.1	0.1	m ³ m ⁻³	F
	KV	5	5	mday-1	С
Saturated/ Groundwater zone	HK- Kalahari	20	23	mday-1	С
	HK- Ecca	6.1	6.3	mday-1	С
	HK - Ghanzi	3	3.3	mday-1	С
	VK - Kalahari	10	13	mday-1	С
	VK - Ecca	0.101	0.12	mday-1	С
	VK - Ghanzi	0.41	1.4	mday-1	С
	VKCB	0.000001	0.000001	mday-1	С
	C Ecca	0.0049	0.0049	m²day-1	С
	C Ghanzi	0.0039	0.0039	m²day-1	С

Table 6: Calibrated parameters for the steady-state model. F indicated that the parameter was fixed while C indicated that it was adjusted during calibration.

The spatial distribution of the HK and VK follow the distribution of soils for the top Kalahari Sand and the geology of the deeper aquifers as shown in Figure 29 below. It was observed that variability of VK and HK both within and between the various layers was low.



Figure 29: Calibrated hydraulic conductivity (mday-1) for the layers

4.4.2. Calibrated heads error assessments

The error assessment of heads of the calibrated model was performed both qualitatively and quantitatively as described in section 3.4.3. The plot of simulated heads versus observed heads is shown in Figure 30 below. Figure 31 shows the distribution of the residual versus the observed heads.

The error assessment from the available piezometers gave a ME of -2.68 m MAE of 5.50 m and an RMSE of 5.72 m (complete list in Section 7.3). According to Anderson et al. (2015), RMSE values of heads which are less than 10% of the head difference in the model domain may be considered acceptable. In this model, the RMSE was 1% the head difference in the model domain. The errors were small and within the calibration target.



Figure 30: Simulated versus Observed heads



Figure 31: Residual versus observed heads

The line of fit (Figure 30) between the simulated and observed heads is almost one-to-one which indicated a good fit. Figure 31 shows the residuals versus observed heads. The residuals were randomly distributed; however, a cluster of overestimation can be observed after 1450 m. Overall, a good match of observed and simulated heads was achieved as described above and therefore the steady-state model met the calibration target.

The likely sources of errors observed in Figures 31 & 32 are: 1) heterogeneities unaccounted for by the model design; 2) model conceptualisation errors; 3) inadequacies and uncertainties of input data that fail to reflect aquifer properties, boundaries, and stresses; 4) uncertainties and errors in heads measurements; and 5) uncertainties in simulated head interpolation within a pixel with head observation



The simulated heads for the three aquifer layers are shown in Figure 32 below.

Figure 32: Simulated heads contours for three aquifer layers.

All the simulated heads were below the surface topography. The Kalahari sand aquifer is spatially discontinuous. The distribution of heads shows that the general flow of groundwater is towards the east. It was observed that where the layers were hydrologically connected, the flow patterns were similar which explains the difference in the flow behaviour between the top Kalahari layer and the Ecca as they are separated by Inter-Karoo confining layer. Ecca and Ghanzi flow behaviours are similar where they intersect. At the southeast section of the modelled area, the direction of the flow of Kalahari is towards the northeast and influenced by topography.

4.4.3. Water budgets for the steady-state model.

The water budget of the steady-state model is presented in two parts: first the water budget between the different zones; and secondly, the water balance of the whole model domain.

Table 7 shows the fluxes between the different layers in the study area. This breakdown shows that the primary source of water into the model layer is recharge that occurs in the Kalahari Sand aquifer. The other layers get the water from the fluxes of between them and the Kalahari. The outflows out of the model domain through the drain boundaries occur in all the three layers but mainly in the Kalahari layer. The amount of surface leakage, hortonian and dunnian flows were negligible (occurs only during the wet seasons and account for <0.1% of the water available).

	Kalahari (mmyear-1)		Ecca (mmyear ⁻¹)		Ghanzi (1	mmyear-1)
	IN	OUT	IN	OUT	IN	OUT
Wells (Q_w)	0.0	0.0	0.0	0.0	0.0	0.0
Drains (q_g)	0.0	0.0	0.0	0.5	0.0	0.8
Sub-surface evapotranspiration (ET_{ss})	0.0	247.9	0.0	0.0	0.0	0.0
Gross recharge (R_g)	290.1	0.0	0.0	0.0	0.0	0.0
Groundwater exfiltration (EXf_{gw})	0.0	40.9	0.0	0.0	0.0	0.0
Hortonian and Dunnian flows	0.6	0.0	0.0	0.0	0.0	0.0
Exchanges with Kalahari	0.0	0.0	51.8	50.5	50.3	49.5
Exchanges with Ecca	50.5	51.8	0.0	0.0	0.0	0.0
Exchange with Ghanzi	49.5	50.3	0.0	0.0	0.0	0.0
Total	390.8	391.0	51.8	51.0	50.3	50.3
IN-OUT		-0.2		0.8		0.0
Percent Error		0%		2%		0%

Table 7: Water Budget components in the different layers.

From Table 7 above and Figure 33 below, it can be observed that the different layers interact with each other. All recharge occurs in the Kalahari, and it is redistributed to the other layers. The other layers depend exclusively on Kalahari layer as a source of water. The interactions between Ghanzi and Ecca was minimal because their convergence area is small. Both Ecca and Ghanzi drain water out of the study with Ghanzi draining more.



Figure 33: Water fluxes between the layers (mmyear⁻¹)

Table 8 below shows the water budget for the whole model domain. The values are related to those of Table 7, but they are some slight differences due to truncation by the ZONEBUDGET.

Volumetric Budget for Entire Model (mmyear ⁻¹)								
	In	Out						
Wells (Q_w)	0.0	0.0						
Drains (q_g)	0.0	.3						
Gross recharge (R_g)	288.2	0.0						
Sub-surface evapotranspiration (ET_{ss})	0.0	246.3						
Groundwater exfiltration (EXf_{gw})	0.0	40.6						
Total	288.2	288.2						
In - Out	C).0						
Percent Discrepancy	0.0%							

Table 8: Water Budget components in the entire model

From the steady-state model, the precipitation (P) applied was equivalent to 338.8 mmyear-1, of this, 288.2 mmyear-1(85.1 % of precipitation) was gross recharge (R_g). This means that 14.9 % of the precipitation was lost to surface interception (ET_{sf}). On the other hand, subsurface zone evapotranspiration (ET_{ss}) accounted for 72.7 % of the precipitation while ground water exfiltration (EXf_{aw}) was 12.0 % of P.

After accounting for all the losses, the net recharge (R_n) was calculated using Equation 25 to be 1.90 mmyear⁻¹ which is equivalent to 0.6% of P. This is comparable to results obtained in the region by: DeVries et al. (2000) (1 - 5 mmyear⁻¹); Rahube (2003) (0.68 - 21.5 mmyear⁻¹) and Petulo (2017) (0.01mmyear⁻¹).

4.4.4. Spatial distribution of water budget components

The spatial distribution of gross recharge, groundwater evapotranspiration, groundwater exfiltration and net recharge were plotted. Their distribution is shown in Figure 34below. The gross recharge mainly follows the pattern of precipitation applied to the area as shown in Figure 18. Despite plant interception (section 4.1.3) which in general is pretty low in Kalahari, the similarity between rainfall and gross recharge patterns, confirm spatial homogeneity of Kalahari Sand material (Obakeng 2007).

Groundwater evapotranspiration (ET_{ss}) is treated as a groundwater sink component and therefore has a negative sign. It has the highest values along the fossil river channels and along the southwest-northeast transect where it is locally believed to be a fault-line. The ET_{ss} distribution is likely to be affected by the topography such that along the deep river channel and the transect, where the depth to water table is lowest, ET_g is high. The distribution of ET_g occurring along the river channels/valleys is in agreement with studies done by Hassan et al. (2014) and Berhe (2017). To the southeastern edge, pockets of high ET_{uz} zones can be seen in locations where seasonal ponds occur during the wet season. These ponds depressions which reduce the depth to groundwater table thus enhancing by plants ET.

The groundwater exfiltration was negligible in the study area due to the deep-water table. The net recharge (R_n) spatial distribution can be seen to be influenced more by groundwater evapotranspiration than gross recharge. Regions of high and low net recharge are adjacent to each other. These are mostly at depressions where water accumulated during the wet season allow for local flux focused infiltration to the groundwater.

The groundwater exfiltration was negligible in the study area occurs only in very few cells along the stream channels where the water table was relatively shallow. The spatial distribution of the net recharge (R_n) seems to be influenced more by groundwater evapotranspiration than gross recharge. Regions of high and low net recharge are adjacent to each other. These are mostly at depressions where water accumulated during the wet season allow for local flux focused infiltration to the groundwater, and the depth to groundwater is shallow.



Figure 34: Spatial distribution of water budget components.

4.4.5. Sensitivity analysis.

The steady-state model was tested on the response of the heads to changes in the calibration parameters. The results are represented in Figure 35 below. The horizontal conductivities (HK) and the vertical conductivities (VK) of all the three layers were tested simultaneously. Sensitivity analysis was also done on the vertical hydraulic conductivity (VKCB) of the Inter-Karoo confining layer and drain boundary conductance for Ecca aquifer and Ghanzi.

The results of sensitivity analysis are shown in Figure 35. The most sensitive parameter was the conductance of the drain boundary (C), followed by vertical hydraulic conductivity of the Inter-Karoo confining layer (VKCB) followed by the horizontal conductivity (HK) and then the least sensitive was the vertical conductivity (VK).

A possible reason for the pattern is the fact that the confining layer overlays the aquifer where two out of the three piezometers are located, and therefore heads are highly sensitive to changes in VKCB. It was observed that there was a failure of the model to converge when VK and HK were adjusted beyond -20% and -30 % respectively. This could suggest that these two parameters highly influence the model, but this effect could not be registered in the sensitivity analysis due to the scarcity of piezometers. The lack of convergence due to either high or low HK and VK values was also observed during model calibration.



Figure 35: Sensitivity analysis for steady-state model

4.5. Transient model calibration results.

The transient state model was calibrated as described in section 3.4.2 above. The results of the calibrations are presented in four sections which are: the calibrated parameter sets, Calibrated heads error assessments, water budgets for the transient model and sensitivity analysis.

4.5.1. Calibrated parameter sets

The HK, VK and VKCB zones and parameter values of the steady-state model were maintained in the transient simulation. Zones for specific yield (SY) and specific storage (SS) were assigned zones TO overlap those of HK and VK. The calibrated parameters are shown in Table 9 below. Table 9: Transient calibrated parameters

Zone	Parameter	Minimum value	Maximum Value	Unit	Comment
Unsaturated zone	NSETS2	50	50	[-]	F
	TRAIL2	15	15	[-]	F
	THT1	0.1	0.1	mday-1	С
	THTS	0.39	0.39	m^3m^{-3}	С
	THTR	0.1	0.1	m^3m^{-3}	F
	KV	5	5	mday-1	С
Saturated/ Groundwater zone	SY- Kalahari	0.20	0.3	[-]	С
	SS_{Ecca}	1.0E-05	4.9E-05	m-1	С
	SS_{Ghanzi}	1.0E-05	5.0E-05	m ⁻¹	С
	C _{Ecca}	0.0055	0.0055	m²day-1	С
	C _{Ghanzi}	0.004	0.004	m ² day ⁻¹	С

4.5.2. Calibrated heads error assessments

The calibration target of the transient was to reduce the error between the observed and simulated heads. The error assessment of heads of the calibrated model was performed both qualitatively and quantitatively as described in section 3.4.3. The plots of simulated heads versus observed heads are shown Figures 36-38.

From the observed heads in the Kalahari layer monitored in BH26674 (Figure 36), it can be seen; the heads fluctuate in response to recharge, which is well-correlated with precipitation. The trend shows that the highest groundwater rise (3.33 m) was during the rainy season of September 2013- May 2014. Such water rise, is highly exceptional in Kalahari, as typical water rises or declines in Kalahari are in order of few centimetres at maximum. The simulated water rise was much lower than the measured one and could not be increased by applying realistic data input. This can, for example, be explained by local scale cavity bypass flow that cannot be accounted by the regional model at 1x1 km grid scale.



Figure 36: Simulated and observed heads for BH26674

The Ecca Aquifer as per the observations BH9245 and BH9294 have more stable heads (Figure 37 &38). The simulated heads of BH9294 and BH9245 closely matched the observed heads. This behaviour can be attributed to the fact that Inter-Karoo aquitard overlay Ecca aquifer doesn't receive recharge directly but through exchanges through the aquitard with the Kalahari layer.



Figure 37: Simulated and observed heads for BH9294



Figure 38: Simulated and observed heads for BH9245

Quantitative error assessments done for the transient model were: Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) as described in Section 3.4.3. The results are shown in Table 10 below.

Table 10: Error assessment of transient model

Observation Name	Х	Y	ME	MAE	RMSE
BH26674	20.901	-21.9155	0.350328	1.160616	1.527737
BH9045	21.0465	-23.0124	-1.21557	1.215565	1.479576
BH9294	21.15833	-22.9933	-0.56051	0.560506	0.332537

The errors were observed to be small and there for the simulated heads matched the available heads well.

4.5.3. Water budgets for the transient model.

The results of water budget of the transient model are presented in three sections: water balance variations temporally, lumped water balance for each hydrological year, and water balance for the entire modelling period.

The variability of the main water balance components Precipitation (*P*), infiltration (*P_a*), gross recharge (R_g), groundwater ET (ET_g), ground water exfiltration (EXf_{gw}) and net recharge (R_n) are shown in Figure 39 below. The variability of the Rg and Rn follow the infiltration applied to the model. The fluxes follow a clear wet and dry season.



Figure 39: Water fluxes

From Figure 39, Four wet seasons can be identified where precipitation and consequently recharge occurs. The highest precipitation occurs during the wet season of September 2013 – March 2014. The peaks of P and Rp coincide but Rp is consistently smaller than P by the amount intercepted.

Groundwater evapotranspiration (ETg) flows a cyclic pattern, but the variations are low. Surface leakage is almost zero throughout the study except in a few pixels. It can be seen that recharge takes place only a few times for the entire modelling period. Wanke et al. (2013) also observed the similar behaviour of recharge taking place in a few days per year. Net recharge (Rn) closely matches gross recharge during the rainy season. Rn coincides with high-intensity precipitation and always occur in the middle of the rainy season when the water content of the Kalahari Sands is high. Most of the year, the net recharge (Rn) is negative, i.e. groundwater loses water.

Yearly variations of water balance components

Table 11 shows the yearly totals of water balance components for the whole of the Okwa Basin aquifer. Equations 20-24 in Section 3.5 were used to calculate them. The hydrological year starts from 12th September of the previous year and ends on 11th September of the following year listed. A comparison was made with the steady-state model water balance results. Statistics were calculated for the three complete years. The highlighted period in Table 11 is the steady state solution and was not used in the calculations of the statistics.

The table shows the relationship between Precipitation (P), total infiltration (P_a) , total evapotranspiration (ET), interception at the surface (ET_{sf}) , evapotranspiration from the unsaturated zone (ET_{uz}) , groundwater evapotranspiration (ET_g) , ET_{ss} as a sum $ET_{uz} \& ET_g$, groundwater lateral through the drain boundary (q_g) , groundwater abstractions (Q_w) , gross recharge (R_g) , groundwater exfiltration (EXf_{gw}) , net groundwater recharge (R_n) and storage changes in the unsaturated (ΔS_{uz}) and saturated (ΔS_{gw}) layers. Storages were calculated as storage in less storage out.

Hydrological year	Р	P_a	ET	ET_{sf}	ET_{uz}	ET_g	q_g	Q_w	R_g	Exf_{gw}	R_n	ΔS_{uz}	ΔS_{gw}
Steady State	338.8	304.9	280.2	33.9	246.3 ((ET_{ss})	0.0	1.3	288.2	40.6	1.3		
12/09/2012 - 11/09/2013	230.7	207.7	192.6	24.0	0.0	168.6	0.9	0.0	194.6	26.6	-0.6	-1.9	-1.2
12/09/2013 - 11/09/2014	487.4	438.7	403.9	50.7	0.0	353.2	0.9	0.0	412.9	57.6	2.1	2.3	1.4
12/09/2014 - 11/09/2015	279.6	251.6	233.1	29.1	0.0	204.1	1.1	0.0	237.9	34.4	-0.5	-1.1	-1.3
Statistics													
Mean	332.6	299.3	276.5	34.6	0.0	241.9	1.0	0.0	281.8	39.5	0.3	-0.3	-0.4
SD	111.3	100.2	91.5	11.6	0.0	80.0	0.1	0.0	94.4	13.2	1.3	1.8	1.2
min	230.7	207.7	192.6	24.0	0.0	168.6	0.9	0.0	194.6	26.6	-0.6	-1.9	-1.3
Max	487.4	438.7	403.9	50.7	0.0	353.2	1.1	0.0	412.9	57.6	2.1	2.3	1.4
% of P (for mean)		90.0%	83.1%	10.4%	0.0%	72.7%	0.3%	0.0%	85.0%	11.9%	0.4%		

Table 11: Water Balance components (mmyear-1).

The various fluxes vary from one year to the other. Using the means, ET accounted for 83.1 % of P. This is typical for arid and semi-arid areas such as Okwa Basin. Interception (ET_{uz}) takes 10.4 % of P. ET_{uz} is negligible while ET_g accounts for 72.7% of P. The lateral flow out of the model domain was calculated to be 0.3% of P. The simulated Q_w values were 0.02 mmyear⁻¹ for all the years. Net recharge was found to be 0.3 mmyear⁻¹ which is equivalent to 0.1% of P.

Net recharge ranged from -0.6 - 2.1 mmyear⁻¹. It was highest in the period of 12/09/2013 - 11/09/2014, at 2.3 mm which coincided with the highest precipitation experienced. Conversely, the lowest net recharge coincided with the lowest precipitation.

A general downward trend was observed for both, measured and simulated heads (Figure 36). This could be due to over abstraction or climate change.

Comparison of steady-state and transient solutions

Figure 40 shows a comparison of the steady state solution and mean of the transient solution. The two solutions were comparable, but the transient solution had marginally less fluxes. This is because rainfall averages of 1276 days were used in steady state solution while in transient, 1095 days (3 years) of precipitation was applied in the model. It can be noted that the two solutions partitions ET. The steady state solutions lump both unsaturated zone (ET_{uz}) and groundwater evapotranspiration (ET_g) as subsurface evapotranspiration (ET_{ss}) . The transient solution partitions ET_{ss} into its components.



Figure 40: steady-state and transient solutions (Based on table 11)

4.5.4. Sensitivity analysis.

The Kalahari Sands unsaturated layer is essential in redistribution of recharge to lower zones. To identify the most important unsaturated zone parameter, sensitivity analysis was done on initial water content (THT1), UZF saturated water content (THTS), UZF residual water content (THTR), ET extinction water content (EXTWC), maximum unsaturated vertical hydraulic conductivity of (KV) and Brooks-Corey exponent (ε). Parameters tested from the saturated layers were: specific storage (SS) for both Ecca and Ghanzi aquifers and specific yields (SY) for Kalahari Sand Layer aquifer. Sensitivity was done against heads (Figure 41) to determine which parameters have a response and then the most sensitive parameters were further investigated against fluxes (R_g , ET_g , $EXF_{gw} \& R_n$).



Figure 41: Parameters sensitivity against heads.

Figure 41 above shows the results of parameters sensitivity against heads the most sensitive parameter were further investigated. The parameters investigated further were: initial water content (THT1), UZF saturated water content (THTS), ET extinction water content (EXTWC), and Brooks-Corey exponent (ϵ).

KV was found not to be sensitive to heads. A possible reason is that the initial value of 5 mday-1 exceeded precipitation rate that occurred. SS was found not sensitive to heads. SY and THTR were found to behave comparably similar.



Figure 42: R_g , ET_g , EXF_{gw} & R_n Sensitivity to Brooks-Corey exponent (ε) and ET extinction water content (EXTWC).



Figure 43: R_g , ET_g , EXF_{gw} & R_n sensitivity to initial water content (THT1) and saturated water content (THTS)

Brooks-Corey exponent (ε) relates water content to hydraulic conductivity (Equation 4) and since it is an exponent, changes highly affect the unsaturated hydraulic conductivity. A decrease in ε results in a large unsaturated hydraulic conductivity being calculated by the model. Figure 42(a) shows drastic increase of R_g as a result decreasing the parameter to 0.5ε . Increase of ε results in reduction of infiltration (Figure 42). Since R_g is affected, R_n is therefore affected as per Equation 25.

A reduction of ET extinction water content (EXTWC) results in more water being lost by ET. This explains the reduction of R_g (Figure 42(e)) when initial EXTWC is reduced by a factor of 0.5. A marginal reduction of ET_g is also observed. These charges affect R_n according to Equation 25. No change is observed when EXTWC is increased by a factor of 1.5.

An increase in initial water content (THT1) greatly influenced R_g (Figure 43(a)). This is because an increase of THT1 by a factor of 1.5 resulted in UZF storages increase. The increased water content results in increase in unsaturated hydraulic conductivity since it is a function of water content, resulting in more infiltration percolating to the saturated zone and thereby more R_g . The increase in R_g leads to rise in water table wich in turn increases ET_g , & EXF_{gw} . R_n therefore, changes according to Equation 25. A decrease in THT1 has no effect in all the fluxes being monitored.

UZF saturated water content (THTS) affected the fluxes when both increased and decreased (Figure 43(e)). An increase results in lower hydraulic conductivities (Equation 4) thus lower infiltration rates resulting in lower R_g . A reduction in THTS leads to the opposite effect. The changes in ET_g and EXF_{gw} is a result of rise or fall of water table.

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

The study aimed to evaluate the water resources of Okwa Basin aquifer with an emphasis on groundwater management purpose. To achieve this objective, a conceptual model was developed which was followed up by an integrated numerical model of Okwa Basin aquifers. In the numerical model, UZF1 package integrated with MODFLOW–NWT was implemented to simulate interactions between the unsaturated and the saturated zones adequately. The model was calibrated in both steady and transient states; the latter time-period was 12th September 2012 to 11th March 2016.

The model was able to derive and partition groundwater fluxes based on applied driving forces such as precipitation diminished by interception (effective infiltration) and potential evapotranspiration. The groundwater fluxes included, gross recharge, groundwater evapotranspiration and groundwater exfiltration, all three used to calculate net recharge.

The calibrated steady-state model simulated the flow patterns of the aquifers and quantifies flux exchange between them. Kalahari Sand layer redistributed recharge into Ecca and Ghanzi aquifer. Minor overlap of Ghanzi and Ecca aquifer minimalise flux exchange. The distribution of water balance components shows that net recharge is influenced more by groundwater evapotranspiration than by gross recharge. Groundwater exfiltration occurred in few pixels along the river valley where depth to water table is relatively low. Net recharge was found to be 0.5 % of the precipitation.

Transient simulations show that net recharge occurs in few days per hydrological year. Net recharge was found to be highly depended on precipitation intensity and only occurs in the middle of the wet season when the unsaturated Kalahari water content is high. Annual variations in net recharge were found to be due to variations in precipitation. The net recharge in the transient was comparable to that of steady state at 0.4% of precipitation.

The calibrated transient model showed that recharge occurs in few days per hydrological year. Recharge was found to be highly depended on precipitation intensity and only occur in the middle of the wet season when the unsaturated Kalahari water content is high. Annual variations in net recharge were found to be due to variations in precipitation. The net recharge in the transient was comparable to that of steady state at 0.4% of precipitation.

A general downward trend was observed for both, measured and simulated heads of the entire modelling period.

5.2. Recommendations

The 1x1 km grid scale is too coarse and might not represent local heterogeneities. That grid should be refined although if applying standard PCs, one should think about computation power that restricts such model refinement.

To better constrain the modelling solution, more piezometers that monitor all the layers need to be used for transient calibration. The piezometers should be automatic to eliminate measurement errors.

An audit of piezometer BH26674 with large water rise should be done to assess the effect of the seasonal stream infiltration on its records since it lies within the stream bed valley.

A general downward trend of both, observed and simulated heads need to be investigated to assess if climate change or over-abstraction is taking place by extending the modelling period to at least ten 10 years.

The Okwa Basin aquifer is shared between Botswana and Namibia, so international treaties for management of transboundary aquifers need to be studied to define joint management strategy.
6. LIST OF REFERENCES

- Anderson M, Woessner WW, Hunt R (2015) Applied Groundwater Modeling, Second Edition: Simulation of Flow and Advective Transport.
- Batjes N (2004) SOTER-based soil parameter estimates for Southern Africa (ver. 1.0). Wageningen

Beard JS (1962) Rainfall Interception by Grass. South African For J 42:12–15. doi: 10.1080/00382167.1962.9629728

Berhe DT (2017) Modeling Groundwater Resources of the Eastern Fringe of Botswana Kalahari Integrated Numerical Groundwater Flow Model. Faculty of Geo-Information Science and Earth Observation of the University of Twente

Bhatti H, Rientjes T, Haile A, et al (2016) Evaluation of Bias Correction Method for Satellite- Based Rainfall Data. Sensors 16:884. doi: 10.3390/s16060884

Bredehoeft J (2005) The conceptualization model problem?surprise. Hydrogeol J 13:37–46. doi: 10.1007/s10040-004-0430-5

Canadell J, Jackson RB, Ehleringer JB, et al (1996) Maximum rooting depth of vegetation types at the global scale. Oecologia 108:583–595. doi: 10.1007/BF00329030

CCI Land Cover team (2017) CCI LAND COVER – S2 PROTOTYPE LAND COVER 20M MAP OF AFRICA 2016. http://2016africalandcover20m.esrin.esa.int/download.php.

Christelis G, Dierkes K, Quinger M, et al (2016) Hydrogeology of Namibia - Earthwise. In: Br. Geol. Surv. http://earthwise.bgs.ac.uk/index.php/Hydrogeology_of_Namibia. Accessed 21 May 2017

Christelis G, Struckmeier W (eds) (2011) Groundwater in Namibia - an Explanation to the Hydrogeological Map, second Edi. Ministry of Agriculture, Water and Rural Development, Namibia.

De Vries J., Selaolo E., Beekman H. (2000) Groundwater recharge in the Kalahari, with reference to paleo-hydrologic conditions. J Hydrol 238:110–123. doi: 10.1016/S0022-1694(00)00325-5

Diersch H-JG (2014) FEFLOW. Springer Berlin Heidelberg, Berlin, Heidelberg

Dintwe K, Okin GS, D'Odorico P, et al (2015) Soil organic C and total N pools in the Kalahari: potential impacts of climate change on C sequestration in savannas. Plant Soil 396:27–44. doi: 10.1007/s11104-014-2292-5

Domenico PA, Mifflin MD (1965) Water from low permeability sediments and land subsidence. Water Resour Res 1:563–576. doi: 10.1029/WR001i004p00563

Domenico PA, Schwartz FW (1998) Physical and Chemical Hydrogeology, 2 nd editi. John Wiley & Sons, Inc.

Dzhamalov RG (2006) Environmental Aspects of Groundwater Pollution. In: Zektser IS, Marker B, Ridgway J, et al. (eds) Geology and Ecosystems: International Union of Geological Sciences (IUGS) Commission on Geological Sciences for Environmental Planning (COGEOENVIRONMENT) Commission on Geosciences for Environmental Management (GEM). Springer US, Boston, MA, pp 183–193

Freeze RA, Cherry JA (1979) Groundwater. Prentice-Hall

- Funk C, Peterson P, Landsfeld M, et al (2015) The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci Data 2:150066.
- Gerrits AMJ (2010) The role of interception in the hydrological cycle. VSSD

Gerrits AMJ, Savenije HHG (2011) 2.04 - Interception. In: Wilderer P (ed) Treatise on Water Science. Elsevier, Oxford, pp 89–101

- Habib E, Haile AT, Sazib N, et al (2014) Effect of bias correction of satellite-rainfall estimates on runoff simulations at the source of the Upper Blue Nile. Remote Sens 6:6688–6708. doi: 10.3390/rs6076688
- Harbaugh AW (1990) A Computer Program for Calculating Subregional Finite-difference Ground-water Flow Model. Reston, Virginia
- Hassan SMT, Lubczynski MW, Niswonger RG, Su Z (2014) Surface–groundwater interactions in hard rocks in Sardon Catchment of western Spain: An integrated modeling approach. J Hydrol 517:390–410. doi: 10.1016/j.jhydrol.2014.05.026

Healy R w, Scanlon BR (2010) Estimating groundwater recharge.

Heath RC (1983) Basic Ground-Water Hydrology.

Howes DJ, Fox P, Hutton PH (2015) Evapotranspiration from Natural Vegetation in the Central Valley of California: Monthly Grass Reference-Based Vegetation Coefficients and the Dual Crop Coefficient

Approach. J Hydrol Eng 20:4015004. doi: 10.1061/(ASCE)HE.1943-5584.0001162

- JJ (2017) MAE and RMSE Which Metric is Better? Human in a Machine World Medium. https://medium.com/human-in-a-machine-world/mae-and-rmse-which-metric-is-bettere60ac3bde13d. Accessed 12 Aug 2017
- Johnson a. I (1963) Specific Yield Compilation of Specific Yields for Various Materials. USGS Open-File Rep 119. doi: 10.1017/CBO9781107415324.004
- Key RM, Ayres N (2000) The 1998 edition of the National Geological Map of Botswana. J African Earth Sci 30:427–451. doi: https://doi.org/10.1016/S0899-5362(00)00030-0
- Kisendi EE (2016) Groundwater Resources Evaluation in Kalahari Karoo Basin(Msc Thesis). University of Twente
- Koch M, Missimer T (2016) Water Resources Assessment and Management in Drylands. Water 8:239. doi: 10.3390/w8060239
- Konikow LF, Kendy E (2005) Groundwater depletion: A global problem. Hydrogeol J 13:317–320. doi: 10.1007/s10040-004-0411-8
- Külls C (2000) Groundwater of the North-Western Kalahari, Namibia: Estimation of recharge and quantification of the flow systems (Phd Thesis). Julius-Maximilian University of Würzburg
- Lekula M, Lubczynski M, Shemang EM (2017) Hydrogeological conceptual model of large and complex sedimentary aquifer systems Central Kalahari Basin (Botswana) (under -review).
- Linton J, Brooks DB (2011) Governance of transboundary aquifers: new challenges and new opportunities. Water Int 36:606–618. doi: 10.1080/02508060.2011.599312
- Machacha T. ., Key RM (1997) The Pre-Kalahari Geological Map of the Republic of Botswana. Scale 1:1 000 000. Lobatse, Botswana
- Maidment DR (1992) Handbook of hydrology. McGraw-Hill

Maliva R, Missimer T (2012) Arid Lands Water Evaluation and Management. Springer Berlin Heidelberg, Berlin, Heidelberg

- Margane A, Wrabel J, Schildknecht F, Wierenga A (2004) Investigation of Groundwater Resources and Airborne-Geophysical Investigation of Selected Mineral Targets in Namibia Volume IV.GW.3.1:Groundwater Investigations in the Eiseb Graben Main Hydrogeological Report. Windhoek
- McCuen RH (1973) The role of sensitivity analysis in hydrologic modeling. J Hydrol 18:37–53. doi: https://doi.org/10.1016/0022-1694(73)90024-3
- McDonald MG, Harbaugh AW, (U.S.) GS (1984) A Modular Three-dimensional Finite-difference Ground-water Flow Model. Scientific Publications Company
- McMahon TA, Peel MC, Lowe L, et al (2013) Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. Hydrol Earth Syst Sci 17:1331–1363. doi: 10.5194/hess-17-1331-2013
- Meek BD, Chesworth W, Spaargaren O (2008) Regosols. In: Chesworth W (ed) Encyclopedia of Soil Science. Springer Netherlands, Dordrecht, pp 605–606
- Mendelsohn JM, Jarvis A, Roberts C, Robertson T (2002) Atlas of Namibia : a portrait of the land and its people. David Philip
- Miller R. (2008) The Geology of Namibia. Geological Survey of Namibia, Windhoek
- Montero-Martínez G, Zarraluqui-Such V, García-García F (2012) Evaluation of 2B31 TRMM-product rain estimates for single precipitation events over a region with complex topographic features. J Geophys Res Atmos 117:n/a-n/a. doi: 10.1029/2011JD016280
- Muzylo A, Llorens P, Valente F, et al (2009) A review of rainfall interception modelling. J Hydrol 370:191–206. doi: https://doi.org/10.1016/j.jhydrol.2009.02.058
- Niswonger RG, Panday S, Ibaraki M, USGS (2011) MODFLOW-NWT, A Newton formulation for MODFLOW-2005. Reston, Virginia:
- Niswonger RG, Prudic DE, Regan RS (2006) Documentation of the Unsaturated-Zone Flow (UZF1) Package for Modeling Unsaturated Flow Between the Land Surface and the Water Table with MODFLOW-2005. In: Techniques and Methods 6-A19. U.S. Geological Survey, Reston, Virginia, p 62
- NOAA (2017) The NOAA Climate Prediction Center African Rainfall Estimation Algorithm Version 2.0.
- Novella NS, Thiaw WM (2012) African Rainfall Climatology Version 2 for Famine Early Warning Systems. J Appl Meteorol Climatol 52:588–606. doi: 10.1175/JAMC-D-11-0238.1
- Obakeng OT (2007) Soil moisture dynamics and evapotranspiration at the fringe of the Botswana Kalahari, with emphasis on deep rooting vegetation. Vrije Universiteit , Amsterdam

- Owais S, Atal S, Sreedevi PD (2008) Governing Equations of Groundwater Flow and Aquifer Modelling Using Finite Difference Method. In: Groundwater Dynamics in Hard Rock Aquifers. Springer Netherlands, Dordrecht, pp 201–218
- Penman HL (1948) Natural Evaporation from Open Water, Bare Soil and Grass. Proc R Soc A Math Phys Eng Sci 193:120–145. doi: 10.1098/rspa.1948.0037
- Petulo TP (2017) Groundwater Resources Evaluation Of The Lokalane- Ncojane Karoo Basin (Botswana) Using Numerical Modelling Groundwater Resources Lokalane-Ncojane Karoo Basin (Botswana) Using Numerical Modelling(Msc Thesis). University of Twente
- Rahube TB (2003) Recharge and groundwater resources evaluation of the Lokalane-Ncojane Basin (Botswana) using numerical modelling (Msc Thesis). Faculty of Geo-Information Science and Earth Observation of the University of Twente
- Reilly TE, Harbaugh AW (2004) Guidelines for Evaluating Ground-Water Flow Models.
- Rientjes T (2015) Hydrologic modelling for Intergated Water Resource(Unpublished).
- SASSCAL (2017) SASSCAL WeatherNet. www.sasscalweathernet.org.
- Scholes RJ, Dowty PR, Caylor K, et al (2002) Trends in savanna structure and composition along an aridity gradient in the Kalahari. J Veg Sci 13:419–428. doi: 10.1111/j.1654-1103.2002.tb02066.x
- Shah N, Nachabe M, Ross M (2007) Extinction Depth and Evapotranspiration from Ground Water under Selected Land Covers. Ground Water 45:329–338. doi: 10.1111/j.1745-6584.2007.00302.x
- Smith R. (1984) The lithostratigraphy of the Karoo Supergroup in Botswana.
- Stadtler C, Margane A, Schildknecht F, et al (2005) Investigation of the Groundwater Resources in the Eiseb Graben in Namibia with TEM Soundings.
- Stone EL, Kalisz PJ (1991) On the maximum extent of tree roots. For Ecol Manage 46:59–102. doi: https://doi.org/10.1016/0378-1127(91)90245-Q
- Teketel AT (2017) Integrated Hydrological Modeling of Surface Groundwater Interactions: The Case Of Denpasar-Tabanan Basin in the Southern Bali Island. University of Twente Faculty of Geo-Information and Earth Observation (ITC)
- Thomas DSG, Shaw PA (2009) The Kalahari environment. Cambridge University Press
- Thornthwaite CW (1948) An Approach toward a Rational Classification of Climate. Geogr Rev 38:55–94. doi: 10.2307/210739
- Tian Y, Peters-Lidard CD, Eylander JB, et al (2009) Component analysis of errors in satellite-based precipitation estimates. J Geophys Res 114:D24101. doi: 10.1029/2009JD011949
- UNESCO-IHP (2016) Stampriet Transboundary Aquifer System Assessment Technical Report. Governance of Groundwater Resources in Transboundary Aquifers (GGRETA) - Phase 1. Paris
- USGS (2017) Daily Potential Evapotranspiration (PET). In: USGS FEWS NET Data Portal. https://earlywarning.usgs.gov/fews/product/81#download.
- Wang X-P, Li X-R, Zhang J-G, et al (2005) Measurement of rainfall interception by xerophytic shrubs in re-vegetated sand dunes / Mesure de l'interception de la pluie par des arbustes xérophiles sur des dunes de sable replantées. Hydrol Sci J 50:null-910. doi: 10.1623/hysj.2005.50.5.897
- Wanke H, Dünkeloh A, Udluft P (2008) Groundwater Recharge Assessment for the Kalahari Catchment of North-eastern Namibia and North-western Botswana with a Regional-scale Water Balance Model. Water Resour Manag 22:1143–1158. doi: 10.1007/s11269-007-9217-5
- Wanke H, Dünkeloh A, Udluft P, Wanke A (2013) A distributed water balance model to estimate direct groundwater recharge : A case study from the Nhoma and. Int Sci Technol J Namibia ISTJN 2:11–32.
- Wheater H, Sorooshian S, Sharma KD (2008) Hydrological Modelling in Arid and Semi-Arid Areas. Cambridge University Press, Cambridge
- Winston RB (2009) ModelMuse A Graphical User Interface for MODFLOW-2005 and PHAST.
- Winston RB (2017) UZF: Unsaturated-Zone Flow Package Pane. In: Model. Help.

https://water.usgs.gov/nrp/gwsoftware/ModelMuse/Help/index.html?uzf_object_pane.htm. WMO (2017) World Weather Information Service.

http://worldweather.wmo.int/en/city.html?cityId=1546. Accessed 31 Jan 2018

- WRC (2006) Matsheng Groundwater Development Project: Final Hydrological Report for the Department of Water Affairs. Gaborone, Botswana
- Wu J, Zeng X (2013) Review of the uncertainty analysis of groundwater numerical simulation. Chinese Sci Bull 58:3044–3052. doi: 10.1007/s11434-013-5950-8

7. APPENDIXES

7.1. Rainfall Data obtained

Appendix 1: weather stations

Station	Х	Y	Elevation	Source	Time Period
Gobabis	18.9620	-22.4510	1448 m	Namibia Meteorological Service	01/01/10- 30/06/17
Ghanzi	21.65317	-21.7151	1137 m	SASSCAL (2017)	13/04/16 - 27/03/16
Xade	23.02983	-22.34072	1004 m	SASSCAL (2017)	22/08/15-30/04/16
Ngwatle	21.07972	-23.7124	1176 m	SASSCAL (2017)	25/08/15-30/04/16
Sandveld	19.1321	-22.0445	1527 m	SASSCAL (2017)	01/09/12 - 30/04/16
Tshane	21.86856	-24.0193	1125 m	SASSCAL (2017)	14/02/14 - 30/04/16
Ghanzi Gauge	21.63333	-21.6833	1131 m	Lekula et al. (2017)	01/09/12 - 301/12/13



Figure 44: Station locations



7.2. Data Periods for the weather stations and Piezometer

7.3. Simulated Heads

Observation Name	Х	Υ	Obs (m)	Sim (m)	Obs-Sim	Obs-Sim	Obs-Sim 2
BH26674	20.9010	-21.9155	1175.71	1178.79	-3.08	3.08	9.50
BH9045	21.0465	-23.0124	1108.22	1112.94	-4.72	4.72	22.26
BH9294	21.1583	-22.9933	1105.86	1102.64	3.22	3.22	10.37
BH01	19.5447	-22.6489	1342.00	1348.97	-6.97	6.97	48.58
BH02	19.9842	-22.2692	1285.00	1291.93	-6.93	6.93	48.02
BH03	19.5128	-22.5440	1388.90	1395.78	-6.88	6.88	47.33
BH04	19.9697	-22.2944	1273.00	1279.84	-6.84	6.84	46.79
BH05	19.1293	-22.0742	1510.00	1516.71	-6.71	6.71	45.02
BH06	19.4176	-22.6034	1389.00	1395.51	-6.51	6.51	42.38
BH07	19.1887	-22.0672	1503.00	1509.48	-6.48	6.48	41.99
BH08	19.3067	-22.3206	1484.00	1490.12	-6.12	6.12	37.45
BH09	19.3990	-22.2467	1467.00	1473.05	-6.05	6.05	36.60
BH10	19.7608	-22.4694	1263.00	1269.04	-6.04	6.04	36.48
BH11	19.0948	-22.1727	1509.00	1514.77	-5.77	5.77	33.29
BH12	19.5700	-22.5088	1335.00	1340.66	-5.66	5.66	32.04
BH13	19.5910	-22.5705	1319.00	1324.46	-5.46	5.46	29.81
BH14	19.6281	-22.4043	1407.00	1411.48	-4.48	4.48	20.07
BH15	20.8500	-22.2000	1175.00	1179.32	-4.32	4.32	18.66
BH16	20.5833	-22.0833	1211.68	1215.17	-3.49	3.49	12.18
BH17	20.5072	-22.0247	1271.81	1275.18	-3.37	3.37	11.36
BH18	19.7645	-22.4482	1270.30	1273.51	-3.21	3.21	10.30
BH19	20.6211	-22.0844	1209.00	1211.07	-2.07	2.07	4.28
BH20	19.8689	-22.4404	1251.00	1252.79	-1.79	1.79	3.20
BH21	19.5717	-22.5545	1325.00	1326.71	-1.71	1.71	2.92
BH22	20.8606	-22.1500	1185.00	1186.71	-1.71	1.71	2.92
BH23	19.5087	-22.6281	1362.00	1363.27	-1.27	1.27	1.61
BH24	20.9105	-21.9031	1190.00	1190.68	-0.68	0.68	0.46
BH25	19.6798	-22.8046	1297.30	1297.31	-0.01	0.01	0.00
BH26	20.9944	-22.1500	1165.00	1163.13	1.87	1.87	3.50
BH27	20.9822	-22.4658	1162.00	1159.64	2.36	2.36	5.57
BH28	19.9764	-21.7945	1336.00	1333.39	2.61	2.61	6.81
BH29	19.9395	-22.3303	1276.00	1273.04	2.96	2.96	8.76
BH30	19.8778	-22.2314	1417.30	1414.13	3.17	3.17	10.05
BH31	20.0516	-21.7234	1345.00	1338.90	6.10	6.10	37.21
BH32	19.7861	-22.1388	1428.20	1421.28	6.92	6.92	47.89
BH33	21.0636	-22.7850	1099.00	1106.61	-7.61	7.61	57.91
BH34	20.7908	-22.9361	1118.70	1117.35	1.35	1.35	1.82
BH35	20.7667	-22.9667	1115.70	1117.43	-1.73	1.73	2.99
BH36	20.9208	-22.9667	1105.70	1111.90	-6.20	6.20	38.44
BH37	20.7656	-22.9797	1114.65	1116.65	-2.00	2.00	4.00
BH38	20.7639	-22.9672	1116.70	1117.43	-0.73	0.73	0.53
BH39	20.9197	-22.9694	1104.70	1111.90	-7.20	7.20	51.84

Table 12: Simulated (Sim) and observed (Obs) heads for Steady state model

BH40	20.7083	-23.0000	1124.70	1122.94	1.76	1.76	3.10
BH41	21.0465	-23.0124	1112.00	1107.91	4.09	4.09	16.73
BH43	20.7036	-23.0742	1120.70	1120.03	0.67	0.67	0.45
BH44	20.7658	-23.1225	1112.70	1114.04	-1.34	1.34	1.80
					-108.06	182.22	955.31
					ME	MAE	RMSE
					-2.35	3.96	4.56