2018

Modeling Water Availability, Risk and Resilience in a Semi-Arid Basin in Southern Africa

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MODELING WATER AVAILABILITY, RISK AND RESILIENCE IN A SEMI-ARID BASIN IN SOUTHERN AFRICA

BY

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A dissertation submitted in partial fulfilment of the requirements for the

Doctor of Philosophy

Major in Civil Engineering

South Dakota State University

2019

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This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy in Civil Engineering degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidates are necessarily the conclusions of the major department.

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To my two little angels

ACKNOWLEDGMENTS

How does one begin to put words together to acknowledge all the great people who made this journey possible? I thought about this moment continuously since my first year and I must acknowledge that it is not easy as it looks. The mind sometimes forgets "some" happenings despite their importance to the owner. I would like to apologize in advance for forgetting to mention everybody that made this possible – your contribution is very important and unique even when you are not mentioned by name.

This work would not have been possible without the contribution of my sponsors the Schlumberger Faculty for the Future (FFTF) and the Botswana International University of Science and Technology through the Department of Tertiary Education Financing (DTEF) and Botswana Embassy in Washington, DC, United States who provided financial support during this study.

My heartfelt thanks go to my advisors; Dr. Suzette Burckhard and Dr. Laurent Ahiablame. Dr. Burckhard has always been available when I needed her help both academically and non-academically. She always found time to advise me in my work and graduate administrative work. Her friendliness and understanding have always made me feel at-ease talking to her about anything. Dr. Ahiablame, thank you for giving me the opportunity to do my PhD research under your guidance. I appreciate your intellectual acumen, scientific rigor and the timely response to all the academic and non-academic matters you provided related to my work. You were accessible 24/7 and I have learned a lot from you. You have always been optimistic and see things in different angles. Your passion for research can only inspire me to do more. Your expertise and knowledge as a modeler helped me a lot to understand how watershed hydrological studies work. You have also played a role of a counselor to my life. There are times I felt so discouraged to continue, but you have always seemed to know my struggles before I shared them with you. I felt like you gave me a platform to grow and you integrated me on a lot of organizations and helped me network with other researchers and professionals around the country. I am seeing the results of those efforts even up to today. Not only did you mentor me, you also allowed me to interact with your family for whom I got to connect, and I can safely say I have a friend in your wife Sheila and your kids. They have been nothing else but a blessing to me and my two girls. Many thanks also go to my committee members who were very approachable and supportive. Dr. Christopher Schmit always gave constructive comments and provided a relaxed and comfortable environment for the examinations.

A word of gratitude also goes to Dr. Srinivasan at Texas A&M and Dr. Bailey at Colorado State University who opened their lab doors for me and allowed me to work with them towards my PhD program as a visiting scholar. They availed their

resources, their expertise and their teams to work with me. They are highly very busy, but they allowed me to knock in their offices anytime I need help and they will provide one. They also have taught me so much in terms of collaboration, humility and different approaches to solving problems.

Thanks go to my colleagues in Dr. Ahiablame's research group; Jiyeong Hong, Alex Boger, Manashi Paul, Ashik Sahani, Sami Shokrana, Utsav Thapa, and Annika Oetken who brought different expertise and were always willing to go an extra mile to help. Alex and Jiyeong, you have been so selfless, approachable and willing to support me even outside school work.

I would also like to thank my FFTF mentor Dr. Diane Dosser at University of Texas at El Paso. You have been available each time I needed to discuss my difficulties with you. You have always shared what you know about life with me and it was fascinating that sometimes we will discuss a specific topic and few weeks later, what we talked about will happen. Usually, I would draw from those conversations and get encouraged to press forward.

Many people and organizations have helped by providing needed data for my studies. A special mention to Olga De Beer and Lebogang Mathume from the South Africa Department of Water and Sanitation (SAWS). Personnel of Meteorological Services in Botswana also deserve a big thank you. Olga and

Lebogang provided timely data and were very patient with me whenever I asked datasets and other information about my watershed. They responded to my emails and were ready to link me with different people who can provide what I needed. Keep it up ladies, it was nice interacting with you.

I was fortunate to meet good people here in the United States, who today I call friends. These people made my experience and stay in the United States very enjoyable. They have taught me lessons that are unforgettable in life. I thank you all, but I want to mention Dr. Woubet Alemu, Dr. Francis Dwomoh, Dr. Rick Brownrigg, Yassah, Norah, Dan and family and Ronald. Woubet and Francis (PhD students at the time I met them) have been more than friends to me. They looked after me as their own sister than a colleague or classmate. They reached out to me concerning school work. Whenever I have trouble processing data, they will set away time to work with me in solving the problem. I cannot mention enough the enormous help I got and still getting from them. Dr. Brownrigg you have been a very big help to me as a IT programmer and a friend. You have been very approachable and have always helped me to the best of your ability. Thank you very much for being there in every pain, struggle and joy I went through. Your empathy has taught me a huge lesson of life. Ron, you were the latest addition to the “circle of friends”, but you have contributed a lot to me. Your support, calm and encouragements will always be remembered. You always made time to

"listen" despite your being far away and your ability to make me look at things differently and help me calm down (make me laugh at you and sometimes at myself) in uncertain situations has positively impacted me. You will always be appreciated.

Friends at home in Botswana worth mentioning are Dr. Bothepha Mosetlhi, Dr. Masego Mpotokwane and Dr. Alphonse Amey. You guys have found it worthwhile to converse with me many times thus encouraging me to push on. Sharing your PhD experiences with me helped me continue knowing someone else went through the same struggles. Everyone one of you have been very awesome to me. Bothepha, you were there in more ways than one to me and words cannot explain the gratitude I have towards you. Thank you for everything you are to me.

To my Botswana family, thank you for believing in me and your supportiveness even when you were very far away. Those long phone calls, text messages and any form you found to reach out to me, and my kids have helped us a lot. Mom, thank you for doing nothing else but support me even when you were not well. You have been strong to the both of us and I thank God you are now back to health. To my Brookings family, (the DeBates family), you were a family away from family. We still missed our family home but you made us feel home. You played a huge role to my success. I could and I still count on you on everything. I thank both families. No words are enough to thank you for all the sacrifices you gave, for me to be successful. If this PhD was shareable, you deserve a huge piece of it. I call myself fortunate to have you.

Kelly and Mimie, I must admit you did not see much of your mother. You have sacrificed a lot and have grown into beautiful young ladies. I am sure you say "having a school going mom sucks" but look at you! you became strong for me.

Last and most importantly; a special honor goes God who brought all the good people, who I call "angels" to my path and provided to all my needs? You deserve all the Glory. You order the path of our footsteps and we will never want. Thank you!

Disclaimer

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ABSTRACT

MODELING WATER AVAILABILITY, RISK AND RESILIENCE IN A SEMI-ARID BASIN IN SOUTHERN AFRICA

ESTHER MOSASE

2019

Climate variability need to be incorporated into the management and planning of water resources, particularly in arid and semi-arid regions, where water availability is more sensitive to rainfall and air temperature. This study used modified Man-Kendall trend analysis test and ArcGIS to process data. Annual means of rainfall, minimum temperature and maximum temperature in the Limpopo River Basin (LRB) varied between 160 and 1109 mm, 8 °C to 20 °C and 23 °C to 32 °C respectively. The spatial pattern is generally increasing from west to east for rainfall and minimum temperature while maximum temperature increases from south to north and west to east. Coefficient of variation (CV) shows an opposite pattern to the annual pattern, with rainfall showing the highest variation compared to other variables. Rainfall and minimum temperature showed an increasing pattern in most of the basin while maximum temperature showed a decreasing pattern.

In-depth understanding of the hydrological processes is important for balancing availability and demand for water. As part of this basin-wide and the basin nations concern, this study examined blue and green freshwater availability and identified water sensitive areas by balancing water availability and demand for the Limpopo River Basin (LRB). The Soil and Water Assessment Tool (SWAT) model, calibrated at multiple locations in the basin for monthly streamflow simulation showed satisfactory results, given the scale and variability in physical characteristics of the basin. Spatial analysis showed a decreasing pattern in freshwater availability from east to west, and from north to south while temporal variation showed alternate episodes between wet and dry years, with deviations from the normal cycle every one to two years for the wet periods and three to five years for dry periods during the study period. 20% in the east of the basin show excess wetness while the rest of the basin is dry areas.

Understanding the rate, timing, and location of groundwater recharge, groundwater levels and discharge characteristics are crucial for efficient development and management of groundwater resources, as well as for minimizing pollution risks to the aquifer and connected surface water resources. SWAT-MODFLOW was used to characterise the distribution of annual and seasonal groundwater recharge, groundwater level, groundwater–surface water interactions in the LRB from 1984 to 2013. The impacts of Low Impact

Developments (LID's) and Best Management Practices (BMP's) on groundwater recharge and water table elevations were also assessed for the Gaborone catchment as a case study in the LRB. Simulation results show relatively high annual recharge along the Limpopo main river and at the outlet of the basin. The groundwater table is generally shallow in the rainy east and along the basin's river network. Seasonal analysis reveals high variability in both groundwater recharge and level. The summer season has the highest groundwater recharge, followed by autumn, spring, and winter as the lowest recharge during the 30-year study period (1984 to 2013). Water table elevations are low in the summer and highest in the autumn. In terms of groundwater-surface water interactions, rivers in the south showed input from groundwater discharge while west river channels appeared to seep to the underlying aquifers. Implementation of the LID practices resulted in 0 to 6% increase in annual groundwater recharge and 0 to 0.11% increase in annual water table elevations.

1. INTRODUCTION

1.1. Problem Statement

Water is an important resource to the economic and social well-being of humankind (Hughes et al. 2014, Botai et al. 2015). In semi-arid regions such as the Limpopo River Basin (LRB), adequate water supply to support agriculture, industry, and domestic needs is a challenge (Petrie et al. 2014). Water scarcity in the LRB is the result of the basin's highly variable climate, typified by frequent extreme seasonality, intense El Niño-Southern Oscillation (ENSO) events which render rainfall and runoff unreliable to support current water demands in the basin (Schulze et al. 2001, Moeletsi et al. 2011, Jury 2016). These ENSO events are often linked to intense drought and flood events (WMO 1984, Glantz et al. 1997a, Kandji et al. 2006, WMO 2012). Of the known floods in the LRB, the flood that occurred in 2000 was the most catastrophic flood which resulted in 500 deaths, displaced two million people, drowned 20,000 cattle and inundated 1400 km^2 of farmland in Mozambique. Climate change projections indicate that there will be increases in temperatures, evaporative demands, and changes in magnitude and timing of rainfall and runoff patterns in Southern Africa region (Strzepek et al. 2011). These changes in hydro-climatology are estimated to result in increased frequency and intensity of flood and drought events (Schulze et al. 2001, Boko et al. 2007, Schulze 2011).

In addition to the climatic caprice which is a major cause of water scarcity in the semi-arid regions, population growth, urbanization, industrial development, and increasing agricultural activities also intensify pressure on water resources in the basin (van der Zaag et al. 2010, Bawden et al. 2014). The main source of surface water in the basin is the Limpopo River and its tributaries. The river's mean annual runoff is estimated at 5,500 million m^3 (MCM) per year with South Africa contributing more than two thirds of streamflow, which is primarily runoff (Nakayama 2003, Mohamed 2014). Due to seasonality and high variability in rainfall, water resources of the basin are unevenly distributed resulting from highly variable streamflow.

Groundwater plays a major role in the LRB, especially in places further away from the Limpopo River and its tributaries. Due to the limited surface water resources and the high transportation costs, areas that are far away from the river or reservoirs within the basin rely heavily on groundwater (FAO 2004). Additionally, groundwater is used as an alternative water source to surface water during drought years to reduce vulnerability of the basin's communities. For example, about 65% of Botswana's water supply is estimated to come from groundwater resources while 850 Mm^3/year of groundwater, approximately, is used for domestic and irrigation demands in South Africa (FAO 2004). Even though groundwater provides a promising avenue to reduce water shortage in the basin, groundwater resources are over-exploited in some watersheds of the basin, leading to water quality issues (Petrie et al. 2014).

Industrial activities such as mining, increased salinization, and lack of infrastructure to support proper sewage disposal have been linked to deterioration of the quality of both ground and surface water in the basin, adding to the scarcity problem (FAO 2004, Petrie et al. 2014).

Efforts to alleviate water scarcity problems at national levels in the countries within the basin translated into expensive measures such as transfer of water from non-urban to ultra-urban locations, regulation of water usage, and increases in water prices (Schulze et al. 2001, Petrie et al. 2014). Although helpful, these measures are not long-term solutions for the water scarcity problem in the region, calling for opportunities to find sustainable solutions to the issue. Sustainable management of water resources in the basin requires understanding of spatial and temporal patterns of different water budget components of the hydrological cycle. The study of spatial and temporal distribution of water budget components can also help water resource managers identify sensitive areas; i.e. areas of low or abundant water availability. Such science-based information is important to inform long-term plans for the formulation and projection of water resource development in the basin. To date, there is still a lack of basin-wide information on groundwater and surface water interactions in the LRB despite the general recognition of the influence of groundwater abstraction on local and downstream water users.

1.2. Description of the Limpopo River Basin

The Limpopo River Basin (LRB) was selected for this study. The Limpopo River is one of the longest rivers in southern Africa, stretching over 1,750 km. The name Limpopo is derived from the original local Sepedi name *diphororo tsˆa meetse* meaning "gushing strong waterfalls" (Chilundo and Kelderman 2008, Maposa 2016). The Limpopo River starts at the confluence of Marico and crocodile rivers in South Africa, later joined by the Notwane tributary from Botswana. The river then flows north in easterly direction, where it forms the border between Botswana and South Africa (Boroto and Görgens 2003), receiving seasonal flows from tributaries such as Bonwapitse, Mahalapswe and Motloutse rivers from Botswana as well as Matlabas, Mokolo, Lephalala and Mogalakwena from South Africa. The Limpopo Rver then flows to the east at its confluence with Shashe River from Zimbabwe, where it makes a border between South Africa and Zimbabwe with inflows from Umzingwani, Bubi and Mwenezi tributaries from Zimbabwe, and Sand and Nzhelele rivers from South Africa before flowing through Mozambique where it gets inflows from Changane and Lumane tributaries in Mozambique, and Steelpoort, Elephants, Luvuvhu and Letaba tributaries from South Africa.

The basin's drainage area is approximately 415,000 km^2, shared among Botswana, Mozambique, South Africa and Zimbabwe, which are 20%, 15%, 45%, and 20% of the total drainage area. The basin is divided into three main regions consisting of the Upper Limpopo, the Middle Limpopo and the Lower Limpopo (Figure 1.1) (Hakala and Pekonen 2008, Kahinda et al. 2016, Maposa 2016). The Upper Limpopo basin starts from Marico and Crocodile Rivers down to the confluence of Shashe River which forms Botswana, South Africa and Zimbabwe borders. The Middle Limpopo basin starts from the confluence of Shashe and Pafuri Rivers which is the location of the border between Mozambique, South Africa and Zimbabwe. The Lower Limpopo which is entirely in Mozambique, starts downstream of Pafuri River to the mouth of the river in Mozambique and finally flows onto the Indian Ocean (FAO 2004, Hakala and Pekonen 2008, Maposa 2016). The LRB is usually subdivided into 27 recognized major watersheds, of which four fall in Botswana, three in Mozambique, 12 in South Africa, three in Zimbabwe, and five shared between at least two countries (FAO 2004, Mosase and Ahiablame 2018) (Figure 1.1 and Table 1.1). The major watersheds areas range from 5, 666 km^2 (Matlabas) to 64, 039 km^2 (Changane) (Table 1.1).

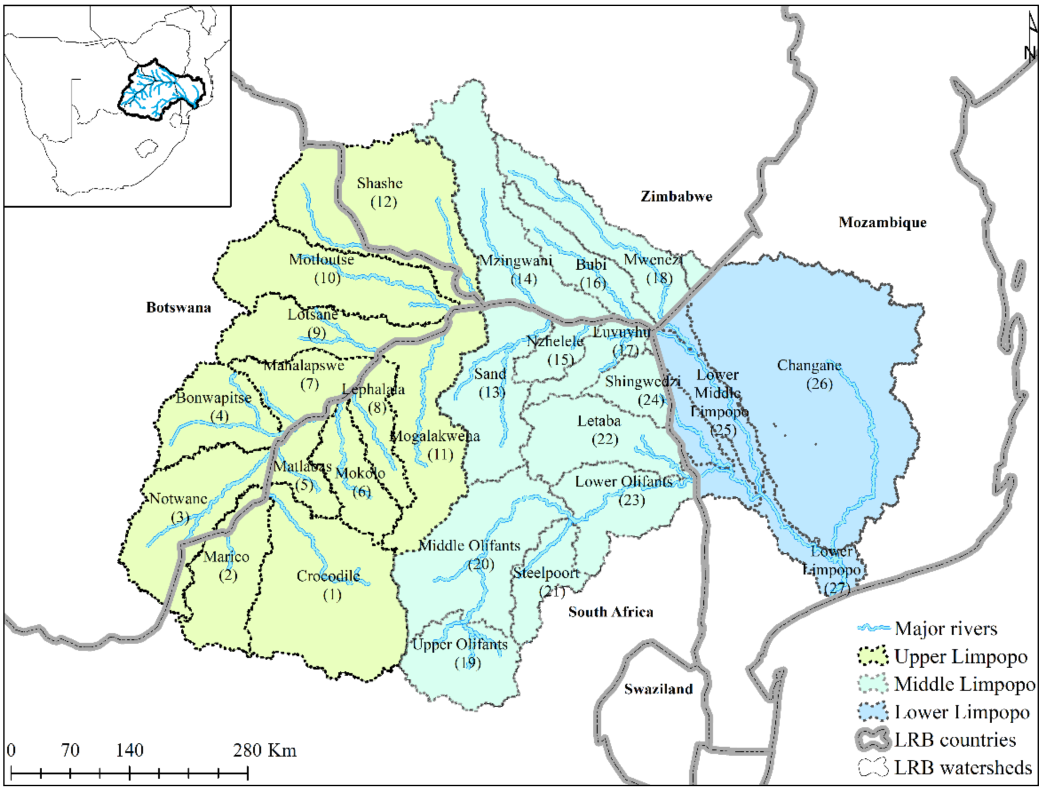

Figure 1. 1: The Limpopo River Basin's three regions and 27 sub-watersheds

Table 1. 1: Major watersheds of the Limpopo River Basin and associated drainage areas riparian countries

Notation	Watershed Name	Area (km²)	% of the Basin	Country
ws1	Crocodile	29696	7	South Africa
ws2	Marico	13291	3	South Africa, Botswana
ws3	Notwane	18137	4	Botswana, South Africa
ws4	Bonwapitse	11975	3	Botswana
ws5	Matlabas	5666	1	South Africa
ws6	Mokolo	8333	2	South Africa
ws7	Mahalapswe	8693	2	Botswana
ws8	Lephalala	6774	2	South Africa
ws9	Lotsane	12599	3	Botswana
ws10	Motloutse	19596	5	Botswana
ws11	Mogalakwena	19196	5	South Africa
ws12	Shashe	29612	7	Botswana, Zimbabwe
ws13	Sand	15729	4	South Africa
ws14	Mzingwani	20747	5	Zimbabwe
ws15	Nzhelele	4246	1	South Africa
ws16	Bubi	8640	2	Zimbabwe
ws17	Luvuvhu	5603	1	South Africa
ws18	Mwenezi	14995	4	Zimbabwe
ws19	Upper Olifants	11629	3	South Africa
ws20	Middle Olifants	23149	6	South Africa
ws21	Steelpoort	6896	2	South Africa
ws22	Letaba	13861	3	South Africa
ws23	Lower Olifants	15773	4	South Africa, Mozambique
ws24	Shingwedzi	9309	2	South Africa, Mozambique
ws25	Lower Middle Limpopo	7980	2	Mozambique
ws26	Changane	64039	16	Mozambique
ws27	Lower Limpopo	5757	1	Mozambique

Rainfall in the LRB is highly variable, ranging from 200mm/year in the west to 1500 mm per year in the Drakensberg escarpment in the south and most parts in east of the basin (Boroto 2001, Busari 2007, Mosase and Ahiablame 2018). Rainfall mainly falls during austral summer i.e., between October and April for

Southern Africa, including the LRB of which peak rainfall is reported in February.

Daily temperature ranges from between 26 and 33 °C during summer months, with maximum temperatures reaching as high as 40 °C. Winter days are generally mild and sunny, with maximum temperatures of between 18 and 20 °C.

The Limpopo River is the main source of surface water for its riparian countries. Agriculture is the main water user activity in the basin. About 295 400 ha of the basin is irrigated area utilizing about 4 700 Mm^3 of water, of which, 62% is in South Africa, 30% in Zimbabwe, 6% in Mozambique and 2% in Botswana.

Nearly 17 million people live and work in the LRB. By 2040, the LRB's population is projected to be 23 million (Earle et al. 2005, LBPTC 2010, Mohamed 2014). In the LRB, urban centres such as Gaborone and Francistown in Botswana, Pretoria, parts of Johannesburg, and Polokwane in South Africa, Beitbridge, Bulawayo and Gwanda in Zimbabwe, Chokwe and Xai-Xai in Mozambique are the major water users with industrial, commercial, and municipal demands. In rural areas, the basin's water is primarily used for irrigation, livestock watering, and domestic purposes (WMO, 2012; Hakala and Pekonen, 2008).

1.3. Goal and Objectives

The goal of this research was to assess water availability in the LRB using historical rainfall and streamflow data, Earth Observation (EO) data on soil, geology, and water table in the basin, GIS tools, and computer-aided models. The specific objectives of this study were to:

1. Assess spatial and temporal trends in rainfall and temperature using reanalysis grid-based data,
2. Parameterize a watershed model with a custom geospatial database for the study basin to quantify blue and green water availability for agricultural and domestic use, and
3. Build a loosely coupled surface water-groundwater model to assess recharge and groundwater-surface water interactions in the LRB

1.4. Significance of the Study

This study contributes to solving a regional water issue in southern Africa. The study adds to the understanding of spatial and temporal variations of past and present climatology as well as availability of freshwater components in the basin. The study also documents hydrologically sensitive areas in the basin (i.e. areas susceptible to droughts and floods). Additionally, the study demonstrates the capability of SWAT-MODFLOW (Soil and Water Assessment Tool - Modular Three-Dimensional Finite-Difference Groundwater Flow

Model) to simulate hydrological processes in Southern Africa region. To my knowledge, this study is the first to validate the use of SWAT-MODFLOW in Africa, and one of the first to evaluate SWAT-MODFLOW at such a large scale. This study also explores the use of curve number (CN) values to represent low impact development (LID) in SWAT model. This study pioneered this approach as a way to represent, simulate, and evaluate LID practices at watershed scales with SWAT.

1.5. Organization of the Dissertation

The dissertation is organized in five chapters. **Chapter 1** presents the overall introduction of the study, including the background, research problem, and objectives of the dissertation. **Chapter 2** assesses long-term variations of climatic variables in recent decades in the basin. **Chapter 3** documents the spatial and temporal distribution of freshwater availability components and water sensitive areas in the basin. **Chapter 4** determines changes in groundwater recharge and water table levels with implementation of selected best management practices in the basin. **Chapter 5** summarizes the findings of this dissertation and identify pathways to recommend for further studies in the region. Besides the Introduction chapter (**Chapter 1**) and Conclusion chapter (**Chapter 5**), each of the remaining chapters is written in manuscript format for publication in peer reviewed journals; therefore, some information may be repeated in more than one place in the dissertation.

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2. RAINFALL AND TEMPERATURE IN THE LIMPOPO RIVER BASIN, SOUTHERN AFRICA: MEANS, VARIATIONS, AND TRENDS FROM 1979 TO 2013

Abstract

Understanding temporal and spatial characteristics of regional climate is essential for decision making in water resource management. Established statistical and GIS techniques were used to evaluate annual and seasonal variations of rainfall and temperature in time and space from 1979 to 2013 in the Limpopo River Basin (LRB). Annual means of rainfall in the LRB varied between 160 and 1109 mm, generally from west to east of the basin during the study period. Annual minimum and maximum temperature ranged from 8 °C in the south to 20 °C in the east of the basin, and 23 °C in the south of the basin to 32 °C in the east respectively. The respective coefficients of variation (CVs) of these variables showed an inverse pattern to the annual values of both rainfall and temperature, with rainfall having high CV values (28% to 70% from east to west of the basin) compared to temperature CV values. Seasonal variations followed similar patterns as annual variations for the individual variables examined. Trend analysis showed upward trends for both annual and seasonal rainfall in most parts of the basin, except for the winter season which showed a decreasing trend. Analysis of minimum temperature on an annual basis and for the winter season and spring season shows upward trends during

the study period over the whole basin while minimum temperature for summer and autumn showed decreasing trends. Maximum temperature, by contrast, showed decreasing trends on an annual, summer, autumn, and spring basis but an increasing trend for winter during the study period in most parts of the basin.

2.1. Introduction

Water is an important resource for the economic and social well-being of humankind (Hughes et al. 2014, Botai et al. 2015). In semi-arid regions such as the LRB, adequate water supply to support agriculture, industry, and domestic use is an enduring problem. Water scarcity in the LRB is the result of the basin's highly variable climate, typified by frequent extreme seasonality, intense El Niño-Southern Oscillation (ENSO) events, and interactions with oceanic climates from both Atlantic and Indian Oceans, that render rainfall and runoff unreliable in the basin (Schulze et al. 2001, Moeletsi et al. 2011, Jury 2016). The ENSO events have been linked to drought and flood events in Southern Africa (Glantz et al. 1997, Kandji et al. 2006). For the past two decades, the LRB experienced some of the most damaging droughts (FAO 2004, LBPTC 2010, WMO 2012). For example, the 1991–1992 drought affected approximately 86 million people, of which 20 million were at serious risk of starvation (WMO 2012). The 2005–2006 drought damaged 72 500 hectares of cultivated cropland in Botswana, resulting in considerable economic losses.

While the LRB is recurrently associated with drought-related influences, flood risks and flood events are also major concerns, particularly in the lower LRB of Mozambique. Of the major floods that occurred in the past, flooding in 2000 and 2013 was the most noticeable. More than 500 deaths were reported for the 2000 flood event, two million people were displaced, more than 20 000 cattle drowned, and more than 1400 km^2 of farmland were inundated in Mozambique (WMO 2012, Spaliviero et al. 2014). Subsequent economic losses for Botswana were estimated to be more than US $285 million (Turnipseed n.d). The 2013 event caused approximately 50 deaths and displaced 150,000 in Mozambique (Spaliviero et al. 2014).

Population growth, urbanization, industrial development, and increasing agricultural activities (van der Zaag et al. 2010, Bawden et al. 2014) continue to place pressure on water resources in the basin. Additional dams are continually built, and groundwater resources are intensively used when rivers and dams are dry (FAO 2004), leading to chronic freshwater problems in the region. The effects of climate variability and change further add uncertainty to the freshwater availability problem. Research shows that climate change will lead to rises in temperature, evaporative demands, and changes in rainfall and runoff patterns in Southern African regions (Strzepek et al. 2011), resulting in increased frequency of flooding and drought as well as a reduction in groundwater recharge (Schulze et al. 2001, Boko et al. 2007, Schulze 2011). These patterns, however, are expected to vary throughout the region, including the LRB, which means different areas may experience different levels of water problems in the future. To effectively manage water resources in the LRB, it is important to understand past and present trends, variability, and characteristics of key factors such as climate that control freshwater availability. The study sought to document precipitation and temperature variations in time and space in the regional basin of Limpopo River as a major step toward increased understanding of regional water distribution for human and environmental needs

2.2. Materials and methods

2.2.1. Study Area

The Limpopo River is one of the longest rivers in southern Africa, with a drainage area of approximately 415,000 km^2. The basin is shared among four countries, namely, Botswana, Mozambique, South Africa and Zimbabwe, which contain 20%, 15%, 45%, and 20%, respectively, of the total drainage area of the basin. The Limpopo River Basin has 27 recognized major watersheds, of which four fall in Botswana, three in Mozambique, 12 in South Africa, three in Zimbabwe, and five are shared between at least two countries (Figure 2.1).

Nearly 17 million people live and work in the LRB. By 2040, the LRB's population is projected to be 23 million (Earle et al. 2005, LBPTC 2010, Mohamed 2014). Agriculture is primarily rainfed despite the high variability of rainfall.

The climate of the LRB is influenced by prevailing dry continental tropical, equatorial convergence zone, moist maritime subtropical eastern, and marine western Mediterranean air masses (FAO 2004). These create an arid climate condition in the basin. Mean annual rainfall in the basin varies considerably, between 200 in the west of the basin and 1500 mm/year in the east, with the bulk of the basin receiving less than 500 mm/year. The rainy season is short, with 95% of the rainfall occurring between October and April. Annual rainy days seldom exceed 50 calendar days. Rainfall in the basin also varies significantly between years, causing frequent flood events during wet years and droughts during dry years. Monthly rainfall during wet years can reach 340 mm, from a minimum of 50 mm to a maximum of 100 mm for normal rainy months. Mean daily air temperature across the basin varies from 0 °C in winter to 36 °C in summer. Evaporation over the basin is 1970 mm/year on average, with a range of 800 to 2400 mm/year (FAO 2004).

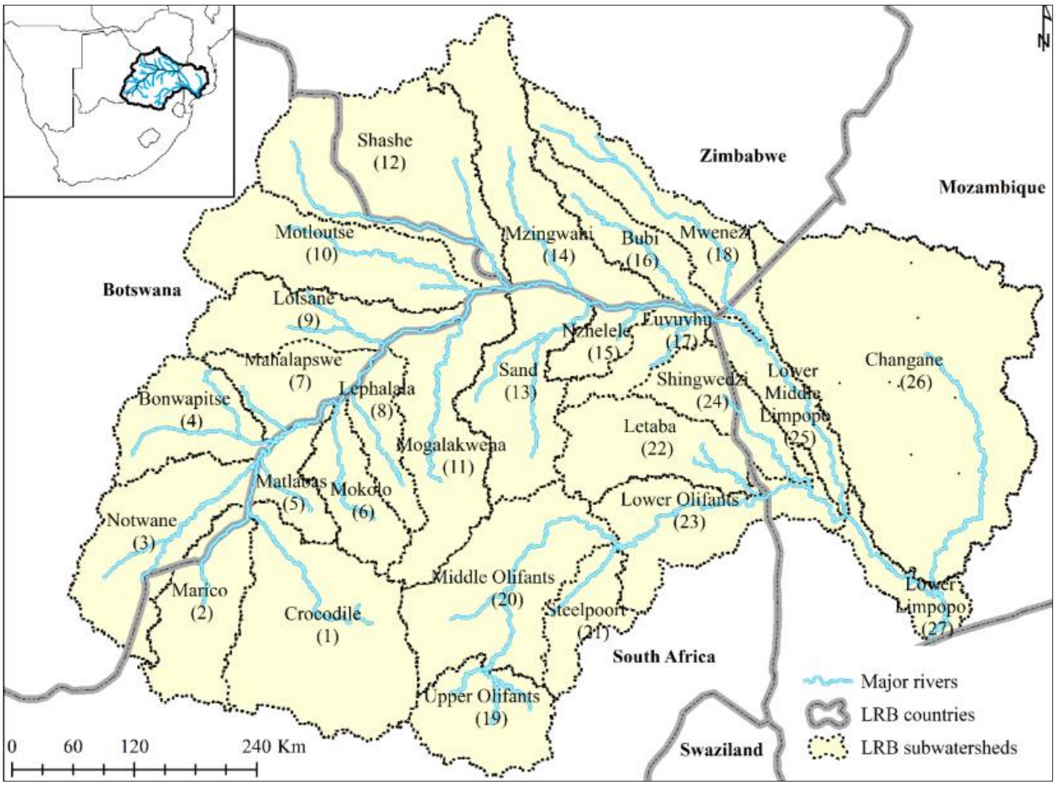

Figure 2. 1: The Limpopo River Basin in Southern Africa and its twenty-seven designated subbasins, herein referred to as watersheds.

2.2.2. Data Used

Daily rainfall, and maximum and minimum temperature gridded data for 375 locations within the LRB were extracted for a period of 35 years (January 1979 to December 2013) from the Climate Forecast System Reanalysis (CFSR) global weather database (https://globalweather.tamu.edu/). The CFSR weather data were generated by using conventional meteorological gauge observations and satellite irradiances coupled with advanced modeling of atmosphere, ocean, and land surface systems at 38 km resolution (Dile and Srinivasan 2014). Daily rainfall values were compiled into total annual rainfall time series while time series of mean annual temperature was used for the analysis. In order to maintain consistency among data sources for the analysis of precipitation and temperature variations in the basin, only CFSR data were used. Some researchers have used more than one reanalysis product to account for uncertainties associated with individual data (Nicolas and Bromwich 2011, Wang et al. 2011, Becker et al. 2013, Worqlul et al. 2017). Depending on regional elevation patterns, one product may capture more realistic variations in precipitation compared with other products (Nicolas and Bromwich 2011, Wang et al. 2011, Becker et al. 2013).

2.2.3. Assessment of Variations in Rainfall and Temperature in the Limpopo River Basin

Daily rainfall, and daily minimum and maximum air temperature records we compiled into annual and seasonal means. Seasonal datasets were obtained by aggregating daily data into monthly values, which were summed to construct four southern hemisphere seasons, consisting of summer (December-January-February), Fall/Autumn (March-April-May), winter (June-July-August), and Spring (September-October-November). Coefficients of variation (CVs) (i.e., standard deviation over the mean, expressed in %) were also computed for annual and seasonal rainfall, and maximum and minimum air temperature. The long-term mean is used in this study because it has long been utilized by hydrologists, climatologists, and producers in Southern Africa to discuss natural calamities such as famine or flood (Schulze 2011). CV has also been used frequently to characterize hydrological systems since it gives an indication of inter-annual or seasonal variability of hydroclimatic conditions of a region (Schulze 2011). Contour maps were created with the calculated means and CVs to show spatial variations of long-term annual and seasonal rainfall and temperature across the LRB.

2.2.4. Trend Analysis of Rainfall and Temperature in the Limpopo River Basin

Temporal trends in annual and seasonal rainfall, and minimum and maximum temperature were determined using the modified non-parametric Mann-Kendall test (MK; (Hamed and Rao 1998, Hamed 2008). Magnitudes of these trends were also estimated with the Theil-Sen slope estimator (TSE; (Hamed and Rao 1998, Hamed 2008). The modified MK test is commonly used in long-term hydrological trend assessment studies owning to its robustness against inherent outliers, autocorrelation, and non-normal distribution of a dataset (Hamed and Rao 1998, Hamed 2008). The test is very reliable for detecting monotonic trends in environmental time series data (Hamed and Rao 1998, Hamed 2008). For a series X1, X2, X3, … Xn, the MK test statistic (S) is calculated as (Kumar et al. 2009, Sagarika et al. 2014):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}\left(X_j - X_i\right) \tag{1}$$

where Xi and Xj represent sequential datapoints in the data, n is the length of the dataset, and

$$\operatorname{sgn}(\theta)=\begin{cases}1 & \theta > 0\\ 0 & \theta = 0\\ -1 & \theta < 0\end{cases} \tag{2}$$

where θ represents the difference between two sequential datapoints. The null hypothesis “H0” of no trend is rejected with a p-value less than the significance level or if the calculated Z-statistic is larger than the critical value of the Z-value obtained from the normal distribution table. The analysis conducted in this study used a 10% significance level. The variance of S is calculated as:

$$V(s) = \frac{n(n-1)\ (2n+5) - \sum_{i=1}^{n} t_i i(i-1)\ (2i+5)}{18} \tag{3}$$

The modified MK trend test statistic Z is given by:

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{V(S)^*}} & for\ S > 0\\ 0 & for\ S = 0\\ \dfrac{S+1}{\sqrt{V(S)^*}} & for\ S < 0\end{cases} \tag{4}$$

where the sign of S gives the direction of the trend. A negative sign indicates a decreasing trend, and a positive value indicates an increasing trend. The modified variance of S denoted by V(S)* is computed as:

$$V(S)^* = V(S)\frac{n}{n^*} \tag{5}$$

and

$$\frac{n}{n^*} = \frac{2}{n(n-1)\ (n-2)} \sum_{i=1}^{n} (n-i)\ (n-i-1)\ (n-i-2) ri \quad (6)$$

where ri is the lag-i significant autocorrelation coefficient of rank i in the time series dataset. The autocorrelation coefficient is calculated as:

$$r_k = \frac{\frac{1}{n-k} \sum_{i=1}^{n-k} (X_i - \bar{X})\ (X_{i+k} - \bar{X})}{\frac{1}{n} \sum_{i=1}^{n} (X_i - \bar{X})^2} \quad (7)$$

Since the MK statistic (S) does not indicate the magnitude of the slope, the TSE was used to compute the magnitude of trend as follows (Thiel 1950, Sen 1968)

$$\beta = median \left[\frac{X_j - X_i}{j-i} \right] for \ \mathrm{i} < \mathrm{j} \quad (8)$$

where β is the median for all possible combinations of pairs of any two datapoints in the entire time series dataset. Xi and Xj are the sequential datapoints, where i < j.

2.3. Results and Discussion

2.3.1. Long-Term Means of Rainfall and Temperature in the Limpopo River Basin

2.3.1.1. Rainfall

Mean annual rainfall over the LRB varied between a minimum of 160 mm in the west of the basin (Notwane, Lephalala, and parts of Lotsane and Motloutse watersheds) to a maximum of 1152 mm (ws 27: Lower Limpopo) in the east of the basin (Figures 2.1 and 2.2). From the 375 gridded locations analyzed for rainfall, 30% of the basin received less than 300 mm, 66% receives more than 300 mm and less than 500 mm while 4% received more than 500 mm/year. Coefficients of variation for annual rainfall calculated for the 1979–2013 period varied from 28% in Lower Limpopo (ws 27) in the east to 70% in the west of the basin. West watersheds include Notwane (ws 3), Bonwapitse (ws 4), Matlabas (ws 5), Mokolo (ws 5), Mahalapswe (ws 7), and Lephalala (ws 8) (Figures 2.1 and 2.3). High CVs were found in the western watersheds, including watersheds in Botswana and southwest of South Africa, classified as a semi-arid region compared to the temperate east part of the basin that includes the east of South Africa and Mozambique (Figure 2.3).

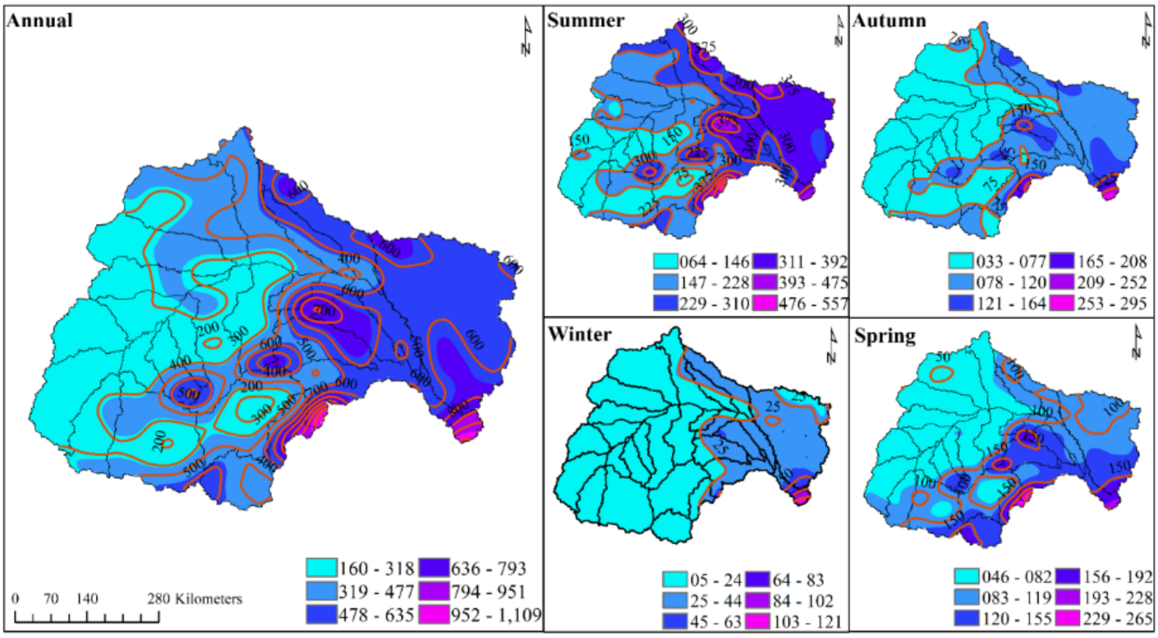

Figure 2. 2: Mean annual and seasonal rainfall from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as Summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

Seasonal analysis showed that most of the basin's rainfall occurred in summer during the 35-year study period (Figure 2.2), with a range of 64 to 557 mm from west (ws 3–8) to east (ws 21: Steelpoort), while minimal rainfall occurred in winter, ranging from five mm in 15 of the watersheds in the west to 120 mm in Lower Limpopo (ws 27) in the east of the basin (Figures 2.1 and 2.2). Autumn and spring rainfall ranged between 33 and 295 mm, and between 46 and 265 mm, respectively (Figure 2.2). The CV values for the seasons revealed high variability comparable to annual CVs, especially for summer and spring seasons whose CVs ranged between 40% and 38% in the east of the basin, and 94 and 82% in the west, respectively (Figure 2.3). Autumn and winter CVs for the east are 44% and 37% (Figure 2.3), comparable to the annual CV values in the same region (east). Calculated CV values are very high in the west of the basin (128% and 221%, respectively) compared to annual CVs in the west. It appears, based on these results, that there was a high variability in autumn and winter rainfall in the west of the basin compared to the temperate east of the basin (Figure 2.3).

Other researchers also reported these east to west and north to south decreasing patterns in rainfall in the Southern Africa region, including the LRB (Schulze et al. 2001, Wamukonya et al. 2007, Jury 2016). Low rainfall in the west of the basin is likely the result of being far from rain forming processes such as the Inter-Tropical Convergence Zone (ITCZ) and southwest Indian Ocean cyclone that control the frequency and duration of incident rainfall events in the northern and eastern parts of the basin (Wamukonya et al. 2007). Migration of ITCZ to south of the equator during the Southern Hemisphere summer leads to abundant rainfall in areas north of the LRB (Figure 2.2) compared to the southern and western parts of the basin (Chigwada 2004, Wamukonya et al. 2007). Low rainfall in the west of the basin in summer is exacerbated by the presence of a seasonal subtropical anticyclone, usually at 700 hPa, known as the Botswana Upper High Influence (BUHI) (Reason and Smart 2015). This influential atmospheric mechanism creates unfavourable conditions for rainfall by diverting the migration of rain-bearing ITCZ out of the region (Chigwada 2004). Although the south of the basin receives low rainfall amounts (Figure 2.2), pockets of high rainfall can be observed around the Drakensberg escarpment in South Africa due to orographic effects (Boko et al. 2007). Orographic effects induce rainfall by forcing moist air to cool rapidly when passing over areas of high relief (e.g., Drakensberg mountains), causing moisture to precipitate in the form of rainfall on the windward side of the relief (Chen and Lin 2005). Winter rainfall in the east is mostly produced by cold fronts and associated tropical cyclones (Blamey and Reason 2007, Philippon et al. 2012). The highly variable rainfall events in Southern Africa as depicted in the LRB can be attributed to the ENSO phenomenon, which strongly influences the south eastern parts of the region where the LRB is located (Richard et al. 2001).

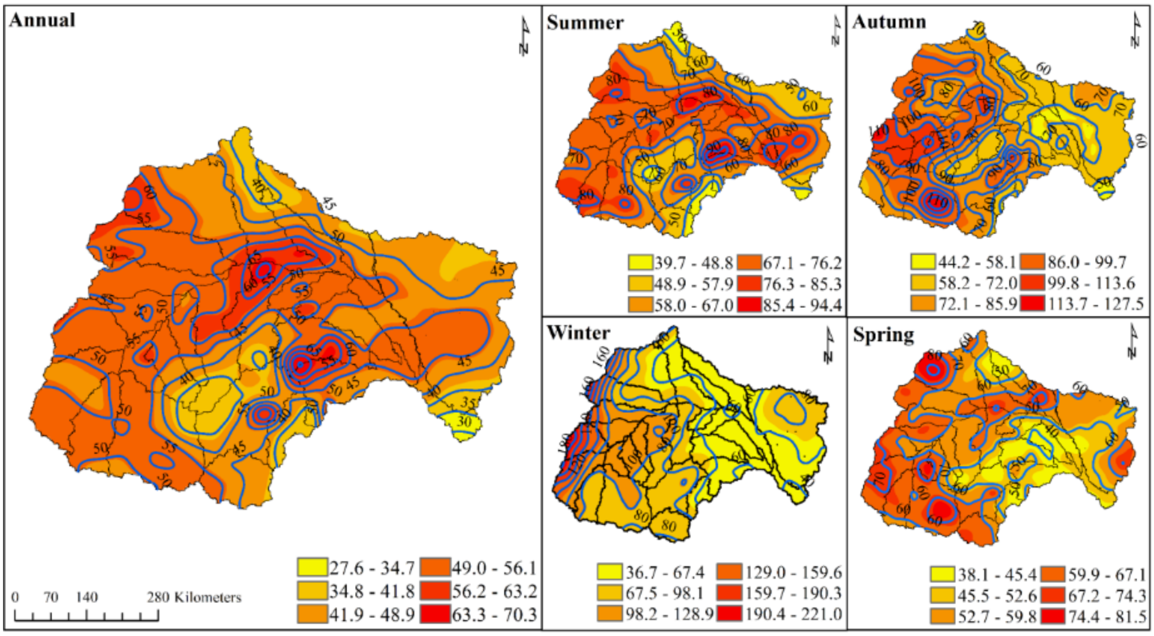

Figure 2. 3: Annual and seasonal CVs for rainfall from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

2.3.1.2. Minimum and Maximum Temperature

Mean annual minimum and maximum temperature showed similar patterns to those of annual rainfall, increasing gradually from west to east and from south to north of the basin (Figures 2.4 and 2.5). Mean annual minimum temperature ranged from 8 °C in the south of the basin (Crocodile (ws 1), Upper Olifants (ws 19), Middle Olifants (ws 20), Steelpoort (ws 21) watersheds) to 20 °C in the east (Lower Middle Limpopo (ws 25), Changane (ws 26), and Lower Limpopo (ws 27)) (Figures 2.1 and 2.4). Mean annual maximum temperature ranged from 23 to 32 °C for the entire basin, increasing from south to east of the basin. Low temperatures in the south and west of the basin, including South Africa, may be attributed to oceanic and elevated altitude influences. The cold upwelling current from the Atlantic Ocean known as the Benguela system brings cold waters to the west coast of the region, which in turn contribute to lowering temperatures in the west (Reason 2017). As expected, high elevation areas of the basin become colder than other regions (Figures 2.4 and 2.5). Coefficients of variation for both annual minimum and maximum temperature ranged from 2% to 10%, and 3% to 6%, respectively during the study period (Figures 2.6 and 2.7). This is indicative of a relatively minimal variability in temperature during the study period (i.e., 1979–2013) (Figures 2.4 and 2.5). This is expected as temperature generally varies less than rainfall (Figures 2.4 and 2.5).

Seasonal analysis showed that summer minimum temperature was higher than the minimum temperature of all other seasons, with a range of 12 °C in the south and some pockets in middle of the basin to 23% in the east of the basin (Figure 2.4). Spring minimum temperature ranged from 9.4 °C to 20 °C, followed by autumn with a range of 7.3 to 20 °C and winter ranging from 1.9 to 16.1 °C.

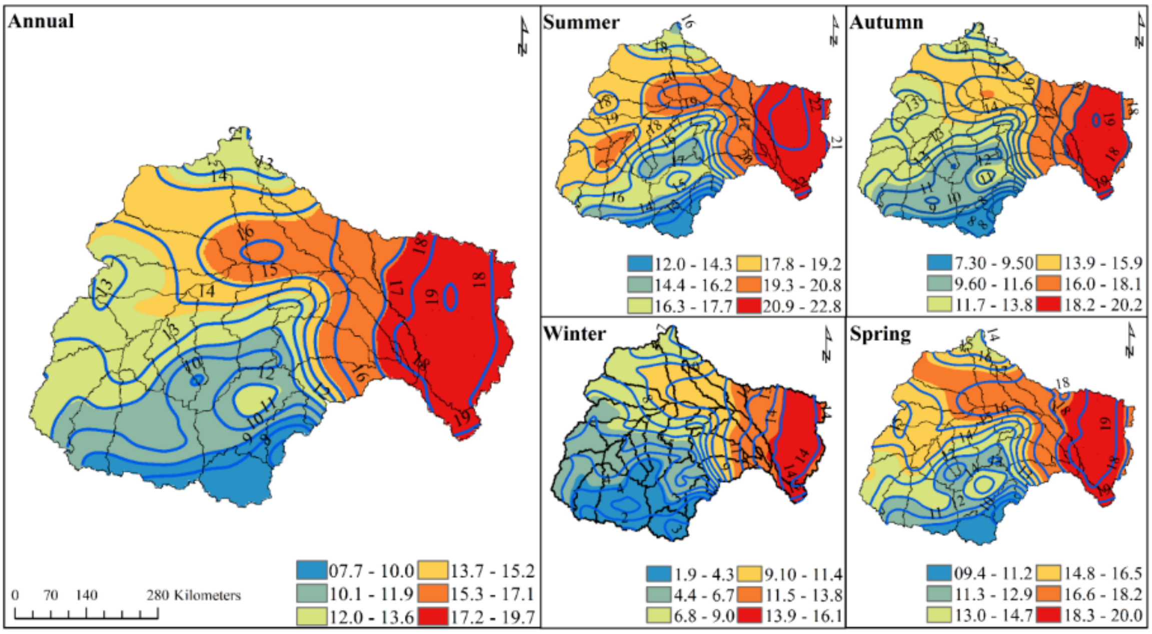

Figure 2. 4: Mean annual and seasonal minimum temperature from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as Summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

Spatial variations in minimum temperature are similar to annual minimum temperature variations (Figure 2.6). In all four seasons, high variability in temperature (i.e., high CV) was observed in the south and southwest of the basin (Figures 2.6) compared to the east of the basin. Less variability in minimum temperature is observed in the summer season (2.2%–6.1%), followed by spring (2.3%–8.3%), and Autumn (2.5%–14.6%), while more variability is experienced in winter, with CVs of 3.5% in the north and east of the basin and over 50% in the south and west of the basin (Figure 2.6).

Seasonal maximum temperature followed the pattern of annual maximum temperature during the study period (Figure 2.5), with summer, autumn, winter and spring seasons' maximum temperature ranging from 25 to 35 °C, 22 to 31 °C, 18 to 28 °C, and 24 to 34 °C, respectively (Figure 2.5). As expected, maximum temperature in summer was the highest, followed by spring, autumn and winter; seasonal variability of maximum temperature is fairly comparable for all the seasons compared to minimum temperatures (Figures 2.6 and 2.7). Unlike minimum temperature, less variation in maximum temperature was detected in middle and east of the basin in summer and winter seasons (Figures 2.1 and 2.7). Less variability is also observed in maximum temperature in the west and northeast of the basin, mostly in spring (Figures 2.1 and 2.7). In autumn, pockets of minimal variability are observable only in the middle of the basin, along the Limpopo River (Figure 2.7).

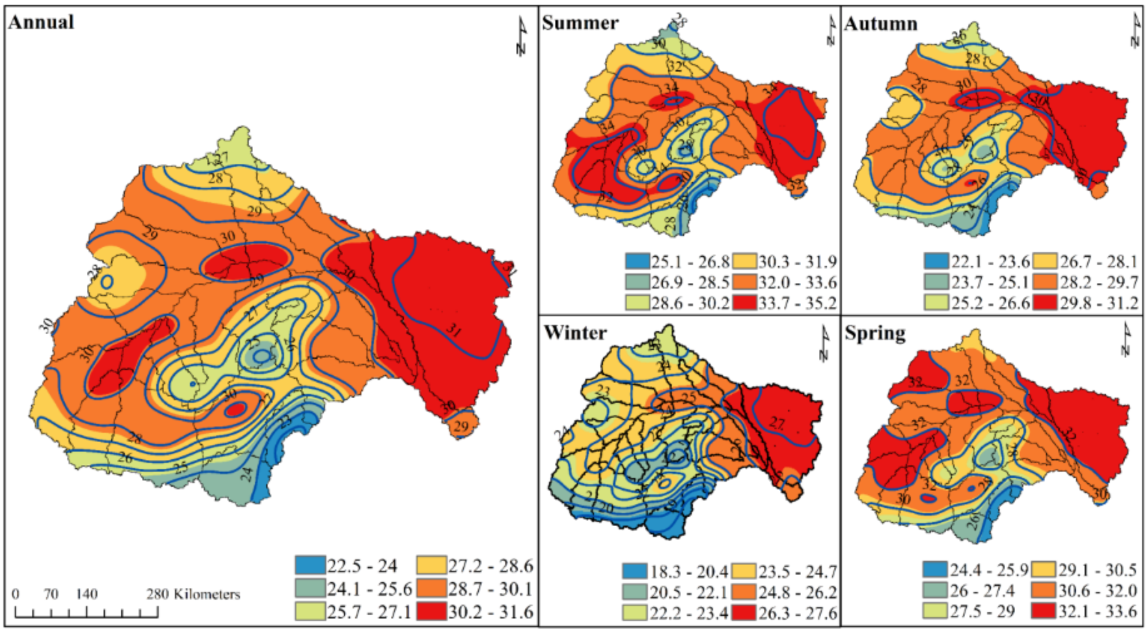

Figure 2. 5: Mean annual and seasonal maximum temperature from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

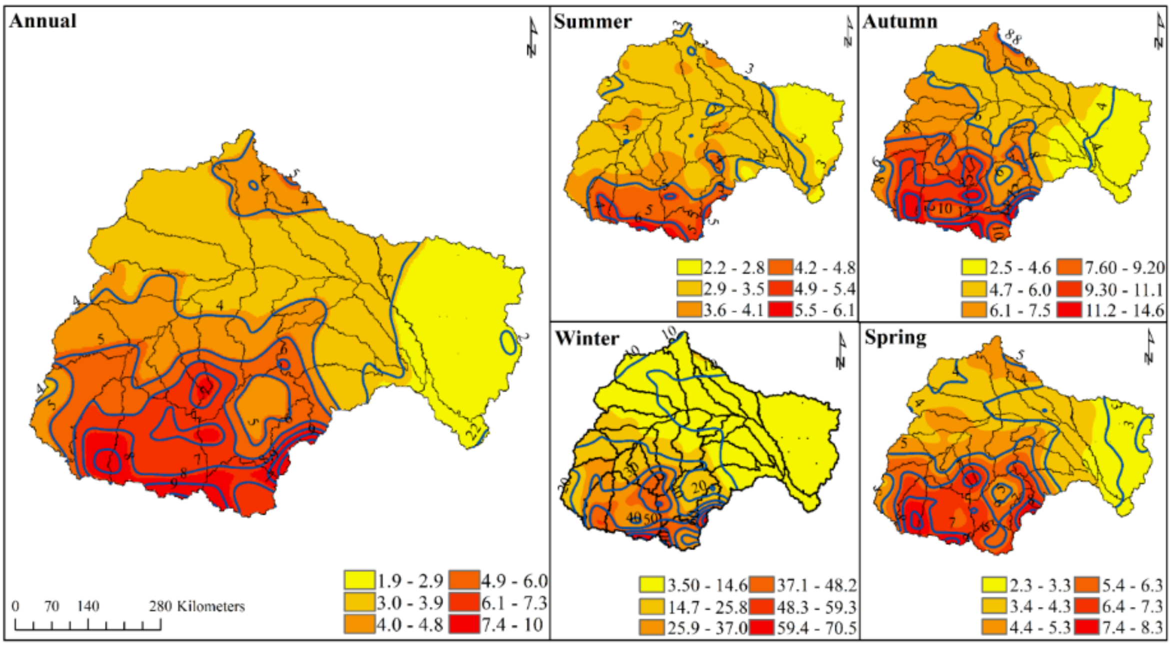

Figure 2. 6: Annual and seasonal CVs for minimum temperature from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

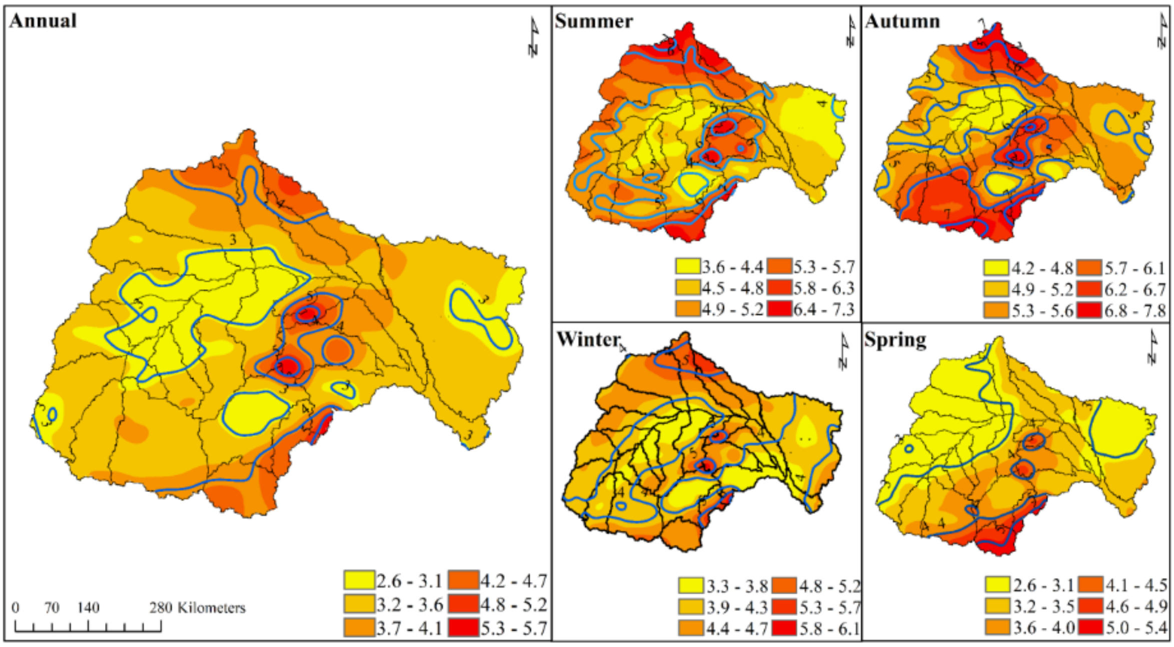

Figure 2. 7: Annual and seasonal CVs for maximum temperature from 1979 to 2013 in the Limpopo River Basin. Southern hemisphere seasons are defined as summer (December-January-February), Autumn (March-April-May), Winter (June-July-August), and Spring (September-October-November).

Spatial variations observed in both minimum and maximum temperature on annual and seasonal time steps in the basin were consistent with observations made by other researchers for the Southern Africa region, inclusive of the LRB (Kruger and Shongwe 2004, Collins 2011, MacKellar et al. 2014). Overall, annual and seasonal rainfall over the study period showed decreasing trends, spanning from east to west of the basin, while minimum and maximum temperatures decreased from south to west and north to east during the study period. The observed patterns in inter-annual rainfall are highly variable throughout the basin across seasons, especially in the west, adding to the complexity of managing water resources in the LRB where events such as floods and droughts are prevalent.

2.3.2. Trends and Trend Magnitudes of Rainfall and Temperature in the Limpopo River Basin

2.3.2.1. Rainfall

Annual rainfall exhibited increasing trends between 1979 and 2013 in most of the watersheds within the LRB, except in three watersheds in the south of the basin (the whole of ws 19: Upper Olifants watershed and a few areas in ws 1 and ws 2 (Crocodile and Marico watersheds)) (see Figures 2.1 and 2.8). Of the 375 gridded locations analyzed for the entire basin, 361 (96%) showed overall increasing trends with 73% being statistically significant. The remaining 14 locations (4%) showed a slightly decreasing trend (Figure 2.8). Magnitudes of upward trends in annual rainfall ranged from 0.02 mm to 0.46 mm during the study period for the whole of the LRB. Downward trends observed in a few locations in the south of the basin varied from a minimum of −0.11 mm in the Upper Olifants (ws 19) to a maximum of −0.003 mm in the Crocodile (ws 1) watersheds (Figures 2.1 and 2.8). Although most studies report no trend in annual rainfall for Southern Africa (including the LRB) prior to 1970, statistically significant increased trends in rainfall events after the year 1970 have been reported in different parts of the region (Kruger 2006, Boko et al. 2007, Matthews et al. 2007). These reports are consistent with the results found in the present study which analysed data from 1979 to 2013. Analysis of future climate scenarios also indicated that there is a slight increasing trend in annual rainfall for western Zimbabwe, Botswana, and Namibia (Schulze et al. 2001).

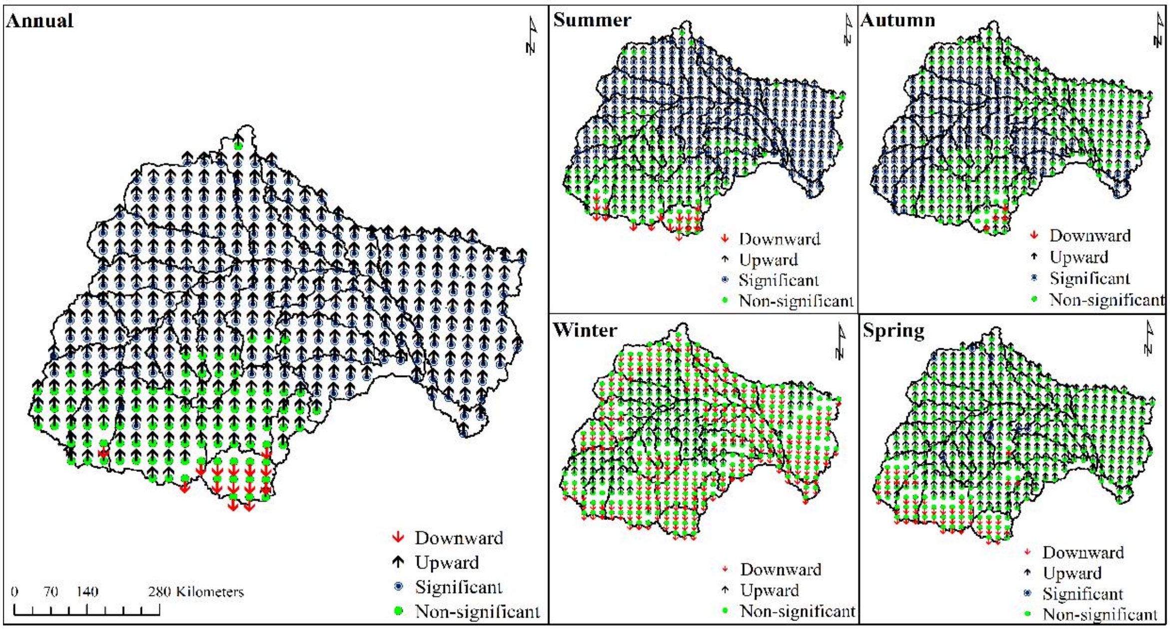

Figure 2. 8: Trends in annual and seasonal rainfall in the Limpopo River Basin.

2.3.2.2. Minimum Temperature

All of the 375 gridded locations examined in the basin showed increasing trends in annual minimum temperature (Figure 2.9). Of the 375 gridded locations, 105 (28%) locations had statistically significant upward trends (ws 3–7 and ws 20–23), while the increasing trends were not statistically significant for the other 270 points (72%) (ws 1, 8–19, 20 and 26) (Figure 2.9). The magnitude of trends in annual minimum temperature ranged from 0.003 to 0.52 °C for the 35-year study period. Among the four seasons, winter showed the highest number of gridded locations for minimum mean temperature (66 points or 18%) with statistically significant increasing trends, followed by spring (61; 16%), summer (22; 6%), and autumn (8; 2%) (Figure 2.9). The spring season also showed many locations with statistically significant and non-significant increasing trends, except for three gridded locations in the south of the basin (0.8%) out of 375, which exhibited a decreasing trend (ws 1: Crocodile) (Figure 2.9). Summer and autumn seasons showed approximately 158 (42%) and 160 (43%) locations with downward trends (Figure 2.9). Magnitudes of trends in minimum temperature for the winter season ranged between 0.003 and 0.37 °C. This is comparable to the magnitudes of annual minimum temperature trends which ranged between 0.003 and 0.52 °C during the study period. The magnitudes of the summer, autumn, and spring trends varied between −0.2 and 0.35 °C, −0.19 and 0.29 °C, and −0.05 and 0.41 °C, respectively.

These results are consistent with other studies conducted for the Southern African region (e.g., (Schulze et al. 2001, Matthews et al. 2007, Jury 2013)), where seasonal and annual minimum temperatures were shown to increase in the region (Solomon et al. 2007). Beside the heavily forested eastern part of the basin that revealed statistically significant increasing trends in minimum temperature, there is no distinct pattern in statistically significant or non-significant trends for the remainder of the basin (Figure 2. 9).

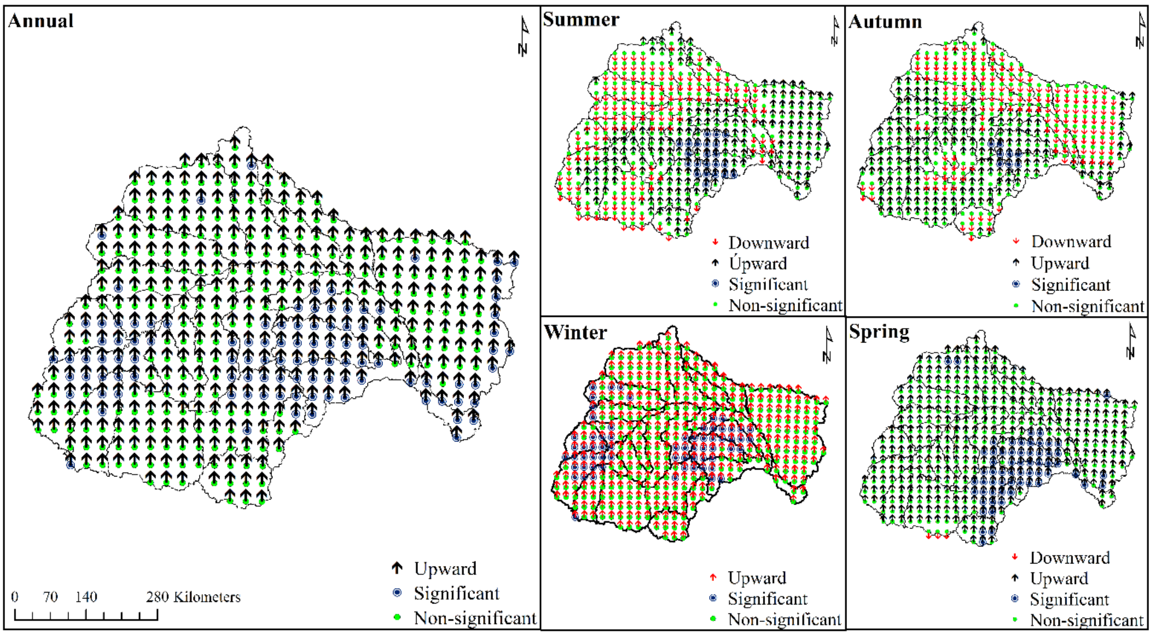

Figure 2. 9: Trends in annual and seasonal minimum temperature in the Limpopo River Basin.

2.3.2.3. *Maximum Temperature*

A total of 36% (136) of the gridded locations analyzed for annual maximum temperature showed increasing trends, extending from the middle to the south of the basin during the study period (Figure 2.10). The basin watersheds with increasing trends include Crocodile (ws 1), Matlabas (ws 5), Mokolo (ws 6), Lephalala (ws 8), Mogalakwena (ws 11), Upper and Lower Olifants (ws 19 and ws 20) (Figures 2.1 and 2.10). A total of 64% (236) of the locations in the basin showed a decreasing trend during the 1979–2013 study period (Figures 2.1 and 2.10). Only 7% of the gridded locations had statistically significant increasing annual trends (Figure 2.10). Magnitudes of increasing trends for annual maximum temperature ranged from 0.003 to 0.39 °C, while decreasing trends ranged from −0.2 °C to −0.003 °C. Trends of annual maximum temperature found in this study coincide with the published literature for the Southern African region where mixed increasing or decreasing trends were reported (Kruger 2006, Solomon et al. 2007, Collins 2011). Maximum temperature for summer and autumn seasons revealed similar patterns to annual maximum temperature trends during the study period, where most of the northern watersheds of the basin exhibited a decreasing trend versus an increasing trend in the south (Figures 2.1 and 2.10). Summer appears to have more temperature measurement locations with statistically significant decreasing trends compared to other seasons (Figure 2.10). Winter and spring maximum temperature showed many of the gridded locations with upward trends, except at very few locations (less than 10 locations) in the south. The spring season also had many locations with statistically significant increasing trends compared to the winter maximum temperature (Figure 2.10). Magnitudes of increasing trends (for both statistically significant and non-significant) in maximum temperature varied between 0.005 and 0.27 °C, 0.03 and 0.21 °C, 0.03

and 0.33 °C, and 0.02 and 0.44 °C for summer, autumn, winter, and spring, respectively. Decreasing trend magnitudes ranged from −0.031 to −0.005 °C, −0.29 to −0.00032 °C, −0.005 to 0.0032 °C for summer, autumn, and winter, maximum temperature, while spring had only one temperature observation location out of the 375 with a decreasing magnitude of −0.002 °C.

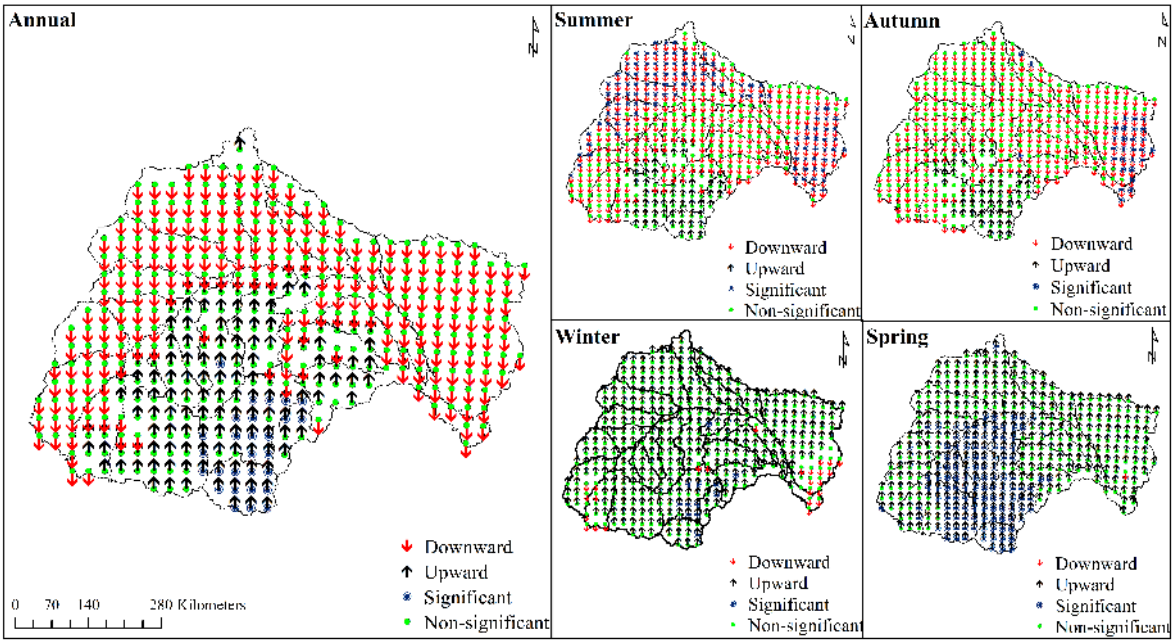

Figure 2. 10: Trends in annual and seasonal maximum temperature in the Limpopo River Basin.

A comparison between the overall minimum and maximum temperature trends revealed an increasing trend for minimum temperature and a decreasing trend for maximum temperature for most of the basin (Figures 2.9 and 2.10), suggesting that the diurnal range between minimum and maximum temperature decreased over time. Similar increasing and decreasing trends in respective minimum and maximum temperature in the region have been by other researchers (Zheng et al. 1997).

In general, rainfall, although increasing, was highly variable in the basin. Other researchers reported decreases in annual rainfall in some parts of the basin (Love et al. 2010). The increasing rainfall trends in this study are generally consistent with a number of studies carried out for the Southern African region (e.g., (Tadross et al. 2005, Schulze et al. 2010). Research also reported no changes in average rainfall events (Mazvimavi 2008), especially in the Zimbabwean part of the basin. The differences in results may be attributable to differences in time frames of the studies. For example, Mazvimavi (2008) (Mazvimavi 2008) used time series data that spanned from 1892 to 2000, and Love’s (2009) (Love et al. 2010) study covered a period of 1930 to 2004. This study used data from 1979 to 2013.

While increasing trends in rainfall will likely result in augmentation of water in the basin, demands from population growth and associated activities in the basin are also increasing, putting constant pressure on water resources (Boko et al. 2007). The highly variable rainfall is not reliable for rainfed agriculture, which is a common practice in the LRB. The analysis shows increasing trends in minimum temperature for the LRB. Not only does this influence ET processes in the basin, but it also has considerable implications for water availability. Increased temperature leads to increased ET, which in turn results in increased irrigation demands in water-scarce areas such as the LRB. While maximum temperature showed non-significant downward trends, minimum temperature showed statistically significant increasing trends in most of the basin, suggesting an overall average temperature increase in the basin. As mentioned above, this would eventually affect ET processes with implications for soil water and streamflow changes (Munro et al. 1998, Seneviratne et al. 2010, Lu et al. 2011).

2.4. Summary and Conclusions

Rainfall, minimum temperature, and maximum temperature were analyzed for annual and seasonal means, variability, and trends in the LRB from 1979 to 2013.

- Annual and seasonal rainfall means were found to decrease from east to west with a range of 1109 mm for watersheds in Mozambique to 160 mm for those in Botswana. Annual and seasonal CV values are high in the west and lowest in the east, indicating high variability in the west compared to the east of the basin. Annual, summer, autumn and spring rainfall showed increasing trends while winter rainfall showed decreasing trends in most locations of the basin, with increasing magnitudes of 0.001 to 0.46 mm, and −0.2 to −0.0003 mm for decreasing trends.

- Minimum annual and seasonal temperature means gradually increased from west to east and from south to north of the basin, ranging from 1.9 in winter to 22.8 °C in summer. Annual and seasonal CV decreased from south to north and was lowest in the east. Annual, winter and spring minimum temperature increased in almost all areas of the basin while summer and autumn had mixed trends. The magnitudes of trends ranged from −0.2 to 0.41 °C across seasons.
- Annual and seasonal means of maximum temperature are lowest in the south and highest in east of the basin, with a range of 18.3 to 35.2 °C. The CVs for annual and seasonal maximum temperature are lowest in the middle of the basin and highest in the south and north. Decreasing maximum temperatures are observed in the northern parts of the basin on an annual, summer and autumn basis, while winter and spring seasons show increasing trends in the basin. The magnitudes of these trends range between −0.29 and 0.39 °C.

Increasing trends in rainfall suggest increased available water in the basin; however, population increase, changes in land use, and intensification of agriculture activities continue to put pressure on water resources in the basin. The high CV values for annual and seasonal rainfall substantiate the highly variable nature of rainfall with the potential to contribute to unpredicted flooding and drought in the region. The trends detected in temperature, especially increasing trends in minimum temperature, are also important for regional energy and water balances.

Water practitioners and policy makers must take these into account when developing flood and drought mitigation strategies and measures. Adoption of sustainable practices to bring changes in management, water technology and infrastructure, and raising awareness would be useful to develop resiliency against water risks in the basin. While this study analyzed climatic variations in the LRB, it did not explicitly include the impacts that these changes in climate would have on water resources (e.g., streamflow, soil moisture). Contingent on data availability, studies of land use change, land management activities, climate variability, and climate change impacts on water resources would provide further insight into the subsequent ecosystem and hydrological responses in the basin.

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3. SPATIAL AND TEMPORAL DISTRIBUTION OF BLUE AND GREEN WATER AVAILABILITY IN THE LIMPOPO RIVER BASIN, SOUTHERN AFRICA

Abstract

Water is vital for human survival and ecosystem health. In arid and semi-arid areas like the Limpopo River Basin (LRB) in Southern Africa, demand for water is as critical as other parts of the world. The study of spatial and temporal distribution of different components of freshwater such as blue and green water availability in a watershed is an important step toward sustainable planning and management of water resources. This study applied the Soil and Water Assessment Tool (SWAT) to characterize blue water (i.e. water yield and deep aquifer recharge) and green water (i.e. actual evapotranspiration and soil moisture) in the regional LRB. This study determined also water risk areas in the basin. SWAT predictions of freshwater components in the basin are generally good when compared to known streamflow records, although uncertainties persist in model estimates. Estimates of blue water varied from 1 to 570 mm/year, from 170 to 1,500 mm/year for green water flow, and from 5 to 100 mm/year for green water storage in the basin between 2000 and 2013. The simulated freshwater components revealed alternating episodes of wet and dry years during the study period. 20% of the basin (mostly east) appears to have excess freshwater, while the remaining 80% seems dry and under water stress.

3.1. Introduction

Global water resources are increasingly experiencing pressure due to rising demands from a range of social and economic driving forces. The problem of adequate freshwater supply to support agriculture, industry, and domestic use in semi-arid regions such as the LRB, is of paramount importance. The LRB encompasses four countries- Botswana, Mozambique, South Africa, and Zimbabwe- with various needs and challenges which are exacerbated by climate variability, frequent extreme seasonality, and intense El Niño-Southern Oscillation (ENSO) events (Schulze et al. 2001, Kandji et al. 2006). These ENSO events are often linked to intense drought and flood events (WMO 1984, Glantz et al. 1997, Kandji et al. 2006, WMO 2012).

Population dynamics, urbanization, industrial development, and increasing agricultural activities in the face of a changing climate continue to add pressure on surface and groundwater resources in the basin (van der Zaag et al. 2010, Bawden et al. 2014). In their efforts to alleviate water availability issues, the four countries have invested billions of dollars in construction of dams and reservoirs; however, these reservoirs often fall short to meet freshwater demands and expectations (FAO 2004, Owen 2013).

Freshwater with its two components- blue and green- plays a major role in sustaining life on earth (Schuol et al. 2008). Blue water refers to the sum of surface runoff and deep aquifer recharge, and green water is the soil moisture from precipitation (green water storage) and the water that contributes to actual evapotranspiration (green water flow) (Falkenmark and Rockström 2006, Schuol et al. 2008, Faramarzi et al. 2009, Zuo et al. 2015).

With recent advancements in computer modeling, studies have been conducted to quantify freshwater components in the southern Africa region (Vorosmarty 2000, Döll et al. 2003, Alcamo et al. 2007, Schuol et al. 2008). However, qualitative information on water risk areas in the LRB is not well document. The contribution of this study is to document LRB-wide spatial and temporal distribution of freshwater components to determine physical surface water risk areas in recent years using simulation modeling. Water risk or sensitive area is defined in this study as an area that has excess surface water (i.e. too wet) or is under stress (i.e. too dry), consequently susceptible to flooding and drought, respectively. The specific objectives are to (1) build a LRB-scale SWAT model; (2) assess the spatial and temporal distribution of blue and green water; and (3) determine physical water risk areas in the LRB.

3.2. Materials and methods

3.2.1. Study Area

The LRB is one of the largest drainage areas in Southern Africa, approximately 412,000 km^2. 20%, 20%, 45%, and 15% of the basin area drains portions of Botswana, Mozambique, South Africa, and Zimbabwe, respectively (Mohamed 2014, Trambauer et al. 2014). The LRB is located at -250 to 2,300 m above mean sea level (USGS 2004). Limpopo River is the main channel of the basin; it stretches over 1,770 km, starting in South Africa and flowing north where it creates the South Africa-Botswana border, then east to form the South Africa-Zimbabwe border, and Southeast through Mozambique before ending in the Indian Ocean (Fig. 1a). The LRB is the second most populated basin in the Southern African Development Community (SADC) region after Orange River Basin which has more than 19 million people (Earle et al. 2005). The LRB is home to nearly 17 million people, consisting of 69%, 22%, 10%, and 7% of Botswana, South Africa, Zimbabwe, and Mozambique's population, respectively (Mohamed 2014). The LRB's population is projected to be 23 million by 2040 (LBPTC 2010). The basin has 27 documented subbasins, which are referred to as major watersheds in this study (Figure. 3.1b; see Table 3.1).

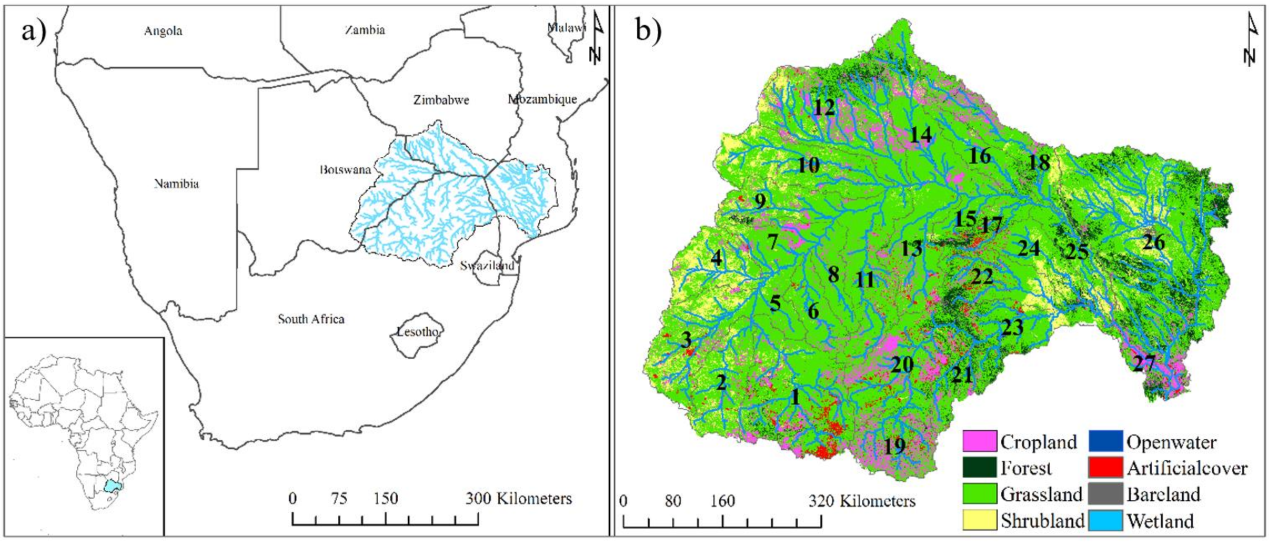


Figure 3. 1: a) Location of the Limpopo River Basin; and b) Major watersheds and land use types based on 2010 globland30 land use database (Geomatics Center of China, 2010)

Table 3. 1: Major watersheds of the Limpopo River Basin and associated drainage areas and locations

Notation	Watershed Name	Area (km^2)	% of the Basin	Location
ws1	Crocodile	29696	7	South Africa
ws2	Marico	13291	3	South Africa, Botswana
ws3	Notwane	18137	4	Botswana, South Africa
ws4	Bonwapitse	11975	3	Botswana
ws5	Matlabas	5666	1	South Africa
ws6	Mokolo	8333	2	South Africa
ws7	Mahalapswe	8693	2	Botswana
ws8	Lephalala	6774	2	South Africa
ws9	Lotsane	12599	3	Botswana
ws10	Motloutse	19596	5	Botswana
ws11	Mogalakwena	19196	5	South Africa
ws12	Shashe	29612	7	Botswana, Zimbabwe
ws13	Sand	15729	4	South Africa
ws14	Mzingwani	20747	5	Zimbabwe
ws15	Nzhelele	4246	1	South Africa
ws16	Bubi	8640	2	Zimbabwe
ws17	Luvuvhu	5603	1	South Africa
ws18	Mwenezi	14995	4	Zimbabwe
ws19	Upper Olifants	11629	3	South Africa
ws20	Middle Olifants	23149	6	South Africa
ws21	Steelpoort	6896	2	South Africa
ws22	Letaba	13861	3	South Africa
ws23	Lower Olifants	15773	4	South Africa, Mozambique
ws24	Shingwedzi	9309	2	South Africa, Mozambique
ws25	Lower Middle Limpopo	7980	2	Mozambique
ws26	Changane	64039	16	Mozambique
ws27	Lower Limpopo	5757	1	Mozambique

Land use in the basin consists of 72% grassland of the total drainage area, 10% cropland, 10% shrub land, and 8% of other land uses which consist of urban areas, open water, and wetlands (Fig. 2). Irrigation is the largest water user in the four LRB countries, with an estimated total water demand of 4,700 million m^3, of which 62% can be allocated to South Africa, 30% to Zimbabwe, 6% to Mozambique, and 2% to Botswana (Mohamed, 2014). The tributaries of the Limpopo main channel support commercial and subsistence agriculture.

Climate in the LRB varies from arid in west to semi-arid and temperate in east of the basin, with a few sub-humid pockets toward the center of the basin. Rainfall is seasonal and erratic, causing frequent droughts and heavy flood events. The LRB's rainfall ranges from 200 in the west to 1,200 mm/year in the east, with an average of 530 mm/year over the basin (WMO 2012, Trambauer et al. 2014). More than 95% of rainfall occurs between October and April (summer months), with January and February being the peak rainfall months. Air temperature across the basin also fluctuates per season, with high temperatures during December-February, and low temperatures during June, July, and August (which are winter months). Average daily temperature during winter can fall below 0 ^{o}C in high altitude areas such as the Drakensberg Mountains, located southeast of the basin (Mohamed 2014). Maximum daily temperature can approximate 34^{o}C across the middle of the basin (Mohamed 2014).

Soils in the LRB consist of moderately deep sandy to sandy-clay loam. A large portion of LRB, mainly the western part, is covered by deep layers of wind-blown Kalahari sand. Soils in the eastern portion (i.e. Mozambique's side) are sandy soils favourable to hardwood timber production. Hilly and sloping areas of the basin have stony soils with little potential for agricultural production (Ashton et al. 2001).

3.2.2. Hydrological model

This study used SWAT, a widely used watershed-scale and process-based hydrological model (Arnold et al., 1998; Srinivasan et al., 1998; Gassman et al., 2007), developed for simulating the long-term impacts of land management practices and climate on hydrologic and water quality conditions of a watershed (Nietsch et al. 2005). The SWAT uses information related to soil, land use, and slope to delineate a watershed into subwatershed, which is further subdivided into hydrological response units (HRU), the smallest modelling unit with a homogeneous area of aggregated land use, soil, and slope. SWAT has been utilized worldwide for watershed modeling in more than 2,500 peer-reviewed studies (Gassman et al., 2007; https://www.card.iastate.edu/swat_articles/). Like any other technology tools, SWAT is constantly evolving for improvement to realistically improve representation of landscape characteristics (e.g. (Arnold et al. 2010, Rathjens et al. 2015, Sun et al. 2016).

3.2.3. Data Used

Input data required to build a SWAT model are meteorological, elevation, soil, and land use data as shown in Table 3.2. Daily meteorological data for the LRB used were Climate Forecast System Reanalysis (CFSR) global weather data for a period of 35 years (January 1, 1979- July 31, 2014). The dataset consists of gridded rainfall, maximum and minimum temperature, wind speed, relative humidity, and solar radiation (Dile and Srinivasan, 2014). The gridded datasets were extracted for 371 locations that fall within the LRB's boundary.

30 m digital elevation model (DEM) was utilized in delineation of the basin. Soil data were used for the definition of HRUs in SWAT. The soil data have information on soil physico-chemical properties such as texture, available water content, hydraulic conductivity, bulk density, and organic carbon content for different layers of each soil type, which are required by the SWAT model. Land cover map used in this study was 2010 land use data extracted as a global map of high-resolution imagery. Landscan population data were used to estimate the total number of people living in the basin between 2000 and 2013 using spatial statistics in ArcGIS.

Table 3. 2: Sources of data sources used for the Limpopo River Basin SWAT

Data Type	Resolution	Sources
Climate	38 m	Texas A&M University Spatial Sciences website: https://globalweather.tamu.edu/
Digital Elevation Model (DEM)	30 m	Shuttle Radar Topography Mission (SRTM): http://earthexplorer.usgs.gov/
Landcover	30 m	National Geomatics Centre of China (NGCC): www.globeland30.org
Soil		WaterBase website: http://www.waterbase.org/download.html/
Landscan (Population)	1 km	Oak Ridge National Laboratory website: http://www.ornl.gov/landscan/

3.2.4. Model set-up, multi-location calibration and validation

Various steps including watershed delineation, HRU definition, parameter sensitivity analysis, and calibration were followed to setup SWAT for the LRB. ArcSWAT Version 2012.10_2 was used to perform all terrain preprocessing and watershed delineation for the study basin. Subbasin parameters including slope gradient, slope length, and stream network characteristics (i.e. channel slope, length, and width) were derived from the DEM. The LRB was discretized into 871 subbasins, and 13,059 HRUs were created based on land use, soil type, and slope characteristics. The original SWAT soil database was modified by appending additional soil characteristics to include the study basin since the original SWAT database does not have soil information of the LRB at the time of this study.

Due to measured streamflow data availability and accessibility issues in the basin, different time periods were used for streamflow calibration and validation of the LRB model (see section 2.3). Monthly streamflow datasets at five locations within the basin were used to calibrate and validate the model as shown in Table 3.3. Only streamflow gauge stations with continuous daily data, not considerably affected by water withdrawal and retention, were selected for the LRB model calibration and validation (Table 3.3). Five years, from January 1979 to December 1983, were used as a warm up period.

Table 3. 3: Streamflow gauge stations used for SWAT calibration and validation

Station Name	Station No.	SWAT Delineated Subwatershed No.	Calibration Period	Validation Period
Beitbridge	A7H004	207	1995-2004 (10 years)	2005-2009 (05 years)
Chibase	AH9003	329	1995-2004 (10 years)	2005-2013 (09 years)
Combomune	1896502	534	1986-1988 (03 years)	1989-1991 (03 years)
Scheerpoort	A2H013	853	1995-2004 (10 years)	2005-2012 (07 years)
Rondebosch	B1H012	861	1995-2004 (10 years)	2005-2013 (10 years)

Sequential Uncertainty Fitting (SUFI-2) algorithm of the SWAT Calibration Uncertainty Procedures (SWAT-CUP) software (Abbaspour, 2015) was used for the LRB model calibration. This software combines parameter calibration and uncertainty predictions and allows for multi-location calibration in large watersheds (Abbaspour, 2015). The SUFI-2 starts with large, physically meaningful parameter ranges and converges to acceptable ranges of parameters to bracket the observed data within 95% prediction uncertainty (95PPU) (Abbaspour, 2015). For this study, the same set of 10 parameters (see

Table 3.4) was selected based on parameter sensitivity analysis for all five streamflow calibration locations.

Table 3. 4: List of parameters used for multi-location calibration and validation of the Limpopo River Basin model

Method	Parameter Name	Definition	Parameter Value		
			Min.	Max.	Best Par
r	CN2.mgt	SCS runoff curve number for moisture condition II	-0.2	0.2	0.04
v	ALPHA_BF.gw	Base flow alpha factor (days)	0	1	0.14
a	GW_DELAY.gw	Groundwater delay time (days)	-30	60	41.7
a	GWQMN.gw	Threshold groundwater depth for returnflow (mm)	-1000	1000	167.5
r	SOL_AWC().sol	Soil available water storage capacity (mm H2O/mm)	-0.05	0.05	0.02
r	ESCO.bsn	Soil evaporation compensation factor	0.5	0.95	0.8
r	SURLAG.bsn	Surface runoff lag time (days)	0	10	9.75
a	REVAPMN.gw	Re-evaporation threshold in the shallow aquifer (mm)	-1000	1000	650
v	GW_REVAP.gw	Groundwater revap. coefficient	0.02	0.2	0.11
a	RCHRG_DP.gw	Deep aquifer percolation fraction	-0.05	0.05	0.03

v: The parameter value is **replaced** by a given value (absolute change); r: parameter value is **multiplied** by (1± a given value; relative change); a: a given value is **added** to the existing parameter value. Best Par indicates parameter values obtained after calibration.

The model performance to predict freshwater components in the LRB was determined with two widely used statistical measures for model evaluation (e.g. Arnold et al., 2012). SWAT simulated monthly streamflow was compared with observed monthly streamflow using Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) and coefficient of determination (R^2). Following (Moriasi et al. (2007), the model performance is deemed ''satisfactory'' if NSE and R^2 are greater or equalled to 0.5 for environmental flows simulated at monthly time step. A perfect fit between the simulated and observed data is indicated by an NSE value of 1, while NSE values less than or equal 0 indicate that the observed data is a more accurate predictor than the simulated output (Arnold et al., 2012). A 0 value for R^2 indicates no correlation and 1 represents perfect correlation between the simulated and observed data (Arnold et al., 2012). The calibrated model was adopted to simulate the LRB's freshwater components for 30 years (January 1984-December 2013).

3.2.5. Estimation of spatial and temporal distribution of freshwater availability

Model outputs consisting of water yield, deep aquifer recharge, actual ET, and soil moisture were used to quantify the spatial and temporal distribution of blue and green water. Blue water was calculated as the summation of water yield and deep aquifer recharge, green water storage as soil moisture; and green water flow as actual ET (e.g. Faramarzi et al., 2009; Falkanmark and Rockstrom, 2006; Schuol et al., 2008). Water yield is the amount of water leaving a SWAT HRU and entering the main channel based on the simulation time step, which is monthly time step in this study. Water availability in the LRB is blue water (i.e. summation of surface water and deep aquifer recharge) (Schuol et al. 2008, Faramarzi et al. 2017).

Temporal variation in freshwater components was determined by aggregating monthly simulations into annual values, and subbasin values (871 SWAT delineated subwatersheds; see section 3.2.4 above) were aggregated into major watersheds of the LRB from 1984 to 2013. Total annual values were used for blue water and green water flow, while average annual soil moisture (i.e. sum of monthly values divided by 12) was used. To determine how freshwater availability varied in the basin, a time series plot of freshwater components was generated, and individual annual values were then compared with the long-term average values for each of the 27 major watersheds during the study period (1984-2013) (see section 3.2.4 above). Following Knapp et al. (2015) and observations of rainfall intensities, flood events, and dry spells in basin, years where rainfall was less than 40% of the long-term average were classified as drought years while years with rainfall more than 50% above the long-term average were considered wet years, with high potential for flooding (Knapp et al. 2015). The wet and dry years determined with the rainfall analysis were propagated into classification of blue and green water in this basin.

Spatial variation of freshwater components was also evaluated at SWAT delineated subbasin scale. Average annual freshwater components for the simulation period (1984-2013) was calculated for each SWAT delineated subbasin. Freshwater availability based over the LRB was estimated with ArcGIS contour mapping. Unlike the temporal variation assessment, annual freshwater components were not aggregated into major watersheds for spatial variation. Four maps were created for rainfall and individual freshwater components (i.e. blue water, green water flow, and green water storage), and to determine areas that have too much or too little water in the LRB.

3.2.6. Estimation of water quantity sensitive areas

Water demand/use is as important as water supply in determining if a community is likely to experience recurrent water shortage or excess.

Knowledge of water demand and supply can be used to determine water sensitive areas (WSAs) of a region. WSA is defined in this study as an area prone to water stress or excess. Relative water demand (RWD) or the ratio of total water consumption/use to water available (Watkins et al. 2004, McNulty et al. 2010, Brown and Matlock 2011), was used as a simple metric to determine WSAs in the LRB. The metric is expressed as (Watkins et al. 2004, Brown and Matlock 2011):

$$\mathrm{RWD} = \frac{\mathrm{TWD}}{\mathrm{TWA}} \times 100 \qquad (1)$$

where TWA is total water available, and TWD is total water demand. Table 3.5 indicates different categories that describe the level of water availability (i.e. too little or more than enough) over an area of interest. For example, if a watershed's total water demand is 540 m^3/ha/year and total available water is 300 m^3/ha/year, then the estimated RWD is 180%, which falls within the category of high stress as shown in Table 3.5.

Table 3. 5: Classification of water sensitive areas in the Limpopo River Basin (from (McNulty et al. 2010, Brown and Matlock 2011)

Category (Index)	Category (%)	Degree of wetness and dryness
0.00 ≤ RWD < 0.01	0.0 ≤ RWD < 1	Potential for high wetness
0.01 ≤ RWD < 0.05	1.0 ≤ RWD < 5	Potential for medium wetness
0.05 ≤ RWD < 0.20	5.0 ≤ RWD < 20	Normal
0.20 ≤ RWD < 0.40	20 ≤ RWD < 40	Low stress
0.40 ≤ RWD < 0.80	40 ≤ RWD < 80	Moderate stress (scarce)
0.80 ≤ RWD	80 ≤ RWD	High stress (scarce)

Total water demand is the sum of water demand/use for domestic, industrial, and agricultural sectors. While there were no detailed data on industrial water use for individual major watersheds in the basin, published reports indicated that less than 10% of the LRB available water was allocated to industrial water demand/use (Rahm et al. 2006, United Nations WWAP 2006, Zhuwakinyu 2012, Business Tech 2015). Based on these reports, 5% of industrial water use was assumed for built-up areas.

Water demand/use in domestic and agricultural sectors was estimated with a water demand estimation tool, the Simplified Hydro-Economic Demand Model, developed by New Mexico State University (Hurd, 2016). Annual domestic/municipal water demand/use within the tool for each SWAT subbasin was calculated as the product of per capita water demand/use and population. While data on estimates of water use South Africa watersheds for were accessible (National Water Resource Strategy (NWRS) 2004), this information was not available for other countries in the LRB. Thus, remotely sensed data were used to estimate water demand/use for the remaining country watersheds in the basin. Population was estimated by spatially aggregating gridded global population data from Landscan database (Bhaduri et al. 2002, Bhaduri et al. 2007) over each subbasin as described in section 3.2.3. The aggregated population was used to estimate water demand for domestic use. For agricultural water use, globland30 dataset (Geomatics Center of China, 2010) were utilized to estimate agricultural areas and crop water use requirements. Although freshwater components were simulated from 1979 to 2013, total water demand/use was only estimated for 2000 to 2013 period because the population data extracted from Landscan were only available from the year 2000. Annual agricultural water demand/use was also calculated for a period of 2000 to 2013 as the product of agricultural land area and water demand/use per square meter. Since crop variety could not be identified in the land use map, maize production was assumed for the crop area as it is the common crop grown in the study area. From published literature, 450-600 mm of water is needed per season to grow maize in Southern Africa (du Plessis, 2003), and 600 mm of water per season was used for maize production in this study. Noted that there is only one growing season per year in this region, which corresponds to the rainy season (i.e. October-March). Total water demand from different water sectors was calculated as:

$$TWD = \sum WD_i \quad (2)$$

where WD is water demand/use, and i is individual water sectors.

3.3. Results and Discussion

3.3.1. Model calibration and validation

Multi-location calibration and validation for the LRB model was performed based on observed streamflow data using SUFI-2 program within SWAT CUP 2012 (Abbaspour 2015). As mentioned earlier, the same set of sensitive parameters were selected for all locations used for streamflow calibration in the basin (Table 3.5; Figure. 3.2). The performance of SWAT for monthly streamflow simulations at the selected gauge stations range from 0.43 to 0.77 for NSE and greater than 0.50 for R^2 during the calibration period, and from 0.57 to 0.82 for NSE and greater than 0.5 during the validation periods (Table 3.5; Figure 3.2). While NSE value for streamflow observation station 534 during the calibration period (Figure 3.2; Table 3.5) falls below model evaluation guidelines (e.g., (Engel et al. 2007, Moriasi et al. 2007), the overall basin-wide model performance is deemed satisfactory for the analysis (Figure 3. 2; Table 3.5). Due to the complexity of SWAT calibration for large-scale simulations coupled with the difficulties associated with data scarcity, researchers have used lower values for model performance statistics (e.g., (Schuol et al. 2008, Abbaspour et al. 2015). The challenge for performing automated multi-location calibration reside in the fact that all streamflow outlets are parameterized and optimized simultaneously to return an overall result for all the selected observation stations (Abbaspour 2015). During the process, some observation stations may be poorly calibrated while others may show better statistics (Abbaspour et al. 2015)

Comparisons of model evaluation statistics between upstream and downstream stations did not show any particular pattern in model performance. The most downstream streamflow observation location (station 534) shows good model evaluation statistics during the validation period

(Table 3.5), indicating that SWAT was able to capture reasonably well variation in streamflow downstream of the LRB (Figure 3.5).

Table 3. 6: Multi-location calibration and validation statistics of SWAT for simulating freshwater components in the Limpopo River Basin

Station Name	Subwatershed	Calibration Period		Validation Period	
		NSE	R^2	NSE	R^2
Beitbridge pumpstation	207	0.55	0.70	0.82	0.86
Chibase	329	0.77	0.80	0.72	0.79
Combomune	534	0.43	0.60	0.60	0.71
Scheerpoort	853	0.72	0.79	0.63	0.79
Rondebosch	861	0.66	0.74	0.57	0.67

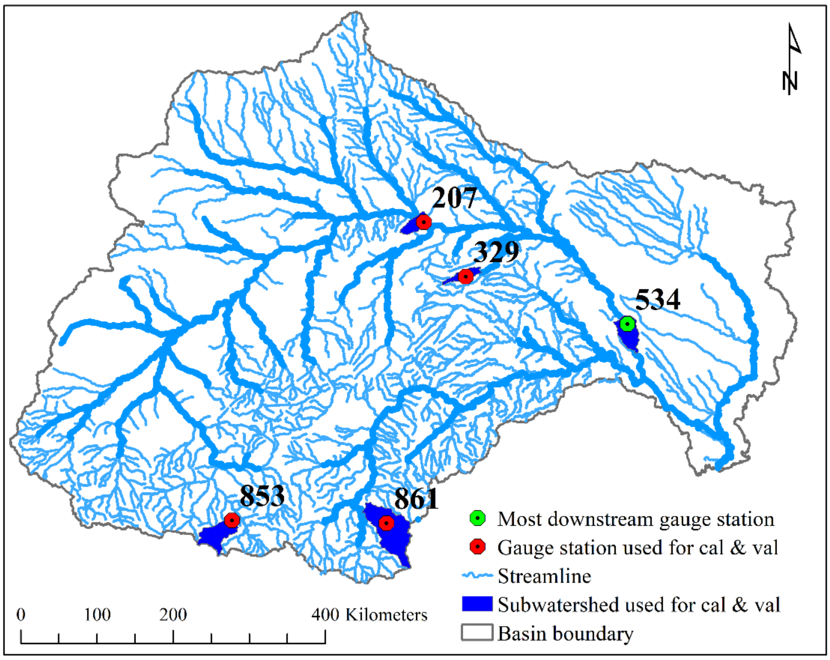
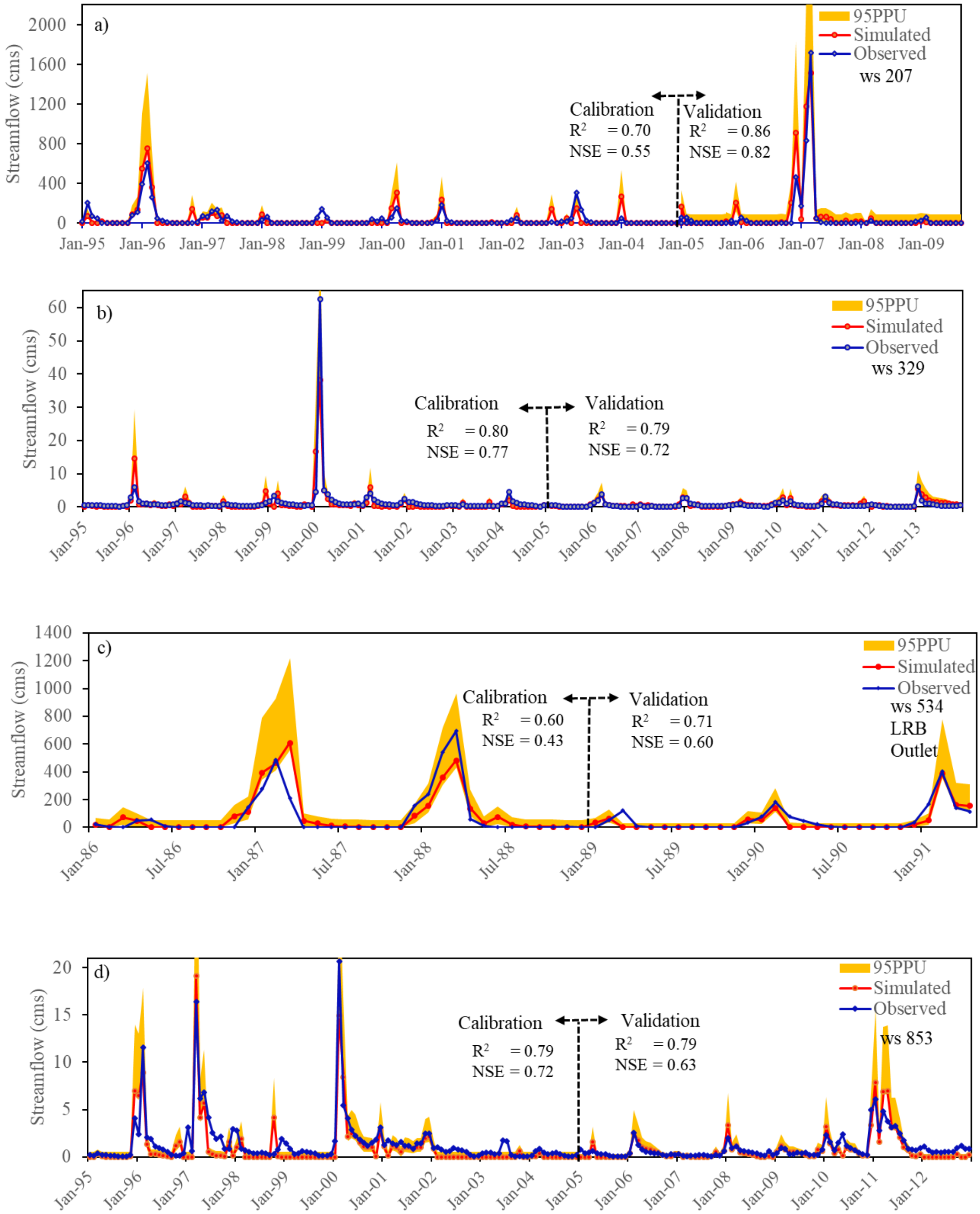


Figure 3. 2: Locations of streamflow observation stations used for SWAT calibration and validation for the Limpopo River Basin



a)
Streamflow (cms)
95PPU
Simulated
Observed
ws 207
Calibration
R^2 = 0.70
NSE = 0.55
Validation
R^2 = 0.86
NSE = 0.82
b)
Streamflow (cms)
95PPU
Simulated
Observed
ws 329
Calibration
R^2 = 0.80
NSE = 0.77
Validation
R^2 = 0.79
NSE = 0.72
c)
Streamflow (cms)
95PPU
Simulated
Observed
ws 534
LRB
Outlet
Calibration
R^2 = 0.60
NSE = 0.43
Validation
R^2 = 0.71
NSE = 0.60
d)
Streamflow (cms)
95PPU
Simulated
Observed
ws 853
Calibration
R^2 = 0.79
NSE = 0.72
Validation
R^2 = 0.79
NSE = 0.63

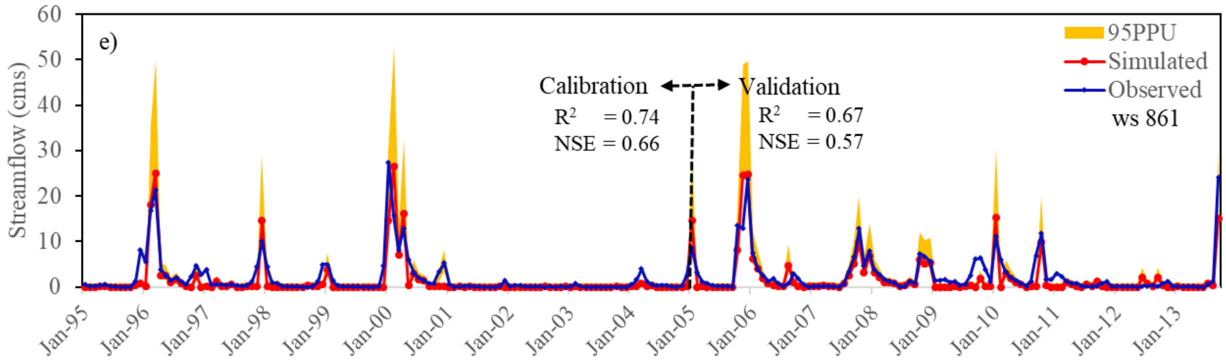


Figure 3. 3: Simulated and observed monthly streamflow with 95% prediction uncertainty bands at the gauge stations used for model calibration and validation in this Limpopo River Basin study. 'ws' represents SWAT delineated subbasins used for model calibration and validation in the Limpopo River Basin.

3.3.2. Temporal and spatial distribution of blue and green components

Distribution of freshwater components (i.e. blue water, green water flow, and green water storage) over time for Notwane (ws3), Motloutse (ws10), and Lower Limpopo (ws27) are shown in Figs. 4a-d to illustrate cases of low, medium, and high freshwater availability, respectively. Rainfall and simulated freshwater components were presented with 95% confidence bands, denoted by 95% Prediction Uncertainty Band (95PPU), providing modeling uncertainties that may propagate into the outputs. The 95PPU were calculated at 2.5% and 97.5% probability levels (Faramarzi et al. 2013, Abbaspour 2015).

Between 1984 and 2013, blue water for the 27 major watersheds ranged from 0.02 to 47 mm/year within 95PPU in Marico watershed (in Botswana) to 7 to 807 mm/year 95PPU in Lower Olifants watershed in South Africa (Table 3.7).

For the same time period, simulated green water flow varied between 142 and 589 mm/year 95PPU in Middle Olifants watershed in South Africa, and between 369 and 1032 mm/year 95PPU in Lower Limpopo watershed in Mozambique (Table 7). Green water storage 95PPU ranged from 3 to 43 mm/year in Middle Olifants watershed in South Africa, and from 29 to 106 mm/year 95PPU in Lower Limpopo watershed (Table 3.7). Overall, annual freshwater components fell below normal (i.e. dry years) in 11 to 16 years for blue water, 0 to 4 years for green water flow, and 2 to 13 years for green water storage (Table 3.7). Above normal years (i.e. wet years) varied between four and 10, 0 and six, and three and 11 for blue water, green water flow, and green water storage, respectively (Table 3.7).

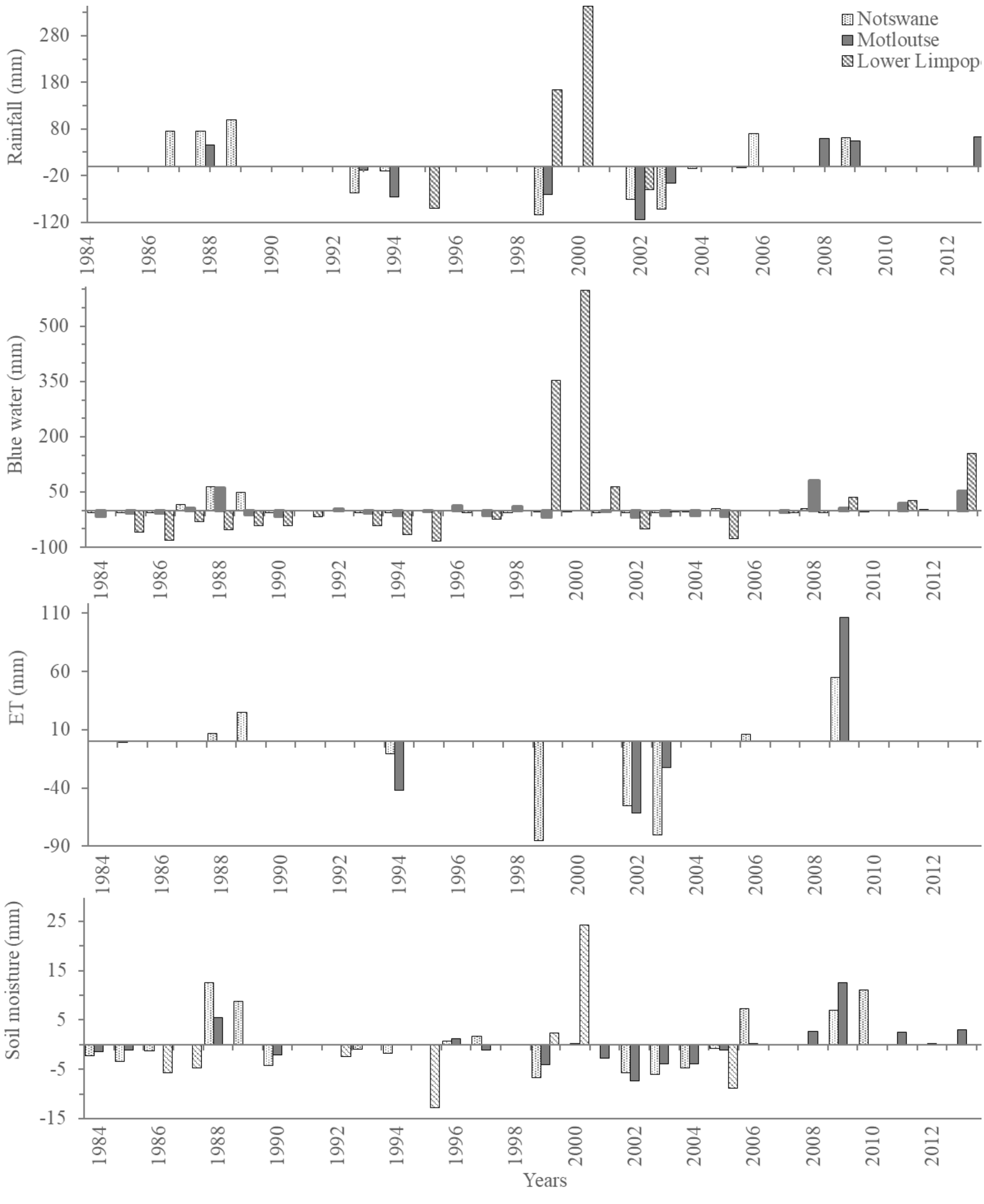


Figure 3. 4: Deviation of a) rainfall, b) blue water, c) green water storage, and d) green water flow from their normal (i.e. long-term average annual values) between 1984 and 2013 for Notwane, Motloutse, and Lower Limpopo watersheds of the Limpopo River Basin.

The LRB freshwater availability components depicted high inter-annual variability (Figure 3.4 b-d; Table 3.7). An analysis of rainfall pattern in the basin (Figure 3.4a) also revealed high variability, suggesting that variability in freshwater components is mostly driven by rainfall. Below average freshwater components (i.e. dry years), which are associated with droughts, are frequent and tend to cluster over extended periods. For example, below long-term annual average blue water started in 1985 and ended in 1990 for one cycle of dry years, and from 1993 to 1997 for a second cycle in the Lower Limpopo watershed (ws27). Similarly, 1984 to 1986 and 2001 to 2005 were cycles of dry year for blue water for Notwane (ws3) and Motloutse (ws10) watersheds (Figure 3.4b-d; Table 3.7). This pattern, with slight differences in years, is observable for other major watersheds in the LRB (Table 3.7). Estimates of freshwater components that fall above the long-term average are not frequent in the LRB (Figures 3.4b-d; Table 3.7), indicating less wet years than more dry and normal years during the simulation period (1984-2013). The years that show high blue water above the long-term average (i.e. wet years) are generally associated with extreme rainfall and flood events in the basin (e.g. Figure 3.4b). While it appears that rainfall in individual years did not substantially deviate from their respective watershed long-term average, streamflow in these years still resulted in flooding due to high intensity rainfall influenced by cyclones (Trambauer et al. 2014, Gebre and Getahun 2016, Maposa 2016). A typical example was the year 2000 flooding in the Lower Limpopo watershed (Figures

3.4a-d), caused by cyclone Elaine. Comparison of freshwater availability components in individual major watersheds in west of the basin shows clustered years (generally more than two consecutive years) that frequently fall below the long-term average than variation in freshwater components in the east (Figures 3.1, 3.4b; Tables 3.1 and 3.6). Green water flow and green water storage reveal similar patterns as blue water; however, the number of years that fall below their respective long-term average are less than those of blue water (Figure 3.4b-d; Table 3.7).

The simulated freshwater components that fall below and above the long-term annual average in the major LRB watersheds are consistent with known drought and flood years reported by other researchers (LBPTC 2010, WMO 2012). For example, the year 2013 flooding, which caused approximately 70 deaths and affected around 4,210 people in Botswana and 213,000 people Mozambique (OCHA ROSA, 2013) is noticeable in the blue water time series of Motloutse and Lower Limpopo watersheds shown in Figure 3.4b-d. These were also revealed by the analysis of rainfall records in that year (not shown in text; Figure 3.4a). Another example is the year 2000 flood in the Lower Limpopo watershed located downstream (eastern part) of the LRB (Trambauer et al. 2014). Above-normal years of 1987 to 1989 for blue water and green water storage for Notwane watershed correspond to high incident rainfall events depicted in this study (Figure 3.4a). (Moses 2016) also found some clustered years of above normal rainfall for this watershed during 1975-2015. Drought events that occurred in the years 1993 to 1995 and 2005 are also observable in the basin (Figures. 3.4b and d; Table 3.7). Due to historically low rainfall in the west, variation of freshwater components from the long-term average in those areas was less pronounced (e.g. Notwane watershed (ws3); Figure 3.4b-d and Table 3.7).

Table 3. 7: Long-term annual average for rainfall and 95% prediction uncertainty (95PPU) of the simulated freshwater components, with the number of wet and dry years from 1984 to 2013 (30 years) in each major watershed of the Limpopo River Basin. Numbers in brackets represent years that exceeded 50% of long-term annual average of a freshwater component, while numbers in parentheses represent years that fall beyond 40% of long-term annual average of a freshwater component.

Notation	Watershed Name	Rainfall (mm/yr)	Blue water (mm/yr)	Green water flow (mm/yr)	Green water storage (mm.yr)
ws1	Crocodile	344	1-179 [16] (7)	170-490 [5] (2)	6-54 [9] (7)
ws2	Marico	295	0.02-47 [17] (4)	188-1475 [4] (1)	8-38 [9] (6)
ws3	Notwane	271	2-26 [18] (5)	190-345 [5] (4)	7-26 [11] (6)
ws4	Bonwapitse	249	1-24 [18] (5)	164-301 [5] (2)	7-19 [13] (8)
ws5	Matlabas	276	5-67 [14] (9)	174-327 [5] (2)	7-18 [8] (7)
ws6	Mokolo	359	6-349 [15] (8)	174-446 [5] (1)	6-31 [4] (3)
ws7	Mahalapswe	281	5-46 [16] (9)	182-324 [5] (1)	8-21 [9] (7)
ws8	Lephalala	317	6-224 [16] (9)	164-414 [5] (1)	8-29 [6] (3)
ws9	Lotsane	306	6-57 [14] (8)	176-323 [3] (1)	10-21 [10] (6)
ws10	Motloutse	319	2-64 [16] (9)	195-364 [3] (1)	11-23 [11] (6)
ws11	Mogalakwena	330	1-101 [16] (9)	259-424 [5] (1)	6-39 [7] (4)
ws12	Shashe	366	7-109 [14] (7)	220-411 [2] (1)	12-41 [5] (4)
ws13	Sand	365	2-228 [19] (10)	180-561 [3] (1)	8-84 [9] (9)
ws14	Mzingwani	409	7-120 [14] (9)	220-606 [2] (0)	10-63 [6] (5)
ws15	Nzhelele	456	50-211 [15] (10)	330-429 [1] (0)	21-35 [9] (5)
ws16	Bubi	506	20-243 [16] (8)	279-1049 [1] (0)	14-70 [6] (3)
ws17	Luvuvhu	530	44-444 [17] (7)	279-600 [1] (0)	13-68 [8] (3)
ws18	Mwenezi	553	34-288 [14] (7)	281-593 [1] (0)	14-76 [7] (2)
ws19	Upper Olifants	446	1-174 [14] (7)	288-516 [6] (2)	15-61 [12] (9)
ws20	Middle Olifants	366	0.2-178 [15] (9)	142-589 [5] (1)	3-43 [11] (6)
ws21	Steelpoort	515	14-546 [14] (8)	260-579 [4] (0)	21-67 [8] (3)
ws22	Letaba	550	12-341 [17] (7)	398-480 [2] (0)	28-42 [10] (8)
ws23	Lower Olifants	562	7-807 [15] (7)	309-649 [2] (0)	16-100 [9] (5)
ws24	Shingwedzi	627	44-409 [16] (8)	330-559 [1] (0)	17-56 [5] (3)
ws25	Lower Middle Limpopo	564	52-267 [18] (7)	332-465 [1] (0)	17-36 [3] (2)
ws26	Changane	600	29-403 [18] (6)	344-766 [1] (0)	25-86 [5] (2)
ws27	Lower Limpopo	730	52-353 [17] (6)	369-1032 [0] (0)	29-106 [5] (2)

Spatial variation of rainfall and freshwater components (i.e. blue water, green water flow, and green water storage) are shown in Figure 3.6a-d. Annual rainfall varied between 176 mm and 1,047 mm, with an average of 334 mm/year for the study period (Figure 3.5a). West of the basin and some parts in the south, display low rainfall amounts while the eastern parts receive high rainfall. Overall, nearly all watersheds in Botswana, west of Zimbabwe and South Africa receive low rainfall. These areas (Figure 3.5a) are prone to droughts and water stress as reported by other studies (LBPTC 2010, WMO 2012, Trambauer et al. 2014).

Annual average blue water (i.e. water yield and deep aquifer recharge) for this study ranged between 1 to 566 mm during the simulation period (Figure 3.5b). Blue water appears high in northeast, east, and southeast of the LRB (e.g. Bubi (ws16), Levuvhu (ws17), Changane (ws26), Steelpoort (ws21) watersheds) (Table 3.7; Figures 3.1 and 3.5b). This can be explained by high rainfall events that are common in these areas (WMO, 2006). North and northeast rainfall is driven by the influence of Inter-Tropical Convergence Zone (ITCZ), while east and southeast rainfall is due to prevailing rain-bearing winds that blow from the Indian Ocean thus bringing rainfall inland (Ashton et al. 2001, LBPTC 2010). The ITCZ is an area of low atmospheric pressure, emanated from mixed wind from northeast southeast of the equator (Wamukonya et al. 2007). This process causes water vapour to be released as rain, resulting in a band of heavy rainfall in countries around the equator (Wamukonya et al., 2007). During the southern hemisphere summer, migration of this phenomenon to the south of the equator leads to abundant rainfall in areas north of the LRB compared to the southern and western parts of the basin which are farther away from the ITCZ (Figure

3.5a). The eastern part of the basin, due to its proximity to the ocean, is influenced by southward-flowing currents (often associated with cyclones), which bring warm seawater and humid air fronts from the equator, creating a humid, warm climate with abundant rainfall (WMO, 2004). The influence of these two natural rainfall-forcing factors is minimal in western LRB; thus less rainfall, mostly convective, is usually recorded in western, leading to less blue water availability (Figures 3.5a and b).

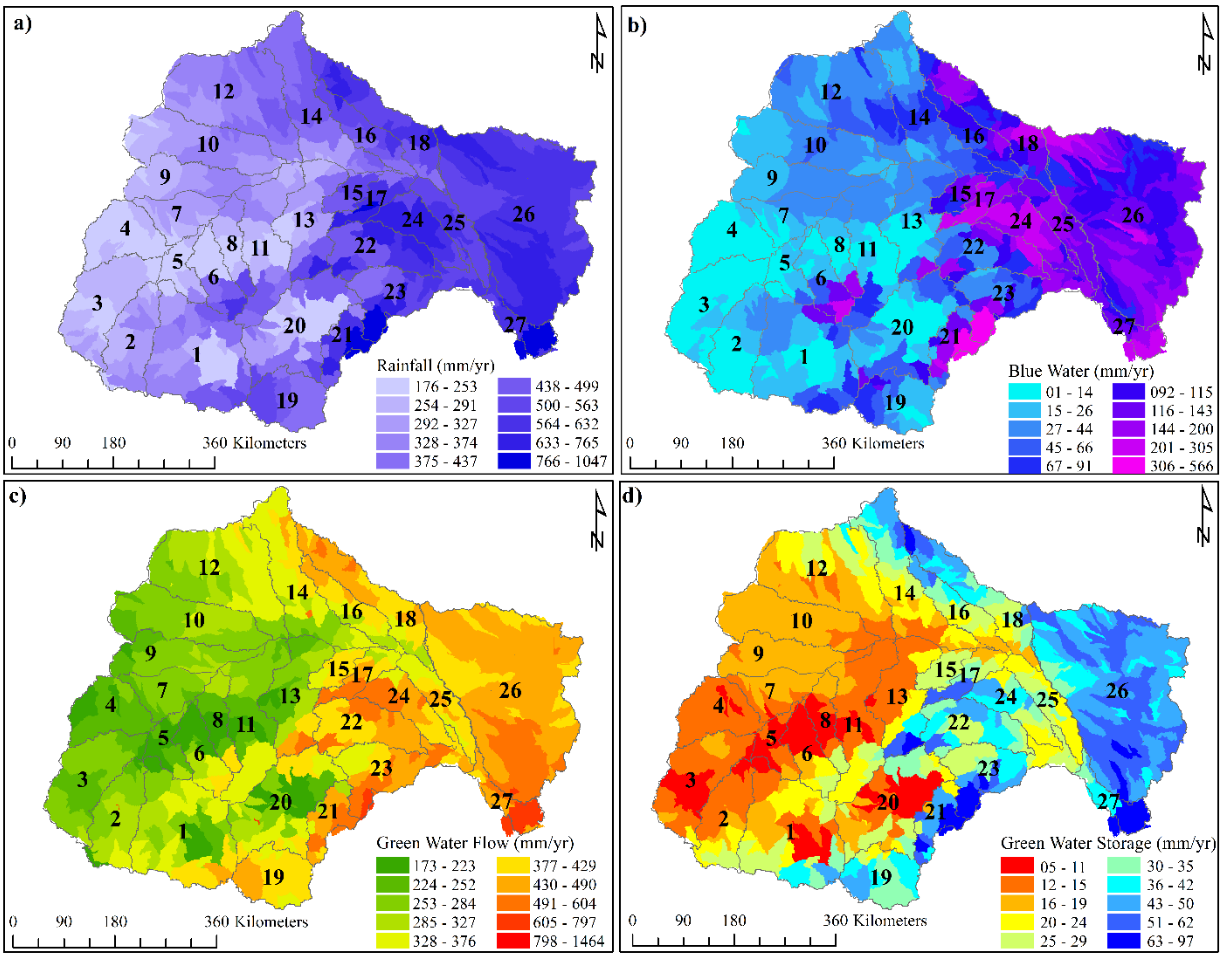


Figure 3. 5: Spatial distribution of average annual (a) rainfall (b) blue water, (c) green water flow, and (d) green water storage in the Limpopo River Basin during1984 to 2013 period

Green water flow (i.e. ET) is higher than blue water in all watersheds in the LRB (Figures 3.5b and c). The high ETs are due to high temperature and high rates of plant transpiration and evaporation from open waters in that region of Africa. ET ranged from 173 mm/year to 1,464 mm/year during the simulation period. Elmi-Mohamed (2014) and Boroto et al. (1999) also reported high ET values for the region averaging approximately 2,000 mm/year, and low rainfall averaging about 500 mm/year for the LRB. Estimates of ET in northeastern parts of the LRB, which cover Bubi (ws16) to Changane (ws26) watersheds (Figures 3.1 and 3.5c; Table 3.1) and pockets in southeast, including Levuvhu (ws17), Letaba (ws22), and Shingwedzi (ws 24) watersheds (Figures 3.1 and 3.5c; Table 3.1), were high compared to ET in northwest, central west, and southwest watersheds (e.g. Notwane (ws3) to Mogalakwena (ws11); Figures 3.1 and 3.5c; Table 3.1). High ET, particularly in central east and northeast, is due to the presence of broad leaf forest, high temperature, and abundant rainfall, which is historically common in that part of the LRB. In general, areas that experience high ET in the LRB generally correspond to areas of forest as shown in Fig. 1. However, in central and south of the basin (i.e. Crocodile (ws1) and Upper and Middle Olifants (ws19 and ws20) watersheds (Table 3.1; Figures 3.1 and 3.5c), estimated high ET values may be the result of agricultural activities.

Green water storage (i.e. soil moisture) ranged from 5 mm/year in west of the basin to 97 mm/year in the east during the simulation period. From 1984 to 2013, green water storage displays similar patterns as that of blue water and green water flow estimates since soil moisture is highly influenced by rainfall. East watersheds including Bubi (ws16), Levuvhu (ws17), Changane (ws26), and Steelpoort (ws21), and south of the basin, especially lower parts of Crocodile (ws1) and Olifants (ws19 and ws20), with high blue and green water flow also showed high green water storage during the study period (Table 3.1; Figures 3.1 and 3.5 b-d). The above mentioned eastern watersheds have high green water storage due to high rainfall and deep soils, capable of retaining moisture over a long period compared to shallow soils in the middle of the basin (Bangira and Manyevere, 1998).

3.3.3. Water sensitive areas within the LRB

The spatial distribution of population and agricultural areas in the LRB (Figures. 3.6a and b) reveals that agricultural activities are concentrated in the south and north of the basin with some pockets in the east (e.g. ws27), where the majority of the LRB's population is concentrated, indicating that these areas are water risks areas.

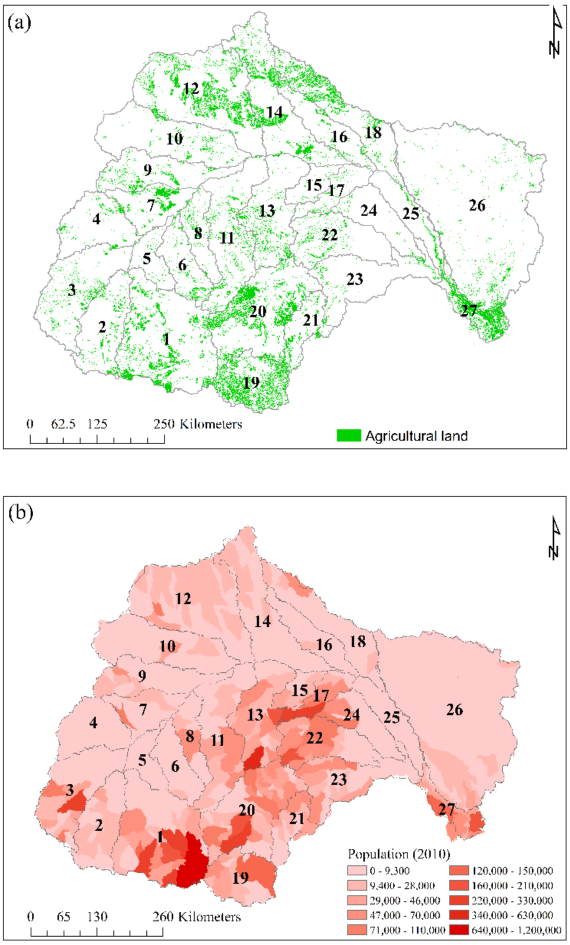


Figure 3. 6: Distribution of (a) agricultural land based on 2010 land use map (National Geomatics Center of China, 2010) and (b) of population based on 2010 population estimates from Landscan database (Oak Ridge National Laboratory; (http://www.ornl.gov/landscan/) in the Limpopo River Basin.

Areas under water stress are prominent in the LRB, especially in the south and west (Figure 3.7). For a total of 27 major watersheds, 22 (i.e. 81%) completely fall within the categories of slight to extreme water stress (Table 3.5; Figure 3.7), while five (19%) fall within normal to potential wet categories. Vörösmarty et al. (2000) also reported that the LRB is one of the highly water stressed basins in the world. Based on Figures 3.5d and 3.7, areas with enough and even surplus freshwater resources exhibited some degree of stress when taking TWD into consideration (e.g. parts of Crocodile, Mokolo, Lephalala and Steelport watersheds). Similarly, areas that showed water deficit (Figure 3.5b) became drier, suggesting that these areas were likely under heavy water stress (Table 3.7; Figure 3.7). Where there is more agricultural land and high population, for instance the Lower Limpopo and Upper Olifants (ws27 and ws19; Figure 3. 6; Table 3.7), the analysis revealed that these areas, despite having high blue water, may still struggle for freshwater (Figures 3.5b-d). Other researchers reported similar levels of freshwater stress for these areas (e.g. Alcamo et al., 2000, 2003b; Vörösmarty et al., 2000; Wada et al., 2011) Watersheds such as Shingwedzi (ws24), Lower Middle Limpopo (ws25), and Changane (ws26) are few of the LRB's watersheds that were in a good shape in terms of freshwater availability. This is understandable since these areas had little cultivated cropland and sparse population but received abundant rainfall (Figures 3.6 and 3.7). Pockets of extreme wetness located toward the middle of LRB could also be explained by minimal agricultural and population water demand (Figures 3.6 and 3.7).

In general, the analysis conducted in this study revealed extreme stress for over 81% of the LRB in west of the basin (Botswana) and south (South Africa), and majority of the north (Zimbabwe) (Figures 3.1 and 3.7). Heavy agricultural activities, increasing domestic water demands due to population growth, and unreliable rainfall are likely the major driving factors of the pressure on freshwater resources in west and south of the LRB (Figures 3.6 and 3.7). East of the LRB (mainly Mozambique) appears to be a land of excess water resources, which is translated by constant frequent flood events recorded in the country (LBPTC 2010).

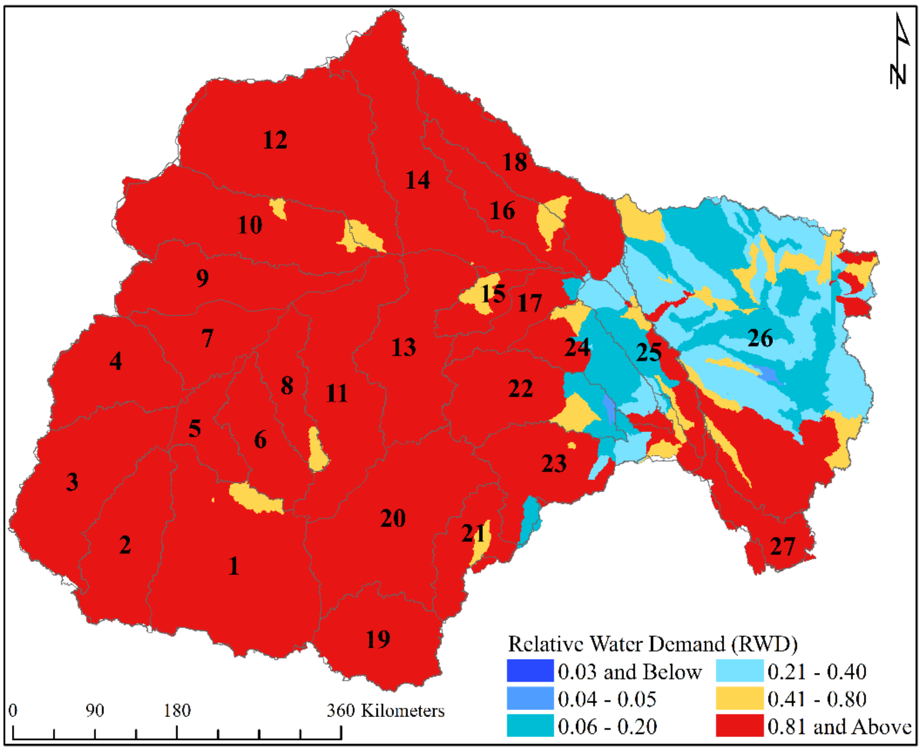


Figure 3. 7: Estimated water sensitive areas in the Limpopo River Basin

3.3.4. Implications for water resources management

Accounting for annual distribution of freshwater components is valuable for water resource management, especially in semi-arid regions where the spatial and temporal variability of rainfall are particularly important for runoff and recharge processes. The simulated water availability showed alternating cycles of drought and flood years, as well as water-stressed areas in the basin.

Historically, both drought and flood periods have notable impacts on agricultural production and water supply for domestic use (FAO 2004, Alemaw and Kileshye-Onema 2014, Trambauer et al. 2014). During drought events, crop failure is common due to low available blue and green water storage. Domestic water supply also decreases due to reduced replenishment in water storage structures (e.g. dams). Flood years in the basin have been associated with both crop failure and property damage including damage of public infrastructure (Kandji et al. 2006). Existing water resources management efforts in the basin utilized wastewater recycling and reuse to meet the needs of different water users (LBPTC 2010). Water conservation strategies such as drought-resistant crop cultivation, crop diversification, rain water harvesting, and terrace farming are also being used to meet both agriculture and domestic water demands (Rockström et al. 2009), although these efforts have been implemented at individual country scales in the basin (Limpopo RAK 2011).

This study shows that more than 50% of the basin is under water stress. This situation may escalate with climate change. Climate change in Southern Africa, including the LRB, is projected to result in increased temperatures, changes in rainfall duration and timing, changes in seasons characterized by shorter summers, and increased climate variability (e.g. more floods, droughts, and heatwaves) (Stocker 2014). These changes will likely amplify water stress in these sensitive areas (Figure 3.8). As population increases in the basin, stress on water resources will likely increase. Improving understanding of long-tern annual variability of freshwater availability would be very beneficial in the future to guide proper use of resources and adaptation to water issues in the basin.

Effective management of water resources would continue to rely on scientific research to identify and deploy sustainable strategies that would help alleviate water issues in the region. Sustainable strategies may include strengthening institutional capacity to encourage more research and improved drought and flood management plans with buy-in from all stakeholders (e.g. the general public, academic researchers, practitioners, and policy makers, among others). Water transfers from water abundant areas, increased water recycling and reuse, and transfer of desalinated water from neighbour countries are plausible solutions to support areas that would experience water deficit. Implementation of best management practices (BMPs) that include principles of low impact development and green infrastructure in urban areas as well farm-level BMPs such as water recycling in water abundant areas could also contribute achievable solutions to water issues in the basin.

3.4. Conclusions

In this study, SWAT was utilized to quantify freshwater availability in the LRB. The SWAT model as calibrated at multiple locations in the basin for monthly streamflow simulation showed satisfactory results, given the scale and variability in physical characteristics of the basin. The simulated freshwater components vary between 1 and 570 mm/year for blue water, 170 and 1,500 mm/year for green water flow, and 5 and 100 mm/year for green water storage over the basin during the 2000-2013 study period. Temporal variability in freshwater components in the LRB revealed alternating episodes of wet and dry years, corresponding to documented drought and flood periods in the basin. On average, deviations from the normal cycled every three to five years for dry periods, and one to two years for the wet periods during the study period. Spatial analysis showed a decreased pattern in freshwater availability from east to west, and from north to south of the basin, consistent with other studies. The analysis of water sensitive areas revealed that more than 80% of the LRB, mainly in the west, experienced some degree of water stress over the study period. East of the basin (20% of the LRB), however, is mostly wet with enough available freshwater, due likely to abundant rainfall and low population of this area of the basin. Despite the uncertainties mentioned above (see section 3.4), this study provides an elaborated view of freshwater availability in the LRB.

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4. CHARACTERIZATION OF POTENTIAL GROUNDWATER RECHARGE IN THE LIMPOPO RIVER BASIN: AN EVALUATION STUDY OF SWAT-MODFLOW

Abstract

Understanding groundwater recharge processes is important for development of water resources in arid and semi-arid regions. The study sought to validate SWAT-MODFLOW, a loosely coupled surface water-groundwater model, with the specific objectives to assess distribution of annual and seasonal groundwater recharge and groundwater interactions with surface water in the Limpopo River Basin (LRB). In addition, the study assessed the effectiveness of selected low impact development (LID) practices for infiltration on annual recharge and water table fluctuations in a small catchment of the basin. Simulation results show relatively high annual recharge along the Limpopo main river and at the outlet of the basin. Groundwater table is generally shallow in the rainy east and along the basin's river network. Seasonal analysis reveals high variability in both groundwater recharge and level. Summer months appears to have the highest groundwater recharge with 147 mm/year over the basin, followed by autumn with an average of 27 mm/year, spring with 3.2 mm/year, and winter with 0.3 mm/year as the lowest recharge during the 30-year study period (1984 to 2013). Water table elevations vary from a minimum of 1300 m/year in summer to a maximum of 1400 m/year in autumn. Model outputs also suggest high spatial variability in groundwater-surface water interactions in the basin's rivers. Rivers in south showed input from

groundwater discharge while west river channels appeared to seep to the underlying aquifer during the study period. Implementation of the LID practices resulted in 0 to 6% increase in annual groundwater recharge and 0 to 0.11% increase in annual water table elevations.

4.1. Introduction

Surface water resources in the LRB are limited and unpredictable due to the basin's location in a semi-arid region and climate variability (FAO 2004, LBPTC 2010, WMO 2012, Maposa 2016). In addition, socio-economic factors such as population growth, urbanization, industrial development and increasing agricultural activities intensify the pressure on the already limited surface water resources in the basin (Kandji et al. 2006, Busari 2007, Baqa 2017). Due to shortage and high costs associated with surface water transport, groundwater is a preferred source of water supply for the communities far away from the river and its tributaries (FAO 2004). Groundwater is also an alternative water supply source in the basin to help strengthen community resistance during drought periods due to its year-round availability (Baqa 2017).

Groundwater is mainly used for domestic needs, livestock watering, irrigation, and mining in all basin countries (Kahinda et al. 2016). In the South Africa part of the basin, irrigation from groundwater is estimated at 69% of the total groundwater use, followed by 22% for domestic, 5% for municipal, and 4% for mining uses (Titus et al. 2009, Mwenge Kahinda et al. 2016).

Groundwater resources in the basin is extensively used and overly exploited in some places due to over pumping (Busari 2007, Aurecon 2011). For example, groundwater use increased by more than 200% in Mogalakwena catchment (South Africa) while groundwater extraction activities in other South Africa catchments only increased by 40% (Aurecon 2011).

Depletion of water supply from groundwater sources is further undermined by improper sewage disposal in locations with shallow aquifers (Petrie et al. 2014, Baqa 2017). This led to abandonment of wellfields in the late 1990's to early 2000's in Ramotswa aquifer despite being an agricultural productive area (Petrie et al. 2014, Baqa 2017). Saltwater intrusion from underlying geologic formations and the Indian Ocean is also a contributing factor in the deterioration of usable groundwater resources, especially in southern Mozambique's part of the basin (Steyl and Dennis 2010, Petrie et al. 2014).

Characterization of groundwater table and recharge is paramount for understanding aquifer water yield and abstraction in the basin (Izady et al. 2015). Recharge may occur naturally from rainfall, lakes and rivers or from human activities such as irrigation practices. This study will focus on natural recharge from rainfall as the main input for groundwater recharge in the LRB.

Even though the topic of groundwater resources prompted interest in research and policy efforts over the past few years to guide sustainable groundwater development and use of in the basin (Petrie et al. 2014), little quantitative information is known about the distribution in time and space of groundwater level, interactions with surface water, and recharge in the basin.

To promote natural recharge, careful and effective implementation of infiltration best management practices (BMPs) can be used for groundwater replenishment in the basin (Dietz 2007, Ahiablame et al. 2012, 2013, Ahiablame and Shakya 2016, Wright et al. 2016). Infiltration BMPs typically allow runoff collected from impervious surfaces to be temporarily stored for slow release to the underlying soils (GWPC 2007). In urban settings, low impact development (LID) techniques are among common infiltration BMPs. Low impact development practices are used to reduce runoff at the source resulting in decreased flow velocity and prolonged travel which ultimately lead to reduced downstream flooding and associated pollutant loading (Hunt et al. 2010, Her et al. 2017). Considerable number of storm runoff and flood flow events were reduced from 0 to 40% with implementation of various levels of three LID practices in the City of Normal-Sugar Creek Watershed in Central Illinois (Ahiablame and Shakya, 2016). In Northern Ohio, three bio-retention cells were found to reduce 24 to 96% of peak flows in 0.19 to 3.6 ha catchment areas (Winston et al. 2016). Implementation of LID infiltration practices in Deer Creek watershed, Missouri resulted in 3 to 19% runoff reduction at the outlet compared to upstream locations of the watershed (Di Vittorio and Ahiablame 2015). Optimal combinations of LID practices were found to intensify runoff reduction in the Crooked Creek watershed in Indiana (Liu et al. 2015).

Managing moisture with infiltration BMPs or LID techniques can be beneficial for drought mitigation in semi-arid and arid regions such as the study basin.

The overall goal of this study was to validate SWAT-MODFLOW's ability to simulate groundwater processes in the LRB. The specific objectives were to 1) assess the spatial distribution of annual and seasonal groundwater recharge, groundwater level, and groundwater interactions with surface water; and 2) Use a small catchment as a case study to illustrate groundwater recharge with selected LID practices.

4.2. Materials and methods

4.2.1. Study Basin

The LRB has approximately 415,000 km^2, shared between Botswana, Mozambique, South Africa and Zimbabwe (Figure 4.1a). The basin is dominated by agricultural land and grassland. 91% of the total LRB's area is rainfed subsistence agriculture. Limpopo River is the longest river which stretches over 1,770 km starting in South Africa and flows north where it creates the South Africa-Botswana border, then flows east to form the South Africa–Zimbabwe border, and finally south-east through Mozambique before ending in the Indian Ocean. The total population living in the LRB is about 18.6 million inhabitants, with 7% based in Botswana, 6% in Zimbabwe, 83% in South Africa and 4% in Mozambique. The 7% Botswana's population living in the LRB translate to 69% of the country total population. In South Africa 22% of the population lives in the basin while 10% and 7% of Zimbabwe and Mozambique's populations live respectively in the basin (Mwenge Kahinda et al. 2016) when considering total population of the riparian states. Groundwater in the basin occurs primarily in unconsolidated aquifers with varying depths ranging from less than 1 m to more than 300 m (Busari 2007). Figure 2 shows The Notwane subbasin, referred to in this study as Notwane watershed, was used for the catchment case study for infiltration BMP implementation (Figure 4.1c).

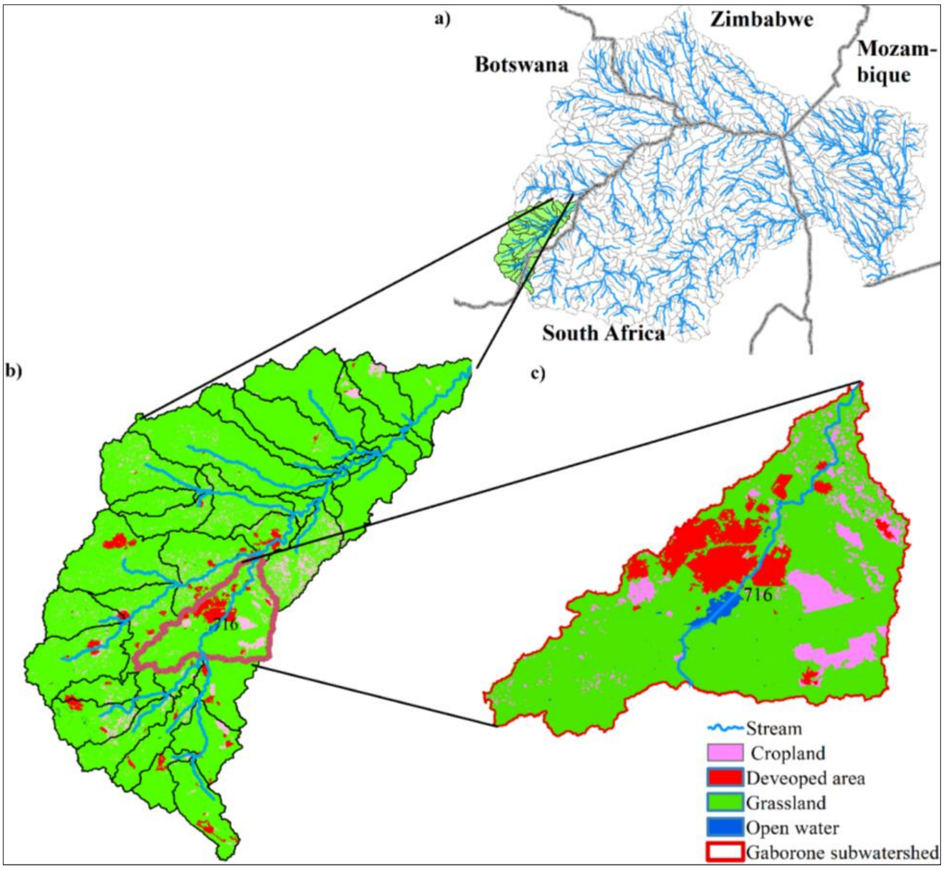

Figure 4. 1: Map showing the a) Limpopo River Basin, b) Notwane subbasin, and c) Gaborone Catchment of the Notwane subbasin.

The Notwane subbasin (Figure 4.1b) has an area of 18, 053 km^2, which is about 4% of the LRB. Notwane watershed is home to approximately one-third of Botswana's 1.6 million population, concentrated in urban centres of Gaborone, Molepolole, Mochudi, Kanye, Lobatse and Jwaneng. Domestic water demands are growing rapidly in the watershed, especially in the Gaborone catchment. This catchment encamps Gaborone (capital city of Botswana) and suburban areas including Mogoditshane, Tlokweng and Mmopane. These urban centres account for more than 60% of the domestic water demands. Gaborone for example, consumes 50% of all urban water uses which is approximately 30% of Botswana's national domestic water use. This is expected to increase by up to 40% by 2020 due to the growing rapid urbanization. In most years, the watershed has water deficit, generally compensated by water importation from other parts of the LRB. Despite water shortage, flooding is frequent in the Notwane watershed including the Gaborone catchment.

The Gaborone catchment was chosen to illustrate groundwater recharge with infiltration LID BMPs in the basin. With an area of 1 356 km^2 (135 556 ha), 137 km^2 (10% of the catchment area) is urban. The remaining land use in the catchment consists of grassland (1 064 km^2), cropland (138 km^2) and water bodies (17 km^2). The City of Gaborone and its suburbs have many impervious areas from roads and parking lots. The soils of the catchment are mainly well drained loamy sand with less than 1.5 meter depth to the underlying aquifer

(Zhai et al. 2003). Annual rainfall ranges from 355 to 915 mm with an average of 457 mm, and average daily temperature varies between 13 ^{o}C in July and 25 ^{o}C in December (Zhai et al. 2003).

4.2.2. SWAT-MODFLOW Description

SWAT-MODFLOW is a loosely coupled model of SWAT and MODFLOW for simulating surface and groundwater hydrology. SWAT, developed by US Department of Agricultural Research Service is a continuous, daily time step model used to simulate surface water flow, sediment and nutrient transport at a watershed scale (Arnold et al. 2012). SWAT subdivide a watershed into sub-watersheds which are further partitioned into hydrologic response units (HRU) based on unique soil, land use, and slope characteristics (Nietsch et al. 2005). SWAT components include climate, hydrology, soil temperature, plant growth, nutrients, pesticides, land management, and bacteria. Detailed information on SWAT is given by Nietsch et.al. (2005) and Arnold et.al. (2012).

Modular Three-Dimensional Finite-Difference Groundwater Flow (MODFLOW) is a physically based, distributed finite-difference three-dimensional (3D) groundwater flow simulation model (McDonald and Harbaugh 1988, Bailey et al. 2017). Using a gridded spatial discretization, SWAT-MODFLOW has the ability to simulate three dimensional groundwater flow processes at the continuum volume of the saturated zone by taking into consideration hydrogeological properties of the aquifer and feedback fluxes between surface water and groundwater interactions as well as occurrence and spatial distribution of discharge. SWAT-MODFLOW simultaneously solves the groundwater flow differential equation using the finite difference approach (Kim et al. 2008, Guzman et al. 2015). In addition, the model is able to spatially represent groundwater head or groundwater elevation (Bailey et al. 2016).

Linkage of the two models allows to pass percolation calculated in each SWAT HRU as recharge to SWAT-MODFLOW at grid cell levels, and SWAT-MODFLOW calculated groundwater-surface interaction fluxes are then passed to the SWAT stream channel (Bailey et al. 2016). In other words, data of groundwater fluxes are passed between HRUs and SWAT-MODFLOW grid cells, and between SWAT-MODFLOW river cells and SWAT stream channels. More details of SWAT-MODFLOW linkage procedure is documented in (Bailey et al. 2016). The output of the model is therefore groundwater recharge, water table elevation and groundwater-surface water interactions. Water table elevation is defined as the elevation of the water table above a datum (Snyder 2008). In this study datum is the average sea level. Groundwater table elevation is referred to as water table in this study.

4.2.3. Input data preparation

The loosely coupled SWAT-MODFLOW requires datasets to simulate surface and subsurface flow processes (Table 4.1). The datasets used for modeling groundwater in the LRB with SWAT-MODFLOW include land use, soil, climate, Digital Elevation Map (DEM), daily streamflow data, and geology, depth to bedrock, and groundwater monitoring wells data as shown in Table 4.1.

Table 4. 1: Data and data sources used for groundwater simulation with SWAT-MODFLOW in the Limpopo River Basin

Data Type	Resolution	Source	Model
Climate	38 m	Texas A&M University Spatial Sciences: https://globalweather.tamu.edu/	SWAT
Digital Elevation Model (DEM)	30 m	Shuttle Radar Topography Mission (SRTM): http://earthexplorer.usgs.gov/	SWAT and SWAT-MODFLOW
Landcover map	30 m	National Geomatics Centre of China (NGCC): www.globeland30.org	SWAT
Soil		United Nation University-Institute for Water, Environment and Health (UNU-INWEH): http://www.waterbase.org/download.html/	SWAT
Geology map		South Africa Department of Water and Sanitation: http://www.dwa.gov.za/; Botswana Department of Geological Survey http://www.gov.bw/en/Ministries--Authorities/Ministries/Ministry-of-Minerals-Energy-and-Water-Resources-MMWER/Departments1/Department-of-geological-surveys/Department-of-Geological-Surveys/; United States Department of the Interior: https://catalog.data.gov/dataset/surficial-geology-of-africa-geo7-2ag	SWAT-MODFLOW
Depth to bedrock	250 m	Land-Atmosphere Interaction Research Group at Sun Yat-Sen University, China: http://globalchange.bnu.edu.cn/research/dtb.jsp and International Soil Reference and Information Centre (ISRIC) -World soil information: http://soilgrids.org/.	SWAT-MODFLOW
Groundwater table depth	1 km	Global Water Scarcity Information Service (GLOWASIS): https://glowasis.deltares.nl/thredds/catalog/opendap/opendap/Equilibrium_Water_Table/catalog.html.	SWAT-MODFLOW

4.2.4. Model set-up and application

The SWAT model used for this study was calibrated and validated for daily streamflow in the LRB (see Chapter 3). over 1979 to 2013 with five years (i.e 1979-1984) used as a warm-up period. The LRB was discretized into 871 subbasins and 13 059 HRUs. This calibrated model was adopted to simulate groundwater for 30 years (January 1984 to December 2013) with SWAT-MODFLOW. SWAT simulated percolation was used as groundwater recharge input into SWAT-MODFLOW.

MODFLOW grid of a total number of 179 250 (2000 x 2000 m) grid cells, 375 rows and 478 columns) for the LRB basin extend (Figure 4.2a). A total of 104 491 cells were classified as active while the remaining cells usually cells outside the area of interest were classified as inactive (Figure 4.2b). An inactive cell in SWAT-MODFLOW is a cell that is not part of the computational domain and hence ignored when presenting results. Cells over areas of the basin that have visible exposure of bedrock, known as rock outcrops, were set as inactive cells to exclude them from the simulations because these areas do not support water fluxes that would take place in non-rock outcrop areas. The rock outcrop constraint layer was created in ArcGIS (Figure 4.2b and c) prior to importing files into the model.

ModelMuse version 3.10.0.0 was then used to create input files for SWAT-MODFLOW. ModelMuse, is a graphical user interface (GUI) created for MODFLOW (Winston 2009). The created grid cells (i.e. 375 rows and 478 columns) was imported into ModelMuse, which was used to create a two layered MODFLOW model used in this study. The top layer was set to surface area elevations while the bottom layer was set to bedrock elevations below the surface. The values assigned to the layers were calculated with inverse-distance interpolation method with ModelMuse based on information of DEM and depth to bedrock (Figures 4.2d and e; Table 4.1). The stress period, defined as computational time interval for a MODFLOW was set at monthly time step for this study. The basin geological information was used to determine and assign values for hydraulic conductivity and specific yield in ModelMuse (Figure 4.2f). SWAT-MODFLOW was then run at a monthly time step for a period of 30 years (1984-2013). While SWAT was calibrated and validated for daily streamflow, SWAT-MODFLOW was not calibrated for all groundwater fluxes. To assess accuracy of the model, the simulated water table depth was compared with water table depth obtained from GLOWASIS (see Table 4.1).

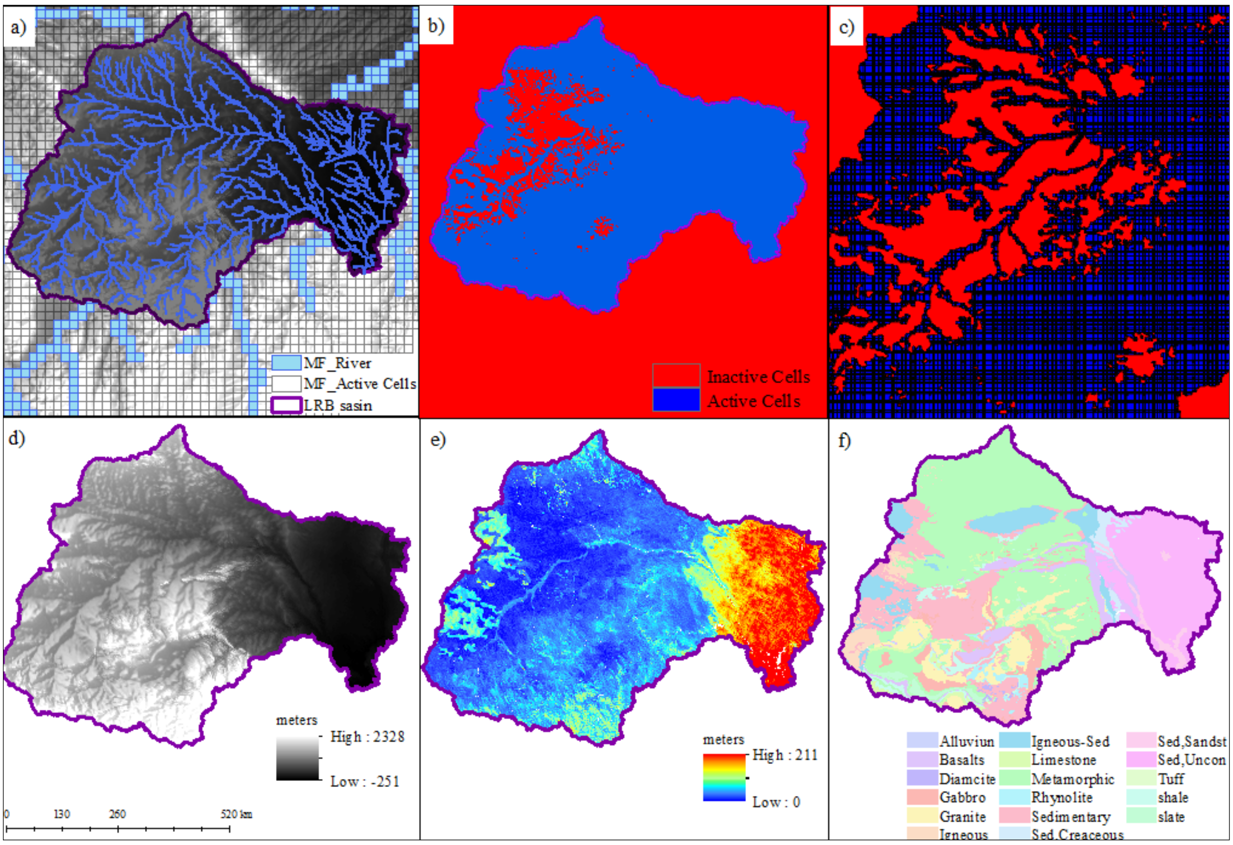

Figure 4. 2: Data of a) Stream and basin grid cells; b) Active and inactive cells; c) Inactive cells; d) DEM; e) Depth to bedrock; and f) Geological characteristics of the LRB for input into SWAT-MODFLOW.

4.2.5. BMP Implementation

Two LID practices were simulated in this study: rain garden (RG) and porous pavement (PP). The RG was implemented in residential areas of the catchment and each RG was assumed to receive storm runoff from 25% of a rooftop. Porous pavement was implemented on residential streets with low traffic. This means that highways were not considered for PP application. Details on the assumptions as well as LID practice (RG and PP) design and implementation for the simulation exercise were discussed in Di Vittorio (2014) and Di Vittorio and Ahiablame (2015). Estimation and classification of urban treatment areas and areas of BMP implementation for the Gaborone catchment was completed using Google Earth (see Figures 4.3a-d) and guidelines given in Di Vittorio (2014) and Di Vittorio and Ahiablame (2015). Google Earth was used to estimate areas occupied by rooftops and streets/roads in the study catchment. A total of 75 000 households was estimated for the Gaborone catchment translating to an area of 47 km^2 and a total of 43 km^2 road pavement was estimated for the catchment.

For each of the two LID practices examined, three implementation levels consisting of 25%, 50%, and 75% were simulated in this study. The two practices simulated were represented in SWAT-MODFLOW by modifying Curve Number (CN) values to estimate runoff. Ahiablame et al. (2012a; 2013) have outlined modified CN values to represent various LID practices. The original CN values of a rooftop and road without LID (98) were replaced by 85 and 70 with an estimated initial abstraction of 0.35 and 0.86 inches, respectively (Sample et al. 2001).

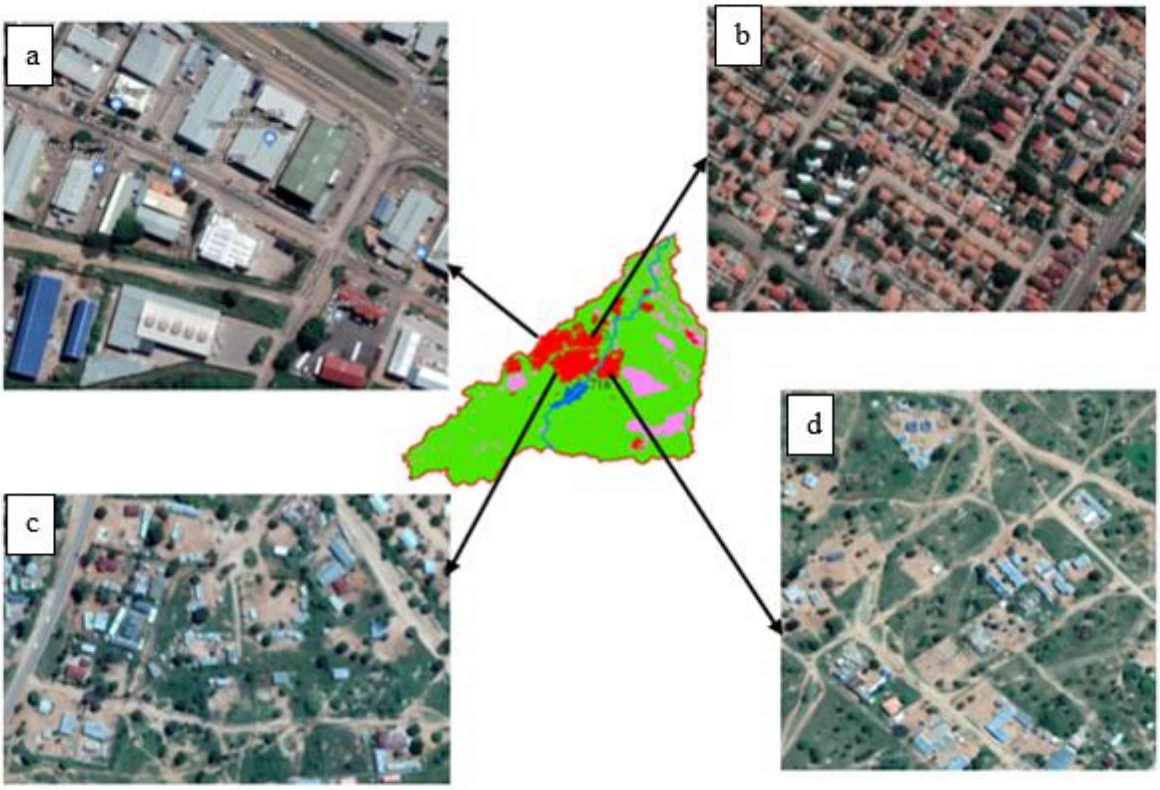

Figure 4. 3: Urban land use in the Gaborone Catchment includes a) Commercial/Industrial area; b) High density urban area; c) medium density urban area; and d) Low density urban area.

Table 4. 2: Area and level of LID implementation in the 1356 km² Gaborone Catchment

	Implementation Levels		
LID Practice	25%	50%	75%
Rain Garden (km²)	11.99	23.98	36.96
Porous Pavement (km²)	10.96	21.98	32.88

4.3. Results

4.3.1. SWAT-MODFLOW evaluation

The SWAT model developed and calibrated in the previous chapter provided recharge data for groundwater simulations with MODFLOW. Due to lack of field measurements of water table depth in the basin, MODFLOW was not calibrated for groundwater simulation. However, estimated water table death reported by Fan et.al. (2013) was used as surrogate to evaluate the model. Fan et al. (2013) used a combination of modeling, remote sensing, and field observations for some locations in the basin to create water table depth (Figure 4.4).

The simulated groundwater elevations with SWAT-MODFLOW in this study compare reasonably well with water table depth from Fan et al. (2013). Groundwater depths or groundwater elevations shallow for low elevation areas in the east and along the stream network of the basin while deep water depth were found in high terrain areas (Figure 4.4). Following this visual comparison, it appears that SWAT-MODFLOW simulations were acceptable for assessing groundwater resources in the LRB.

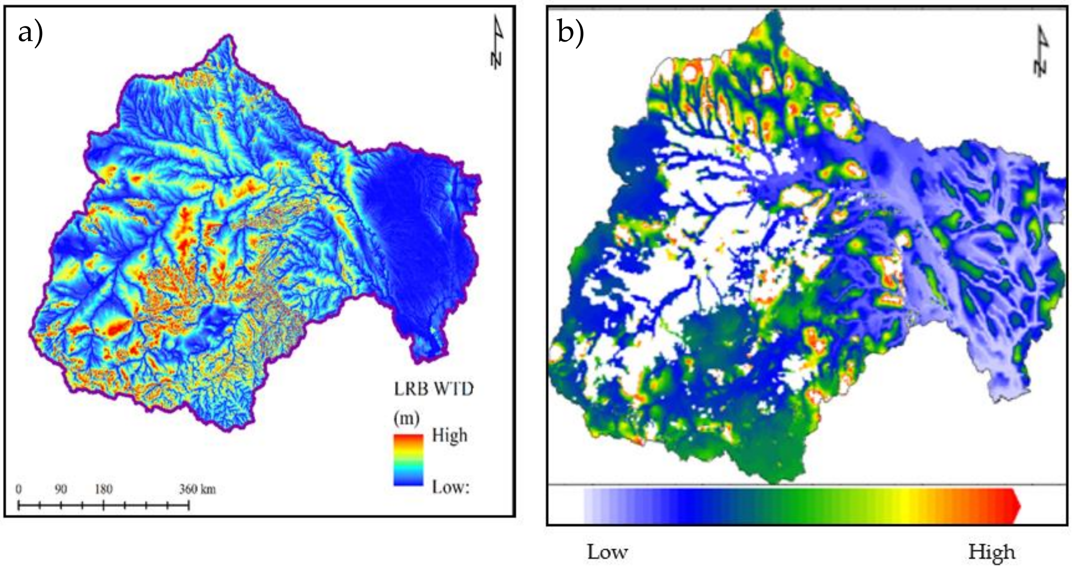

Figure 4. 4: Comparison between a) estimated water table depth obtained from Fan et.al. (2013) and b) simulated groundwater table elevation with SWAT-MODFLOW for the Limpopo River Basin.

4.3.2. Groundwater recharge

Average annual recharge (i.e., 1984-2013) varied from 0 to 530 mm, with a spatial annual average of 44.3 mm over the basin. Although there is no clear spatial pattern, the simulations suggest high recharge amounts at the outlet of the basin, which is south east and along the Limpopo River (Figure 4.4a). Generally, the simulation results show low recharge basinwide as most areas receive low annual average recharge between 0 and 120 mm.

Seasonal analysis of groundwater recharge shows a distinct variation between the seasons for the 30-year study period (Figure 4.5a). Groundwater recharge ranges from a minimum of 0 mm in winter and a maximum of 825 mm in summer. The highest groundwater recharge occurred during summer months followed by autumn, spring, and winter. This is understandable as 95% of rainfall in the basin occurs between October and April. Autumn recharge ranged from 0 to 296 mm with an average of 27mm over the basin. A range of 0 and 35.8 mm with an average of 3.2 mm was simulated for spring while winter recharge varied between 0 and 13 mm with an average of 0.3 mm during the study period. As mentioned earlier seasonal recharge follows rainfall pattern with high rainfall events attributable to summer and autumn and low rainfall events to winter and spring seasons. The model suggests high recharge in east and south of the basin during winter and spring coinciding with rainfall events in these areas during those seasons.

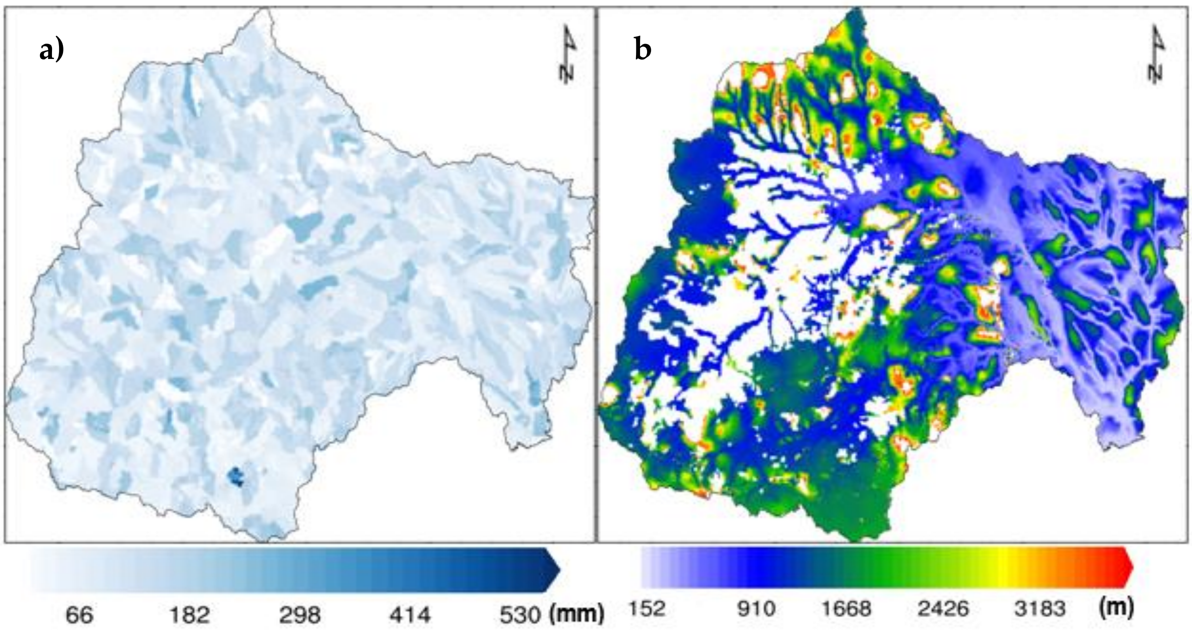

Figure 4. 5: a) Simulated a) average annual recharge (mm) and b) average annual groundwater table from 1984 to 2013 in the Limpopo River Basin.

4.3.3. Groundwater level

Average annual water table elevation (i.e., elevation measured from average sea level) for the LRB range between -1.9 m and 3183 m. High groundwater table elevations is simulated for high terrain areas which is in the north of the basin and the Drakensberg mountains located in the south (Figures 4.4b). While groundwater table elevation is low along the Limpopo River network and east of the basin, the depth to groundwater in these areas is shallow (Figure 4.4b). High water table elevations means the distance from the mean sea level to the water table is long while low water table means the distance is short. Similarly, groundwater table elevation is low at the outlet of the basin. In autumn, groundwater table elevation generally increases, thus resulting in shallow water table, followed by spring, winter, and summer months (Figure 4.5b; Figure 4.6). Even though summer have the highest recharge (see Section 3.1.1.), groundwater table elevation during summer months is generally lower than that of other seasons. The lower groundwater table means that the groundwater table is deeper compared to other seasons.

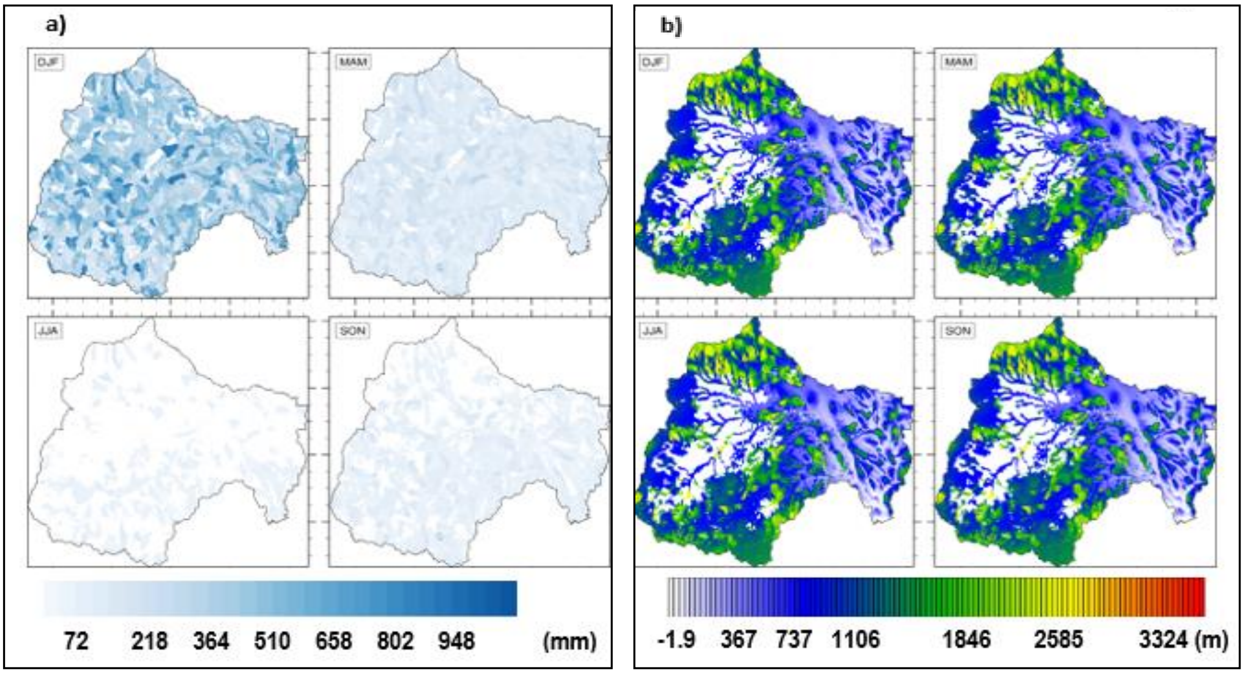

Figure 4. 6: Simulated seasonal groundwater a) recharge and b) table from 1984 to 2013 in the Limpopo River Basin. December-January-February (DJF) are summer months, March-April-May (MAM) are autumn months, June-July-August (JJA) are winter months as JJA for, and September-October-November (SON) are spring months in the Limpopo River Basin.

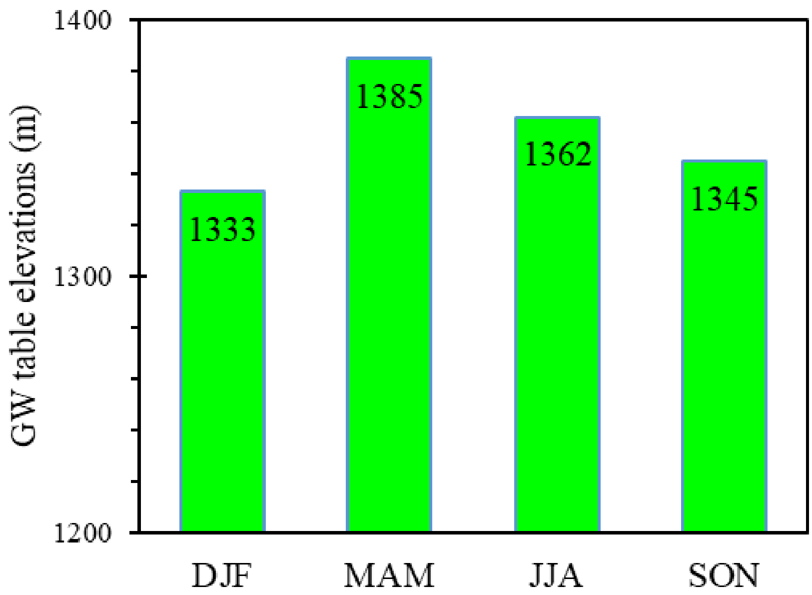

Figure 4. 7: Seasonal groundwater (GW) table from 1984 to 2013 in the Limpopo River Basin. December-January-February (DJF) are summer months, March-April-May (MAM) are autumn months, June-July-August (JJA) are winter months as JJA for, and September-October-November (SON) are spring months in the Limpopo River Basin.

4.3.4. Groundwater-surface water interactions

Monthly time series between 1984 to 2013 of representative locations of the basin are shown in Figure 4.7. Negative values indicate seepage from the streams to the aquifer while positive values indicate discharge from the aquifer to the streams. Annual discharge rate on one hand varies from 0 to 0.06 m^3/s with an average of 0.01 m3/s. Seepage on the other hand ranges from 0 to -1.15 m^3/s with an average of -0.003 m3/s. The simulation results show high seepage rates in east of the basin with an exception of the basin outlet while minimal seepage is simulated in the west (Figure 4.7). Of all the 13 selected locations, three locations (two in south and one in north of the basin) display positive values, suggesting groundwater discharge into the streams. All other locations show negative values, indicating that the streams seep to groundwater.

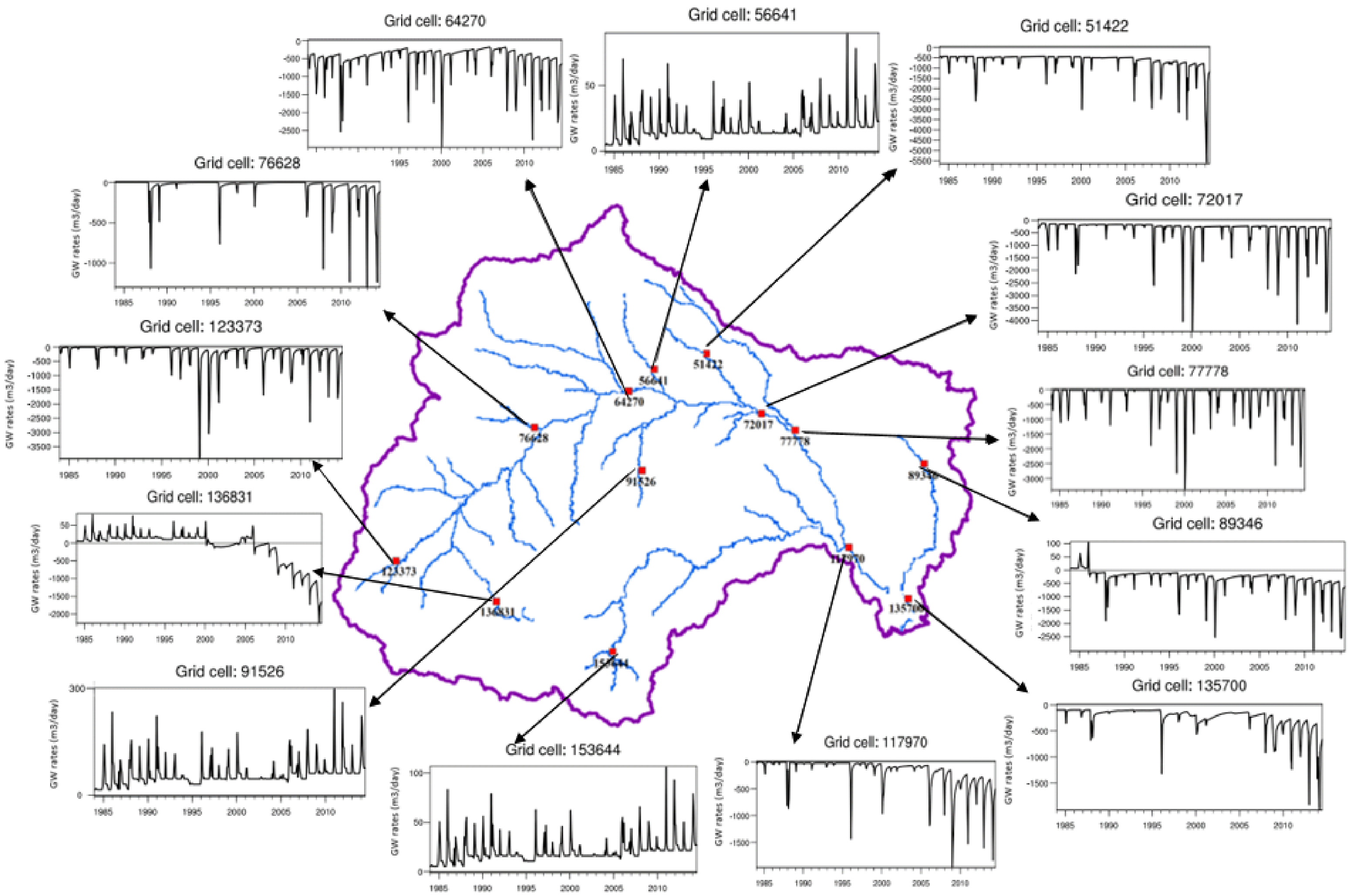

Figure 4. 8: Time series of groundwater discharge into Limpopo River channels for selected locations within the basin.

4.3.5. Groundwater recharge with implementation of selected LID practices in the Gaborone Catchment

Compassion of groundwater between the baseline (without BMP) and scenarios (with BMP) shows increased groundwater recharge for the Gaborone catchment ranging from 11.43 to 11.47 mm/year for RG and from 11.81 mm to 11.83 mm/year for PP (Figure 4.8). This translates to 0.38 to 0.75% for RG and 5.53 to 5.56% of groundwater recharge for PP, an equivalent of an average of 94 mm/year and 573 mm/year per hectare for RG and PP respectively. Simulation of PP resulted in higher recharge compared to RG, and recharge increased with increased implementation levels in the case study catchment (Figure 4.8).

Groundwater table level also increased in BMP implementation scenarios compared to the baseline simulated groundwater table. Overall, RG achieved the lower changes in groundwater table compared to implementation of PP during the simulation period. The incremental scaling of LID implementation resulted in increased water table from 1598.9 to 1599.2 m/year for RG and 1599.5 to 1600.2 m/year for PP (Figure 4.9). Increase from the baseline groundwater table ranges from 0.025 to 0.047% for RG practice and from 0.06 to 0.107% for PP. Although differences between the baseline and LID implementation may appear negligible in terms of depth, they are quite substantial when converted into volume. For example, 0.75 m difference between the baseline and the 75% RG implementation scenario translates into 7528 m^3 per hectare. This amount of water can support about 1300 people in a day in Botswana based on the Botswana water use footprint of 5.6 m^3/person/day. (https://www.watercalculator.org/footprints/water-footprints-by-country/).

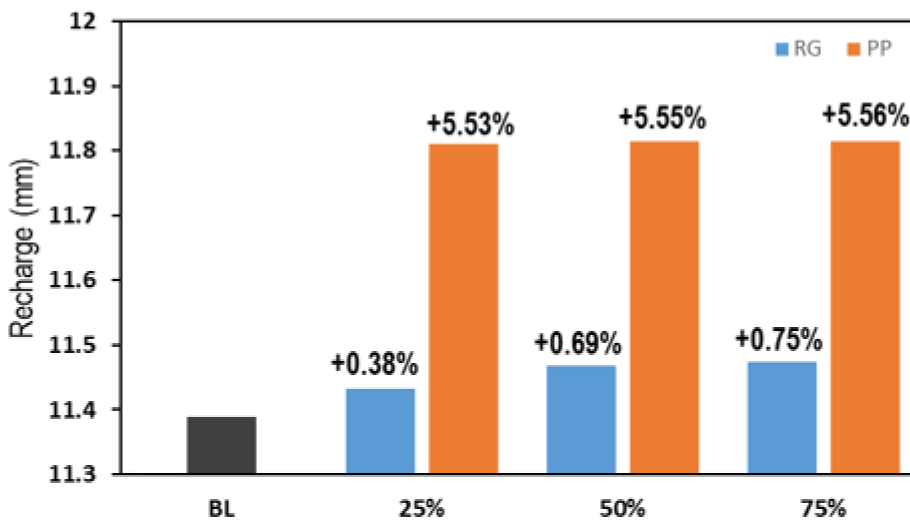

Figure 4. 9: Average annual groundwater recharge response with rain garden (RG) and porous pavement (PP) under different implementation levels compared to the baseline (BL).

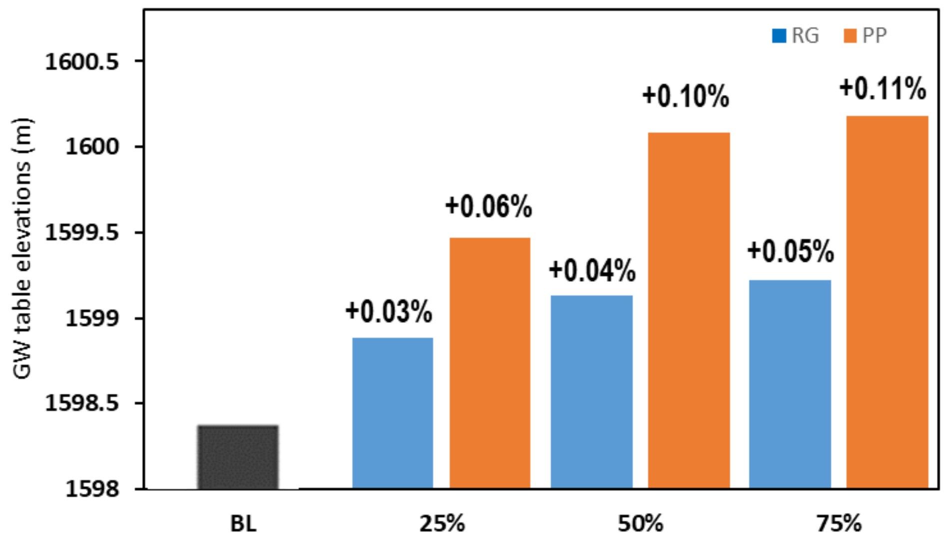

Figure 4. 10: Average annual groundwater table response with rain garden (RG) and porous pavement (PP) under different implementation levels compared to the baseline (BL).

4.4. Discussion

The study used SWAT-MODFLOW to simulate groundwater recharge and table for the LRB. Simulation results are comparable to groundwater recharge published by other researchers for the region. For instance, Xu and Beekman (2003 reported annual average recharge of 10 to 50 mm/year for the western part of the basin while a recharge of 2.4 mm/year to 69 mm/year was reported for south of the basin. These estimated recharge values represent 0.4% and 14% of the average annual rainfall over the basin (Baqa 2017). Groundwater recharge does not show any distinctive spatial pattern, but there are some locations in east and along the Limpopo River network that show high recharge. Even though recharge in the basin is mostly influenced by rainfall, it does not follow the spatial pattern of rainfall where east of the basin receives more rainfall compared to the west. Petrie et al. (2014) note that it is not normal rainfall events that really contribute to recharge but high and intense events. This study indicates that groundwater recharge is greater in summer and much less in winter, suggesting that recharge in the basin is highly dependent on rainfall (Xu and Beekman 2003, Snyder 2008, Manning et al. 2013, Petrie et al. 2014). Majority of the rainfall events in the basin occur during summer months compared to other seasons (LBPTC 2010, Petrie et al. 2014, Mosase and Ahiablame 2018). Recharge, is also affected by evapotranspiration losses, discharge losses into the streams, soil properties, and topographic features as well as geological characteristics of a region (Xu and Beekman 2003). Minimal recharge can still occur with high rainfall amounts if, for example, the underlying geological formations have a low storativity and a shallow aquifer (Le Maitre and Colvin 2008, Abiye et al. 2018).

The simulation results show groundwater level of the LRB is high in high terrain areas like north of the basin and the Drakensburg mountain in the south. East of the basin and vicinity of the Limpopo River and its tributaries appear to have low and shallow groundwater table. This pattern compares well with findings from other researchers. Fan et.al., (2013) showed shallow groundwater depths for low elevation areas in the east and along the streams while high and deep groundwater levels were found in the high terrain areas of the LRB. Snyder

(2008) also noticed the same similarities in water table and surface elevation in Portland, Oregon where shallow water table is found in low terrain areas and deep water table is found in high elevation areas. Groundwater table fluctuates continuously in response to changes in recharge or discharge from the aquifer since it is not a stationary surface. Seasonal fluctuations of the water table in the LRB are related to seasonal changes in groundwater recharge from rainfall, losing streams, irrigation, or from seasonal changes in discharge due to evapotranspiration or pumping of boreholes (Xu and Beekman 2003, Snyder 2008, Abiye et al. 2018). Groundwater level in the LRB is shallower during autumn following the rainy summer period while groundwater level decreases during summer in response to groundwater over-pumping during winter.

Surface water-groundwater interactions assessment shows that most of the LRB experience seepage into aquifers compared to discharge. This could be attributed to low rainfall occurrences in the basin, causing insufficient recharge to foster sustained groundwater discharge (Xu and Beekman 2003, Le Maitre and Colvin 2008, Hassan et al. 2014). Additionally, aquifer discharge to river systems depends on aquifer storativity and transmissivity that influence water tables groundwater discharge zones (Le Maitre and Colvin 2008). Most aquifers in the LRB are shallow but due to low rainfall and high evapotranspiration discharge is rarely experienced. Few locations in south of the basin seem to foster groundwater discharge into the rivers. This could be due to irrigation practices and dam facilities as well as waste water releases into the rivers in addition to rainfall (Abiye et al. 2018). These activities can result in high recharge which in turn could result in increased water table and discharge into the rivers.

Implementation of LID practices resulted in an increase in groundwater recharge and level. Implementation of PP resulted in more recharge than RG in the case study catchment. While information on LID impact on groundwater is very limited, studies showed that LID practices can reduce runoff with increased implementation levels (Di Vittorio and Ahiablame 2015, Liu 2015, Ahiablame and Shakya 2016). Reduction in runoff suggest a great potential for increased water infiltration, which will ultimately affect recharge and water table. The differences in the performance of the practices simulated might be attributed to the size of the areas treated with individual practices (Di Vittorio and Ahiablame 2015). For example, the areas for PP would capture more rainfall than RG areas which only received rainfall from 25% of the rooftop in this study.

4.5. Summary and conclusion

This study used SWAT-MODFLOW to characterise distribution of annual and seasonal groundwater recharge, groundwater level, groundwater–surface water interactions in the LRB from 1984 to 2013. The impacts of LID BMPs on groundwater recharge and water table elevations were also assessed for the Gaborone catchment as a case study in the LRB. The findings of this study are as follows:

- Annual average groundwater recharge, groundwater table elevations and groundwater exchange rate over the entire basin are 44 mm, 1406 m, and 0.04 m^3/s, respectively. Spatially, groundwater recharge does not show any distinctive spatial pattern although some locations in east and along the Limpopo River network show high recharge. Groundwater level is shallow in east and along the streams. Analysis of water fluxes between groundwater and surface water reveals seepage in most of the 13 groundwater-surface interaction locations examined, except three locations where groundwater discharge occurred during the simulation period.
- Seasonal assessment shows limited recharge and water exchange between groundwater and surface water in winter, and the decrease of water table in summer. The simulation results reveal high recharge and groundwater-surface water exchanges in summer season. Water table elevation are highest autumn depicting shallow water table levels.
- Implementation of LID practices suggest that infiltration BMPs can be used to increase groundwater recharge. In this study, the simulated LID

practices resulted in an increase of 0.38 to 0.75% for RG and 5.53 to 5.56% for PP for recharge, and 0.025 to 0.047% for RG and 0.06 to 0.107% for PP for groundwater table elevations compared to the baseline scenario.

Results from this study provide an insight about groundwater recharge in the LRB. The recharge of 150 mm/year simulated in this study corresponds approximately to 15% of annual rainfall. This suggest that replenishment of groundwater resources is not proportional to water demand and evapotranspiration losses in the basin. As suggested by the simulations, most of the streams in the LRB seep to groundwater, leading to deteriorating impacts on stream health ecosystems. Adoption of LID practices or infiltration BMPs can be a viable strategy to contribute to groundwater replenishment in the basin.

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5. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1. Summary and conclusions

The LRB in Southern Africa is faced with water scarcity problems. This research was carried out to assess water availability, risks and resilience in the basin using long-term rainfall, streamflow and EO data (soil, geology, and water table), GIS tools, and computer-aided models. The specific objectives of the study were to:

1. Assess spatial and temporal trends in rainfall and temperature using reanalysis grid-based data,
2. Parameterize a watershed model with a custom geospatial database for the study basin to quantify blue and green water availability for agricultural and domestic use, and
3. Build a loosely coupled surface water-groundwater model to assess recharge and groundwater-surface water interactions in the LRB

The first objective (Chapter 2) assessed long-term annual and seasonal variations of rainfall and temperature from 1979-2013 in the LRB. Rainfall and minimum temperature showed an increasing trend while maximum temperature showed a decreasing trend during the 1979-2013 period. Annual means of rainfall and temperature increased from west to east with an inverse pattern for the CV's for all studied variables. Seasonal means and CV's follow the same patterns as annual means for all the three variables examined. Seasonal means in rainfall and minimum temperature showed an increasing trend and a decreasing trend for most of the seasons except for winter season which showed the opposite in trends. Seasonal means for maximum temperature showed a decreasing trend for summer and autumn while spring and winter showed an increasing trend.

Objective 2 **(Chapter 3)** documents the spatial and temporal distribution of freshwater availability components and water sensitive areas in the basin. SWAT, in combination with ArcGIS was successfully applied to quantify the freshwater availability for the basin from 1979 to 2013. Estimates of blue water varied from 0 to 570 mm/year, 170 to 1,500 mm/year for green water flow, and 5 to 100 mm/year for green water storage in the basin. Temporal variability in freshwater components in the LRB revealed alternating episodes of wet and dry years, corresponding to documented drought and flood periods in the basin. East of the basin (roughly 20% of the total basin's area) appears to have abundant freshwater, while the remaining 80% is under water stress.

Objective 3 (Chapter 4) determines changes in groundwater recharge and water table levels in the basin. The results show an average recharge of 150 mm/year over the basin in this study, corresponding to approximately to 15% of annual rainfall. This suggests that replenishment of groundwater resources is not proportional to water demand and evapotranspiration losses in the basin. As shown with the simulations, most streams in the basin appear to seep to groundwater. This can lead to deterioration of stream ecosystems. The study shows that adoption of infiltration BMPs can be a viable strategy to contribute to groundwater replenishment in the basin. A case study of LID implementation in a small catchment of the basin reveals 0 to 6% increase in annual groundwater recharge and 0 to 0.11% increase in annual groundwater table elevations in the case study catchment.

Chapter 5 summarizes the findings of this dissertation and identify pathways to recommend for further studies in the region. This study provides an elaborated view of the distribution in time and space of both surface and groundwater and climate input in in the LRB.

5.2. Recommendations for future research

The methodologies used, and results presented in this study provide opportunities worthwhile pursuing in the future.

- Following the analysis of rainfall distribution, future studies should focus on patterns of rainfall intensity in the basin. This would provide useful information to better understand recharge patterns and potential occurrence of flooding and drought events.
- In terms of water resources components, future work should focus on quantifying the lag time between rainfall and water level response,

intermittent recharge and water table forecasting with regard to climate change.

- One major challenge encountered during this study is data scarcity from two angles. On one hand, the data were available but inaccessible. On the other hand, the data needed were accessible but have poor quality. An opportunity for future research in the region would be to consider intensifying data collection campaigns throughout the basin and developing protocols for data collection, quality assurance, and archiving. Data should be made available to researchers.
- Due to the importance of this basin in the livelihood of the people in the region, a network for research from across the world should be set up to develop a base-model using a flexible platform (e.g. web based) to study all aspects of water system dynamics in the basin.
- Further research should also focus on evaluation of LID techniques over different rainfall regions in the basin. Further, appropriate LID practices could be implemented and evaluated with respect to water supply provision and flood mitigation in the basin as well as provide field data for modeling.