Management of water resources and impacts of climate change in the Upper Pungwe River Basin

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Management of water resources and impacts of climate change in the Upper Pungwe River Basin

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Declaration

I, the undersigned, Anesu Dion GUMBO, declare that this dissertation submitted to the University of Venda for the degree of Master of Science (MSc) in Environmental Science in the Department of Hydrology and Water Resources in the School of Environmental Sciences at the University of Venda is my original work. It has not been submitted previously for a degree at this or any other university and all the sources that I have used or quoted have been indicated and acknowledged by means of complete references, and that this work has not been submitted to any other tertiary institution.

Signature............................. **Date.................................**

Dedication

This research work is dedicated to my aunt, Irene Mawoyo, who is currently receiving dialysis treatment. I know God will continue to bless and protect you in this battle with kidney problems. Regardless of your terminal condition, you continue to pray for me in my studies and my safety away from home. That is boundless love you have shown to me and I will forever be grateful. I also dedicated this research to my other two mothers, Joyce and Florence Mawoyo. The three of you have been in my educational journey since I began, and you have supported me spiritually, mentally and physically. It is your prayers that have brought me thus far because if it was just hard work alone, I know I would have not got this far because you know I am lazy. Whenever it got tough you guys were there to give me hope and I will forever remember our family anthem:

"Mhuri dzedu Baba"

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Abstract

Developing countries are largely characterized by rural-based communities often settled in headwater catchments whose livelihoods are dependent on natural resources available. As the climate changes, hydrological regimes are also altered affecting these communities. Assessing available water resources and their management becomes crucial to inform sustainable resources management, planning and development. This study quantified water resources in ten selected headwater sub-catchments of the Pungwe River Basin using the Pitman model in (SPatial And Time Series Information Model) SPATSIM_V3 and ten statistically downscaled climate datasets from the Climate Systems Analysis Group forced with RCP 4.5 and RCP 8.5 emission scenarios. Rainfall and potential evaporation data were used to setup the model while streamflow data was used for model calibration. The calibrated model parameters were used to project future water resources using stochastic rainfall ensembles derived from the delta change method in SPATSIM. Interviews were also carried out with natural resources managers to understand how headwater sub-catchments were being managed using a case of Pungwe Sub-Catchment. The interviews revealed that headwater catchment management is not yet incorporated in the management procedures of water resources in the sub-catchment, but the principles of integrated water resources management are being fully implemented. The Pitman- SPATSIM showed that water resources in the headwater sub-catchments to be adequate to meet ecological and human needs. Near-future (2020-2060) and far-future (2061-2099) projections using RCP 4.5 varied from the current period (1960-2010) with a percentage difference in mean monthly flow within the range of -9% to 7% for all sub-catchments. Under RCP 8.5, the near and far-future had similar projections, with both periods showing a minor reduction in water availability with a few sub-catchments showing a reduction as high as 71% (sub-catchment E72) which could possibly be attributed to streamflow datasets used for the calibration process. It was concluded that future water resources availability in the study area will be stable, with the key assumption that climate change is the sole variable driving water availability. To fully understand the water resources availability in the future, other factors such as land use changes need to be incorporated in the simulation of future water resources.

Keywords: ecological flow, integrated water resources management, SPATSIM, river processes, uncertainty, water security, headwater catchments, hydrological modelling, Pitman model.

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LIST OF ACRONYMS

AGRITEX	Agricultural Technical and Extension Services
ARA-Centro	Administração Regional de Águas
EMA	Environmental Management Agency
HCM	Headwater Control Movement
INAM	Instituto Nacional de Metereologia
IPCC	International Panel on Climate Change
IWRM	Integrated Water Resources Management
JWC	Joint Water Commission
MCM	Million Cubic Meters (x 10^6 m^3)
RDC	Rural District Council
RPC	Representative Concentration Pathways
PRB	Pungwe River Basin
PSC	Pungwe Sub-Catchment
PSCC	Pungwe Sub-Catchment Council
ZINWA	Zimbabwe National Water Authority

1: INTRODUCTION

1.1 Background

Safeguarding available freshwater resources has become a priority in regions that have been flagged to have declining water resources (Niang *et al.,* 2014; UN-Water, 2015). Southern Africa is one of the regions predicted to be worst hit by water shortages as a result of its low adaptive capacity to impacts of climate change (Niang *et al.,* 2014). Climate change, coupled with human activities such as intensive agricultural activities, mining, logging, fishing, and a growing population are the major challenges to sustainable water resources availability and general water security. Most future climate projections point towards a drier and more drought-prone climate in the region (Hewitson, 2017). With this grim future in mind, water resources need to be quantified and their future availability must be reliably simulated to aid in decision making for water, power, and food secure tomorrow. Projections of water resources availability depend on the use of environmental (hydrological models and climate) models, which are practical tools that generate data and information used for decision and policy making and development of management strategies.

However, these tools are abstractions of reality, making them prone to some uncertainties which affect the accuracy of predictions they provide. Notwithstanding this apparent problem, the scientific community continues to upgrade and update these tools using current information and technology to improve its utility. This research examined improved headwater management as a necessary requisite for sustainable water resources management in a transboundary catchment, the Pungwe River Basin (PRB), shared between Zimbabwe and Mozambique. Water is usually a shared resource and it is particularly important in transboundary catchments that water resources management benefits all involved avoiding the eruption of conflicts (Rieu-Clarke and Spray, 2006). The demand for water resources is forever increasing because of population growth, improved socio-economic development and climate change resulting in growing pressure especially on the inland freshwater systems (Barker *et al.,* 2007; Okello *et al.,* 2015). The coming decades are crucial for authorities to focus on water management.

The world population is projected to reach approximately 9.8 billion by 2050 and 11.2 billion by 2100 (UN DESA, 2017), and 50% of the world's population will be "water-stressed" by 2030. The challenges of diminishing freshwater resources and access have made sustainable management of water resources a priority in the face of a changing climate, requiring revision and improvement of management strategies. This study puts emphasis on headwater catchment management as an important management strategy to safeguard the integrity of an entire river basin. The headwater catchment of the PRB was chosen as a case study for examination in this research as it represents most of the problems that face water resources management today which include shared water stewardship, inclusive transboundary resource management, the upstream-downstream dichotomy of use and resource quality and quantity changes.

1.1.1 Headwaters

Rivers emerge as a result of the convergence of many small rivulets and wetlands whose waters join above and below ground going downstream (Meyer *et al.,* 2003). River characteristics are influenced by the state of the streamlets that contribute to the flow. If the flow quality from each streamlet is affected by poor management policies, they will collect in the river formed. As such, good headwater catchment management promotes and maintains the integrity of the whole river system. The contribution of a headwater streamlet along a river introduces change along the river depending on what activities are occurring in the headwater catchment contributing to the river. This means that a single tributary not managed well has the potential to change the hydrology of the river. Headwater catchments are often unmarked on maps, yet their health is very crucial to the integrity of the entire river. They provide important connections between the riverine and the terrestrial systems. Headwaters are the source regions for a basin's water resources, a place where water flow lines originate (Haigh, 2010). These are areas with no upstream contribution of flow, and they are generally located at the highest elevation of the stream. They provide many benefits to the whole stream, as they are often groundwater recharge zones (Ohio Environmental Protection Agency, 2015).

Catchment management recognizes headwater catchments as important components of ecosystems and landscapes (Danehy and Johnson, 2013). If the flow quality and quantity of a headwater stream are compromised in any way, downstream areas are ultimately affected (Storey *et al.*, 2011). As such, the importance of headwaters is significant and needs to be understood and appreciated. The health of headwater catchments is influenced to a large extent by management policies. These catchments are generally geographically isolated due to their location in remote, densely forested and, usually, hard to reach areas (Gomi *et al.*, 2002). This gives these areas their unique identity of holding some of the rarest and most diverse animal and plant species, influencing significant ecosystem goods and services. Species and natural interactions are key to nutrient generation. The nutrients generated are transported from the headwaters to the river channel. This process ensures the sustainability of other riparian and riverine ecosystems along a river channel (Meyer *et al.*, 2003). Headwater catchments support many processes which have a direct influence on the quality and quantity of water resources in the river system. Often, the importance of a healthy river system goes unnoticed until such tragedies as a prolonged drought prove how important a well-managed catchment is.

The location of headwater catchments in forested areas implies that they are responsible for providing habitat for aquatic invertebrates, fish and amphibians. Combined with the surrounding environments, these areas provide a good environment for organic matter deposition, storage, processing, and transportation to downstream areas (Wallace and Eggert, 2009). Headwater catchments provide ecosystem services through, amongst others, nutrient retention and transformation, hydraulic retention, sediment retention and thermal refuge (Wallace and Eggert, 2009). Processes that occur upstream are linked to the downstream communities. These linkages need to be understood so that the importance of these areas can be recognized and incorporated into water management structures. The management of headwaters is different from that of large watershed systems because of the different processes that occur in these areas. When the health of a headwater catchment is compromised, water flow is disrupted, algal blooms can become prominent resulting in reduced biodiversity and the area may become prone to flooding (Dallas and Rivers-Moore, 2014).

The fact that in a river basin, headwater catchments are scattered and/or found in very remote reaches may imply that their roles and the links that exist between them and the downstream communities are underestimated and not clearly understood within water management institutions and policies (Nepal *et al.,* 2014). Their individual areal coverage is often significantly small that the dominant vegetation can easily absorb these areas making them less obvious (Danehy and Johnson, 2013). However, cumulatively these areas have a significant influence on water resources availability, the role they play to ensure that the river system is maintained (Meyer *et al.,* 2003). The importance of headwater catchments inadvertently implies a necessity for proper management practices to be implemented. This is particularly true in Africa, where the implementation of proper water resources management principles is still difficult to execute. This study selected and assessed ten headwater catchments located in Upper Pungwe to investigate how climate change can potentially affect water resource availability.

1.1.2 A changing climate

Climate change is a major challenge for natural resources management (Barker *et al.,* 2007; Pohl *et al.,* 2007; Andersson *et al.,* 2011; Faramarzi *et al.,* 2013). The Intergovernmental Panel on Climate Change (IPCC) report of 2014 showed that near-surface temperatures have increased by 0.5 °C or more during the last 50 to 100 years over most parts of Africa. This translates to an increase in livelihood vulnerability as a result of these anomalies. In areas that are poverty-stricken, climate change magnifies the problems that are already experienced (Andersson *et al.,* 2011). The study area is predominantly rural with the inhabitants dependent on rain-fed agriculture which is affected by changes in rainfall patterns. Zimbabwe is susceptible to droughts and periodic floods due to climate variability. Recent droughts, floods, and extreme weather events have contributed to food shortages, infrastructure damages, and natural resources degradation (Chipindu, 2008). Climate change affects food production, land use, management of water resources and forests, leading effectively to food security issues. In Zimbabwe, agriculture is the backbone of the economy and will be greatly affected by frequent harsh weather. It is, therefore, important to re-emphasize that the integrity of headwater catchments is threatened by both human-induced as well as natural changes.

1.1.3 Hydrological modelling in water resources estimation

Hydrological systems are highly complex environmental realities and to understand them, some abstraction is necessary (Xu, 2002; Zhang *et al.,* 2016). Thus, in this study it was necessary to use models of catchment behaviour and response to rainfall input. The reason for using hydrological models is to reveal the main elements of the physical environmental process, their combination into a simple or comprehensive tool and the importance of this assembled tool in solving typical practical problems related to water management (Beven, 2001). A physical model can be used to represent a system but often the system is represented mathematically using equations that fulfill the laws or concepts that appropriately describe the behaviour of the system (Larsen *et al.,* 2016). Water management is based on what the decision-makers believe, and hope would. Such decisions could either be backed up by qualitative or quantitative scientifically-sound information.

There is a need to quantify the historical and/or present-day available water resources in an area, and their projected future availability. Such an assessment would help to understand how changing human activities and climate, including the uncertainties related to them, are affecting the resource. The incorporation of relevant uncertainties should increase the value of the model generated data and/or the information and increase the confidence that can be expressed in the use of model results (Dobler *et al.,* 2012). It becomes a crucial part of incorporating uncertainty that it be reduced to produce better results. This research used the Spatial and Time Series Information Modelling (SPATSIM) version of the Pitman rainfall-runoff monthly hydrological model (Pitman, 1973; Hughes *et al.,* 2006) to quantify the water resources present in the catchment.

1.2 Statement of the Problem

Headwater catchment management in southern Africa needs to be promoted, especially for countries like Mozambique and Zimbabwe to illustrate their importance. Researches such as Magrin *et al.* (2007), Andersson *et al.* (2011) and Marengo, *et al.* (2017) have predicted that water resources are diminishing as a result of climate change, a phenomenon that has not been fully understood and incorporated into the natural resource management strategies of both Zimbabwe and Mozambique. Headwater catchments are highly sensitive to any changes that they may be subjected to, thereby affecting the services offered by the ecosystem of the entire river basin. This makes the case of Pungwe headwater catchments interesting in that much of the productive headwater catchments are in Zimbabwe. The transboundary nature of this river brings about a lot of management problems that require an integrated water resources management (IWRM) approach for effective and sustainable water and natural resources stewardship.

The headwater catchments are in rural setups whose communities are heavily dependent on natural resources available for their daily survival (Jansky *et al.,* 2006). Consequently, any alterations to the hydrologic regimes by human activities and climate change in the headwater catchments would be transferred to Mozambique affecting the riparian communities. Proper and reliable quantification of available water resources in the area will provide a solid hydrological basis in the basin. Such knowledge will promote integrated water resources management and an appreciation of the upstream-downstream linkages. This will hopefully lead to improved management of the headwater catchments and shared responsibility in the transboundary basin where nearly 95% of the water users are downstream in Mozambique which is relatively drier than the Zimbabwean part (SWECO, 2004). Climate change is predicted to affect water availability and without scientific research to quantify the extent, development of the area and livelihood enhancement of all the communities that depend on the river will be put at risk.

1.3 Research Questions

The study focused on the following research questions:

1. How are the headwater sub-catchments understudy being managed by relevant authorities?
2. What is the impact of climate change on water resources availability of the headwater sub-catchments of the Pungwe River Basin?

1.4 Aims and objectives

The main aim of this study is to evaluate management and climate change impacts on the availability of water resources (current and future) in the headwater sub-catchments of Pungwe River Basin (PRB) towards integrated water resources management, a transboundary river basin using a chosen hydrological model that will be driven by projections from a suite of climate models. To achieve this aim, the following specific objectives were formulated:

- To assess the management of the headwater catchments by the responsible institutions in the study area, and
- To assess the effects of climate change on current and future water resources in the headwater catchments of Pungwe River Basin (PRB) using the Pitman-SPATSIM based on projected data/information from regional climate models under high and low mitigation scenarios.

1.5 Justification

Several studies have been carried out in PRB by organisations and researchers on the status of water resources in the basin, stakeholder participation as well as climate change impacts (e.g. SWECO, 2004; Swatuk and Van Der Zaag, 2010; Andersson *et al.,* 2011; Nyikadzino *et al.,* 2014; Terink and Droogers, 2014). These studies examined fundamentals of sustainable water resources management in this transboundary catchment, but nothing much on the impacts of headwater resources management on the entire basin. This study was motivated by the fact that the natural environment is not static, and there is a need to improve the understanding of the physical (and human) processes that occur upstream of rivers and how these processes affect downstream areas. Although headwater catchment management has been on the agenda (Jansky *et al.,* 2003; Dodds and Oakes, 2008), their management has not been topical in Zimbabwe. This gives reason to study these areas for their proper management, especially in a changing climate.

The Pungwe River cover parts of Zimbabwe and Mozambique, with Zimbabwe occupying about 5% of the basin area but contributing about 30% of the water resources (SWECO, 2004). Poor management of the headwater catchment has the potential to adversely affect downstream users, creating conflicts between the two riparian countries. Southern Africa has been experiencing a decline in water resources availability and subsequent access by riparian populations (Kapangaziwiri *et al.,* 2012). Three factors have been singled out as the main reasons for the decline which are climate, population growth, and management (Granit, 2000). There is a need to understand the complex upstream-downstream hydrological linkages for the management of water resources in the catchment. The change in the physical environment upstream of the catchment due to changes in land-use practices, climate change, and variability, influence the availability of water resources downstream.

1.6 Organizational structure of the research

Chapter 1 is the introductory chapter of this research. It explains the background of this study shading light to why this research was carried out and what it hoped to achieve. Chapter 2 reviews the literature on headwater management in a changing climate. Chapter 3 provides an overview of the study area. Chapter 4 describes the main components of the Pitman-SPATSIM – especially its structure and parameters that are of importance for simulation of water resources and the model calibration process. Chapter 5 provides an assessment of the management of headwater catchments in PRB, especially concentrating on the current management of the resource and challenges faced. Chapter 6 presents and discusses the quantification of current and future water resources in the headwater catchment of PRB. The key findings, conclusions and recommendations of this dissertation are provided in Chapter 7.

2. REVIEW OF RELEVANT LITERATURE

2.1 Introduction

Sustainable headwater management has become an important approach that can influence socio-economic development in poor and marginalised communities. This is especially so when the possible adverse impacts of a changing climate are considered. Thus, it is always instructive that the potential impacts of climate change and/or variability be considered when developing water management policies (Chikodzi *et al.,* 2013). The effects of climate change affect hydrologic processes that can alter water resources availability. This chapter reviews work done by several authors on the management of headwater catchments and the potential effects of climate change on water resources availability.

2.2. Definition of a headwater catchment

A headwater is defined as a tributary stream of a river close to or forming part of its source. As such, the source or headwaters of a river or stream is the furthest place in that river or stream from its estuary or confluence with another river, as measured along the course of the river. Rivers, including headwaters, provide many important ecological functions to downstream systems and can be broken down into three major categories:

- ✓ Hydrologic:
    - Provide a source of water
    - Influences the timing and response of water
    - Allows for direct interactions at the groundwater-surface water interface
- ✓ Chemical:
    - Initially characterizes the chemistry and quality of water entering streams
    - Important source of nutrients
- ✓ Biological:
    - Are characterized as areas of high productivity
    - Increase of local and regional biodiversity
    - Increases ecosystem stability

Based on stream ordering (e.g. Strahler, 1952) studies, headwaters generally consist of the first order to third order streams. This is the definition taken in this study. Headwater catchments are, thus, small in size as they comprise the first lower order streams. Small headwater catchments are found throughout all river systems draining about 70 to 80% of the total basin area, making them important determinants of the characteristics of the river system.

2.3. Headwater catchment management

Headwater management as a concept was introduced in 1989 at the International Conference on Headwater Control held in Prague, Czech Republic (Haigh, 2010). This conference produced principles of management and protection of headwaters. It gave birth to the Headwater Control Movement (HCM) founded by Dr. Josef Křeček, whose mandate is to promote sustainable headwater management practices through research, environmental reconstruction and conservation, and designing better management policies that cater for headwater management (Haigh, 2010). The idea that drives this movement is that when the headwaters of a river receive proper management practices, fewer problems are transported downstream (Jansky *et al.*, 2003). It acknowledges that for proper management of headwater catchments that benefits both the environment and communities, management policies should focus on conservation and restoration of the headwaters while empowering the locals (Kaplan *et al.*, 2008). It also relies on a coalition of ideas from the researcher, environmental practitioner, and the policymaker to come up with improved approaches for good water resource management (Haigh *et al.*, 2005).

The headwater catchment control acknowledges that human activities in headwater catchments pose a threat to the headwater environments through unregulated utilization of natural resources which leads to headwater environment decay. With climate change, the decay is even worsened. Therefore, there is a need to intervene in the management and protection of headwater catchments for sustainable water resources management (Haigh, 2010). Research in headwater management is expected to be practical, ever-evolving, comprehensive, integrated and sustainable for the benefit of the livelihoods that depend on them (Danehy and Johnson, 2013). The ability of headwater catchment management to integrate with many different disciplines requires research to be conducted regularly to keep up with discoveries from other disciplines that might affect the management of headwater catchments (Haigh, 2005).

Institutional development is of importance, especially in developing nations (like Mozambique and Zimbabwe) where the concept of headwater management is not a priority and requires policy change to achieve sustainable headwater catchment management. Local communities need to participate in the management and protection of their environment and encourage natural resource utilization that promotes the development of community-based, environmentally informed and holistic local management administrations (Frone and Simona, 2011). Empowerment of local communities is one of the valuable outcomes of good headwater management policies. Headwater areas are usually located in isolated, hilly areas (Meyer *et al.,* 2003; Haigh, 2010; Danehy and Johnson, 2013; Nepal *et at.,* 2014). Because of this, communities located in these areas are usually rural and need self-sustaining systems to enhance their livelihoods and the environment (Haigh, 2010).

Successful management of headwater catchments needs organized implementation of solutions through the integration of all environmental management organizations and communities that are present to come up with sustainable policies to manage their headwaters (Haigh, 2010). Environmental education plays a pivotal role in changing the mind-sets of people in the management of headwater catchments as well as those utilizing them. Furthermore, environmental knowledge will enable communities to understand the importance of headwater catchments in water resources management and be able to incorporate them into water resources management.

2.4 Management of catchments and water resources management

Freshwater resources have been constantly threatened by an increasing human population, pollution of rivers, climate change and changes in land-use practices (DeFries and Eshleman, 2004). The threat on freshwater resources resulted in the creation of a management approach that promotes the coordinated development and management of water, land and other related resources to maximize the resultant economic and social benefit in an equitable manner without compromising the sustainability of vital ecosystems (Global Water Partnership and International Network of Basin Organization, 2009). This is the definition of integrated water resources management (IWRM), a management approach that was developed to fight the increasing pollution and scarcity of freshwater resources. Since its inception as a management approach to water resources management, IWRM has moved to a more modernized concept of integrating use, demand, the environment and stakeholders in its management approach (Frone and Simona, 2011).

2.5 Integrated Water Resources Management

The efficient and effective management of freshwater resources has generally been agreed to be reached at river basin or catchment level. This is because there is a need to manage and account for all the aspects of the hydrological cycle. Using a catchment-based approach, a balance is achieved between the inter-dependent roles of resource protection and resource utilization (Ashton, 1996). This approach uses the topographically delineated area drained by a river and all its tributaries as the boundary for water resources management. It encourages collaboration amongst specialists in varying disciplines of natural resources management giving a transdisciplinary approach to the analysis of a watershed (Wang *et al.*, 2016). IWRM incorporates linkages between the biophysical and socio-economic environments because of its transdisciplinary approach to water resources management providing research that is holistic and relevant to practical world issues (Wang *et al.*, 2016). Such linkages can be seen through upstream-downstream linkages and those linkages that exist among natural resources management sectors in a catchment or in a transboundary river basin (Nadeau and Rains, 2007; Nepal *et al.*, 2014).

Environmental management studies and strategies are affected by many uncertainties that can influence policy implementation. IWRM as an approach recognizes the need to incorporate these uncertainties in decision making (Larson *et al.*, 2015). IWRM has brought to the attention of decision-makers the importance of other natural resources in a watershed and not just the hydrology alone (Acheampong *et al.*, 2016). This approach to environmental management balances human and environmental needs maintaining the ecosystem and biodiversity. Sustainable headwater management requires IWRM as a management approach as it captures all the components required in the management of a headwater catchment such as the need for adequate research, development of natural resources management institutions and empowering the locals through sustainable utilization of the available resources. This is an important tool in developing a management framework for a headwater catchment.

2.6 River management approaches in the Pungwe River Basin

The management of water resources in the PRB falls in the hands of the Pungwe River Basin Commission established through the Joint Integrated Water Resources Management Strategy developed between 2002 and 2006 and came into effect on February 2006 as a collaborative initiative between Mozambique and Zimbabwe (Earle and Malzbender, 2006). Though the Joint Water Commission (JWC), as it is commonly referred to, is responsible for the management of PRB, Zimbabwe National Water Authority (ZINWA) and *Administração Regional de Águas Centro* (ARA-Centro) manage the daily water affairs of Zimbabwe and Mozambique respectively (Virtanen, 2005). The management of water resources is guided by the Water Act and the ZINWA Act on the Zimbabwe side, and by the Water Law 16/91 on the Mozambique side. The effectiveness of these laws, though founded on the same IWRM principles, is dependent on how each country administers them. Such differences in the administration of these IWRM principles by the different countries have the potential to bring about conflicts especially if upstream management is not carried out sustainably. The JWC ensures the cooperation and integration of the different legislation in both countries implementable for the management of PRB.

2.7 Potential effects of climate change on water resources

2.7.1 Climate Change

Two ways in which a change in the climate can occur is through human activities, termed anthropogenic climate change, and that change which occurs naturally (UNEP, 2009). Changes caused by human activities have been seen to be more rapid than those due to natural change. According to Andersson *et al.,* (2011), climate change brings about general air and sea surface temperatures increase, an increase in the intensity and frequency of extreme weather events, changes in rainfall patterns and rising sea levels amongst other changes. These may impact negatively on both the human and natural systems. What has been used interchangeably, or confused, in literature is climate change and global warming even though the two are closely related.

Climate change is that deviation from the mean regional climate statistics (temperature, rainfall, extreme weather events, humidity) over a long period of time which is generally agreed at thirty years and more (Luo *et al.,* 2018). Werndl (2015) defined climate change as a slow and gradual shift of average climate conditions which is a very difficult phenomenon to detect and trace. Global warming, on the other hand, is an increase in the global average temperature over a long period of time (Lewis *et al.,* 2017). Global warming is measured using temperature only, the other parameters that characterize a climate are not taken into consideration. Global warming and climate change are related in that as the temperatures increase this affects hydrological processes such as evapotranspiration and air current movements altering the hydrological regime of an area through intensification and frequency of weather extremes and increased seasonal variability.

The study of climate change requires the knowledge of climate variability; an approach many climate change researchers have adopted. Climate variability results from deviations in the average state and other climatic statistics, such as standard deviations or occurrence of extremes, amongst others, on all temporal and spatial scales beyond those of individual weather events (Werndl, 2015). These variations could be a result of natural internal processes within the climate system or from variations in natural or anthropogenic external forces. Inter-annual climate variations have the potential to disrupt seasons and can have detrimental effects on communities (Ray *et al.,* 2015). Barker (2007) stated that the frequency and intensity of extreme weather events as well as climate variability are expected to increase in some areas in the future. Our day to day state of the atmosphere and its short-term (from hours to a few weeks) variations in parameters such as temperature, humidity, and rainfall are what is known as weather (Werndl, 2015).

2.7.2 Impacts of climate change on water resources in southern Africa

Callaway (2004) describes the African region as being highly vulnerable to climate change because of its low adaptive capacity to the changes and its vulnerability. Within Africa, the literature reveals that the southern African region is one of the most vulnerable regions of Africa (IPCC, 2007b). Climate change studies have shown that water resources are at the epicentre of projected climate change impacts. The observed climate changes for the past century suggest that if the same trend continues, the potential impacts on water resources are likely to increase in magnitude, frequency, and severity (IPCC, 2007). Given the already large spatial and temporal variability of climatic factors in southern Africa (Gallego-Ayala, 2011), climate change impacts on water resources are likely to be more pronounced in the future than previously foreseen (IPCC, 2007b).

The region has seen changes in water resources availability for many decades with changes in reduced groundwater resources, deterioration in the quality of water, variations in rainfall occurrences and increased or lowered rainfall (Niang *et al.,* 2014). Climate change, thus, accelerates the rate at which these changes occur which affects communities' ability to respond to these changes. The uncertainties associated with understanding the changes in climate patterns give water managers and planners challenges in trying to cope with the changes. Modelling work in southern Africa (Andersson *et al.,* 2011; Mujere and Mazvimavi, 2012) has been carried out in trying to quantify the magnitude of changes likely to seen in the future.

Climate change impacts on water resources will have both direct and indirect effects on the socio-economic and the biophysical environments (Arnell, 1999a; Bates *et al.,* 2008; Kundzewicz *et al.,* 2008; Rutashobya, 2008; Schulze, 2005). Already, this is evident in several sectors, such as agriculture (Crane *et al.,* 2011; Pielke *et al.,* 2007; Vermeulen *et al.,* 2012), health (Bunyavanich *et al.,* 2003; Gage *et al.,* 2008), ecosystems and biodiversity (Eriksen and Watson, 2009) and energy generation (Magadza, 1995, 2000; Yamba *et al.,* 2011). Reduction in water resources will have a bearing on these sectors which affects their livelihoods, plunging some communities into absolute poverty. This accentuates the inequalities between the 'haves' (developed nations) and the 'have nots, (third world countries) as well as within communities. Trying to eradicate extreme poverty, one of the millennium development goals (MDGs) would, therefore, become a mammoth task to achieve.

2.7.3 Adaptability, resilience and the vulnerability of African natural systems

In areas that are poverty-stricken, climate change magnifies the difficulties that are already being experienced such as hunger, lack of access to clean water. This is true for many regions of Africa which are affected by poverty and disease outbreaks. Many communities in Africa have limited adaptive capacity to cope with changes in climate patterns and with any variations from their normal seasons, serious consequences may be experienced in such areas (Ziervogel and Calder, 2003). While global warming is attributed to the emission of greenhouse gases into the environment; Africa, though with a small carbon footprint contribution, is the most seriously affected continent by the effects of a changing climate. Predictions made suggest that radical temperature and rainfall shifts will take place in Africa, with southern Africa and north of the Sahara getting drier (Toulmin, 2009). As climate change intensifies so will the problems faced in Africa mainly because of its inability to adapt to, and mitigate, the effects of a changing climate.

In the context of uncertainty, management that accounts for high rates of changes is what is demanded for the region of Africa (Niang *et al*., 2014). Building resilience at the household, community and regional levels is a very crucial response to climate change. This is particularly true for people in Africa who are already living in poverty and at the mercy of the natural environment to be able to respond and recover from disasters with swiftness and agility. The issue of climate change needs to be made a priority in national agendas, eradicating poverty in communities and the information be made readily available to be people. These have been the key elements in building resilience.

2.8 Global climate models and regional climate models

The prediction of past and future climate scenarios depends on Global Climate Models (GCMs) (Andersson *et al.,* 2011). A number of GCMs are recommended by the Intergovernmental Panel on Climate Change (IPCC) because of their robustness in the prediction process (Pohl *et al.,* 2007).

Hydrological models are used together with GCMs and future greenhouse gas emission scenarios to simulate impacts of climate change on water resources availability (Viola *et al.,* 2015). GCMs are, due to their coarse resolution, limited in their ability to represent detailed topography and small-scale processes, which brings about biases in the prediction of rainfall and temperature (Wang *et al.,* 2013). To achieve finer resolution from GCMs, downscaling techniques are employed and the most common techniques used are statistical and dynamic downscaling approaches (Andersson *et al.,* 2011). Regional climate models (RCMs) are climate models that are used for area-specific studies.

They are mainly used for model development, the understanding of climate processes that occur at the regional level, studies that analyze the sensitivity of regional climate upon changes and regional climate change studies (Andersson *et al.,* 2011). Data of good quality and quantity are required in climate change studies with 30 years of data being the generally agreed upon norm. This has been the common practice in climate studies to obtain the climatological values but however, new research is coming up with what is now termed "new normal", which is usually used to refer to extreme events which have become "normal" (Lewis *et al.,* 2017).

2.9 Uncertainty in estimating water resources

The understanding of regional climate is affected by the existence of uncertainties which affect the climate modelling process. Climate models are an abstract of the real earth systems and are limited in their ability to account for every process that occurs in the natural world. This brings about some degree of doubt to the results they generate. Decision making based on the results generated from environmental models for effective policy implementation, therefore, requires uncertainties that are present during the modelling process to be acknowledged, identified, and quantified scientifically. This process enables decision-making to be based on a sound knowledge of the underlying conditions that produced such results. It is, however, difficult to get rid of all the uncertainties that affect the modelling process, but their sources should be acknowledged (Beven, 2012). Good modelling practice goes beyond acknowledging uncertainties and tries to quantify the uncertainties within the modelling process, playing a crucial role in generating comprehensive information for decision-making. There are three major sources of uncertainty according to Northrop and Chandler (2014) which are:

a) The choice of climate model,
b) The choice of emission scenarios, and
c) The internal variability of the modeled climate system.

The choice of the climate model is based on the objectives that the research intends to address. As such, the choice of the climate model, if it does not address the aim of the study then the results that will be produced will not be reliable, bringing about uncertainty. The selected climate models should, as a starting point, be able to sufficiently reproduce the recorded historical climate. Emission scenarios that are given by the IPCC change with time and these are crucial in water studies. Emission scenarios that are most likely to occur in an area (basing on the amount of carbon released in that area) should always be used to avoid uncertainty with the results. The climate system understudy should account for internal variability that is likely affect the results of the modelling process. Accounting for all sources of uncertainty is very difficult but it is becoming a good hydrological practice over the past decades to increase give confidence in the model-generated data that is used to aid in decision-making.

2.10 Estimation of basin hydrology and water resources

2.10.1 The use of environmental models

The environmental system comprises of many components which are chemical, physical or biological, and social. Scientists utilize three ways of attaining knowledge of the environmental system; through direct field observations, laboratory and physical modelling studies and mathematical modelling (Aral, 2010). Environmental models are thus an abstraction of a system or physical process. This research utilized mathematical models to predict the historical and future water resources of the identified headwater catchment of the PRB. Many processes occur in the environmental system such that in trying to model them, many different environmental models are generated (Beven, 2001). Environmental systems can be categorized into three main systems which are hydrological, ecological and climatic. It is important to note that the variables that are input into environmental models are commonly extremely heterogeneous, varying significantly even over small spatial and temporal scales which warrants the use of data gathered on a smaller scale as that gathered on larger scales is not adequate to fully characterize the variability of the modeled system.

2.10.2 Hydrological models

The processes that take place in the hydrological cycle are complex and require sound scientific principles and procedures to fully understand them. Sustainable water resources management requires that water managers understand and reliably quantify hydrological variables (Kuchment, 2004). Hydrological models are thus simplifications of the storages and fluxes in the hydrological cycle (Beven, 2012), where the fluxes are represented by mathematical relationships. As a result of variations in the hydrological processes that occur in any catchment, general models are then difficult to construct. Hydrological modelling often uses models that represent important and relevant processes, not the hydrological cycle in its entirety (Beven, 2012). The modelling process differs in complexity, ranging from the reproduction of the real world on a smaller scale to representation of storages by conceptual 'tanks' that are recharged and depleted using mathematical principles and run through computer code.

2.10.3 Reasons for using hydrological models

Often, scientists understand a concept and try to prove it using mathematical relationships which test the hypothesis. This becomes the basis for scientists to carry out modelling exercises (Hevner *et al.*, 2004). In the event of the results not being satisfactory, it gives them the latitude to question the guiding principles and to research further on the subject. Prediction in natural resources management aims to produce operational estimates that aid in decision making (Nadeau and Rains, 2007). Past historic hydrological events that might have occurred but were not recorded, can be reconstructed through simulations (Mann *et al.*, 2006). However, this depends on the reliability and accuracy of the available model input data. Disaster and risk management can be achieved using hydrological simulations. Scenarios are produced by model simulations to aid decision-makers on a decision path that will work well with the simulated future scenarios.

Scientists carry out a post-prediction audit to prove the capabilities of a model to predict future events. This is another aim of hydrological modelling, i.e. to try and improve the predictive accuracy of existing models (Green and Armstrong, 2013). Scientists are carrying out hydrological modelling to understand the physical processes that occur in the natural system, predict future events for practical purposes in decision making and eliminate, as much as possible, the uncertainties associated with the modelling process.

2.10.4 Modelling guidelines

The general modelling guidelines are given in Beven (2012). Beven (2012) came up with a set of questions that should be answered by modelers and stakeholders involved. This approach helps in accounting for potential uncertainties that can be involved in a modelling exercise. The questions are as follows:

a) *Is the context of the problem defined?* This requires the knowledge of what type of predictions are required from the modelling exercise. Data availability is of great importance, their length and quality are paramount. The uncertainties involved with the prediction must be known to assure understanding of the results that come out of the prediction process.

b) *What is the modelling approach to be used?* With any given problem, the model that clearly aligns with the context of the problem must be chosen. The selected model must be scrutinized to understand if the results being sought will be produced. If the problem is not fully addressed the modeler will have to find out if additional models must be implemented to solve the problem.

c) *Was the model carefully set up?* Data deficiencies must be noted during the model set up. As the modelling process occurs the procedures carried out should be double-checked to assure the results produced.

d) *Was the performance of the model checked?* The calibration of the model should be done with accuracy using sound statistical functions. Ideal uncertainty checks should be implemented and inherent uncertainties within the model must be noted before the modelling process begins.

e) *Can the uncertainties from the modelling process be addressed?* Consideration should be taken on the uncertainties associated with the model predictions whether they can be constrained. This is the process that refines the modelling system and the outputs generated from the modelling exercise.

2.10.5 Evaluating model performance

Rainfall-runoff models rely on the use of objective functions to ascertain the goodness of fit between the observed and simulated flows, regardless of the method of calibration used. This is achieved by measuring the extent to which the simulated flow time series match that of available historical observations. Besides a visual inspection of the two-time series hydrographs, usually associated with manual calibration, more objective statistical measures are also used. A statistical criterion referred to as an 'objective function', is normally used to objectively assess the correspondence between the two-time series. The aim of the calibration process, therefore, is to optimize (either minimize or maximize depending on the type of statistical measure being used) this objective function.

There is a wide variety of objective functions available and a modelling application usually uses a subset of these. All the methods aggregate the time series of the residual errors over the modelling period. Given that there is so much information that can be obtained from an observed flow time series, it is not possible for all the different flow components (e.g. peaks, low flows, and recessions) of the data to be sufficiently evaluated by a single performance criterion. It is therefore advisable that for a complete assessment, several objective criteria should be used. The most commonly used objective functions are the Nash-Sutcliffe Efficiency (NSE), the Coefficient of Determination (R^2), the Kling-Gupta Efficiency (KGE), Mean Square Error (MSE) and the Root Mean Square Error (RMSE) (Croke, 2009). It is important to note that these functions do not speak to how well a model is representing the system being modeled but rather show how the model fits the observed data (Croke, 2009). This is attributed to the fact that there are many sources of uncertainty associated with any modelling process, given that a model is merely an imperfect abstraction of reality. The major sources of uncertainty are input data, model structure, and parameter estimation.

The NSE is the Nash and Sutcliffe (1970) model efficiency criterion, with its values ranging between -∞ and 1. NSE (or Coefficient of Efficiency - CE) is a dimensionless relative index of correspondence between the simulated and observed time series, thus determining the efficiency (CE) of the simulation. The best goodness of fit with this function is a value closer to 1 (Gupta *et al.,* 2009). However, NSE has been observed to give relatively high values even for some visually poor simulations. It is also difficult to get high NSE values in basins or periods where the variation of streamflow is low and the value of NSE generally believed to be sensitive to systematic errors in a time series record. It is calculated mathematically as:

$$\boldsymbol{NSE} = 1 - \left[\frac{\sum_{\mathrm{i-1}}^{\mathrm{n}}(\mathrm{O_i}-\mathrm{S_i})^2}{\sum_{\mathrm{i=1}}^{\mathrm{n}}(\mathrm{O_i}-\overline{\mathrm{O}})^2}\right] \qquad \text{(Equation 2.1)}$$

Where O_i is the observed streamflow, S_i is the simulated streamflow, $\overline{O}$ the statistical mean of the observed streamflow and n is the total number of observations.

The coefficient of determination (R^2) describes a linear relationship between the observed and simulated variables (Croke, 2009), thus basically relates to the proportion of variability within an observed time series data set that is explained by the simulated one. A range between 0 and 1 is used to assess the goodness of fit of the simulated against observed time series, with values greater than 0.5 accepted as good correlation. While the NSE is sensitive to systematic errors (general over- or under-estimation), R^2 is not similarly affected and a value close to 1 does not always necessarily imply a good simulation. Where both the NSE and R^2 are used as assessment criteria, large differences between them indicate systematic errors. The metric of measurement is represented mathematically as:

$$\boldsymbol{R^2} = \left[\frac{(O_i-\bar{O})(S_i-\bar{S})}{\sqrt{\sum_{i=1}^{n}(O-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(S_i-\bar{S})^2}}\right]^{\mathbf{2}} \qquad \text{(Equation 2.2)}$$

Where O_i is the observed streamflow (in Mm^3/month in the case of the Pitman model), S_i is the simulated streamflow (in Mm^3/month), $\bar{O}$ the statistical mean of the observed streamflow series, n is the total number of observations and $\bar{S}$ is the statistical mean of simulated flow. The KGE came as a solution to address some of the weaknesses that were observed with the use of NSE (Gupta *et al.,* 2009). It takes values from -∞ to 1, with 1 being perfect fit value. It is mathematically written as:

$$\boldsymbol{KGE} = 1 - \sqrt{(r-1)^2 + (\propto -1)^2 + (\beta - 1)^2} \qquad \text{(Equation 2.3)}$$

Where r is the linear correlation coefficient between the observed and simulated flows, $\propto$ is equal to the standard deviation of the simulated flow over observed flow and β is equal to mean of simulated flow over mean of observed flow.

The PBIAS equation represents the mean bias between observed and simulated time series. It is the most uncontested indicator of the performance of a model with its values ranging from -∞ to +∞ (Moriasi *et al.*, 2007). A value of zero is the most desirable, negative values indicate model underestimation, while positive values indicate model overestimation. PBIAS, however, varies more during dry years than in wet years.

$$\boldsymbol{PBIAS} = \left[\frac{\sum_{i=1}^{n}(O_i-S_i)\times 100}{\sum_{i=1}^{n} O_i}\right] \qquad \text{(Equation 2.4)}$$

Where O_i is the observed streamflow (in Mm^3/month in the case of the Pitman model), S_i is the simulated streamflow (in Mm^3/month).

The Pitman-SPATSIM model uses six statistical objective functions of goodness of fit between the simulated and observed flow time series. In addition to these metrics, this research also used the flow duration curves (FDCs), monthly distribution curves (MDCs) to give the seasonal distribution of flow, scatter plots - all generated by the SPATSIM software - and visual observations of the observed and simulated hydrographs. Flow duration curves (FDCs) represent the relationship that exists between the magnitude and frequency of occurrence of a streamflow value in a given catchment. It gives an estimate of the percentage of time a certain river flow level was either equalled or exceeded over a historical period (Mckay and Fischenich, 2016). FDCs are simplified yet comprehensive graphs that enable the viewing of the variability of the flow of water over time at a given point in a catchment (Mckay and Fischenich, 2016). When examining the FDCs a large deviation of the simulated graph from the observed graph does not only show a lack in the goodness of fit but has a serious effect on decision making using one of the datasets, and an inspection of either time series is therefore necessary.

If the historical observed flow time series is deemed reliable, simulations that are not close to the observed graph indicate a problem with simulation process, and thus necessitates a revision of the modelling before the generated data could be considered to inform decision making on the water resources variability in a sub-basin. Pitman-SPATSIM constructs its FDCs from the whole record of non-negative observed and simulated streamflow data (at a monthly time resolution) and is ideal for impact assessments within a catchment. An FDC enables water practitioners to understand the flow characteristics of a sub-basin for the purpose of building structures along the river and defining water availability within the catchment (Tumbo and Hughes, 2015). These curves can be used to demarcate seasons in a year, i.e. High Flow Season (HFS) and the Low Flow Season (LFS). In this study, Monthly Distribution Curves (MDCs) are used to show the seasonal distribution characteristics of flow in a sub-basin and the goodness of fit between the simulated and observed hydrographs.

2.11 Chapter Summary

This chapter reviewed literature related to the sustainable management of headwater catchments in a period where human activities, climate change, and its variability threaten the availability of water resources. Through analysing published sources, an informed review of the important aspects governing the management of water resources in a headwater catchment was presented and identified the gap to be filled by this study. The review provided a description of what headwaters are, why they are important and the interactions that exist between headwaters and the entire river basin. The sustainable management of water resources in a headwater catchment requires a reliable quantification of water resources produced by these areas. In the absence of historical observations of sufficient quality, this can be achieved using hydrological models to provide hydrological time series upon which the effects of climate change could be quantified.

3: THE PITMAN MODEL

3.1 Introduction

As the Pitman model is the main tool for the assessment of the availability of the water resources for this study, it is therefore necessary to give a brief description of this model to explain how it works, why it was chosen and how it was used. It has been over four decades since this model was designed for use in hydro-climatic conditions prevalent in most southern African countries was developed through the pioneering work of Pitman in 1973 at the University of the Witwatersrand, South Africa (Hughes, 2004). Different versions (see Pitman, 1973; Hughes, 1997; Hughes and Parsons, 2005; Hughes et al., 2006) of this model have been widely used in southern Africa and beyond. The Pitman model has been used for regional studies in the Congo River basin (Tshimanga *et al.,* 2011), the Okavango basin (covering Angola, Namibia, and Botswana - see Hughes *et al.,* 2006), and in selected basins during the Flow Regimes from International Experimental Network Data (FRIEND) project (Hughes, 1997), water resource assessment studies in the Pungwe basin (which covers Mozambique and Zimbabwe) (SWECO, 2004), the Kafue basin in Zambia (Mwelwa, 2004), for regionalization studies in Zimbabwe (Mazvimavi, 2003), and for simulation of arid climatic conditions in Namibia (Hughes and Meltzer, 1998).

The choice of the Pitman model was informed by (a) data requirements of the model and the relatively easy availability of monthly data in the study area (it is worth noting that reasonably good quality data without too many gaps at finer resolution are more difficult to access, especially in Mozambique, (b) the model has already been previously set up and used in this basin (e.g. Mazvimavi, 2003; SWECO, 2004; Kapangaziwiri, 2007; Kapangaziwiri and Hughes 2008), (c) the ability of the model to represent hydrological responses in the area, (d) the new changes to the model that enable it to incorporate uncertainties related to data input, model parameterization and climate change, and (e) the ability of the model to use a number of climate models at the same in order to simulate future scenario of water resources availability. This chapter, thus, gives a brief description of the model structure and its parameters to give a clear picture of the tool used in answering some of the study questions and achieving some the study objectives.

The Pitman model (Pitman, 1973; Hughes *et al.,* 2006) is a monthly step rainfall-runoff model, originally developed in 1973 for water resources simulation. The version of the model used in this study is the one developed by the Institute for Water Research (IWR) at Rhodes University. This version is hosted on a water resources data management platform known as SPatial And Time Series Information Management (SPATSIM; Hughes and Forsyth, 2006) system. The structure of the model sufficiently addresses the natural and anthropogenic hydrological processes that are of importance in the southern Africa region including the study area. A good understanding of the structure of the model and the hydrological as well as anthropogenic processes it represents, thus, guided the model setup and calibration processes. Consequently, it was a lot easier to decide on the parameters of importance for that study area with intelligence based on previous work and knowledge of the area. SPATSIM houses an ensemble of environmental models (including the Pitman model) and has flexible functions for analysis of input data and model simulation outputs.

The Pitman model has found favour for water resource assessment, development, and planning purposes in the southern Africa region because of its relatively simple and flexible structure that can describe most hydrological response conditions in the region with some reasonable degree of confidence. Also, the data demands can generally be met in a region that is haunted by problems of data scarcity (Kapangaziwiri *et al*., 2012) with the most significant advantage being the rather coarse temporal scale at which the model operates. While data are scarce in the region, monthly records of evaporation, rainfall, and runoff are not so difficult to get from various sources. Overall, the model simulations in the region have been considered acceptable by a wide group of scientists and practitioners (Hughes, 1997; Kapangaziwiri and Hughes, 2008; Tumbo and Hughes, 2015).

3.2 General structure of the Pitman model

The Pitman model (Pitman, 1973; Hughes *et al*., 2006) is a semi-distributed, conceptual model which is run on monthly values (Tumbo and Hughes, 2015). This rainfall-runoff model requires time series data of catchment average rainfall, the area of the catchment, and potential evapo(transpi)ration as an annual value or as monthly distributions. The model can also be run on a nodal basis if required. Other optional requirements are available depending on the scope of the study which include run-of-river or ground water abstractions, time series of upstream inflow, transfer inflow, and downstream compensation flow requirements (Bharati and Gamage, 2011). Several parameters are used in this model which need to be calibrated to achieve better simulations. Figure 3.1 represents the main components of the Pitman model.

3.3 SPatial And Time Series Information Modelling framework (SPATSIM)

SPatial And Time Series Information Modelling framework (SPATSIM) is an integrated hydrology and water resource information management and modelling system developed by the Institute for Water Research (IWR) of Rhodes University in South Africa (Hughes and Forsyth, 2006). The system uses ESRI Map Objects as a tool for managing and modelling the data that are usually associated with water resource assessment studies. It was developed in the Delphi programming language. SPATSIM has an integrated database management system which uses GIS shapefiles as the main form of data access. Many utilities for data importation of many types, editing data, viewing even data sharing amongst user are included in the SPATSIM package. Access to a range of linked models and data analysis procedures that are used in water resources assessments are provided by the package such as rainfall-runoff models and design floods. Currently, SPATSIM version 3 is the latest being implemented.

3.4 Consideration of some of the parameters of the Pitman model

Data inputs for this model are monthly total precipitation and potential evaporation time series (Bharati and Gamage, 2011). The first model process starts by distributing the input driver rainfall (using a rainfall Distribution Factor (RDF) parameter, usually taken as 1.28 (Pitman, 1973; Kapangaziwiri, 2007), then the interception by vegetation of the precipitation input (based parameter PI (in mm), which is considered for the two dominant vegetation types in a basin to give (PI1 and PI2, for summer (PI1s) and winter (PI1w) seasons (Table 3.1). Scientific relationships among monthly rainfall, interception storage (PI) and total interception loss by Pitman (1973) are used to determine actual evaporation from the intercepted water (Ido, 2008). The remaining rainfall input then reaches the surface which determines the amount of surface runoff and absorbed rainfall using parameters AI, ZMIN, ZAVE and ZMAX (Kapangaziwiri, 2007). AI is the proportion of impervious catchment directly linked, and therefore contributes flow directly, to the channel system. The absorption rate of the catchment, which effectively determines the surface infiltration, is said to follow a triangular frequency distribution (Pitman, 1973; Kapangaziwiri and Hughes, 2008; Ido, 2008) with maximum, average and minimum absorption rates represented by, respectively, ZMIN, ZAVE and ZMAX. Potential evaporation for the month and other parameters related to runoff generation determine the balance between the water that returns to the atmosphere as evaporation and that which reaches the river system of all the water that enters the soil. Water availability in the soil is controlled by the following factors:

- PEVAP, the potential annual pan evaporation (mm), which depends on climatic conditions and vegetation cover.
- ST (mm/month), the maximum soil moisture storage capacity,
- GW (mm/month), maximum recharge rate to the groundwater store,
- SL (mm/month), storage level below which no recharge can occur,
- FT (mm/month), maximum runoff rate when the soil is saturated (i.e. soil moisture (S) is at level ST)
- R, an evaporation coefficient (varying between 0 and 1) that determines the rate at which evaporation decreases from the potential at S=ST to zero at a storage defined by PEVAP.

PEVAP is an input for the model whereas ST and R are model parameters. Satisfying the water balance of the catchment will determine the current value of soil moisture storage, S.

Table 3. 1: The description of the parameters and the units of measurement of the third version of SPATSIM-Pitman model including parameters related to reservoir simulation (Hughes *et al.*, 2006).

RDF	-	Controls the distribution of total monthly rainfall over four model iterations
AI	Fraction	Impervious fraction of sub-basin
PI1 and PI2	Mm	Interception storage for two vegetation types
AFOR	%	% area of sub-basin under vegetation type 2
FF	-	Ratio of potential evaporation rate for Veg2 relative to Veg1
PEVAP	Mm	Annual sub-basin evaporation
ZMIN	mm month^{-1}	Minimum sub-basin absorption rate
ZAVE	mm month^{-1}	Mean sub-basin absorption rate
ZMAX	mm month^{-1}	Maximum sub-basin absorption rate
ST	Mm	Maximum moisture storage capacity
SL	Mm	Minimum moisture storage below which no GW recharge occurs
POW	-	Power of the moisture storage- runoff equation
FT	mm month^{-1}	Runoff from moisture storage at full capacity (ST)
GPOW	-	Power of the moisture storage-GW recharge equation
GW	mm month^{-1}	Maximum groundwater recharge at full capacity, ST
R	-	Evaporation-moisture storage relationship parameter
TL	Months	Lag of surface and soil moisture runoff
CL	Months	Channel routing coefficient
DDENS	-	Drainage density
T	m^2 d^{-1}	Groundwater transmissivity
S	-	Groundwater storativity
GW Slope	%	Initial ground water gradient
AIRR	km^2	Irrigation area
IWR	Fraction	Irrigation water return flow fraction
EffRf	Fraction	Effective rainfall fraction
NIrr Dmd	Ml a^{-1}	Non-irrigation demand from the river
MAXDAM	Ml	Small dam storage capacity
DAREA	%	Percentage of sub-basin above dams
A, B	-	Parameters in non-linear dam area-volume relationship
Irr Area Dmd	km^2	Irrigation area from small dams
CAP	Mm^3	Reservoir capacity
DEAD	%	Dead storage
INIT	%	Initial storage
A, B	-	Parameters in non-linear dam area-volume relationship
RES 1–5	%	Reserve supply levels (percentage of full capacity)
ABS	Mm^3	Annual abstraction volume
COMP	Mm^3	Annual compensation flow volume

The amount of soil water that gets to the river channel system is thus dependent on parameters ST, S, FT, POW, and SL. Runoff from the infiltrated and stored soil moisture (i.e. basically interflow, both rapid and delayed) is controlled by parameters POW (the power of the storage-runoff curve), ST and FT. The time delay of runoff is modeled by applying a lag, TL (months).

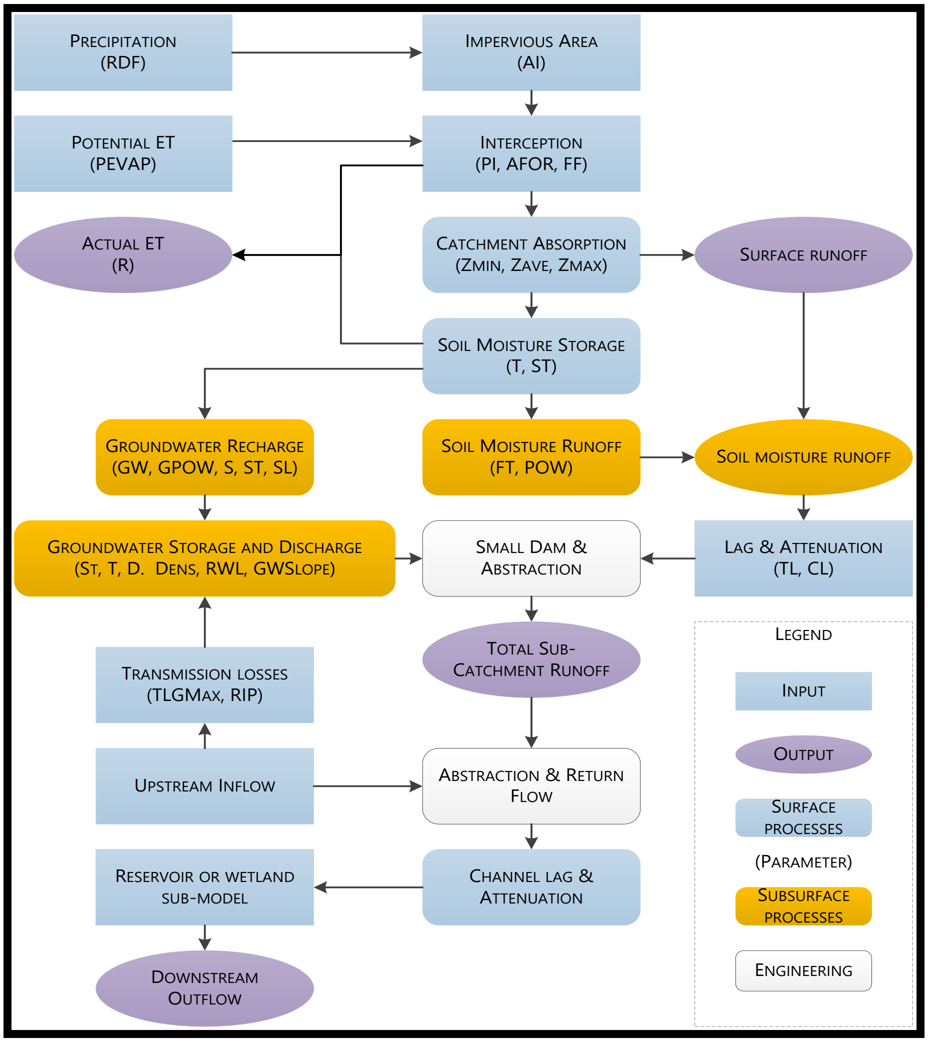


Figure 3.1: A flow diagram of the main components and parameters in brackets of the SPATSIM version of the Pitman Model, used in this study (Kapangaziwiri *et al.*, 2012).

3.4.1 Model calibration and validation

The Pitman-SPATSIM guidelines for calibration are explained by Hughes (2018). The model has 21 parameters (Table 3.1) which represent the main water balance components (Hughes, 2006). Of these parameters, 10 are in direct relation to the generation of streamflow. The original calibration guidelines for the model are provided by Pitman (1973). The parameters are listed in Table 3.1, and those of importance during the manual calibration process depend on the environmental conditions of the sub-basin under study which determine its hydrological response to rainfall input. ZMIN and ZMAX are not usually used in the calibration in catchment areas with good vegetation cover, temperate to humid climates and naturally perennial flow systems because such areas are assumed to experience more infiltration and therefore have a higher chance of saturation runoff than infiltration dependent Hortonian surface runoff generation mechanism. ZMIN and ZMAX parameters are, however, important in the calibration of semi-arid to arid catchments taking precedence over FT, POW, R and GW (Kapangaziwiri and Hughes, 2008) where the Hortonian overland flow mechanism is assumed to be more prevalant than saturation excess flow. In this case, the study area is well-vegetated, especially in the upper reaches of the sub-catchments in the Eastern Highlands of Zimbabwe. This implies that the saturation excess parameters (i.e. FT, POW, R and GW) are important. Downstream, however, the Pungwe River Basin experiences more human influences and therefore reduced natural vegetation cover, making Hortonian overland flow parameters (i.e. ZMIN and ZMAX) are more important. Headwater catchments are generally well vegetated with mostly perennial flow systems and the absence of human influence (Meyer *et al.,* 2003). The calibration of the model will thus be more concentrated on the saturation excess flow generation parameters.

In catchments that have evidence of the presence of seasonally water-logged landscapes such as *vleis* (or dambos), the parameter ST for saturation excess runoff function has a significant influence on the calibration results (Hughes and Mazibuko, 2018). Altering the ST has substantial impacts on the runoff generated during low rainfall months through its effect on the non-linear runoff generation equation involving parameters FT and POW. The optimization of FT, maximum rate at which water is drained from saturated soils, was guided by that catchments in the Eastern Highlands of Zimbabwe would have a high FT value as they have high Mean Annual Runoff (MAR) and are mostly perennial based on physical characterisation of the area and examination of the available flow records, an obvious consequence of high mean annual precipitation (MAP) figures and steep slopes. It then becomes necessary to adjust ST, POW, and FT to achieve reasonable simulations across a range of different rainfall total months.

Adjustments to POW and GW can be made to improve the fit to recessions into the dry season and the dry season flows. The validation of the model is achieved when there is acceptable goodness of fit between the simulated and observed streamflow graphs. The goodness of fit can be achieved by altering the parameter values. However, at the same time, these parameter values need to have hydrological relevance to the processes that occur. Mazvimavi (2003) explained the importance of testing the parameter values for confirming if the values satisfy underlying hydrological principles. Values that come about as a result of a purely curve fitting exercise have little validity in hydrological modelling. To validate a model, several approaches are available, two of which are the Split-Sample and Proxy-Basin tests.

- *Split-Sample testing* involves separating the time series data used into two parts. The first part of the time series will then be used to calibrate the model while the other part will be used to test if the calibrated parameters can produce simulations which satisfy the goodness-of-fit tests as good as those from calibration. To have meaningful validation from this technique, catchments with long time series data are suitable for this technique.
- *The Proxy-Basin approach* to model validation relies on calibrating one catchment and adopting the parameter values from that catchment to a physically similar one which would be expected to have a similar hydrological response. This model type can be useful in catchments where the time series data is of shorter duration.

4: OVERVIEW OF THE STUDY AREA

4.1 Introduction

This chapter describes the study area (i.e. upstream of PRB) where the headwater sub-catchments of importance for this research are located. Headwater catchments of a river basin are very crucial in water resource management. This study was concerned with headwater sub-catchments of the Pungwe River Basin. These sub-catchments are

In Zimbabwe:

- the Upper Pungwe (from the source of the Pungwe river to the outlet of the river into Mozambique at Katiyo, marked by flow gauge F22),
- the Honde river to its confluence with the Pungwe river in Mozambique,
- the Mapopo catchment, with flow gauge F1 at the outlet

In Mozambique:

- the Pungue Fronteira from Katiyo when the Pungwe river enters Mozambique, marked by flow gauge E64,
- The Nhazonia river whose outlet is marked by flow gauge E72
- Nhacangara river whose outlet is marked by flow gauge E70

This chapter describes the location, climate, hydrology, drainage, and socio-economic activities in the area of study.

4.2 Description of the study area

4.2.1 Location and drainage

The Pungwe River originates in the foothills of Mount Nyangani, in the Eastern Highlands of Zimbabwe. The river flows down from a source which is high up in the Nyanga Hills at altitude of over 2000 m.a.s.l. It travels in an easterly direction passing through Mozambique, with its estuary just to the south of the city of Beira, into the Indian Ocean. The estimated length of the river is 400 km, covering a total catchment area of 31 151 km^2 (Swatuk and Van Der Zaag, 2010). 4.7% of the total basin area is in Zimbabwe, with the remainder in Mozambique. The major tributaries of the Pungwe River in Zimbabwe are Nyazengu, Chiteme, Nyamhingura, Nyawamba, Nyamukombe, Honde and Rwera rivers. Tributaries to the Pungwe River pass through protected lands such as national parks and inhabited that suffer from various human influences such as agriculture. In the case where agricultural and mining activities are high (see sections below), the hydrology of the available water in the Pungwe River is affected in terms of nutrient load, sediment load and quantity that flows. Figure 4. 1 shows a general location of the basin in southern Africa and the headwater sub-catchments that were used for this study.

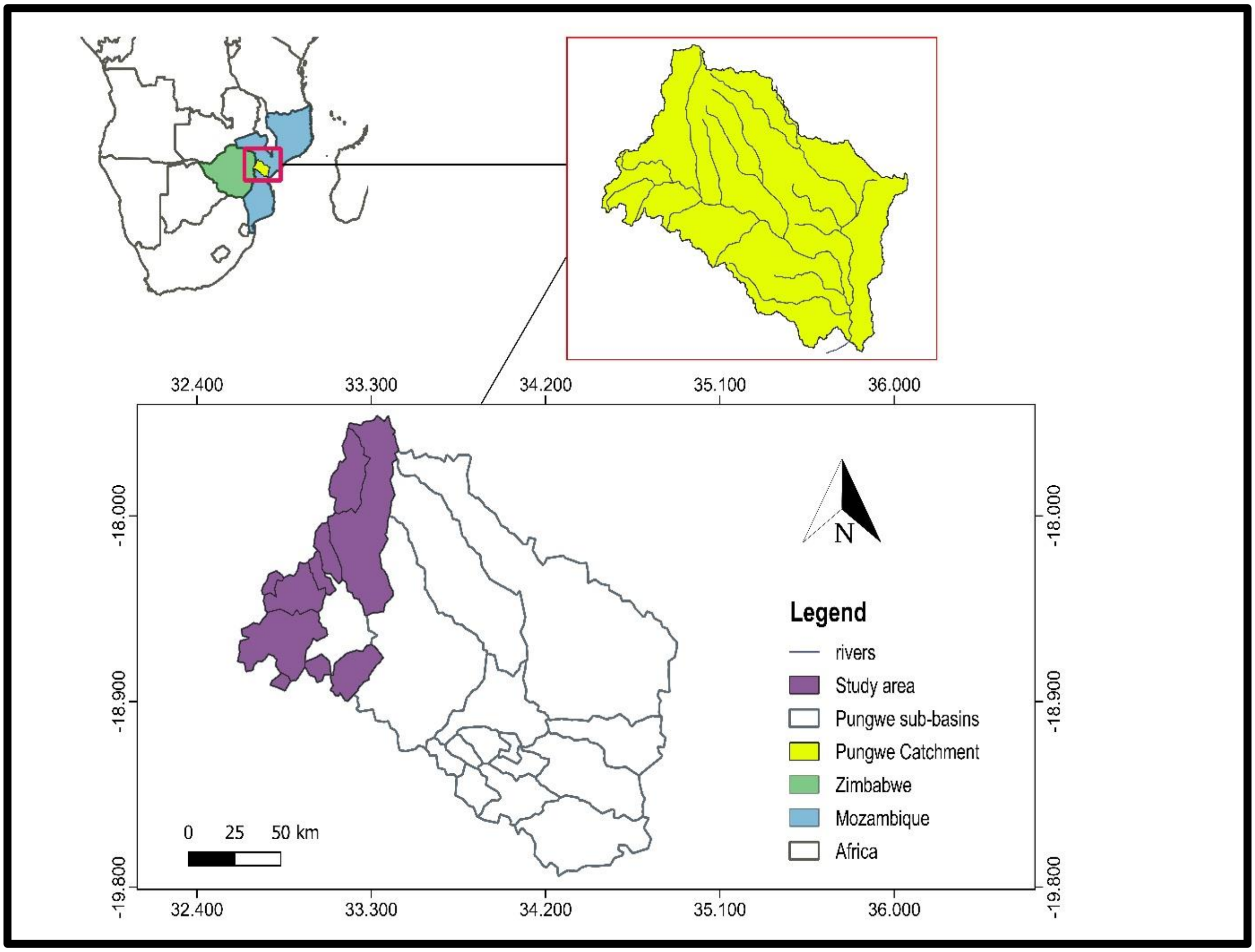


Figure 4. 1: A map of the location of the Pungwe River Basin in southern Africa and the headwater catchments that were studied.

4.2.2 Topography

The river flows from a point 2500m amsl (above mean sea level) then proceeds southwards for an estimated 20 km where it suddenly changes its course at the Pungwe Falls into the forested Pungwe Gorge (SWECO, 2008). The cool river waters at this point coupled with the geographical characteristics of the area give rise to spectacular scenic views which are diverse in flora and fauna. The river proceeds through Honde Valley crossing the border between Zimbabwe and Mozambique near Katiyo Estate. This area is a combination of the national park area, exotic forest plantations mainly in the upstream reaches of the area with mixed agriculture in the middle and lower valleys (SWECO, 2008). Figure 4. 2 shows the elevation of the study area with high altitude in most of the sub-catchments under study.

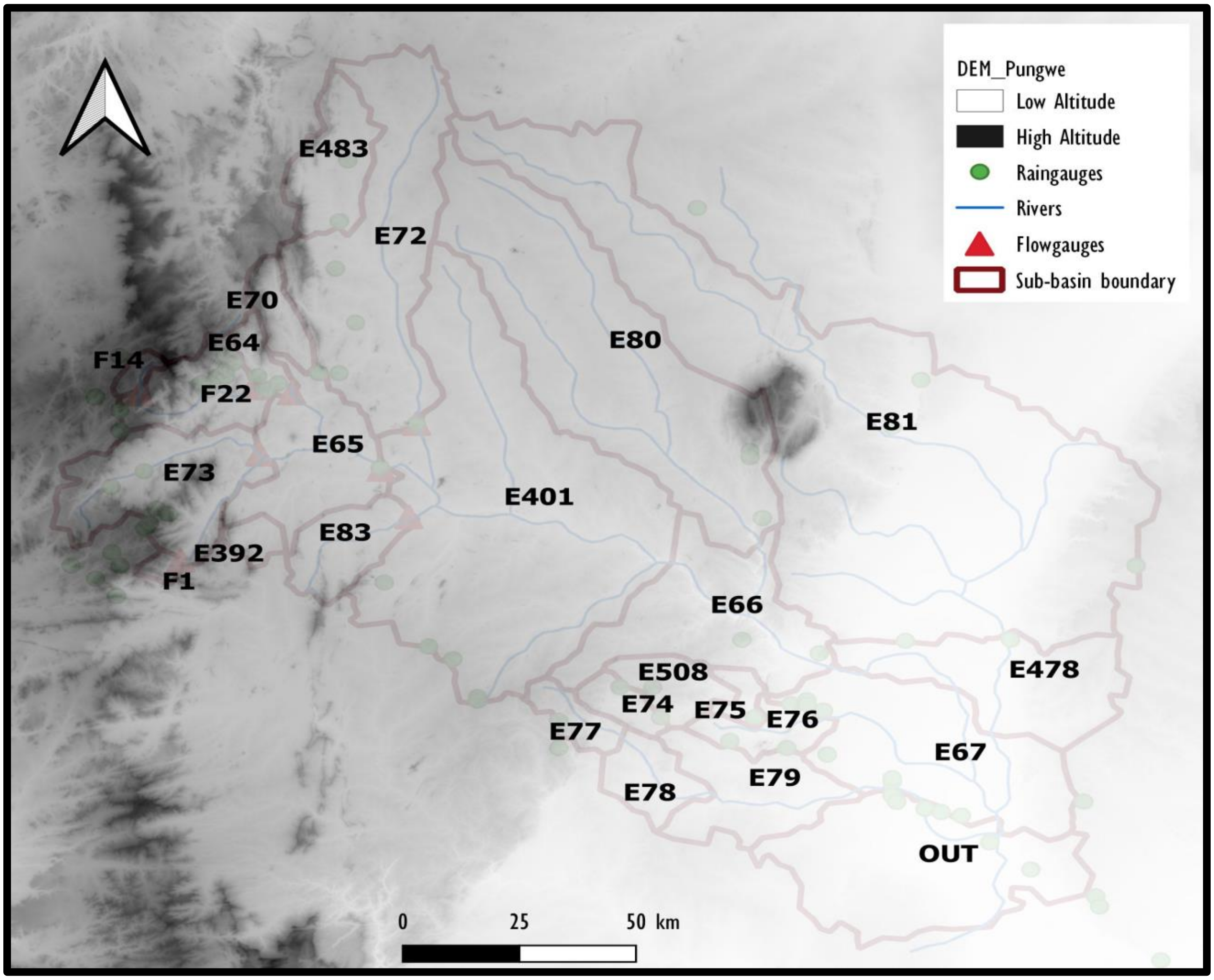


Figure 4. 2: A map of the Pungwe River Basin showing the sub-basins, location of rain and flow gauges, and the drainage system.

4.2.3 Geology

The high mountain peaks, gorges, rapids, falls and valleys present especially in the headwater catchments that were studied are a result of the presence of granites with occasional dyke intrusions (SWECO, 2008). The Honde Valley drainage system also has occasional gneissic rock (Department of the Surveyor-General, 1979). The geology of the low-lying areas in Mozambique paves way to sandstones. The headwater catchments studied are dominated by red soils, derived from iron-rich geological formations. These soils are deep (upwards of 2m) in some areas promoting agricultural activities but shallow on the slopes of hilly areas (Thompson, 1966). In areas where rainfall exceeds 1500mm annually, clay fractions contain small amounts of gibbsite (Thompson, 1966).

4.2.4 Climate

The altitude, relief as well as the distance from the ocean of the basin plays a major role in influencing the general climate of the headwaters of Pungwe River Basin. The area from the Mozambique Channel is generally low-lying. Moving westwards towards the Eastern Highlands of Zimbabwe the altitude increases steadily. This makes for pronounced orographic influences and rainfall in the Eastern Highlands of Zimbabwe. Air currents from the sea are forced to rise on the eastern slopes, usually resulting in high precipitation exceeding 1500 mm per year. The altitude and frequent cloudiness in the Eastern Highlands result in the general coolness of the area. Average minimum temperatures in the study area are at 9.9^{o}C, whereas in the coastal areas, it is around 22^{o}C (SWECO, 2004). The maximum temperature in the study area ranges between 20-29^{o}C as we move from the Eastern Highlands towards the coastal areas (SWECO, 2004). Net annual pan evaporation averages 1400 mm/yr in the study area. In the Eastern Highlands of Zimbabwe, the mean annual precipitation ranges between 1380-1590 mm/year (SWECO, 2008)

The movements of the Inter-Tropical Convergence Zone (ITCZ) and the southeast trades are the major influencers of rainfall in the PRB area (Andersson *et al.,* 2011). The influence of the ITCZ usually extends from January to March, during the late summer rainy season of Zimbabwe. The Mozambique side of the basin is frequently flooded by tropical cyclones from the South West

Indian Ocean. The 2019 Cyclone Idai is a typical example which flooded the Pungwe River Basin. Winter rainfall in the study area PRB is mainly influenced by the southeast trades between April and September. About 12% of the total annual rainfall occurs in winter (May-July) (Terink and Droogers, 2014). This then gives rise to the perennial nature of the rivers that are in the Eastern Highlands of Zimbabwe. More precipitation results in more surface flow into the rivers whereas ground flow is affected by other basin characteristics such as the geology of the basin and the nature of groundwater movements.

4.3 Water resources availability and use

4.3.1 Surface water resources

The major source of water in the basin is surface water resources and understanding the future availability of the resource in the basin is of paramount importance for sustainable development. Based on data collected, the Zimbabwean part of the PRB produced about 30% of the total mean annual runoff as shown in Table 4.1. Zimbabwe contributes about 5% of the total area of the river basin but accounts for almost 30% of the total runoff in the basin (Terink and Droogers, 2014). This shows how vital that part of the basin which is in Zimbabwe to the integrity of the whole basin. Water use and management practices in Zimbabwe have a direct bearing on the availability of the resource to water users in Mozambique.

Table 4. 1: Area and Mean Annual Runoff generated in the parts of the Pungwe Basin in Zimbabwe and Mozambique (SWECO, 2004).

Part of the Basin	**Area (km^2)**	**Natural MAR (mil m^3/year)**
Zimbabwe	1 463 (5%)	1 191 (28%)
Mozambique	29 687 (95%)	3 004 (72%)
Total	31 150	4 195

4.3.2 Groundwater Resources

Groundwater resources in the PRB are moderate to low with the Upper and Lower Pungwe areas having a high groundwater potential (SWECO, 2004). Headwaters are generally known for their ability to allow for groundwater recharge due to their close proximity to groundwater, wetlands and subsurface water flows is another function of headwaters controlling flow of water to large streams (Ohio Environmental Protection Agency, 2015). Depending on the geology, areas that are close to the river channel might have high groundwater yields. Groundwater is utilised by communities for daily uses. The basin only has Beira as a major city, otherwise, the greater part of the basin is in rural areas where poverty is high (SWECO, 2004).

4.4 Human population characteristics

With a total population of 1 199 567 in the Pungwe basin as at 2008, only 8% were residing in Zimbabwe (SWECO, 2008). This total population was project to reach two million by 2023, based forecasts. The inhabitants of the PRB are largely rural communities that are engaged in both dry land and irrigated agro-based economic activities. This is expected to intensify agricultural activities in the area, leading to increased clearing of forests for agricultural purposes – an important change in land use and land cover. Such changes in land cover and land use practice have the potential to adversely influence water resources quantity and quality through increased nutrient loads, sedimentation and increased levels of run-of-river abstractions and small-scale impoundments for irrigation purposes. The Zimbabwean part of the PRB is the most densely populated, while in Mozambique the densities increase around administrative areas, towns and main roads. Population increases on the Zimbabwe part would result in the degradation of natural resources which, if they are not managed sustainably, would depreciate the natural ecosystem values and functions whose effects would be carried downstream affecting the population in Mozambique that depends on the river for sustenance.

4.5 Agriculture

The basin's economy is dominated by agricultural activities. These activities contribute about 11-14% in Zimbabwe and 21.84% in Mozambique to GDP (gross domestic product) (Juana and Mabugu, 2005; FAO, 2019). These agricultural activities are more pronounced in the upstream areas of the Pungwe River (Chitiyo and Duram, 2017). This is because of high annual precipitation and the rich soils. There are some tea and timber estates, in the Zimbabwean part. Areas like Honde Valley and Nyanga are well known for large scale production of bananas by both small-scale and large-scale farmers. The predominance of rural communities in PRB makes subsistence farming the major source of livelihood with some donor-funded agricultural projects (the rehabilitation of small dams to facilitate agricultural production, e.g. Barue, Gorongoza and Nhematanda). Horticultural crops are grown all year round due to the abundant water resources. Small irrigation schemes have been established through donor funding has promoted agriculture in the area, such as Chidzinzwa irrigation scheme, and have helped in promoting good farming practices.

4.6 Datasets, data collection, and collation

There is a network of monitoring stations in the PRB for collecting hydrological and meteorological data whose management falls under relevant authorities in both countries. On the Zimbabwe side ZINWA and the Meteorological Services Department (MSD) are the responsible authorities for the collection and custodianship of runoff and rainfall data respectively, while on the Mozambique side ARA-Centro and the *Instituto Nacional de Metereologia* (INAM) has these responsibilities. Rainfall records, however, have a longer collection period as opposed to flow data. This is due to the complexity of constructing and maintaining flow gauging stations as opposed to setting up rain gauges. Flow data are collected from gauging stations that have been established along the river. Four gauging stations are present in the Eastern Highlands of the Pungwe River before it crosses into Mozambique (i.e. F1, F14, F22 and F23). Some of these stations are relatively new and others also contain large gaps of missing data that their use requires screening and repairing the data using statistical methods (Terink and Droogers, 2014). Mozambique gauging stations are affected by flooding, the data collection instruments are often destroyed. Historical observed rainfall data records also have gaps of missing data due to poor road networks as well as inadequate field labour that hinder the collection of these data types.

5: WATER RESOURCES MANAGEMENT IN PUNGWE HEADWATER CATCHMENT

5.1 Introduction

Water resources management in southern Africa has seen a rise from the colonial centralized frameworks to decentralized, stakeholder-oriented frameworks that aim to ensure equitable, more representative and sustainable management of water resources. The PRB is one of the many basins in southern Africa that are managed using a decentralized water management approach. Since the inception of IWRM in 1992 at the Dublin Conference, many countries have taken up the initiative to upgrade their water management frameworks towards an integrated approach. Mozambique and Zimbabwe have a long history of cooperation dating back to the liberation struggle and share water resources through transboundary basins that originate from Zimbabwe into Mozambique (e.g. Pungwe, Save, Budzi). These rivers, for all involved to rip benefits, must be sustainably managed. PRB, through the Joint Water Commission (JWC), implements IWRM as the basis of its management strategies. This study sought to assess the water management strategies being implemented in the headwater catchments of the PRB. This chapter presents the methodology and results obtained from the survey that was carried out to understand current water resources management in the Pungwe Sub-catchment Council (PSCC). The research design, sample size, data collection procedures, analyses, ethical considerations and the research instruments used are discussed.

Managers from several natural resources management institutions in Zimbabwe were interviewed and their responses were analysed using a thematic approach. The institutions that participated in this research are the Environmental Management Agency (EMA), Zimbabwe National Water Authority (ZINWA), Pungwe Sub-Catchment Council (PSCC), Mutare Municipality, Forestry Commission, Agricultural Technical and Extension Services (AGRITEX) and Meteorological Service Department (MSD). The main question that is answered in this chapter relates to the existing water resources management strategies that are being employed in the headwater catchment of

Pungwe River. Water resources and environmental management frameworks are key to this study, and their integration is important to the achievement of sustainable headwater catchment management. Existing legal frameworks governing natural resources, their regulation and enforcement by the responsible institutions and the challenges being faced in their implementation are discussed.

5.2 Methodology

This study utilized a desktop review approach, supported by interviews that were conducted in the area and using the PSCC to assess water resources management in the headwater catchment. Information about water resources management in Mozambique was obtained solely from ZINWA Save, which is involved in the Joint Water Commission (JWC), a bilateral board created for the management of common water resources between Mozambique and Zimbabwe, including the PRB. Review of literature related to water governance in Zimbabwe was used to understand the management of water resources.

5.2.1 Research design

A descriptive research design was used to address the issue of water resources management in the area. The scope of the research, the idealness of the research design to address this objective as well as the time and financial constraints justified the use of this approach. This research design helps to provide information on the what, when, where and how questions that are associated with an investigated problem, trying to explain the reasons behind the problem under study (Melorose *et al.,* 2015). Descriptive research does not clearly fall into either qualitative or quantitative research methodologies, but it has the ability to use elements from both methodologies to conduct one study (AECT, 2001). The desired objective was to describe, or rather, bring to light the water resources management strategies that are being implemented in the Pungwe Catchment and affecting subsequently the headwater areas. During the design phase, the following were being sought:

- Clearly identifying the research problem,
- Coming up with questions that are important to addressing the objective of the study,

- Producing quality data that can be used in policy change, and
- Description of data analysis methods applied to the research.

5.2.2 Target population and sampling techniques

Respondents were selected for interviewing from the natural resource management institutions responsible for the Upper Pungwe where the headwater catchments are located. More respondents could have been interviewed but the research noted that at each institution, only a few people were involved directly in the management of Pungwe headwaters; thus, even at seven respondents, sample adequacy was reached. This study used purposive sampling which is effectively synonymous with qualitative research because the way the sample is chosen is tied to the objectives. This research was interested in understanding the opinions of natural resources managers on the importance and management of headwater catchments, and therefore make instructive deductions on how water resources of the headwater catchments are affected by various important and influential institutions. Since the people interviewed are involved in the management of important environmental aspects that have the potential to affect water in the study area, the responses they gave were regarded as adequate by the researcher to address the objective of the study.

5.2.3 Research instrument

A semi-structured approach, using an interview guide, was employed in this research, allowing the interviews to be less formal, and making participants more comfortable to participate. The responses were captured as voice notes using a phone and the voice records were erased after transcription and analysis in order to protect the identity of the participants. The interview questions were structured in a way that allowed for the understanding of water resources management strategies being implemented (Appendix A). The collected data were then thematically analysed.

5.2.4 Data coding and analysis

Recorded responses from interviews were transcribed for each respondent and analysed. The initial stage of analysis involved reading all the transcripts as a bunch making notes on things that stood out from the interviews on first impression. Each transcript was then carefully assessed labelling pieces of information relevant to the scope of the study. The labelling of these relevant pieces of information was the coding phase. The coding of the transcripts generated themes that are explained in the results section of the case study as sub-headings. The relevancy of information during the coding was based on (a) information that was constantly repeated by several respondents, (b) responses that the respondents explicitly or implicitly declared as important, (c) similarities of responses to what is known in literature, and (d) responses that came as surprises to the interviewer. To help the coding process, preconceived theories and concepts guided the coding as well as being open-minded to new information and suggestions.

5.2.5 Ethical considerations

To safeguard the dignity, rights, safety and wellbeing of all the participants in the research, the ethical considerations of this research needed to be identified. With such considerations in mind, the research observed confidentiality of the information given by participants. The university's ethical committee approved this research and an ethical clearance form was issued and a consent form. The consent form signed by respondents ensured that all participants were made aware of their role in the research and that their participation was voluntary with the full knowledge of the risks and benefits as they were explained to them. Prior to interviews, informed consent was sought from individual participants. To maintain anonymity, the respondents were coded as "Respondent 1" through to "Respondent 7".

5.3 Results and discussion

5.3.1 Natural resources management in Zimbabwe and Mozambique

Natural resources management attempts to achieve the utilisation of natural resources that is sustainable, striking a balance between economic and social development with the implementation of sustainable ecological practices in an area (Flintan and Tedla, 2010). Proper management of water resources requires the integration of all aspects that affect the quality and quantity of water resources. Zimbabwe and Mozambique have made some remarkable strides from the colonial centralised way of natural resources management to a decentralised, participatory approach for natural resources management (Nyandoro, 2012). However, despite good governance, there are many factors that affect natural resources management in developing nations (Heltberg, 2002).

5.3.2 Water management policies in Zimbabwe and Mozambique

The water resources of Zimbabwe have been closely tied to land since colonialism (Nelson *et al.,* 2009). Many reforms took place in the country that saw the natives receiving areas that were arid while the white minority got areas with a good climate favourable for crop production (Nyandoro, 2012). This prompted white farmers to be given priority to water resources causing unequal distribution of the resource. The Water Act of 1927, and its successor in 1976, allocated water on a first come first served manner which resulted in unfair water resources distribution (Tom and Munemo, 2015). The water 'rights' subsequently issued meant that the holder had the right to be allocated water regardless of situations where equitable distribution of water would serve more people, as in the case of droughts. White commercial farmers had access to these rights as they held title deeds to properties making the black communal farmers rely on rain-fed agriculture (Makurira, 2003).

These issues prevailed in post-independence Zimbabwe and pushed for reforms in the land and water sectors. Foreign aid was injected to promote the water sector reforms and saw the replacement of the Water Act of 1976 with the Water Act of 1998 (Chapter 20:24) and the establishment of ZINWA (Makurira, 2003). The introduction of the Water Act brought a decentralized water resources management approach (Nyikadzino, *et al.,* 2014). These acts have been the water management guidelines in Zimbabwe to date and seven so-called catchments were delineated for IWRM to be implemented effectively as shown in Figure 5.1.

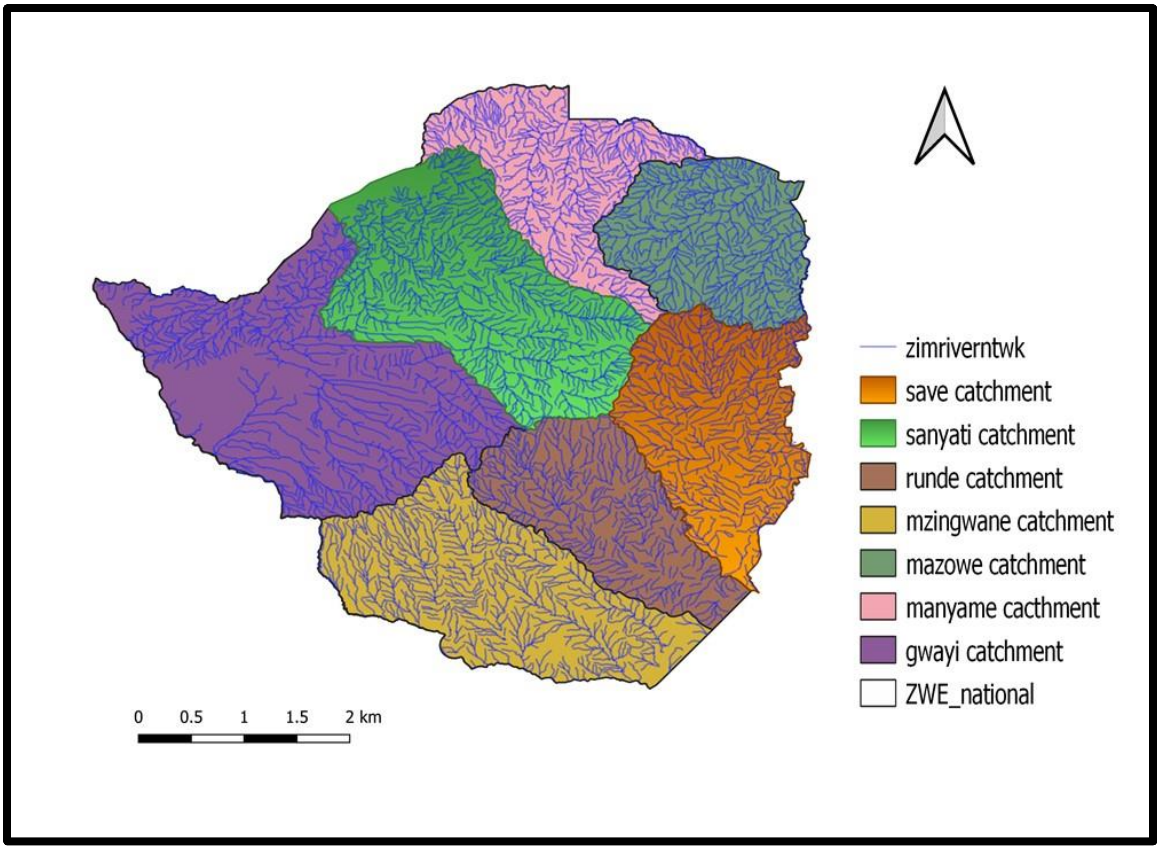


Figure 5. 1: A map of Zimbabwe with its seven catchments. Pungwe sub-catchment is incorporated into the Save catchment for administrative purposes but it is in Pungwe River Basin, adjacent to the Save catchment.

Mozambique adopted IWRM in their water resources management strategy through creating legislation, setting up institutions and policy formulation (Sokile *et al.,* 2005). These resulted in the establishment of the 1991 Water Law which created the institutions responsible for water resources management at central and local levels. Stakeholder participation and tariffs for water usage came because of the Water Policy that was established in 1995. These water reforms aimed to decentralize water resources management in the country (Chilundo *et al*., 2010). During the colonial era, the Portuguese law regulated water usage using decrees established in 1914. As independence was gained in 1975, the Ministry of Water and Public Works was responsible for the management of water resources in the country, but the Portuguese Law was still being used. This law was replaced by the Water Law (Law no. 25/29) of 1991 (Chilundo *et al*., 2010). *Administração Regional de Águas* (ARAs) were established (shown in Figure 5.2) as a result to manage regional water resources at the catchment level, with each ARA having jurisdiction over a selected number of catchments.

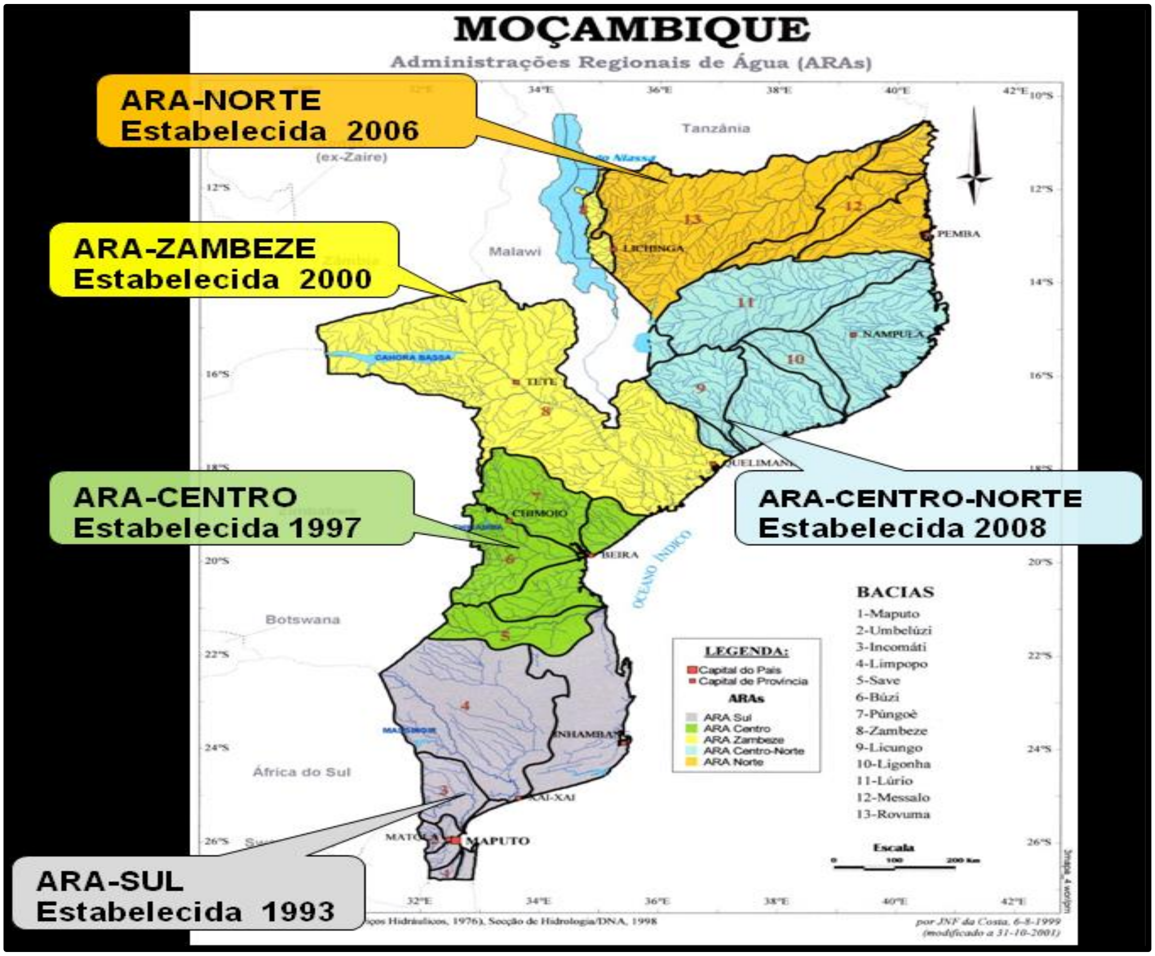


Figure 5. 2: A map of Mozambique showing the main rivers and their administrative agencies. The Pungwe River Basin falls within the ARA-Centro administrative boundary which manages central Mozambican catchments. (Source: Chilundo *et al.,* 2010).

5.4 Case study: Water resources management in Pungwe Sub-Catchment

5.4.1 Water resources management

The management of water resources is guided by the Water Act (20:24) and is implemented by ZINWA on behalf of the state. The Water Act (20:24) is useful for water resources management at the catchment level bringing about the integration of different natural resources management institutions and stakeholders. The management of headwater catchments is not clearly defined by the Water Act (20:24) as they are part of the whole basin. The same management strategy that is applied to the management of the entire catchment is also employed in the management of headwater catchments. This was corroborated by Respondents 1 (2018) who explained that water management in the case study area follows IWRM principles though there are no clear- cut and separate procedures to manage headwater catchments. This makes sense as catchment councils generally do not seem to have an appreciation of the importance of headwater catchments as a separate entity that requires special attention. IWRM has eased water management and the 'permits' system (as opposed to water rights) not only the more efficient accountability of water usage, but also equitability in resource use. Regardless, water management still faces a considerable number of problems such as aging infrastructure, pollution from human activities, economic factors which are seeing natural resources management institutions putting more effort of revenue generation to meet salaries and political interference in the management of water resources.

5.4.2 Structure of the Pungwe Sub-Catchment Council

The management, development and conservation of water resources of the PRB presently fall in the hands of the JWC. ZINWA manages water resources on the Zimbabwean side while the ARA-Centro manages the same on the Mozambican side. ZINWA, through the Pungwe Sub-Catchment Council (PSCC), is responsible for administrative duties in the Pungwe River Basin with technical assistance from ZINWA Save catchment. Respondent 1 (2018) gave a narrative of the management structure in the Pungwe sub-catchment council (PSCC). The respondent explained that fifteen councillors are selected for a three-year term selected from various water users in the catchment (e.g. municipalities, energy companies, commercial and non-commercial farms, villagers, traditional leaders, natural resources management institutions, etc.). While water resources are vested in the state, the PSCC is responsible for the day-to-day management PRB in Zimbabwe. The PSCC employs its own staff. Among the staff is a river inspector who operates as the man-on-the-ground with respect to water issues, manages the office and carries out field activities related to water use on behalf of the Sub-Catchment Council.

5.4.3 Stakeholder participation

Stakeholders in the study area comprise of small-scale and large-scale commercial farmers, communal farmers, power generating companies, local authorities, government institutions among others which make up the totality of water users. Currently, efforts made by the JWC have seen the active participation of most of these water users in water management issues (Nyikadzino *et al.*, 2014). This was concurred by Respondents 1, 2 and 4 who said that stakeholder participation was a reasonable success in the catchment with more women taking up active roles. There has been the development of irrigation schemes which have helped in livelihood enhancement. Small irrigation schemes have enabled the locals to farm crops for their own consumption while some produce is sold at the nearby growth point, Hauna, and some as far as Mutare and Harare. This has reduced food shortages at household levels and generates income for daily household needs and sending children to school. The participation also involves natural resource management institutions who occasionally team up to carry out field observations and training to raise awareness among the general population in the basin. This has promoted institutional integration and the incorporation of government arms during quarterly meetings helps to deliberate issues. Inclusion of stakeholders in the decision-making process of water management can bring about improved water management strategies that can be beneficial to all water users promoting livelihoods enhancement in that area (Rieu-Clarke, 2006).

Respondents attributed the willingness to participate stemming from the time of inception of the Water Act (20:24). With help from the Swedish International Development Agency (SIDA), the PSCC was one of the first sub-catchment councils to be established, and functional, in the Save Catchment. The availability of foreign aid helped in the promotion of participation in the area. Awareness programs apparently helped educate the locals on good water resources management and helped in making PSC be the first standalone sub-catchment in Zimbabwe, according to Respondent 1.

5.4.3.1 Shortcomings of participation

Women participation initially was low at less than 20%, but strides have been made and more women now actively participate in water management issues (SWECO, 2004). Their inclusion has been noted but there is still concern over the voices they represent because of the patriarchal social fabric in the rural-dominated headwaters on PRB. There is a need to encourage their participation to be from themselves rather representing what their husbands think is the right way to water management (Respondent 2, 2018). As far as the general aspect of participation is concerned, Respondent 5 concluded that gender imbalances are being dealt with as more women are now participating. Some participants do it for a personal agenda, such as garnering votes for local leadership posts than for good water resources management or politicize the process of water governance (through possible manipulation of the permit process). There is, therefore, a need to keep refining the participatory process.

5.4.4 National policies that impact on good resources management

Derman and Manzungu (2016) documented the evaluation of the fast-track land reform that occurred in Zimbabwe in the early 2000s. Participation was greatly affected as the fast-track redistribution of land meant a fast-track water allocation process. There was abstraction of water resources for commercial use without payment for the resource. Urging the users to pay during this time was interpreted as being against the national agenda of empowerment and reviving the economy through agriculture. This negatively impacted the management and maintenance of water managing institutions which ultimately lead to infrastructure degradation, collapse of water reticulation facilities and an exodus of skilled water resources management personnel. Political interests such as the redistribution of land affected the process of good water management policies such as water allocation, which saw a reduction in the revenue generated from water use for the maintenance of water infrastructure.

Participation was disrupted during that time as politics affected major aspects of governance in Zimbabwe (Derman and Manzungu, 2016). The redistribution of land caused a lot of uncertainties in the country which affected investment and aid from developed nations. The water supply of the country was greatly affected as infrastructure continued to crumble and people continued using water resources without realising the need to pay for the resource. This affected the operations of the water governing board which could not do much as water was regarded as a universal right which had to be made available for all. The dilemma of many developing nations is that written policies and legal frameworks capture the fundamentals of environmental and water resources management but the reality of what happens on the ground is far from the intended (Cosgrove *et al.*, 2015).

Respondent 6 reiterated that the economic collapse that followed land reform saw the migration of skilled labour to other countries and the loss of data collection stations which were operated by established large-scale estates as they closed. As nature dictates, with the collapse in environmental managing institutions and a crumbling economy, immediate survival needs overrule sustainable natural resources utilization and management. This is one of the reasons prompting humans to access hitherto inaccessible headwater catchment areas for exploitation of the fragile resources they may contain. Human interference through mining and agricultural activities has been noticed in the headwater catchments of Pungwe River and has a serious impact on the quality and quantity of water resources available (Respondent 2, 2018).

5.4.5 Challenges of effective water resources management

5.4.5.1 Human resources

The structuring of catchment councils in Zimbabwe requires employment of technicians, accountants, policymakers and monitoring teams to fully manage water resources in any area as specified in the Water Act (20:24). The PSCC, which manages the headwater catchment of Pungwe River is understaffed (Respondent 1, 2018). This was attributed to the fact that the PSCC is underfunded to employ the required number of employees for effective management. All respondents from the interviews concurred that sub-catchment councils (SCCs) are structured in such a way that each has a different organizational structure according to the size of the catchment and financial capacity. Typical SCCs generally have one office and some field personnel. This is difficult for good water resources management considering the spatial coverage which must be under constant monitoring. The PSCC office has three staff members, a number which is very small considering the terrain and the total area (Respondent 1, 2018) that need to be covered for effective water resources management services.

5.4.5.2 Data collection, management, and access

Hydrological studies rely on data of sufficient quality which spans a very long time. Data collection has been a nationwide problem in Zimbabwe since the economic turmoil that saw the collapse of many state functions (Tiwari *et a.l,* 2013). Respondent 3 explained how the closing of estates in the study area affected data measurement. The respondent mentioned that some collected data were rendered useless as the collection methods employed did not conform to the international standards of rainfall collection. This made the data unreliable for use. Strides are being made, however, by managing institutions to improve and digitize data collection. The respondents that participated in this study are located mainly in Mutare which does not form part of the study area but acts as the provincial offices for these natural resource management institutions.

Mutare is also a huge stakeholder of the Pungwe River Basin as it draws water directly from the river for domestic and industrial uses. As much as the daily operations are conducted by the institutions in Pungwe, the data they collect are sent for analysis and storage in Harare, which is the headquarters for most of these institutions. Permissions must be requested to acquire the datasets which can be strenuous as a chain of command has to be followed. Data collection instruments have also been a subject to vandalism and general dilapidation as resources for this kind of work have dried in the recent past. Streamflow data collection, however, has seen improvement as new automatic data loggers have been installed as shown in Figure 5.3 and Figure 5.4. The data loggers collect data without human aid. This has lessened human induced errors in the data collection process, addressing some of the uncertainties in data collection which the previous collection methods did not.

Figure 5. 3: Pictures of the automated data loggers that have been installed at the flow gauging stations the Pungwe River on the Zimbabwean side. From Left, Ecolog500 data logger at F22 and to the right, Thalimede data logger for F24.

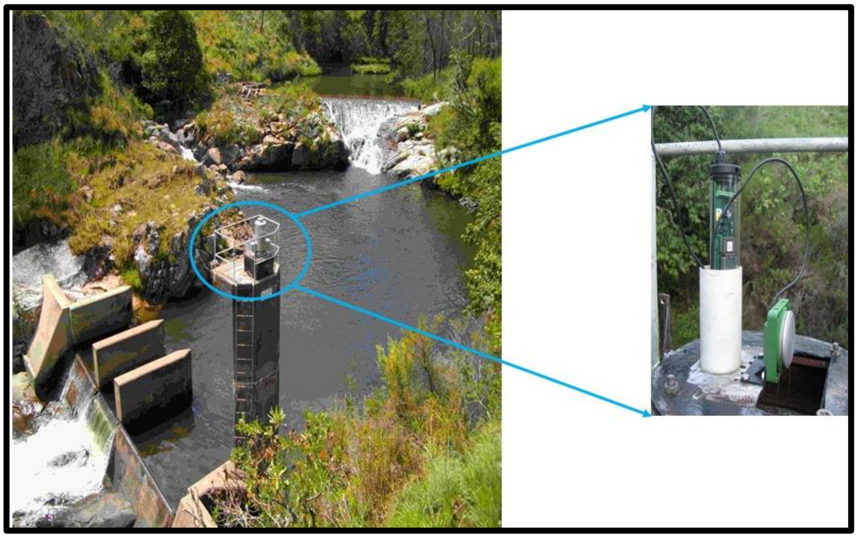


Figure 5. 4: The new data logger for flow measurement at gauging station F14.

Data collection in Mozambique always makes use of collection techniques that have a lower reliability especially for peak flows (SWECO, 2004). This is attributed to their construction, they are generally natural gauging sites with no sturdy constructions such as weirs and whose rating curves are not consistent and with flow levels being easily affected by seasonality (SWECO, 2004). Figure 5.5 shows a staff gauge for streamflow measurement at a station in Mozambique.

Figure 5. 5: A picture that serves as an example of the staff gauge used in Mozambique to collect streamflow data at identified natural control sections.

Respondent 3 (2018) emphasized the efforts made by ZINWA to automate all the gauging stations present on the Zimbabwean side of Upper Pungwe. The respondent further emphasized that to avoid data gaps, old instruments are running concurrently with the new data loggers until such a time when they can be removed. Human inefficiency was also reported to be a major factor affecting data collection in the area. Personnel responsible for the daily collection of data face many challenges in accessing their data collection points. Data of good quality must be maintained to eliminate the uncertainties associated with the initial stages of scientific research, that is, data collection. Constructing weather stations and creating environmental and data collection clubs at schools can significantly add to the pool of data the area can produce (Respondent 1, 2018).

5.4.5.3 National Policies and management

Institutions that took part in this research tend to have clear-cut policies for the management of their respective natural resources. Several acts have been developed especially during the post-independence era as the Water Act of 1976 did not cater for everyone, especially the marginalized black Zimbabweans (Makurira, 2003). However, policy implementation was affected by lack of funding. Many sector reforms have been carried out in Zimbabwe to suit current environmental management needs. The Water Act in Zimbabwe has not fully incorporated climate change in the management strategy. There is a need for climate change to be fully incorporated into national strategies (Respondent 5, 2018). Effective natural resources management requires the separation of policy from politics, something which is almost impossible. This is a very critical aspect in natural resources management in Zimbabwe as politics influences on natural resources management policies through influencing decisions.

Attitudes of locals have been another hindrance to policy implementation. Natural resources are considered as "God-given" and anyone can use them without being monitored (Clover, 2005). This has led to illegal water abstractions (non-permit users who derive economic benefits from using water resources), extinction of plant and animal species, pollution of the environment, illegal mining, poaching in national parks and utilization of wetlands for farming purposes. The perpetrators of such activities are either unaware of the legislation that does not allow them to carry such activities or they decide to pay no attention to the requirements of proper resources utilization. Management deficits are also present in local authorities who deliver water to the users. The City of Mutare has been recording losses in treated water pumped out daily (Kanjanda, 2014). Marunga *et al.,* (2006) showed that about 50% of the total water abstracted from the Pungwe River for use by the City of Mutare was unaccounted for. A lot of water losses have been recorded in the town which influences water abstractions in the Pungwe headwaters. Downstream users are ultimately affected as a result of unaccounted for water used upstream.

5.4.5.4 Funding

The functions of an SCC are funded by the levies that permit holders pay towards service provision. PSCC is mainly comprised of primary water users, those that use water for non-economic benefits. The major water users have since downscaled water usage because of low production. This reduces the amount of money that could have been realized from the utilization of water resources. The economic crisis has also led the water users not to pay for the water they have utilized. Millions of dollars are locked up in the form of debt. Funds should, therefore, be made available to promote water resources management in the headwaters of Pungwe River.

5.4.5.5 Alien invasive plants on water resources management

Regarding the issue of alien invasive plants affecting the water resources of the area and indigenous plant species, there were mixed concerns amongst the respondents. Respondent 1 had the notion that species that utilize more water contribute to evapotranspiration which is essential for creating precipitation though groundwater resources can be affected. Respondents 2 and 5 believed these alien species are playing a significant role in catchment protection as they have been present for a long time. Respondent 3 agreed with this but, however, pointed out that indigenous plant species have been suffocated making the foreign plant species "indigenous" to the area considering the time they have been present. What seemed to be a general agreement amongst all the respondents was that in as much as a lot of scientific research has been carried out in the region, especially in South Africa, to determine the extent to which these alien invasive plants are affecting the area's hydrology and biodiversity, Zimbabwe needs to do more to understand these effects at a local level in the country.

5.4.5.6 River pollution and sedimentation

Water quality data analysis is conducted by the environmental agency. Monthly field samples from the rivers in the Pungwe headwater catchment are collected and analysed. The parameters of importance usually analysed are Biological Oxygen Demand (BOD), dissolved oxygen (DO), nitrates, phosphates, iron, and pH. These are processed, stored and are free to the public for research purposes. Respondent 1 and 2 confirmed that the water resources situation in the area is still good as most of the areas in the region are not easily accessible and some are protected by national parks. Water quality samples that are collected on monthly time intervals showed that the levels of nutrient load are not alarming. The nutrient load varies with the seasonality as well, said Respondent 2 with more load during the farming period. The issue of sedimentation was, however, an issue of concern where gold panning was occurring. Respondent 2 (2018) explained that land degradation by mining activities is influenced by a sudden realization of gold deposits at a place. Within a short space of time there will be massive land degradation causing water pollution.

5.5 Summary

Based on the foregoing descriptions and discussions, it can be concluded that headwater management in the PRB is not of high priority though the management of water resources using the national frameworks created for water resources management are being implemented. Deliberate and concerted headwater catchment management is being hindered by the lack of resources (including skilled human capacity and financial) to carry out the requisite data collection and monitoring related to water quality and quantity at the PSCC. National policies on water resources management have not yet addressed headwaters as priority areas of water resources management due to lack of knowledge and understanding of these fragile but important environments which provide high value ecosystem services and goods. This means that uniform management policy is being implemented in the management of water resources across the whole basin without separate and deliberate strategies to fully address the needs of sensitive managing headwater catchments. It was noted that the quality of water resources is currently good. This is especially true of the water resources found in the upper reaches of the catchment in protected national parks whose access is restricted, implying therefore that generally undisturbed, near pristine water conditions exist, regardless of there being no deliberate headwater management strategy in place. These water resources are used for consumption by local communities and by the City of Mutare without any (or with little) treatment. These good water resources need to be protected; however, it is possible that a changing climate which may affect availability and quality, as well as a growing population which may lead to changes in land-use practices, might ultimately affect these water resources.

6: ASSESSMENT OF CURRENT AND FUTURE WATER RESOURCES OF PUNGWE HEADWATER CATCHMENT IN A CHANGING CLIMATE

> "All models are wrong; some are useful"
>
> George Box, 1976

6.1 Introduction

Hydrological systems are highly complex, therefore, understanding them requires some abstraction, to at least understand or control some aspects of their behaviour (Xu, 2002). According to Beven (2012), the actual reason for using hydrological models is to demonstrate the main elements of the hydrological process, and their combination into a simple or comprehensive model, and the importance of the model in solving typical problems related to water management. This chapter focuses on the quantification of current water resources available in the headwater catchment of PRB using the Pitman model in SPATSIM. The model was set up using hydro-meteorological datasets obtained from natural resources management institutions in Zimbabwe and Mozambique. Rainfall and temperature were the data inputs that drove the Pitman model while streamflow time-series datasets were used for the calibration phase. The calibration was done using both manual and automatic techniques and model performance was assessed for validity using statistical functions in SPATSIM. Future water resources assessment, then, used the calibrated Pitman model, and relied on projections from ten selected climate models 'forced' with RCP4.5 and RCP8.5 (Moss *et al.,* 2008) to assess the availability of water resources into the future period from 2020 to 2100. This chapter presents and discusses the results obtained from this undertaking.

6.2 Methodology

6.2.1 Introduction

The model selection process considered such issues as the physical processes involved, the intended use of the model, the quality of data available and decisions that rest on the outcome of the model-generated data/information. The following criteria were used to choose the model for use:

1. *The modelling purpose* - Streamflow simulation was the focus of the study and a model that can simulate flow with a degree of accuracy was selected.
2. *The data requirements to run the model* - Data availability in the study area was minimal, a common issue with studies done in southern Africa, such that a model that requires the least amount of data but produce satisfactory results were selected.
3. *Model accessibility* - For a postgraduate undertaking, the funds available to carry out the extensive research are generally limited which precludes the use of costly commercial models. Free, open-source software are therefore ideal in that case.
4. *Ease of use of the model* - For first-time modelers, a less sophisticated but effective model needs to be selected.
5. *Availability of expert guide* in the modelling process is of paramount importance for the model selection process.
6. *Model usage in water management research* - A widely used model would show that researchers have confidence in its use and outputs.

Using this selection criterion, the Spatial and Time Series Information Modelling version of the Pitman rainfall-runoff hydrological model (Pitman-SPATSIM) was selected for use in this study for the assessment of the water resources of the headwater sub-basins of the Pungwe River Basin.

6.2.2 Modelling period

Selection of the modelling period was guided by the data available. Available climatic (i.e. rainfall, evapotranspiration) data did not cover the same period as that for which historical observed river flow data were also available in most of the headwater sub-basins. This therefore resulted in the use of gridded Climatic Research Unit (CRU) datasets (https://crudata.uea.ac.uk/cru/data/precip/).

The CRU datasets meant that the modelling period able to be extended to cover 1901 to 2016, which also covered the different periods for which observed river flow data were available for model calibration and parameter setting.

6.2.3 Observed hydro-meteorological data

The Pitman model is driven by two inputs; monthly precipitation totals and a similar time series of potential evaporation (Pitman, 1973). Table 6.1 shows the observed monthly A-Pan evaporation data as a percentage of the annual mean used for the model. Rainfall data used for this research came from many various rainfall stations that are distributed around the study area. The rainfall data are captured, analysed, cleaned and stored by the Meteorological Services Department (MSD). Table 6.2 shows a summary of rainfall data that was used for the research. The length of the rainfall time series varied across catchments and in some cases was not in the same year range with which streamflow was observed. Simulations in Pitman-SPATSIM can only be done for the time period where observed rainfall was recorded. Calibration process becomes affected as the hydrograph of the observed flow will fall in a different time period with the simulated graph to allow for comparison. The choice of the CRU datasets was based on them having been assessed to determine accuracy and used in the same model by, among others, Tirivarombo (2013) in their work on the Zambezi River.

6.2.3.1 CRU data processing for use in the model

The CRU gridded dataset, cru_ts4.01.1901.2016.pre.dat, Climatic Research Unit Time-series version 4.01 (CRUTS v.4.01) (Climatic Research Unit, 2018) was downloaded from https://crudata.uea.ac.uk/cru/data/precip/. A midpoint was used for this downloading step to generate average rainfall time series for each sub-basin. A factor based on available MAP of observed to CRU data was used to preserve the statistical characteristics of the historical observed rainfall where necessary, i.e. where there was a huge difference between the CRU and observed datasets. Table 6.1 and 6.2 shows the summary of the observed historical rainfall characteristics and evaporation distribution of the sub-basins used in this study. The flow and rainfall gauging stations used for this study are shown in Figure 4.2.

Table 6. 1: Observed rainfall data summary for Pungwe headwater catchment.

Station	Data coverage	No. of years	Catchment Area (km²)	Mean annual precipitation (mm)
E64	1959-1999	41	46	1708.56
E70	1959-1999	41	177	1612.32
E72	1959-1999	41	2000	1445.52
E73	1959-1999	41	1095	1208.28
E83	1959-1999	41	550	1178.04
E392	1959-1999	41	66	1227.96
E483	1959-1999	41	100	1185.24
F1	1954-1996	43	6.5	1640.40
F14	1960-2001	42	86	1657.20
F22	1960-2001	42	555	1953.60

Table 6. 2: Observed mean monthly potential evaporation for the stations as a percentage of the average yearly total.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual Average
E64	11.261	11.194	10.115	11.531	8.429	8.833	7.350	5.664	4.113	5.125	7.283	9.036	1483
E70	11.261	11.194	10.115	11.531	8.429	8.833	7.350	5.664	4.113	5.125	7.283	9.036	1483
E72	11.261	11.194	10.115	11.531	8.429	8.833	7.350	5.664	4.113	5.125	7.283	9.036	1483
E73	11.431	9.992	8.706	9.235	7.646	8.251	6.964	6.737	5.678	6.207	8.403	10.674	1321
E83	11.431	9.992	8.706	9.235	7.646	8.251	6.964	6.737	5.678	6.207	8.403	10.674	1321
E392	11.431	9.992	8.706	9.235	7.646	8.251	6.964	6.737	5.678	6.207	8.403	10.674	1321
E483	11.261	11.194	10.115	11.531	8.429	8.833	7.350	5.664	4.113	5.125	7.283	9.036	1483
F1	11.431	9.992	8.706	9.235	7.646	8.251	6.964	6.737	5.678	6.207	8.403	10.674	1321
F14	12.076	10.240	7.980	8.121	7.062	7.910	7.274	6.709	5.862	6.568	8.757	11.441	1416
F22	10.622	9.234	9.354	8.690	8.509	8.751	7.423	6.216	4.647	5.311	8.932	12.372	1657

6.2.3.2 River Flow Data

The choice of river flow stations that were used in this study are located on the streams of the headwater sub-basins of interest. Ten headwater sub-catchments of the PRB were selected for this study. The location and names, summary descriptions of available data and the mean monthly potential evaporation for the river flow gauging stations used in this study are given in Table 6.3.

Table 6. 3: The country location and names of the observed flow data for the headwater sub-catchments under study.

Station	Station Name	Available monthly flows (years)
Zimbabwe		
F1	Mapopo	1961 - 1997 (37)
F14	Pungwe Falls	1971 - 2017 (47)
F22	Katiyo U/S Border	1997 - 2016 (20)
Mozambique		
E64	Pungue em fronteira	1957 - 1973 (17)
E70	Rio Nhacangara	1960 - 1982 (23)
E72	Nhazonia	1952 - 1973 (22)

E83	Rio Mavuzi	1959 - 1977 (19)
E392	Rio Mavhuzi	1964 - 1978 (15)
E483	Rio Nhazonia	1973 - 1982 (10)
E73	Honde River	1961 - 1976 (16)

6.3 Assessment of water resources availability for the current and future periods

6.3.1 Calibration of the SPATSIM-Pitman

During the calibration process, good hydrological practice dictated that for grouped sub-catchments, the calibration starts with the uppermost sub-catchment. Calibration of the model sought to achieve goodness of fit between the simulated and the observed hydrographs. Visual analysis was used to spot the differences in the observed and simulated hydrographs and the changes that occurred when a parameter value was changed. Statistical functions in SPATSIM-v3 (scatter plotting (using Nash-Sutcliffe efficiency, R^2 and percentage difference of means for both the normal and natural logarithm transformed values), flow duration curve (FDC) and monthly distribution curve (MDC)) were used to validate the observations. The calibration process preceded with manual calibration (trial and error) before the automatic process in which the parameters derived from trial and error were varied through a range of possible values based on the physical relevance of the parameter in the model and how each is expected to behave in different climate conditions (Kapangaziwiri and Hughes, 2008). Model parameters used for the study relied on those used for the Pungwe River Monograph (SWECO, 2004) as the starting set. The SPATSIM-Pitman is designed to send an error message if a parameter range is exceeded which greatly aided in the model calibration by minimising uncertainty in the modelling process.

6.3.2 Validation

A Proxy-Basin approach was used for validation purposes as the data used for the study was not enough to be split into two parts. Model parameters used for the study were guided by the Pungwe River Monograph (SWECO, 2004). Parameter ranges are very useful in validating the model results by giving a guideline in which the parameter value should fall under to have hydrological meaning. The values assigned to the parameters have a correlation with the runoff generation processes taking place, thus, assigning random values produces results that cannot be validated. The Pitman-SPATSIM version (SPATSIM_V3) used has a built-in mechanism to aid in model calibration, validation, uncertainty analysis for current/past and projected future water resources. The model will not run when parameter values used for the calibration process do not fall in the expected range for a given parameter, thus, addressing uncertainty in model validation.

6.3.3 Selection of Regional Climate Models (RCMs)

The underlying understanding of future predictions is that any scenario, no matter how seemingly absurd, might become our future reality such that any future possibility must be considered. This then rules out the use of only one climate scenario to predict impacts on future water resources of an area. An ensemble of ten (10) statistically downscaled Global Climate Models (GCMs) forced with the Representative Concentration Pathways (RCP) 4.5 and 8.5 were used for this study and these are represented in Table 6.4. The climate models were accessed from the Climate Systems Analysis Group (CSAG) at the University of Cape Town. There are a lot of climate models for the simulation of water resources, but good hydrological practice promotes the selection of an ensemble of climate models based on their ability to replicate observed conditions of a given area under study (Hughes *et al.,* 2015).

6.3.4 Downscaling of RCMs

The assessment of the water resources of the near (2020 to 2060) and far (2061 to 2100) futures depends on utilization of projections made by GCMs and RCMs. In practice though, during the hydrological assessment of catchments, downscaled datasets derived from these models are used in the simulation of water resources rather than the GCMs and RCMs themselves. This is because GCMs and RCMs have the tendency to generalize spatial and temporal differences in the grids they represent. The generalization is because these models have a coarse spatial resolution which is not adequate to show area differences when assessing water availability in an area. This affects results of the modelling process and brings bias or uncertainty to the generated results. There are two types of downscaling techniques - dynamical and statistical downscaling techniques (Andersson *et al.,* 2011). This study used statistically downscaled datasets downloaded from the Climate System Analysis Group (CSAG) at the University of Cape Town website (http://www.csag.uct.ac.za/). The gridded data were interpolated to generate sub-basin averages for use in the Pitman model. Table 6.4 shows the details of the models that were used in this study.

Table 6. 4: Details of the ten statistically downscaled GCMs obtained from Climate System Analysis Group (CSAG) at the University of Cape Town used in this study.

Model	Institution	References
MIROC-ESM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute	Watanabe *et al.*, 2011
MIROC-ESM-CHEM	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute	Watanabe *et al.*, 2011
CNRM-CM5	Météo-France/CNRS) and CERFACS	Voldoire *et al.*, 2013
CanESM2	Canadian Centre for Climate Modelling and Analysis	Chylek *et al.*, 2011
FGOALS-s2	Laboratory of Numerical modelling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences (LASG/IAP)	Zhou *et al.*, 2018
BNU-ESM	Beijing Normal University	Ji *et al.*, 2014
GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory in the United States	Delworth *et al.*, 2006
GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory in the United States	Delworth *et al.*, 2006
MRI-CGCM3	Meteorological Research Institute	Yukimoto *et al.*, 2012
Bcc-csm1-1	Beijing Climate Center	Ren *et al.*, 2016

6.3.5 Uncertainty analysis of the modelling process

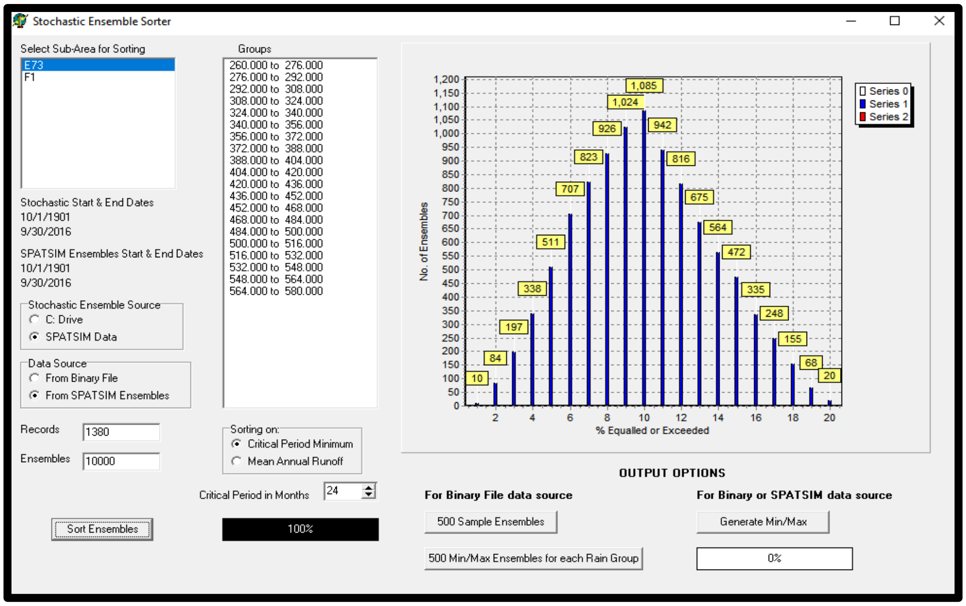
The modelling process aims to generate data and/or information that can be used by decision-makers to come up with solutions for day to day environmental problems. The data generation process is, however, affected by uncertainties that arise from the modelling process. There are many sources of uncertainty which range from the quality of data used, ability of the modeller to carry out the modelling process and the inherent uncertainties of the model structure itself. Modelling studies are adopting the process of incorporation of different sources of uncertainty in water resources assessment to explicitly account for the uncertainties likely associated with the modelling process for the purpose of generating results that can aid decision-making with increased confidence. Uncertainties in the quantification of future water resource availability were addressed by the delta change method in SPATSIM which allows for an ensemble of climate models to be utilized within an uncertainty framework to model future water resources (Hughes *et al.*, 2015; Kapangaziwiri *et al.*, 2018). An ensemble of stochastic rainfall data generated from ten (10) statistically downscaled GCMs "forced" with RCP4.5 and RCP8.5 emission scenarios was then used to assess the impact of a changing climate on the water resources of the headwater sub-catchments of the PRB in the Pitman model.

6.3.6 The delta change approach

Estimation of the impacts of climate change on future water resources was based on the delta change approach (Andersson *et al.,* 2011). The delta change approach is an uncertainty-based hydrological modelling method that utilizes stochastically generated rainfall data from several climate models to analyse catchment scale changes in water resources (Hughes *et al.*, 2015; Kapangaziwiri *et al.,* 2018). This method allows for different results generated by the several climate models to be utilized within an uncertainty framework for assessing future water resources. A maximum of ten climate models can be analysed simultaneously in the delta change approach. Several sub-models are used within SPATSIM in carrying out the delta change approach. The input requirements for the model are a site name, observed historical rainfall (this study used CRU datasets), an option of ten climate models, and mean and standard deviation parameters of a delta change table used to calculate and then output a final stochastic rain ensemble. The following steps are undertaken for this task:

Step one: *Stochastic climate change model:* This step analyses projected climate change rainfall from up to 10 GCMs using the delta change approach to generate stochastic ensembles of rainfall (Figure 6.1). A total of 500 stochastic ensembles are output from this step based on the input climate models.

Step two: *Ensemble sorter model:* Given the huge size of the data generated, a sorting model (i.e. the ensemble sorter model) (Figure 6.1) is used to enable the generated ensembles to be compared to the observed record and visualize the expected changes to, and distribution of, the rainfall based on the GCMs used (Hughes *et al.,* 2015). Time series of minimum, maximum, 95th, 50th and 5th percentiles can be generated for each specified site.



Stochastic Ensemble Sorter

Select Sub-Area for Sorting: E73

Stochastic Start & End Dates
10/1/1901
9/30/2016

SPATSIM Ensembles Start & End Dates
10/1/1901
9/30/2016

Stochastic Ensemble Source
○ C: Drive
● SPATSIM Data

Data Source
○ From Binary File
● From SPATSIM Ensembles

Records: 1380
Ensembles: 10000

Groups
260.000 to 276.000
276.000 to 292.000
292.000 to 308.000
308.000 to 324.000
324.000 to 340.000
340.000 to 356.000
356.000 to 372.000
372.000 to 388.000
388.000 to 404.000
404.000 to 420.000
420.000 to 436.000
436.000 to 452.000
452.000 to 468.000
468.000 to 484.000
484.000 to 500.000
500.000 to 516.000
516.000 to 532.000
532.000 to 548.000
548.000 to 564.000
564.000 to 580.000

Sorting on:
● Critical Period Minimum
○ Mean Annual Runoff

Critical Period in Months: 24

100%

OUTPUT OPTIONS

For Binary File data source

For Binary or SPATSIM data source

0%

Figure 6. 1: A screengrab of the stochastic ensemble sorter model showing the distribution of future rainfall for sub-catchment E73.

Step three: *Global threaded Pitman model*: This step uses the model parameters from the calibration step to generate cumulative present-day or historical water resources conditions.

Step four: *Ensemble sorter (runoff investigation)*: This step analyses the generated runoff ensembles from step three for their authenticity (through available observed flow data or, if these are not available, reliable simulated flows) to check that the models used are producing sensible runoff conditions before the future conditions are generated with stochastic rainfall ensembles.

Step five: *Cumulative uncertainty with stochastic rainfall inputs:* At this stage, the uncertain parameter sets from the calibration step are used together with the stochastic rainfall inputs to produce ensembles of expected future runoff conditions. Caution must be employed at this stage to ensure that stochastic rainfall sets, and the uncertain parameter sets are in the right order and making sense before the model is run. The results generated (about 250 000 ensembles) can be transported to an Excel spreadsheet for post-processing and analyses. For this study, the effects of changes in evapotranspiration were assumed between a +/- 50% range. This large uncertainty range was used because there were no data collected for evapotranspiration into the future and, thus, a larger uncertainty range was deemed adequate to cater to the data inadequacies.

Step six: *Ensemble sorter (runoff analysis)***:** The simulated runoff ensembles are analysed at this step. This study extracted scenarios through the ensemble sorter model that compared the baseline period or historical or present-day (1960-2000) to the near (2020-2060) and the far-future (2061-2099) scenarios. These results are drawn and analysed on a spreadsheet as flow duration curves (FDCs) for the three timelines.

6.4 Results and Discussion

6.4.1 Calibration results (current water resources)

Using the scatter plot analysis function in SPATSIM, the coefficient of determination (R^2) values, percentage difference between the observed and simulated hydrographs and the Nash-Sutcliffe (1970) coefficient of model efficiency (NSE) were calculated for all the calibrated stations at both low and peak flows to assess the predictive accuracy of the SPATSIM-Pitman. Given the uncertainty related to the quality of the historical observed streamflow data, this study regarded a percentage difference of +/- 10% to be an acceptable variance. The low-medium to low flows were based on the natural logarithm transformed values. The final model parameters values used in this research are given in Table 6.5. Figure 6.2 shows the graphical representation of the simulated and observed hydrographs.

Table 6. 5: Final model parameter values generated from the calibration process.

Station	Calibration period	Average Monthly Rainfall	PEVAP	ZMIN	ZMAX	FT	ST	ST fraction for sat. excess runoff	POW	GPOW
E64	1956-1973	142.38	1483	27.5	955.8	83.9	370.6	0.209	2.2	6.8
E70	1955-1982	134.36	1483	46.7	1212.3	10.0	1000.0	0.721	2.9	6.4
E72	1960-1974	120.46	1483	100.0	2900.0	1.0	3000.0	0.700	1.2	3.0
E73	1956-1983	100.69	1321	20.6	943.7	2.4	46.7	1.000	1.2	3.4
E83	1957-1977	98.17	1321	30.0	1000.0	5.0	340.0	1.000	3.0	1.0
E392	1962-1979	102.33	1321	30.0	1001.2	3.6	38.6	0.800	2.8	8.4
E483	1972-1982	98.77	1483	100.0	1200.0	15.0	900.0	0.400	1.5	3.0
F1	1954-1997	136.70	1321	34.5	936.7	75.0	500.0	1.000	1.2	1.0
F14	1970-2017	138.11	1416	27.9	1013.2	203.9	492.9	0.500	1.0	3.1
F22	1996-2017	162.79	1657	30.0	1300.0	120.0	300.0	0.500	3.0	3.5

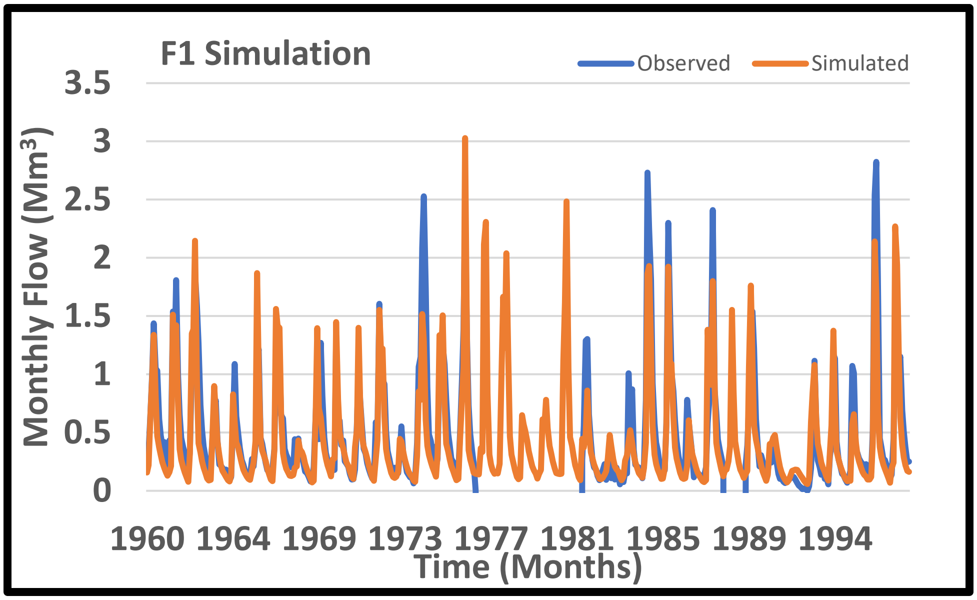
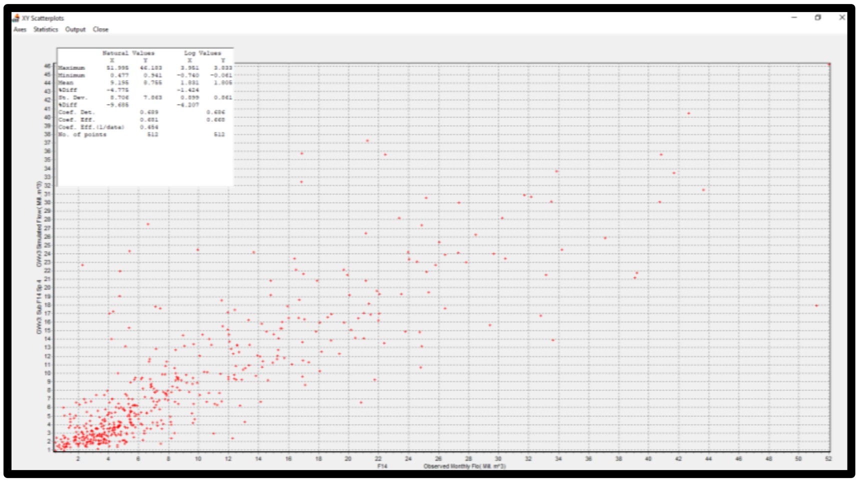


Figure 6. 2: Time series visualisation of the observed and simulated flows used for visual analysis of calibration results at gauging station F1.

6.4.1 Scatter plot objective function

The results in Table 6.6 were generated for both low and peak flows and Figure 6.3 presents the graphical results of the scatter plot (Appendix B shows the graphs for all sub-catchments). Most of the sub-catchments performed well based on the results of the statistical objective functions used (coefficient of determination (R^2) and Nash-Sutcliffe coefficient of efficiency (NSE)).



```
                   Natural Values          Log Values
                     X         Y          X         Y
Maximum          51.995    46.183     3.951     3.833
Minimum           0.477     0.941    -0.740    -0.061
Mean              9.196     8.766     1.831     1.806
%Diff            -4.775              -1.424
St. Dev.          8.706     7.863     0.899     0.861
%Diff            -9.686              -4.207
Coef. Det.                 0.689               0.686
Coef. Eff.                 0.681               0.668
Coef. Eff.(1/data)         0.454
No. of points                512                 512
```

Figure 6. 3: A screengrab of the scatter plots from SPATSIM that were used to assess simulation results at F14. The analysis is given in the table to the top left-hand corner of the image. Results for both R^2 and NSE are presented for both high and low flows and have been tabulated for clarity in Table 6.6 and Appendix B.

Table 6. 6: Summary of scatter plot results (top left-hand side of Figure 6.3) for the headwater sub-catchments of the PRB based on the mean values of historical observed (obs) and model simulated (sim). * indicates values that were regarded as not suitable for the simulation periods.

Station	Peak flows (MCM)		Low flows (MCM)		% Difference of Means		Coefficient of Determination		NSE Values	
	Obs. (mean)	Sim. (mean)	Obs. (mean)	Sim. (mean)	Peak flows	Low flows	Peak flows	Low flows	Peak Flows	Low Flows
F14	9.195	8.755	1.831	1.805	-4.775	-1.424	0.689	0.686	0.681	0.668
F22	31.441	58.508	1.911	3.57	86.092*	86.879*	0.354*	0.235*	-0.121*	-0.141*
E64	63.112	65.086	3.862	3.886	3.12	0.64	0.633	0.799	0.525	0.791
F1	0.524	0.476	-1.054	-1.092	-9.198	3.603	0.766	0.757	0.756	0.755
E73	43.329	41.941	3.332	3.271	-3.203	-1.831	0.789	0.807	0.740	0.796
E72	26.307	31.179	2.731	2.798	18.518	2.466	0.704	0.803	0.148	0.786
E483	5.825	5.819	1.429	1.485	-0.117	3.899	0.785	0.734	0.745	0.725
E70	4.530	7.862	1.095	1.089	73.557*	-0.480	0.752	0.759	-2.226*	0.365
E392	1.956	1.915	-0.719	-0.702	-6.440	-7.097	0.827	0.755	0.826	0.752
E83	11.380	13.003	2.025	1.993	14.258	13.182	0.694	0.695	0.648	0.671

N.B. MCM = Million Cubic Metres

The goodness of fit analyses through visual assessment (Figure 6.2) of the simulated and observed hydrographs was confirmed by statistical functions (see Appendix B for the results of all sub-catchments). R^2 and NSE analysis play an important role in establishing the relationship between the simulated and observed hydrographs, enabling the modeller to have confidence in the model's ability to simulate the future (Croke, 2009). However, they are limited in giving hydrological explanation as to how the flow is distributed. NSE is more robust than R^2 but using both methods of analysis is good practice. While the NSE is sensitive to systematic errors (general over- or under-estimation), R^2 is not similarly affected though a value close to 1 does not necessarily imply a good simulation. Where both the NSE and R^2 are used as assessment criteria, large differences between them indicate systematic errors. This is evident for the gauged basin E70 which has significant differences between R^2 and NSE. Using percentage difference of the mean monthly flow of simulated and observed hydrographs, the closer the mean of the simulated is to that of the observed, the lesser is the percentage difference but does not give clarity as to the distribution of these differences. Using FDCs and MDCs helps to show how these differences are distributed.

6.4.2 Flow duration curves and monthly distribution curves

FDCs and MDCs were also used to judge the performance of the model, and naturally confirmed the results of the R^2 and NSE analyses (Figure 6.4, Figure 6.5). Table 6.7 and Table 6.8 presents the qualitative descriptions of the results of the visual analyses of FDCs and MDCs respectively (see Appendix B for results of the FDCs and MDCs of all the sub-catchments under study).

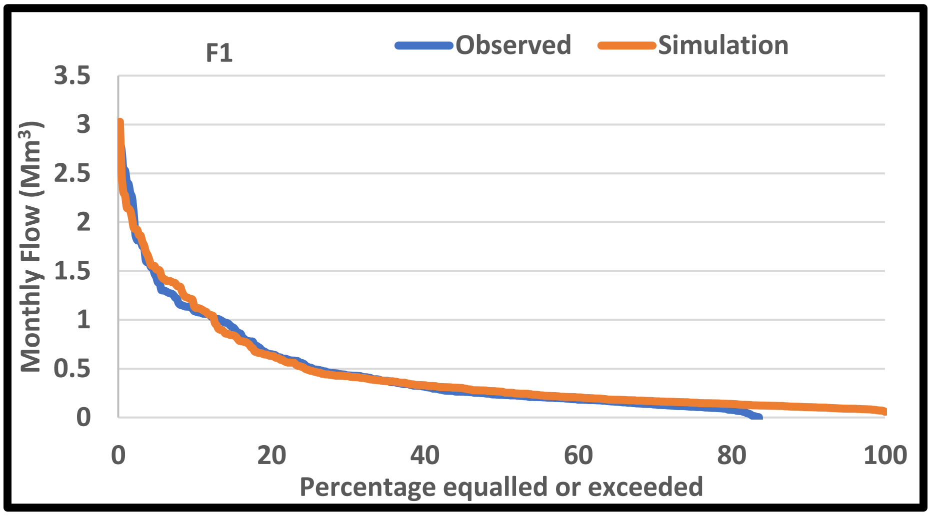


Figure 6. 4: An example of a flow duration curve for F1. The blue curve represents the simulated graph while the brown curve is the observed graph. The x-axis represents streamflow in million m^3 and the y-axis presents percentage time equalled or exceeded.

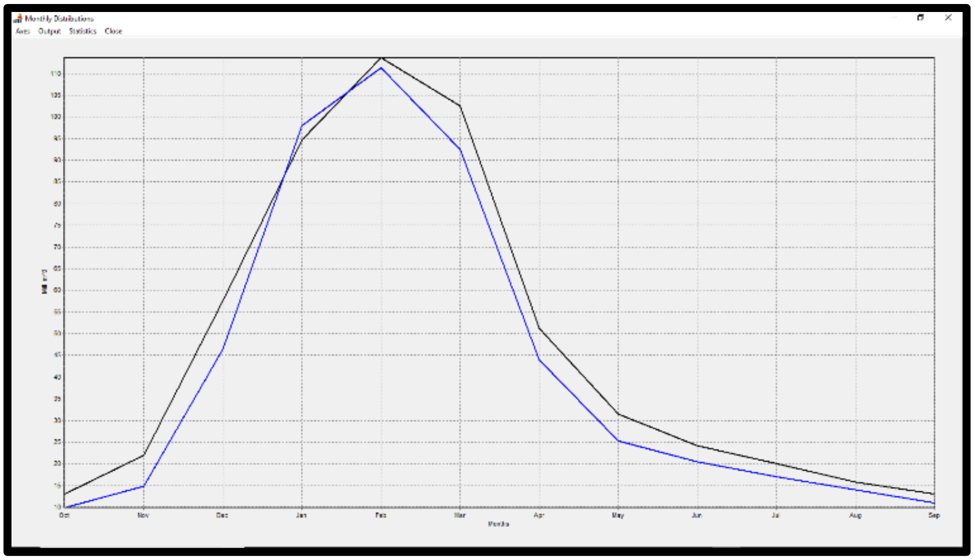


Figure 6. 5: An example of a monthly distribution curve for E73 with the blue line representing the simulated graph while the black line represents the observed graph. The x-axis represents monthly flow in million m^3 and the y-axis represents time in months (starting from October).

Table 6. 7: Summary of results and comments from the analyses of flow duration curves (FDCs).

Station	Overall comments	
	Peak flows	**Low flows**
F14	Observed flows well produced.	Observed flows well produced
F22	Over-simulation.	Distinct over-simulation.
E64	General over-simulation.	Observed flows well produced.
F1	Observed flows well produced with slight under-simulation of the recession curves.	Observed flows well produced.
E73	Observed flows well produced with slight under simulation of the recession curves.	Observed flows well produced.
E72	Slight problem with rising limbs of hydrographs indicating slight late rise for the simulations.	Observed flows well produced.
E483	Slight under-simulation.	Slight under-simulation.
E70	General late rise of the rising limbs for the simulations.	Slight under simulation.
E392	Observed flows well produced with generally slightly lower peaks in places.	Observed flows well produced.
E83	Some problems with recession curves. Simulations generally fall much slower than observations.	Observed flows well produced.

Table 6. 8: Summary of results and comments from the analyses of results from seasonal/monthly distribution curves.

Station	Overall Comments	
	Peak flows	**Low and medium flows**
F14	Observed flows well produced.	Observed flows well produced.
F22	Over-simulation.	Slight over-simulation.
E64	Under-simulation of rising curve and over-simulation of the peak flows.	Good simulation of recession curves.
F1	Observed flows well produced.	Slight under-simulation of recession curves.
E73	General under-simulation.	General under-simulation.
E72	General over-simulation.	Observed flows well produced.
E483	Observed flows well produced.	Slight under simulation.
E70	Over-simulation of observations.	General under-simulation of observations.
E392	Observed flows well produced.	Generally observed flows well produced.
E83	Over-simulation.	Observed flows well produced.

FDCs provide an easy to use graphical and computational format for examining the flow events according to their frequency, magnitude, and duration (McKay and Fischenich, 2016). Illustrating the percentage of time a flow occurred during a given period of collected data, FDCs can explain how the difference in the simulated and observed hydrographs is distributed. In this study FDCs were used to ascertain the results of the scatter plot analysis and quantification of future water resources. Generally, the FDCs that were produced have a steep curve which indicates high flows that occur for a very short period. This is indicative of small catchments that experience rainfall-induced flows (Oregon State University, 2019). It was noticed from the FDCs of the sub-catchments that low flows are predominant in the area occurring between 65-80% of the time. Based on the FDCs, there was no period with zero flows, indicating the perennial nature of the rivers in the study sub-catchments.

Monthly Distribution Curves (MDCs) were used to show the seasonal distribution of the flow in the rivers throughout the year, and, thus, provided information on the variation of streamflow. High flows generally occur around February and March after the rainy season, while the driest period occurs from July to October after cessation of rains and indicating that low flows are thus sustained by groundwater through spring discharges which occur in most of the sub-catchments. This information is important for water resources management and development. Water resources practitioners make use of this information to know what river levels to expect at a point in time when projects along the river such as construction of hydraulic infrastructure can be done and gives farmers a crop production period which depends on rainfall and that which depends on irrigation.

6.4.3 Available water resources in the headwater sub-catchments of Pungwe River Basin

Table 6.9 shows the current water resources available at the outlet of each headwater sub-catchments, defined by the relevant gauging station in the PRB. The average yearly total rainfall ranges between 1178 and 1954 mm which is above average for both Mozambique and Zimbabwe’s average yearly total rainfall (Mozambique has a low of 300 mm and a high of 1420 mm while Zimbabwe averages between 500-900 mm). Average annual streamflow ranged between 6 MCM for F1 sub-catchment to 757 MCM for E64 sub-catchment.

Table 6. 9: A summary of the available historical water resources of the headwater sub-catchments of the Pungwe River Basin. Mean annual precipitation (MAP) and mean annual runoff (MAR) are represented (Source: SWECO and Associates, 2004).

Station	Calibration period	MAP (mm/yr)	MAR (MCM/yr)
E64	1956 -1973	1709	757
E70	1955 -1982	1612	50
E72	1956 -1973	1446	316
E73	1956 -1983	1208	546
E83	1957 -1977	1178	137
E392	1962 -1979	1228	23
E483	1972 -1982	1185	70
F1	1954 -1997	1640	6
F14	1970 -2017	1657	111
F22	1970 -2017	1954	377
Average			
Mozambique		1029	101
Zimbabwe		1680	814

6.4.4 Future water resources in the headwater sub-catchments

Figure 6.6 (a) and (b) are examples of the generated FDCs from the delta change method. All the FDCs results for future water resources availability under RCP 4.5 and RCP 8.5 for each sub-catchment are presented in Appendix C. Quantification of future water resources using FDCs showed how both high and low flows could be affected by climate change. Future projections based on different representative pathways had different outcomes as expected. RCP 4.5 was expected to produce scenarios that are less drastic than those of RCP 8.5 because of the carbon dioxide emission scenarios represented by both RCPs. RCP 4.5 represents carbon dioxide emissions that reach their peak around 2040 then remain constant to the end of the 21st century whilst RCP 8.5 shows emissions that continue to rise to the end of the century (Moss et al., 2008).

6.4.4.1 RCP 4.5 projections

Near-future (2020-2060) - There was a general increase in water resources available for this period. Using the percentage difference, an increase in water availability was noticed for most of the sub-catchments with E73 projecting the highest increase of 7.13%. It was observed that during this period the sub-catchments that showed a reduction in water resource availability were those that underperformed during their assessment with R^2 and NSE. E483 had the highest reduction in water resources available for the period with a percentage reduction of -7.90%. Basing on the reliability of the data used for the research, a 10% increase or decrease in water resources availability was considered not to yield significant change in water resources availability. The changes in water resources availability for this period under RCP 4.5 scenario were regarded as less significant.

Far-future (2061-2099) - This period showed a decrease in water resources availability across all sub-catchments compared to the near-future period. Except for E70, E72 and E483 that showed a negative decrease from the current period, the remainder of the sub-catchments still had more water resources available compared with the current period (see Appendix C). RCP 4.5 generally projected a future where water resources will be slightly more than what is currently available, a future possibility that is not deprived of water resources compared with the current period. The FDC (Figure 6.6 (a)) suggested the same with high and low flows for the near and far-future looking almost like that of the current period for all sub-catchments.

6.4.4.2 RCP 8.5 projections

Near and far-future- RCP 8.5 represents a future were carbon dioxide emissions continue throughout the 21st century due to continuous and increased use of fossil fuels. This is the RCP that projects the worst-case scenario and it was discovered that both the near and far-future periods had similar changes comparing with the current period (Table 6.10). There will be a decline in water resources available for all the sub-catchments understudy with varying magnitudes. F1 showed the least decline in water resources availability with a percentage decline of -4.17%. The highest percentage decline was recorded for E70, E72, and E483. The rest of the sub-catchments recorded a decline in water resources availability which ranged from -4.17% (F1) to -13.33% (E64), which, according to the assumption that a 10% increase or decreases is regarded as less significant, do not deprive water availability in the future. It can be concluded with RCP 8.5 that even though water resources are projected to decline, the decline is not an extreme deviation from the current water resources available except for E70, E72, and E483 which showed significant percentage decrease, 48.5%, 71.7%, and 68.9% respectively (Table 6.10). These sub-catchments' water resources availability will be significantly reduce posing a lot of threat to the environment and the communities that rely on the water. Such reductions can lead to water scarcity in the area.

Figure 6.6 (b) showed the FDC created for the future projections under RPC 8.5 scenarios. However, such severe changes in a region that receives an abundant amount of rainfall brings about uncertainties and confidence in the results. The results of these sub-catchments could be as a result of systematic errors as shown by their NSE results. NSE is sensitive to systematic errors and if that is the case, uncertainty arises over the results of these sub-catchments.

The results inform water planning and management to come up with mitigatory strategies that can be implemented now to safeguard the resource’s availability into the future. Reduced water availability in headwater sub-catchments has a continuous effect that will be felt and magnified going downstream in most cases. As the rivers become intermittent as a result of reduced water resource availability in the future, socio-economic activities in the area such as irrigation of crops, fishing, domestic use and renewable energy production as well as downstream riparian communities will be greatly affected hindering sustainable development of these areas. What can be noted for this study is that only uncertainty in model parameterization was accounted for as it was assumed that the SPATSIM model was able to correctly reproduce current and future water resources in the study area based on its performance in other studies carried out in southern Africa and other regions (Hughes, 1997; Bharati and Gamage, 2011; Hughes *et al.*, 2015; Kapangaziwiri *et al.,* 2018). The modelled results will be different if other factors, other than climate change alone (land-use changes, sedimentation, abstractions, etc.), were modelled.

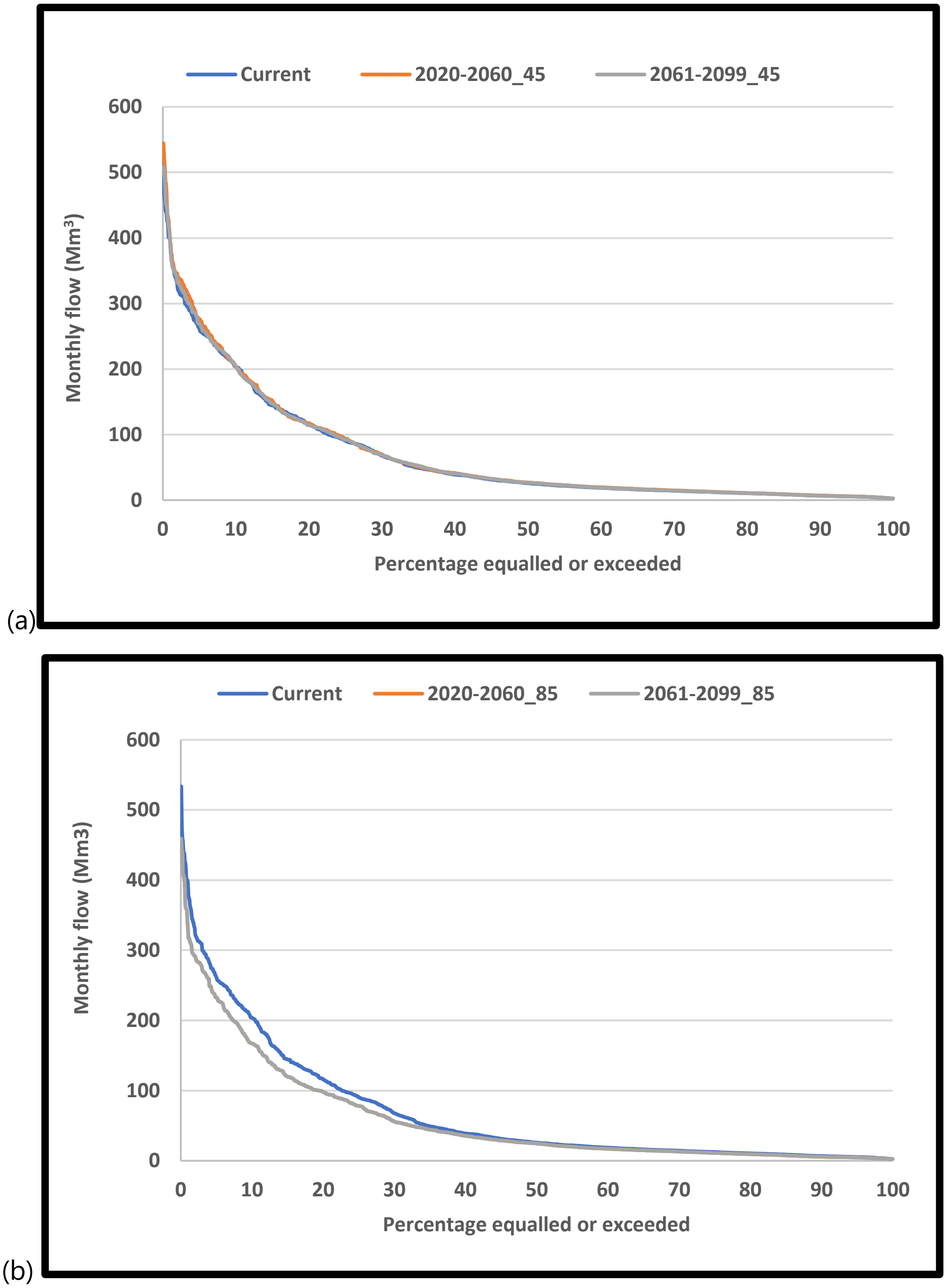


Figure 6. 6: An example of flow duration curves for the assessment of future water resources in the near-future (2020-2060) and far-future (2061-2099) for (a) RCP 4.5 and (b) RCP 8.5 (Sub-basin E64).

Table 6. 10: Results of mean monthly flow (in MCM) of water resources and the percentage difference of the current flow compared to the future simulated flows in the selected headwater sub-catchments of the Pungwe River Basin.

Station	Current (Historical)	RCP4.5 Flows (MCM)		RCP8.5 Flows (MCM)	
		2020-2060	2061-2099	2020-2060	2061-2099
E64	67.21	69.12	68.10	58.25	58.24
% Diff of mean		**2.84**	**1.32**	**-13.33**	**-13.35**
E70	8.93	9.02	8.71	4.60	4.61
% Diff of mean		**1.01**	**-2.46**	**-48.49**	**-48.38**
E72	62.38	58.28	56.45	17.67	17.66
% Diff of mean		**-6.57**	**-9.51**	**-71.67**	**-71.69**
E73	47.00	50.35	48.00	43.72	43.71
% Diff of mean		**7.13**	**2.13**	**-6.98**	**-7.00**
E83	19.84	20.26	20.40	18.68	18.67
% Diff of mean		**2.12**	**2.82**	**-5.85**	**-5.90**
E392	2.29	2.41	2.34	2.07	2.07
% Diff of mean		**5.24**	**2.18**	**-9.61**	**-9.61**
E483	5.57	5.13	5.16	1.73	1.73
% Diff of mean		**-7.90**	**-7.36**	**-68.94**	**-68.94**
F1	0.48	0.50	0.49	0.46	0.46
% Diff of mean		**4.17**	**2.08**	**-4.17**	**-4.17**
F14	8.81	9.02	8.94	8.12	8.12
% Diff of mean		**2.38**	**1.48**	**-7.83**	**-7.83**
F22	63.47	65.33	64.32	55.59	55.58
% Diff of mean		2.93	1.34	-12.42	-12.43

6.4.5 Importance of current low flows in the area

The sub-catchments that were studied are characterized by perennial rivers which promote their ever-green dense riparian forests. The perennial nature of these rivers is promoted by the low flows for the most part of the year. The perennial nature of rivers in the study area indicates that the river catchment consists of a series of interlinked storages which can recharge, store and discharge water at any time controlled by the physiographic characteristics of the catchment (Meyer *et al.,* 2007). Such processes as infiltration, hydraulic characteristics, evapotranspiration rates, climate of the area, recharge and distribution of vegetation have a direct influence on recharge, storage, and discharge of water in a catchment (Feng *et al.,* 2013). The perennial flow in the rivers has made possible the creation of hydropower stations in some these sub-catchments, leading to an improvement in the livelihoods of the rural populations.

6.5 Summary and conclusion

The study evaluated current and future water resources availability in the headwater catchment of PRB. Current water resources available in the sub-basins were shown to be adequate to maintain riverine and riparian ecosystems. Future projected rainfall data obtained from CSAG forced with RCP 4.5 and RCP 8.5 were used to drive the calibrated Pitman-SPATSIM to project water availability scenarios to the end of the 21st century. RCP 4.5 simulated almost similar projections of future water resources available to the current period. Reduction in water resources by the end of the 21st century for all sub-catchments studied at varying magnitudes was more pronounced using the RCP 8.5. The differences in the results of the scenarios used for the projections bring about a management dilemma in which future water resource uncertainty affects the right course of action to take. It could be good management practice to plan for the most drastic outcome to ensure that if this becomes reality then measures would have been put in place to manage such a scenario but not always the case. Uncertainty analysis was carried out for both current and future projections though the analysis was limited to the parameter optimization process in quantifying current water resources. Despite the limitation, SPATSIM_V3 is a robust model which has been extensively used for similar studies in southern Africa producing good results and was able to show how water resources in the area will be affected by climate change into the future. The level of confidence in the generated results is adequate to help decision-makers in coming up with sustainable management strategies for these sub-catchments based on these scenarios. The implementation of long-term developmental plans will, however, need to rest on stronger results that encompass a lot of factors that affect water resources availability in rivers to improve on the results. This will be achieved by incorporating other hydrological models that can assess other elements of the environment (land-use changes, temperature changes, etc.).

7: CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusion

The study of water resources availability is very important in natural resources management at a time when water scarcity is reported to soar in the future putting many lives at risk. Developmental issues are centred on the availability of water resources. This study looked at how headwater catchment management is being implemented in southern Africa in the face of a changing climate. A case study of Pungwe headwater catchment was used which is a transboundary catchment shared between Mozambique and Zimbabwe. The aim was to contribute to the understanding of headwater catchments in a river basin to create a foundation for further studies on how best headwater management can be incorporated into the current water management policies. This area of study represents most of the problems in water resources management such as shared waters, pollution, upstream land-use changes, damming along a river and participation in water resources management. The issue of data, in terms of its availability and quality, was one of the problems the study faced.

Policy development and decision-making rest on the availability of quality data. Models, as tools to aid decision making, rely on data that can generate outputs with some level of confidence. Water resources estimation for both current and future rested on the ability of hydrological and climate models, respectively to simulate them. Assessing future water resources management using a group of models surely increases the level of confidence in the results generated. The literature reviewed showed that headwater catchment management has not yet been adopted in most of southern Africa as a management approach to water resources management. It acknowledges that adoption of integrated water resources management (IWRM) has been successful in this part of the region but there is need to effect policy changes and to adopt most recent water management approaches. Headwater management as a catchment management approach in a world that has a changing climate has proved to be an effective tool for sustainable catchment management in first world countries (Haigh, 2010). There is, therefore, a need to bring headwater catchment management approach to water resources management in Third World nations who face the grim impacts of a changing climate due to their limited adaptation capacity to climate change.

7.1.1 Evaluation of the management of the Pungwe headwater catchment

The assessment of water management strategies in the headwater catchment of PRB showed that integrated water resources management (IWRM) is being implemented. Under the IWRM principles, a JWC was established to effectively govern the water resource of this transboundary basin. National water management institutions from both countries, i.e., ZINWA from Zimbabwe and ARA-Centro from Mozambique, agreed to cooperate in the management of water resources in the basin. The evaluation of water resources management discovered that:

- Participation is highly encouraged in the area with an emphasis on equal representation between man and women.
- Funding plays a major role in promoting community engagement and adoption of new management strategies.
- There is a need to promote incorporation of climate change in the management of these headwater catchments for proper decision making.

7.1.2 Evaluation of the modelling process and climate change assessment

Present/historical water resources in the study area were assessed using the hydrological model Pitman-SPATSIM. Using the model, rainfall and potential evaporation data were used to drive the model which produced observed and simulated hydrographs that were used to assess water resources availability in the study area. A total of ten sub-basins were selected for the study. The delineation of these sub-basins and assessment of how the water flows from sub-basin to sub-basin aided the modelling process to know the sub-basins to calibrate first (good modelling practice starts calibrating from the upstream sub-basin to the downstream). During the modelling process, the following were noted:

- The modelling process was affected greatly by data availability, its quality, and length. This introduced uncertainties in the modelling as confidence in the results generated relies on good input data.

- There was a general good simulation of low flows which are very important in maintaining the ecological functions of headwater catchments. From the assessment of current/historic water resources availability, it was concluded that water resources currently available are enough to meet the needs of both the users and the environment.
- The future water resources quantification proved that there will not be a significant decline in water resources available. It was, however, noticed that uncertainties that surround future water resources estimation and results can vary from sub-basin to the other affecting the credibility of the results generated.

7.2 Limitations and recommendations

IWRM was a step in the right direction to effective water resources management in a basin. Modern-day water resources management depends on an interdisciplinary approach to natural resources management to encourage sustainable water resources utilization and development. Headwater catchments are fragile and changes that occur to then have the potential to affect far reaches of the river system. Headwater catchments are better managed using IWRM which promotes research, education of the stakeholders on good natural resources utilisation and promotes sustainable development in the area. Utilization of resources in headwater catchments sustainably can promote the development of the area.

7.2.1 Limitations

- There is limited research in the management of headwater catchments of PRB. Research is a pillar of headwater catchment management and its importance is that it informs on the areas to protect, conserve and develop sustainably whilst maintaining the integrity of the river system.
- The research only quantified water resources into the future using climate change without the influence of human behaviour. There is a need to incorporate both to see the full picture.

7.2.2 Recommendations

For policy and good management:

- Improve data collection mechanisms and increase the number of data collection sites through initiatives such as installing weather stations at government institutions (police camps, clinics, schools). In headwater catchments, access to data collecting stations is usually difficult, and therefore, there is a need to install automated data collection stations.
- There is a need to create national frameworks for the management of headwater catchments and implemented into water resource management.

For livelihood enhancement in Pungwe River Basin:

- There is a need to carry out inventories in headwater catchments and identify the resources that are mostly used by locals to create a sustainable way of resource utilization.
- Due to the perennial nature of flows in the headwater catchment of PRB, there is a strong possibility for increased investments in hydropower plants by building more small-scale stations that provide electricity to the locals. This will significantly improve the way of life of the locals.

For further research:

- Natural resources management institutions should increase the research output and allow ease of access of datasets to researchers to aid in the research output.
- This research can further be improved by incorporating anthropogenic effects to water resources availability (land-use changes).
- The modelling of future water resources is an undertaking with a wide range of uncertainties that produce a range of possible future climate possibilities. It is, thus, paramount to acknowledge uncertainties and incorporate them in the understanding of future water resources availability.

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APPENDIX A: Interview guide

The following guide was developed to understand the state of headwater catchment management in the Pungwe River Basin. The informants that took part in this data collection process where from key natural resources management institutions that are present in the area.

Introduction

My name is Anesu Dion Gumbo, a masters' student with the University of Venda in South Africa. I am currently doing research on Sustainable headwater catchment management under a changing climate in Pungwe River Basin. This research relies on the knowledge of how water resources management is being done in the headwater catchment of Pungwe River, and thus, the need to conduct interviews with the persons involved in the management of such areas. Natural resources management institutions are the target group for this research and their integration in the management of headwater catchments will be assessed. Confidentiality is key to this research and information that the respondent gives will not be divulged to anyone. Your participation in this research is voluntary and you may withdraw from the session at any time or decline to answer any questions that make you uncomfortable. The benefit of the study, scientifically, is to evaluate sustainable headwater catchment management and how climate change affects it. If there is a need to clarify questions as we proceed with the interview feel free to ask me at any point of the interview. If you have understood the process and willing to take part in the research may you kindly sign the consent letter provided?

Water resources management in Upper Pungwe

1. What approach to water resources management is used in Upper Pungwe?
a) ____
b) ____
2. Who is responsible for managing the water resources in Upper Pungwe?
a) ____
3. How does the Save Catchment and Pungwe Sub-Catchment Council operate?
a) ____
4. Do you understand what headwater catchments are?
a) ____

5. What is the level of cooperation between your organization and other natural management institutions?

a) ____

6. How is the current state of stakeholder participation in the area?

a) ____

7. What/who are the major water users in the area?

a) ____

8. Does the abstraction of water by the City of Mutare upstream of the Pungwe River pose any threats to downstream users?

a) ____

9. How many hydropower plants have been developed in the area and do they have any effects to water resources availability?

a) ____

10. How is climate change implemented into the management of natural resources in your organisation?

a) ____

11. Does your institution carry out scientific researches to find out trends in climate change and publish its works for other institutions to access it?

a) ____

12. Is the management of natural resources management following current global trends or it is just guided by the act that governs it?

a) ____

13. Does your organization carryout awareness campaigns to empower the locals in the area and advise them on good natural resources management?

a) ____

14. With the fragility of headwater catchments, do you think the current water management strategies being used in the area are adequate for sustainable headwater catchment management?

a) ____

15. Are there any hinderances in managing natural resources in the area?

a) ____

16. Are the gold panning activities done in the area of concern to natural resources management?

a) ____

17. What do you think can be done in your organization to improve water resources management in Upper Pungwe?

a) ____
b) ____
c) ____

APPENDIX B: Visual and statistical analysis of the calibration results

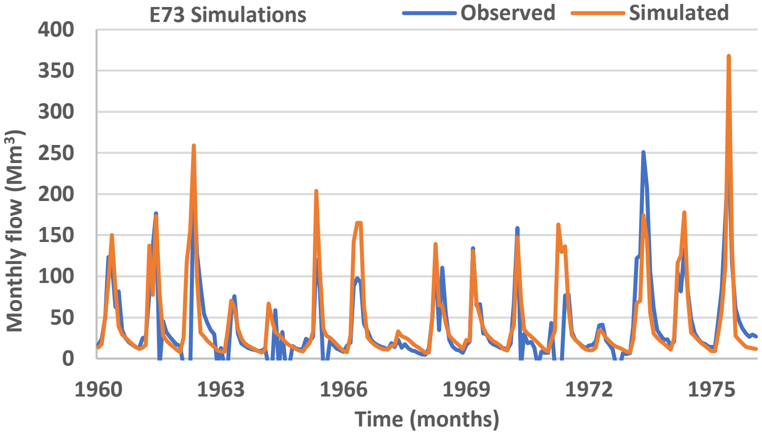


Figure B 1: Observed and Simulated monthly streamflow using Pitman-SPATSIM for station E73.

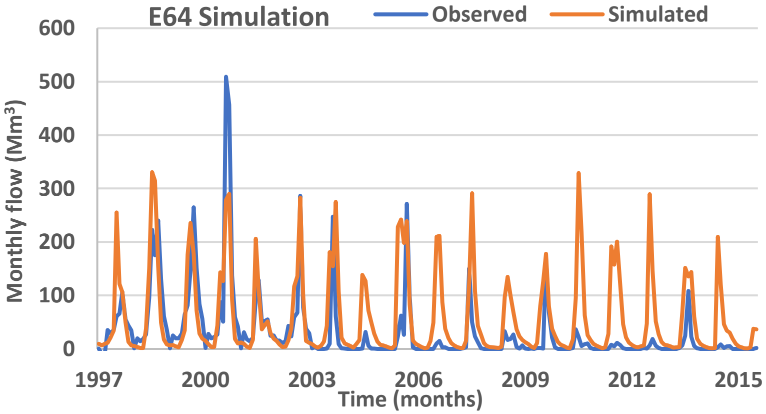


Figure B 2: Observed and Simulated monthly streamflow using Pitman-SPATSIM for station E64.

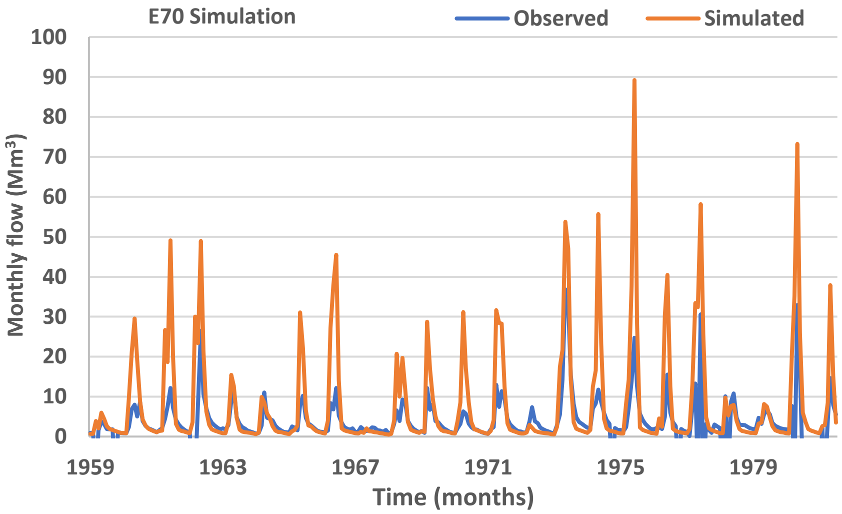


Figure B 3: Observed and Simulated monthly streamflow using Pitman-SPATSIM for station E70.

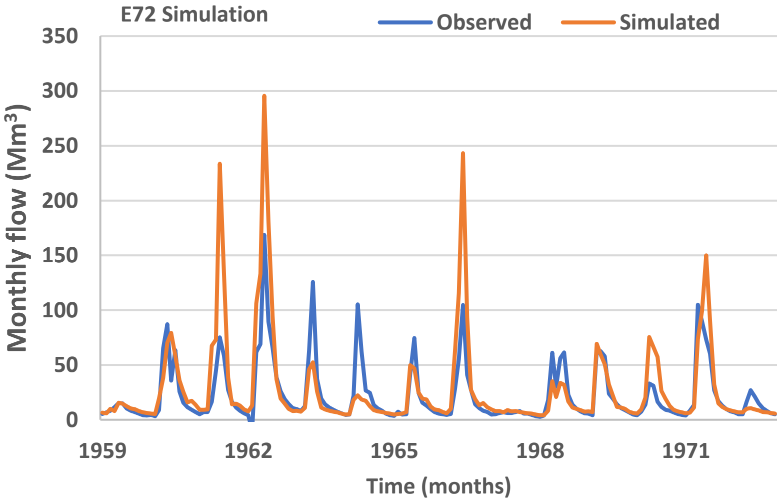


Figure B 4: Observed and Simulated monthly streamflow using Pitman-SPATSIM for station E64.

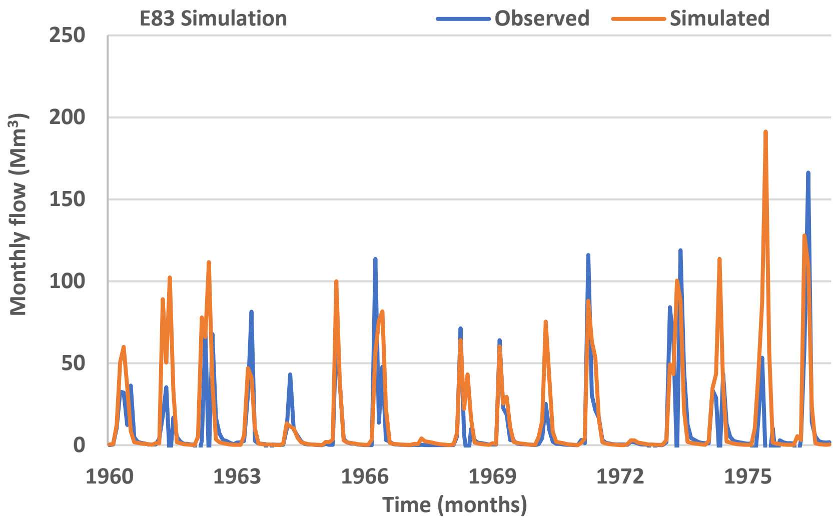


Figure B 5: Observed and Simulated monthly streamflow using Pitman-SPATSIM for station E83.

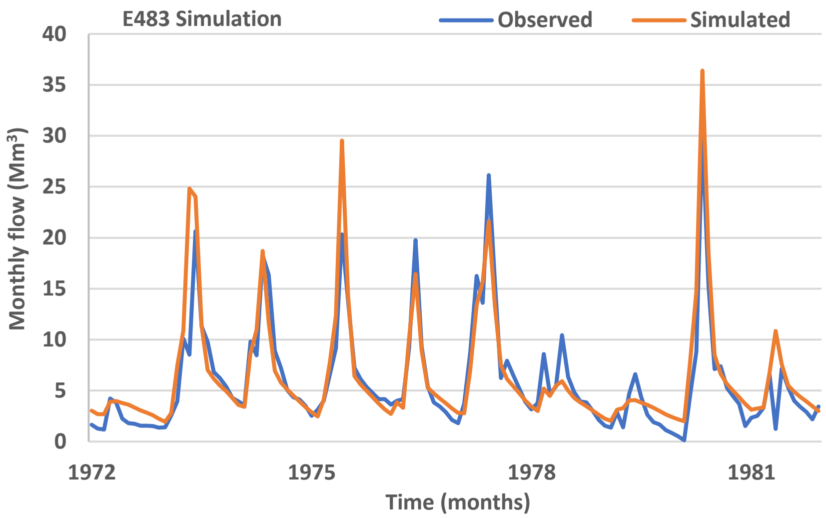


Figure B 7: Observed and Simulated monthly streamflow using Pitman-SPATSIM for station E483.

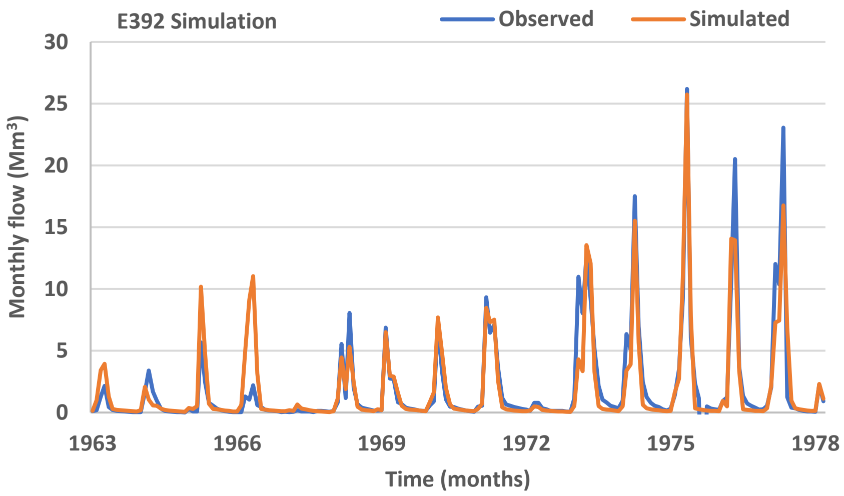


Figure B 6: Observed and Simulated monthly streamflow using Pitman-SPATSIM for station E392.

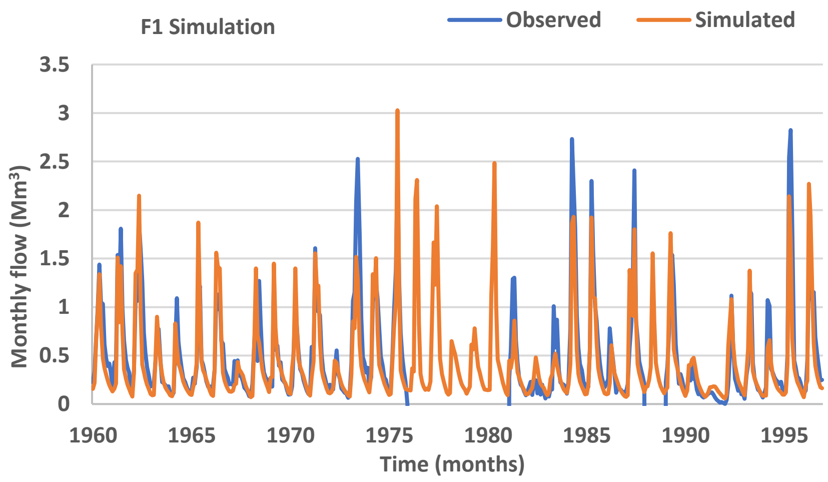


Figure B 8: Observed and Simulated monthly streamflow time series using Pitman-SPATSIM for gauging station F1.

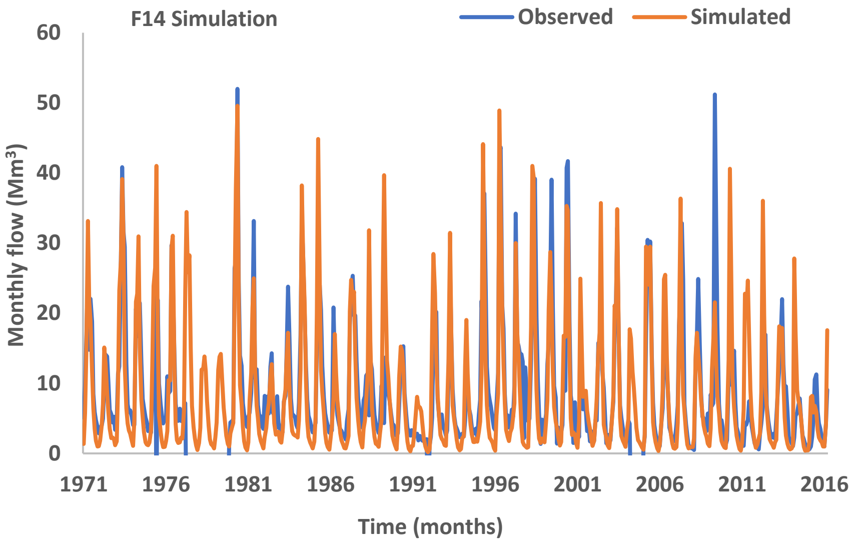


Figure B 9: Observed and Simulated monthly streamflow time series using Pitman- SPATSIM for gauging station F14.

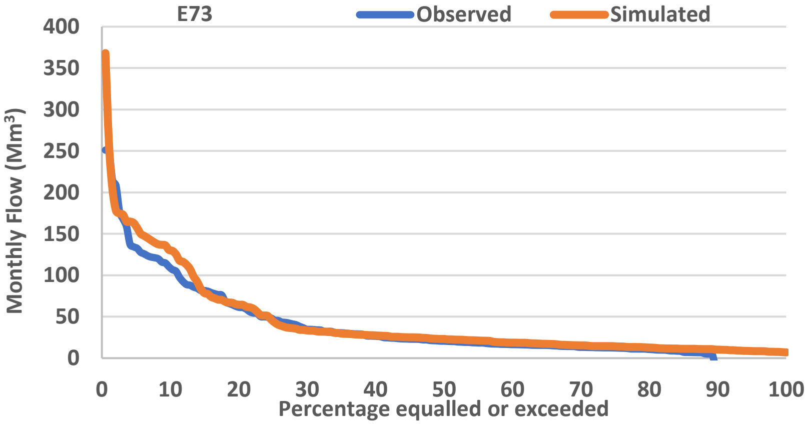


Figure B 10: Flow duration curve results for Station E73

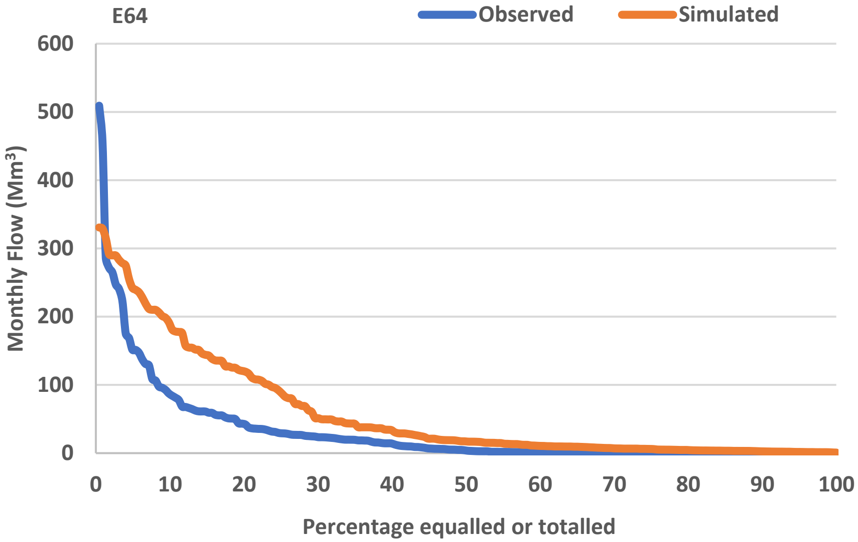


Figure B 11: Flow duration curve results for Station E64. NB: this shows possible problem in simulation process.

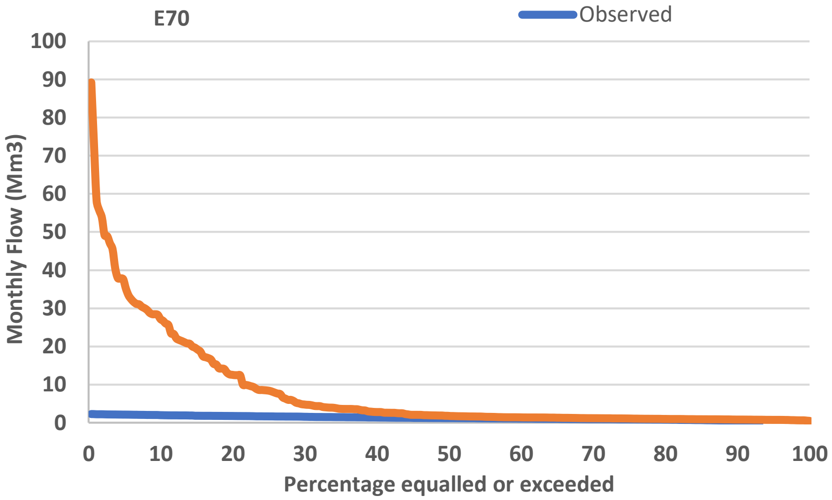


Figure B 12: Flow duration curve results for Station E70. NB: this shows possible problem the available observed dataset.

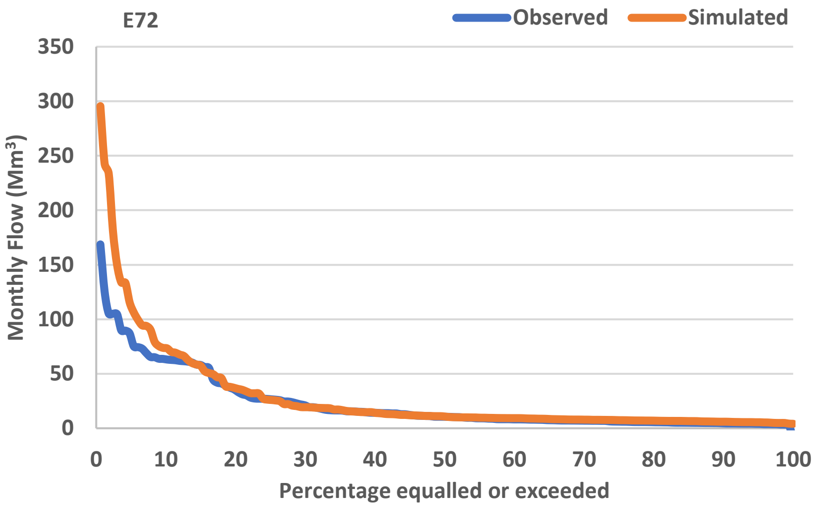


Figure B 13: Flow duration curve results for Station E72

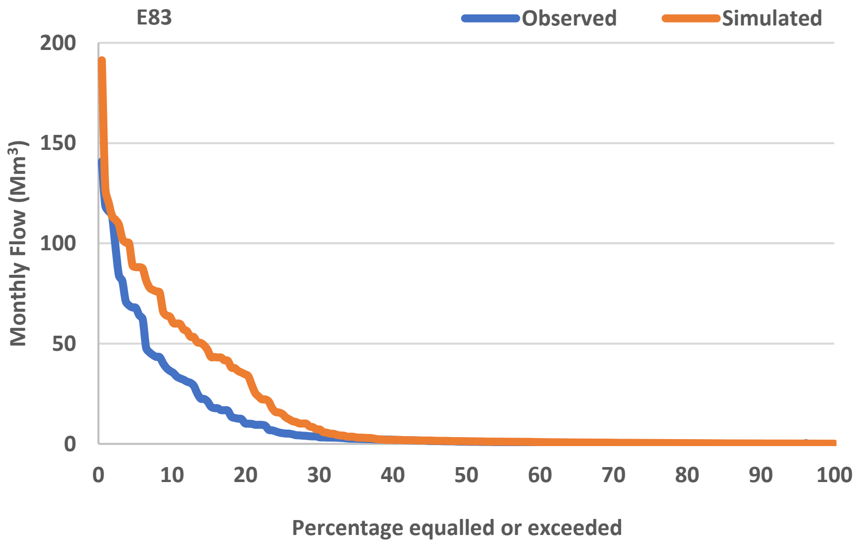


Figure B 14: Flow duration curve results for Station E64. NB: this shows possible problem in simulation process.

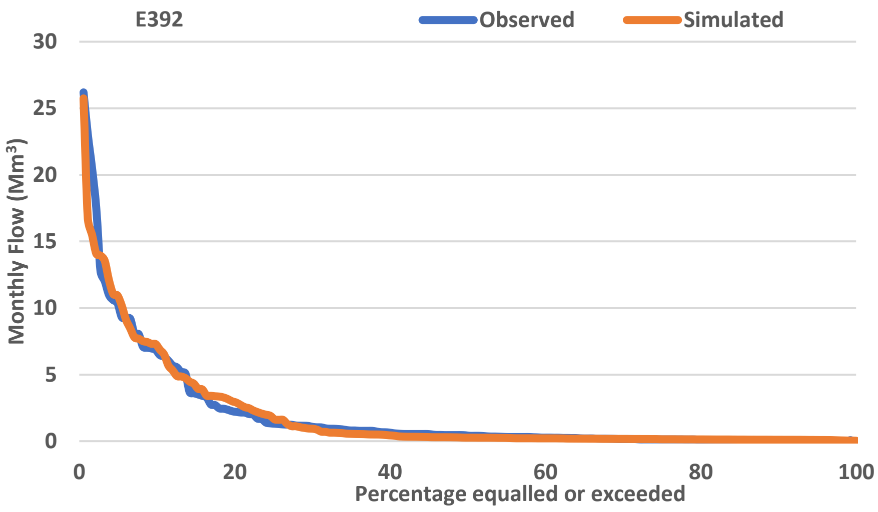


Figure B 15: Flow duration curve results for Station E392

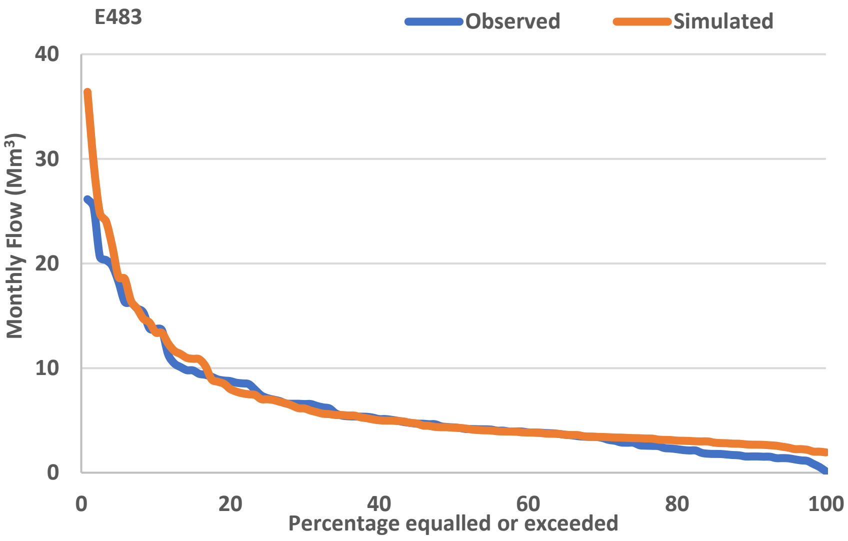


Figure B 16: Flow duration curve results for Station E483

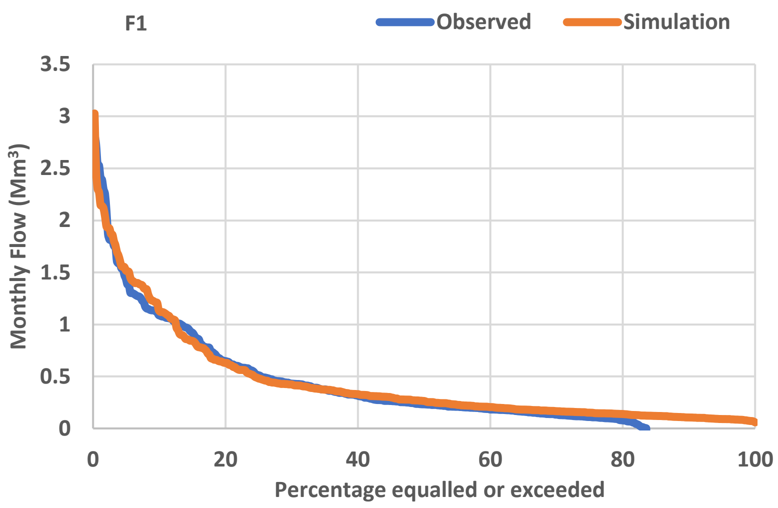


Figure B 17: Flow duration curve results for Station F1

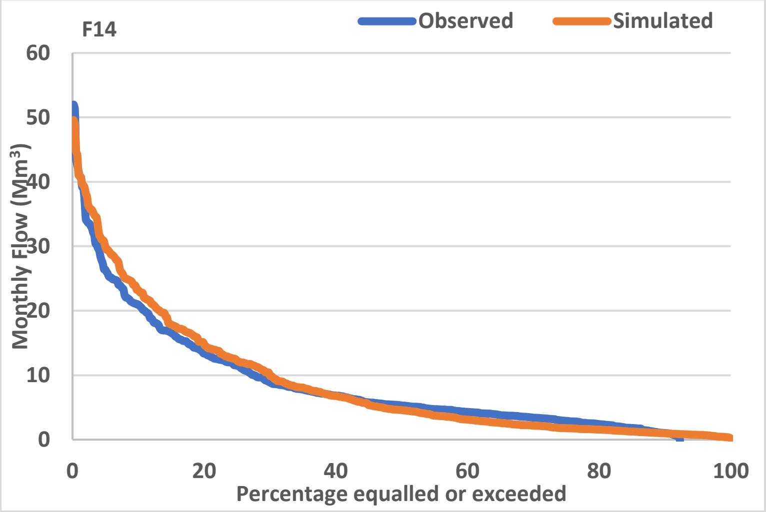
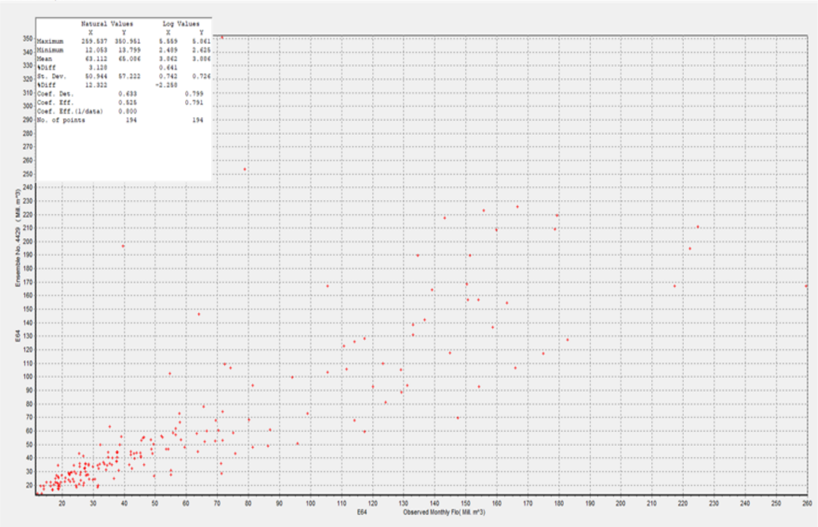
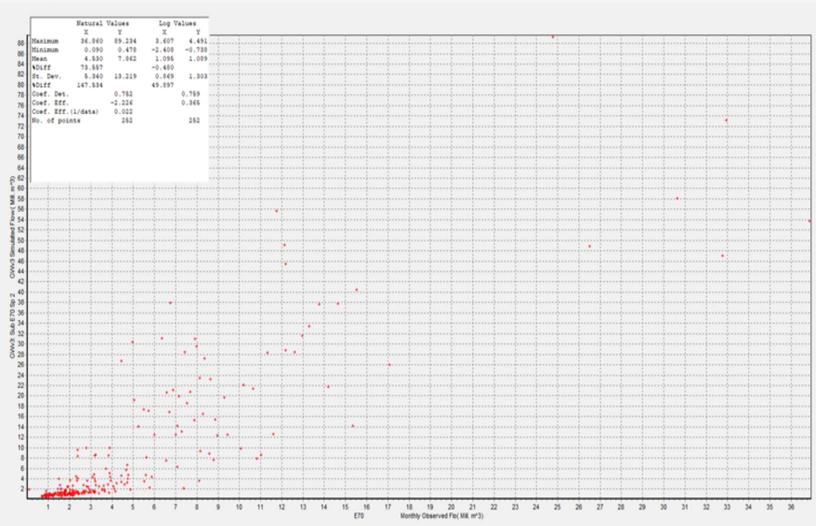


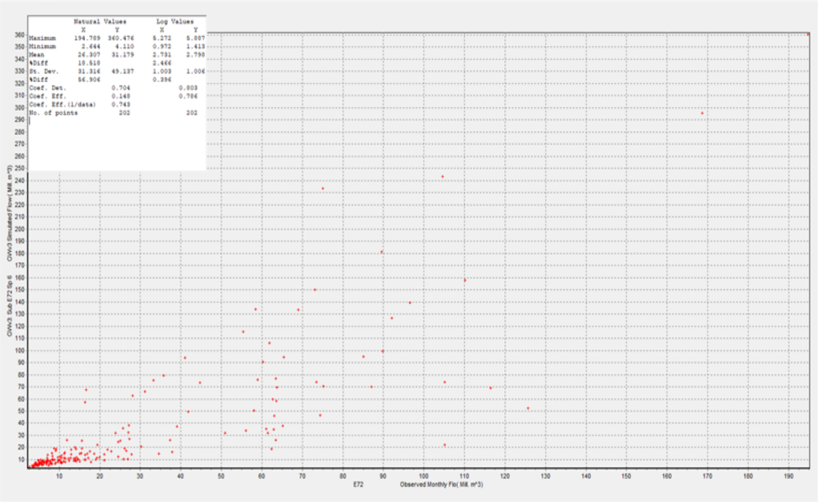
Figure B 18: Flow duration curve results for Station F14



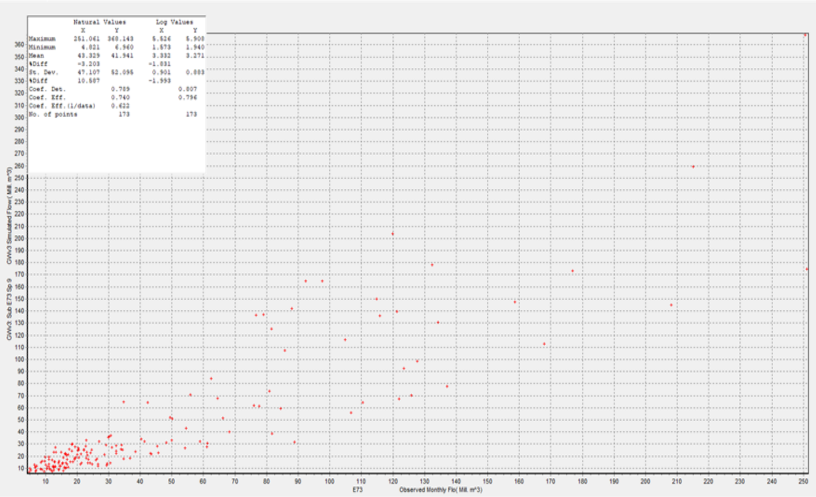
Station E64



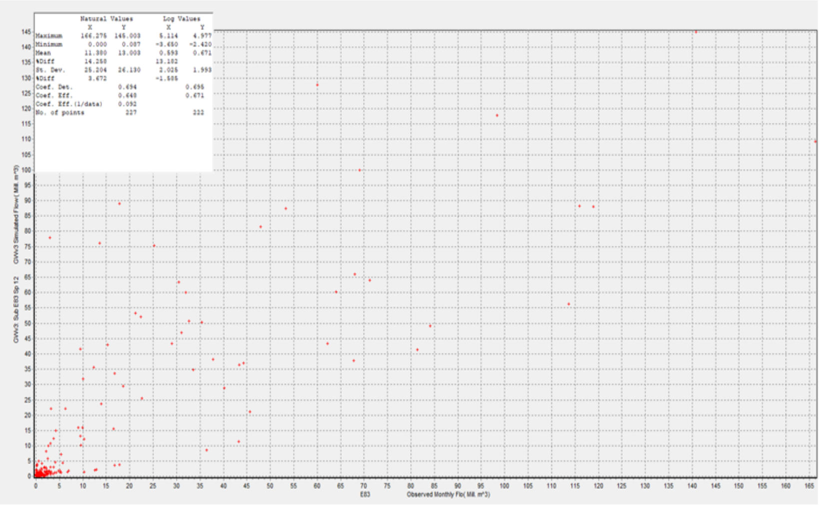
Station E70



Station E72

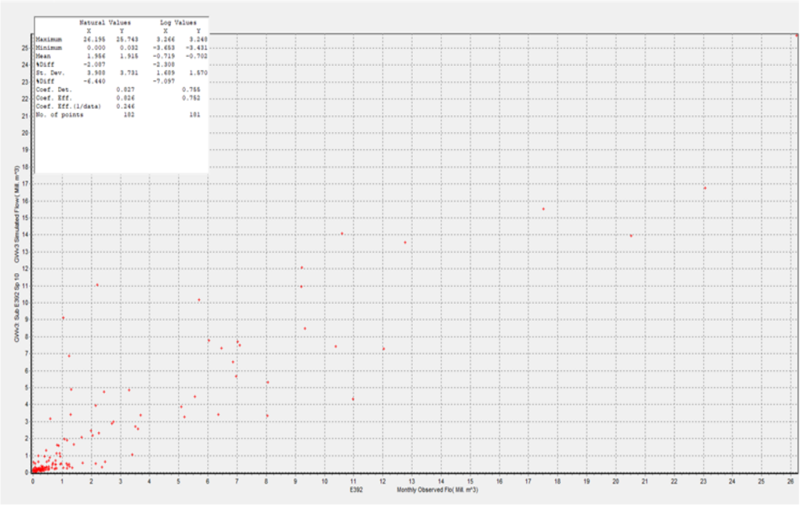


Station E73



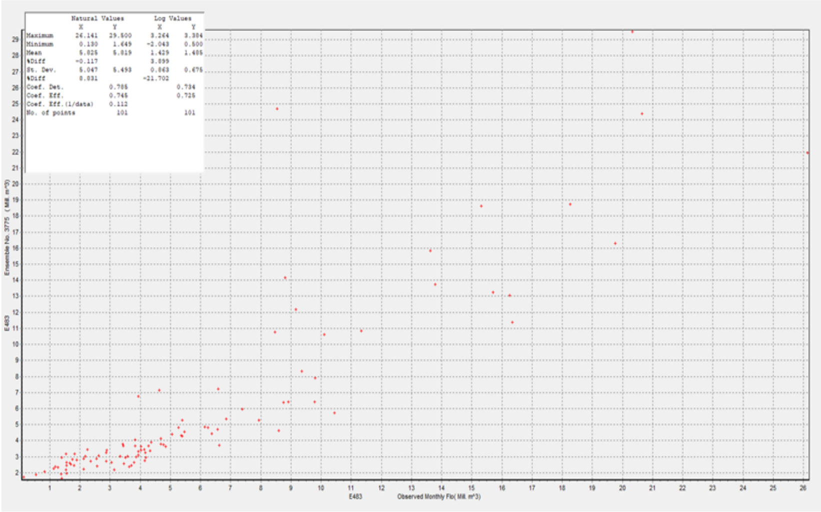
	Natural Values		Log Values	
	X	Y	X	Y
Maximum	166.275	145.003	5.114	4.977
Minimum	0.000	0.087	-3.650	-2.420
Mean	11.380	13.003	0.593	0.671
%Diff	14.258		13.102	
St. Dev.	25.204	26.130	2.025	1.993
%Diff	3.672		-1.585	
Coef. Det.		0.694		0.695
Coef. Eff.		0.648		0.671
Coef. Eff.(1/data)		0.092		
No. of points		227		222

Station E83



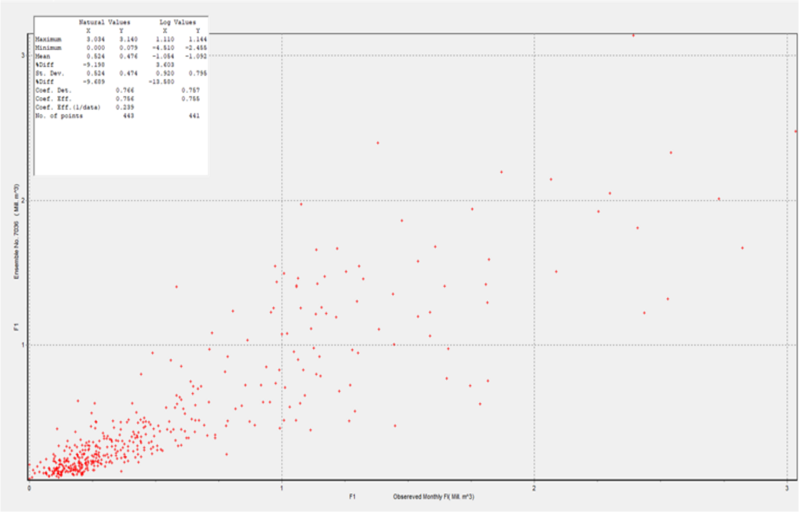
	Natural Values		Log Values	
	X	Y	X	Y
Maximum	26.195	25.743	3.266	3.248
Minimum	0.000	0.032	-3.453	-3.431
Mean	1.956	1.915	-0.719	-0.702
%Diff	-2.087		-2.308	
St. Dev.	3.988	3.731	1.689	1.570
%Diff	-6.440		-7.097	
Coef. Det.		0.827		0.755
Coef. Eff.		0.826		0.752
Coef. Eff.(1/data)		0.246		
No. of points		102		101

Station E392



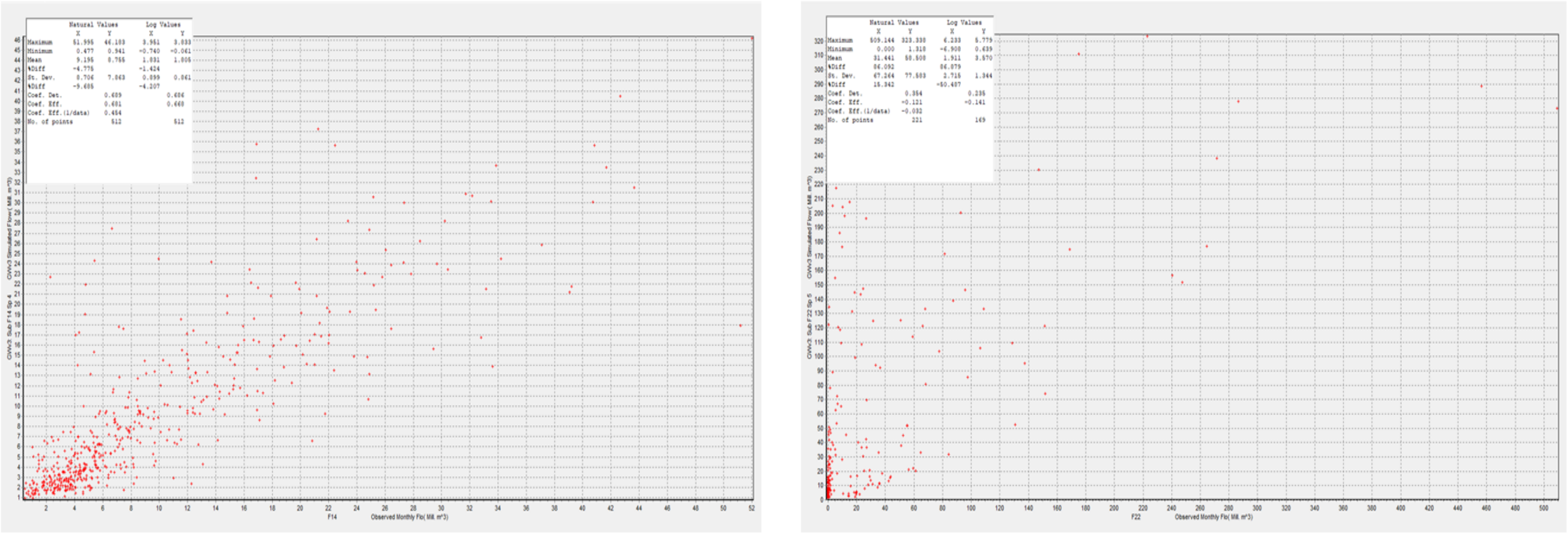
	Natural Values		Log Values	
	X	Y	X	Y
Maximum	26.141	29.500	3.264	3.384
Minimum	0.130	1.649	-2.043	0.500
Mean	5.025	5.019	1.429	1.485
%Diff	-0.117		3.899	
St. Dev.	5.047	5.493	0.863	0.675
%Diff	8.831		-21.702	
Coef. Det.		0.785		0.734
Coef. Eff.		0.745		0.725
Coef. Eff.(1/data)		0.112		
No. of points		101		101

Station E483



	Natural Values		Log Values	
	X	Y	X	Y
Maximum	3.034	3.140	1.110	1.144
Minimum	0.000	0.079	-4.510	-2.455
Mean	0.524	0.476	-1.054	-1.092
%Diff	-9.198		3.603	
St. Dev.	0.524	0.474	0.920	0.795
%Diff	-9.609		-13.580	
Coef. Det.		0.766		0.757
Coef. Eff.		0.756		0.755
Coef. Eff.(1/data)		0.239		
No. of points		443		441

Station F1



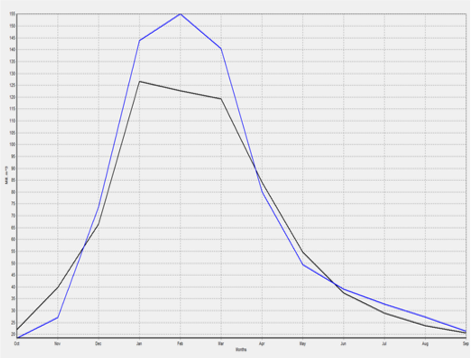
	Natural Values X	Natural Values Y	Log Values X	Log Values Y
Maximum	51.995	46.103	3.951	3.833
Minimum	0.477	0.941	-0.740	-0.061
Mean	9.195	8.755	1.831	1.805
%Diff	-4.775		-1.424	
St. Dev.	8.706	7.863	0.899	0.861
%Diff	-9.605		-4.207	
Coef. Det.		0.609		0.606
Coef. Eff.		0.601		0.668
Coef. Eff.(1/data)		0.454		
No. of points		512		512

Station F14

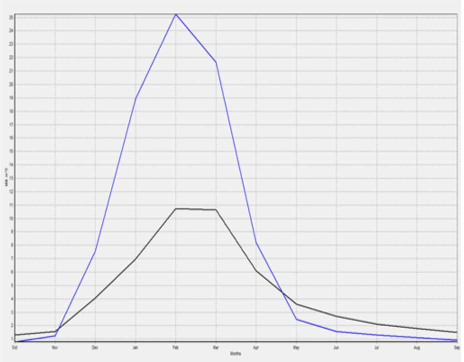
	Natural Values X	Natural Values Y	Log Values X	Log Values Y
Maximum	509.144	323.330	6.233	5.779
Minimum	0.000	1.310	-6.908	0.639
Mean	31.441	58.500	1.911	3.570
%Diff	86.092		86.079	
St. Dev.	67.264	77.583	2.715	1.344
%Diff	15.342		-50.487	
Coef. Det.		0.354		0.235
Coef. Eff.		-0.121		-0.141
Coef. Eff.(1/data)		-0.032		
No. of points		221		169

Station F22

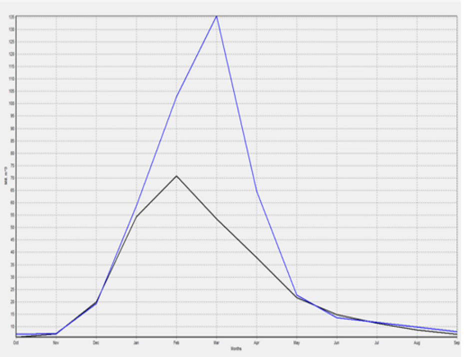
Figure B 19: Scatter plot analysis of the model results for each sub-catchment in the headwater catchment of the Pungwe River Basin.



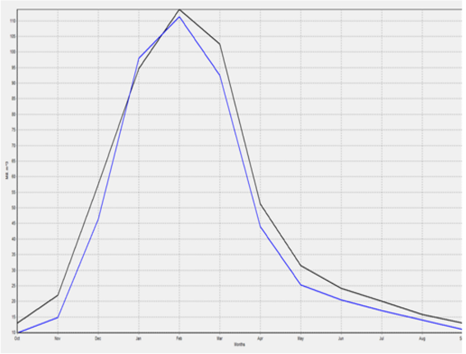
Station E64: —— Obs —— Sim



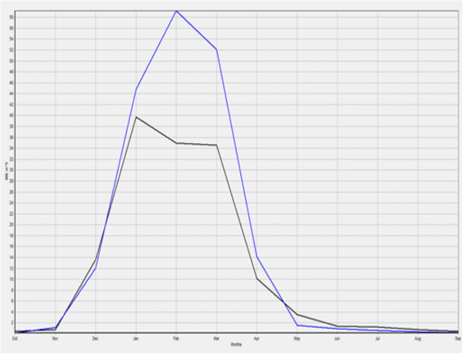
Station E70: Obs —— Sim ——



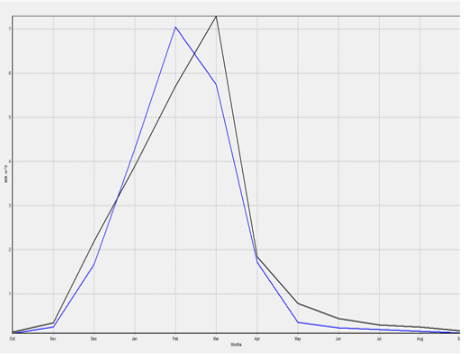
Station E72: —— Obs —— Sim



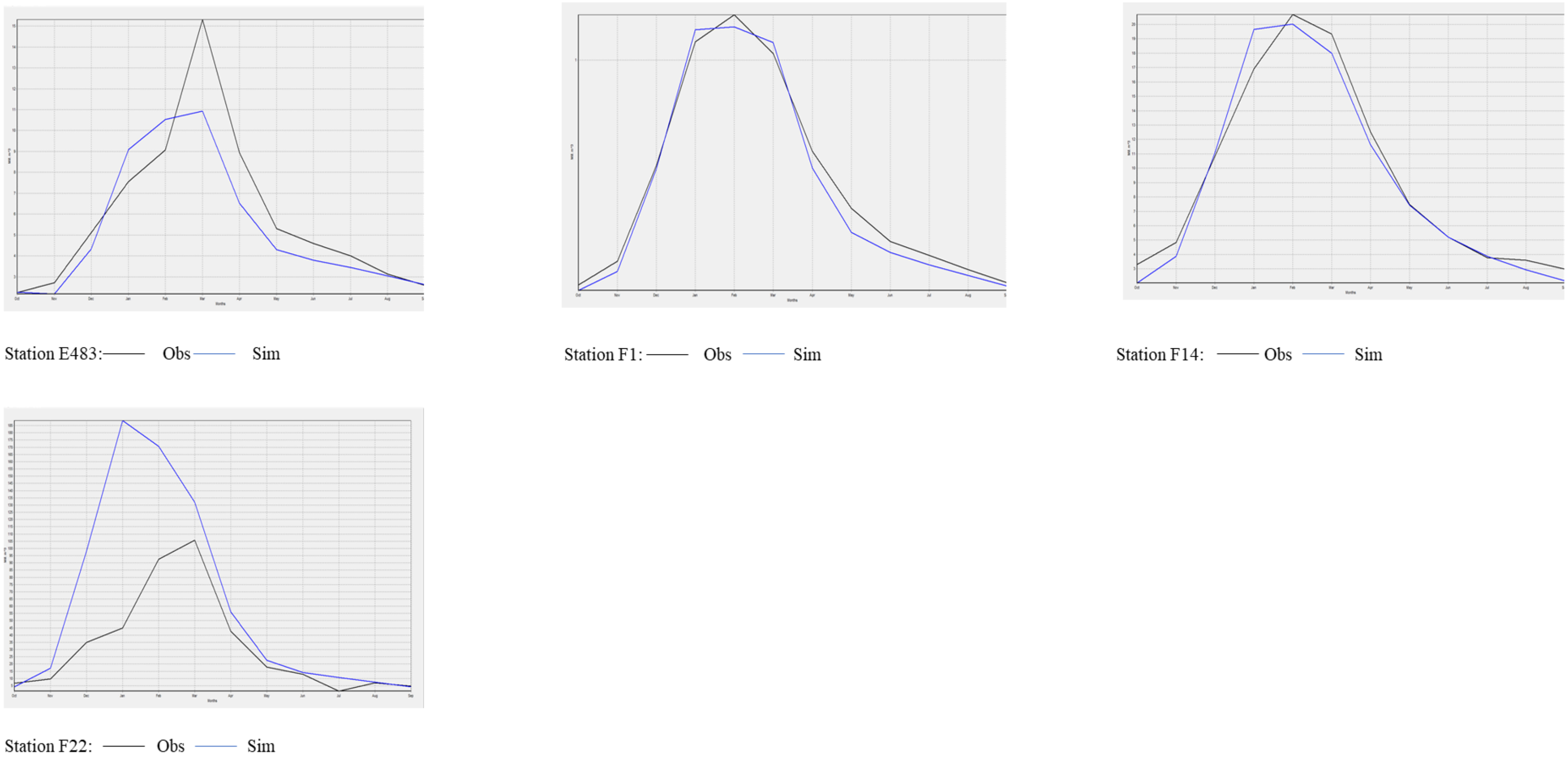
Station E73: —— Obs —— Sim



Station E83: —— Obs —— Sim



Station E392: —— Obs —— Sim



Station E483: —— Obs —— Sim

Station F1: —— Obs —— Sim

Station F14: —— Obs —— Sim

Station F22: —— Obs —— Sim

Figure B 20: Monthly duration curves of the model results for each sub-catchment in the headwater catchment of the Pungwe River Basin. NB: some graphs (e.g. E70, E72, E83, E483, F22) clearly indicate possible problem in simulation process or the quality of the available observed datasets.

APPENDIX C: Results from the future climate change predictions

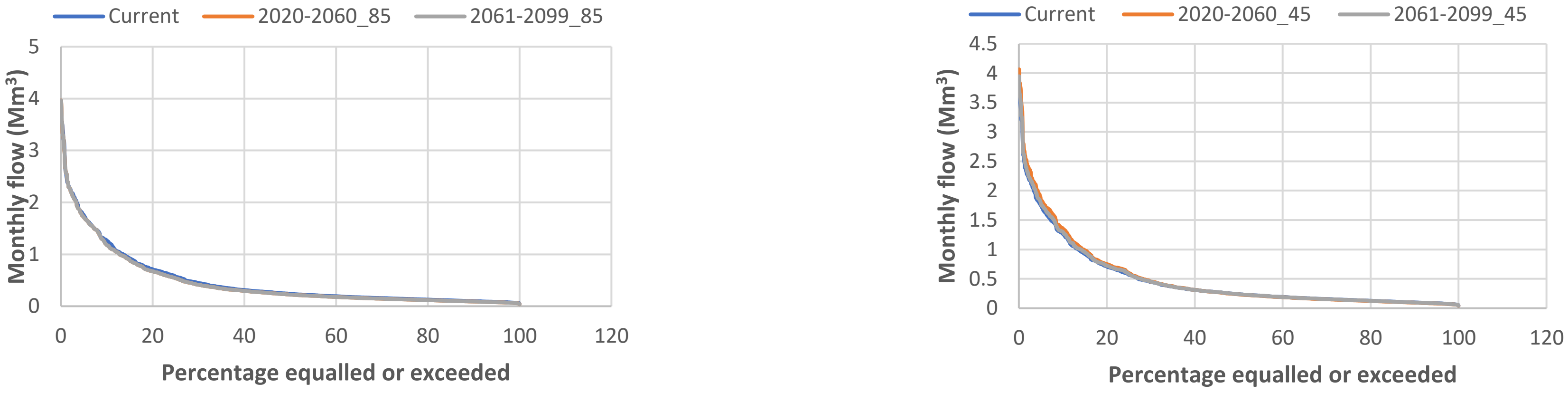


Figure C 1: Future water resources results for F1 sub-basin

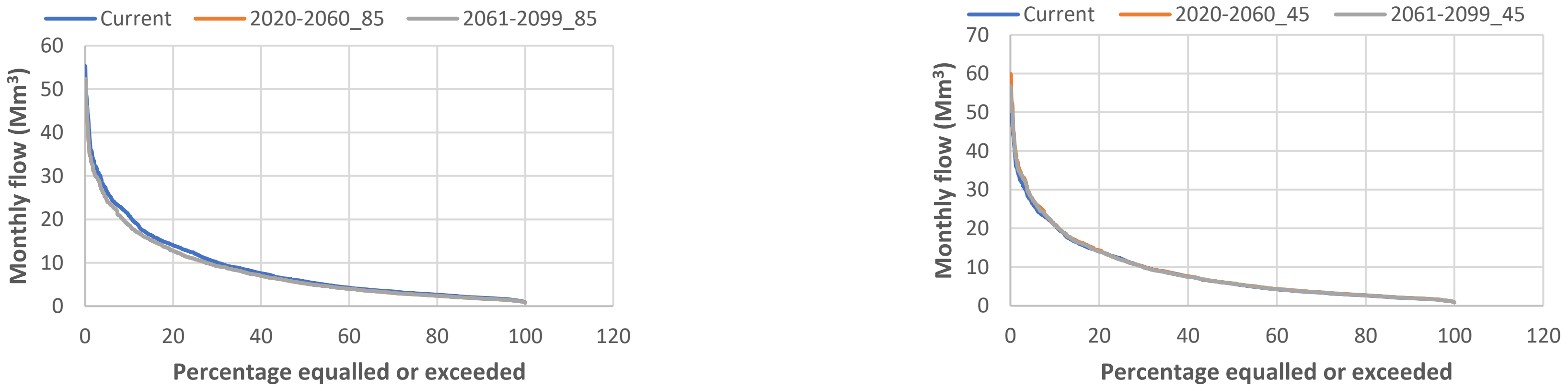


Figure C 2: Future water resources results for F14 sub-basin

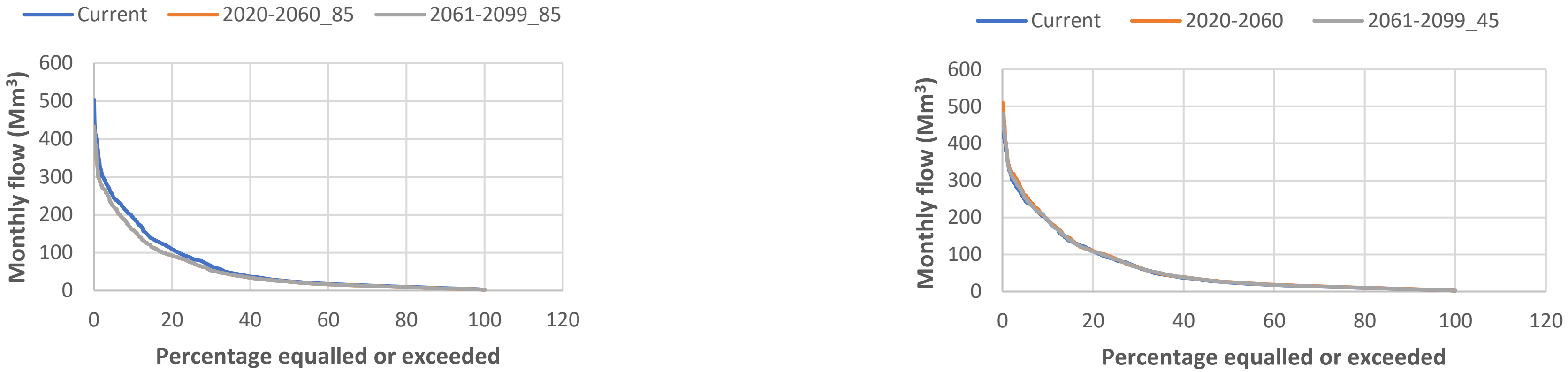


Figure C 3: Future water resources results for F22 sub-basin

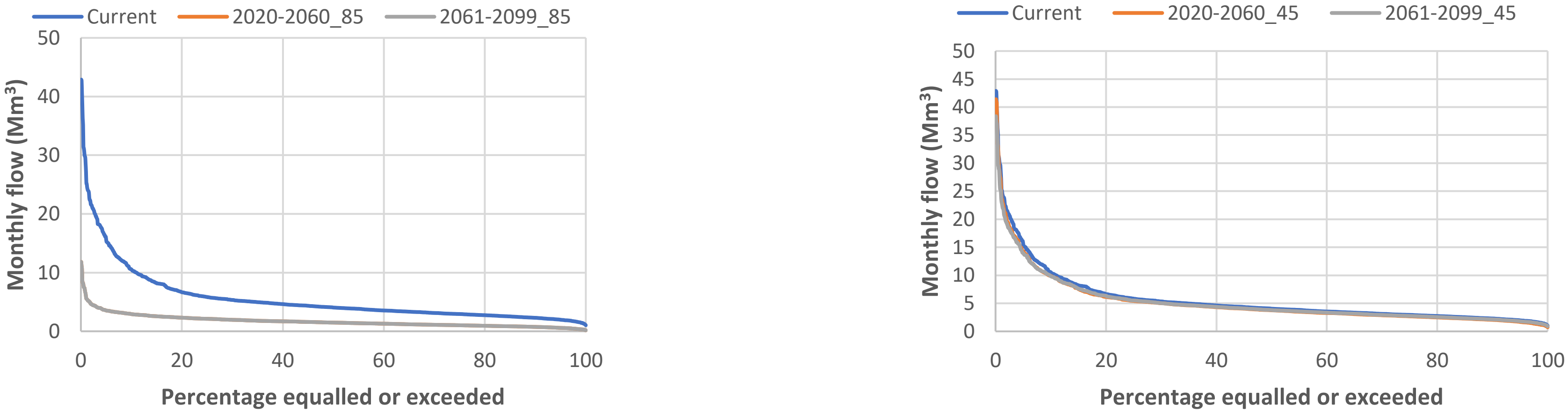


Figure C 4: Future water resources results for E483 sub-basin

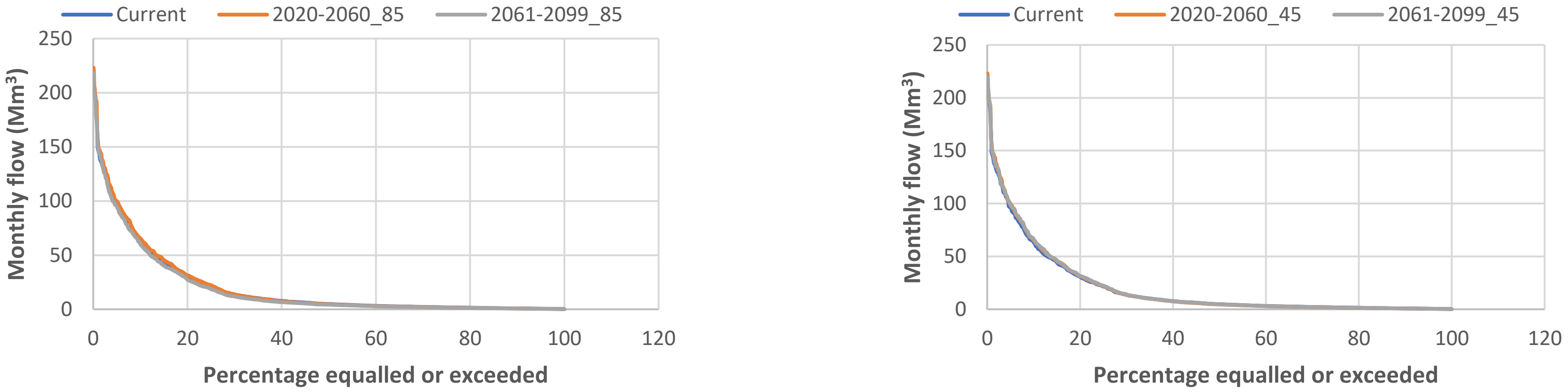


Figure C 5: Future water resources results for E83

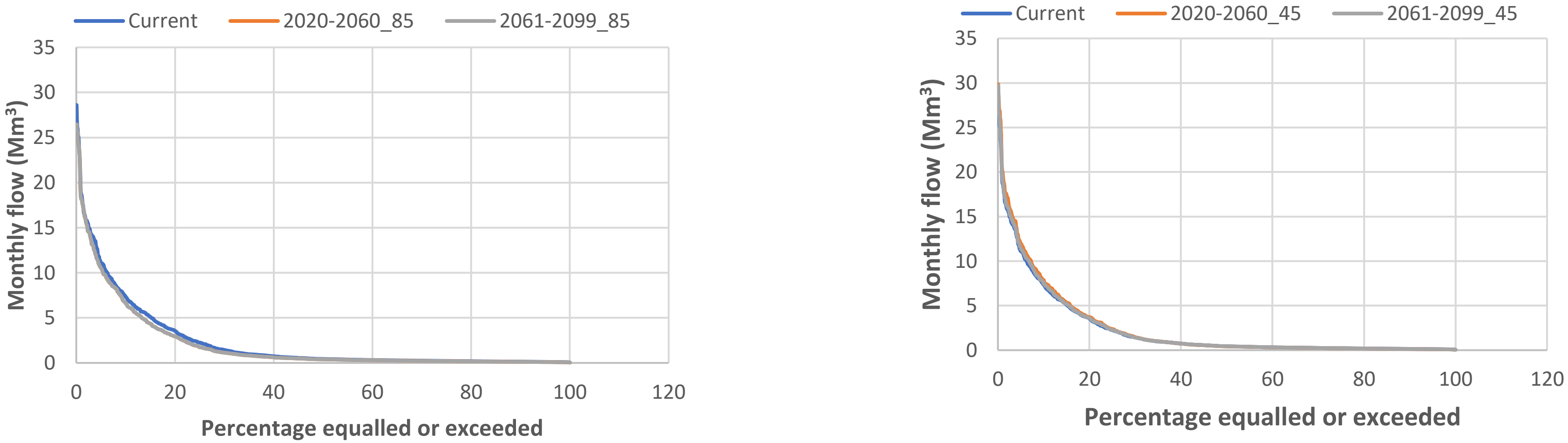


Figure C 6: Future water resources results for E392

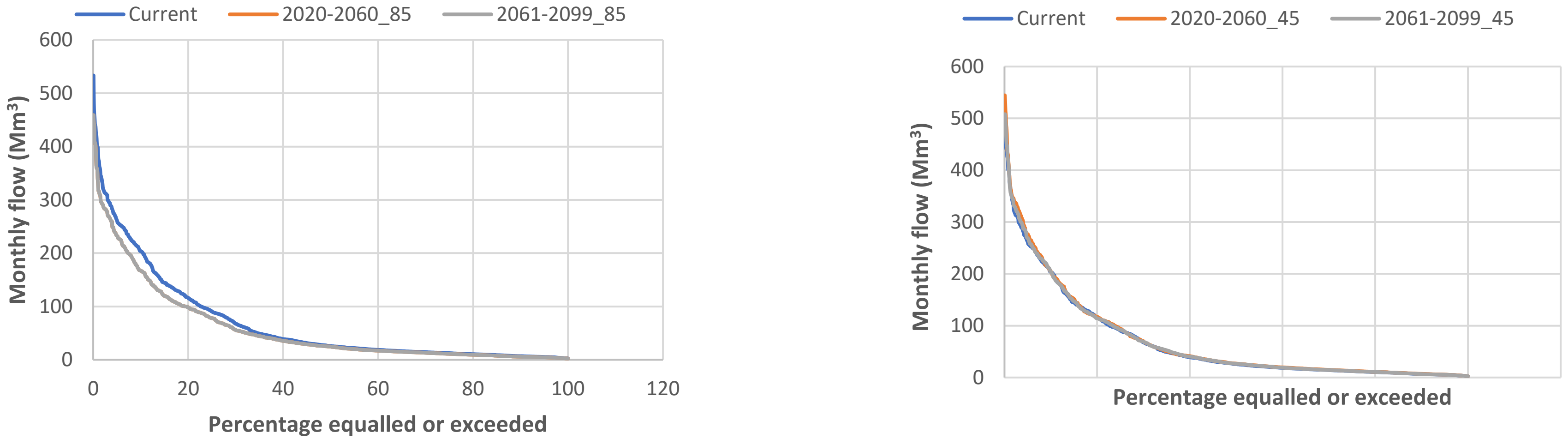


Figure C 7: Future water resources results for E64

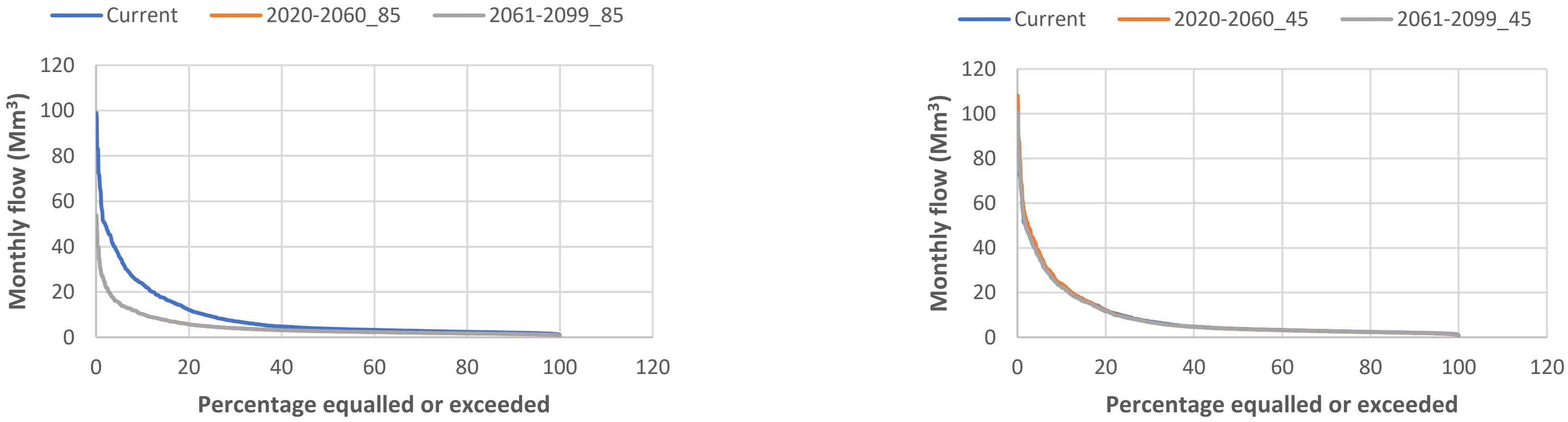


Figure C 8: Future water resources results for E70

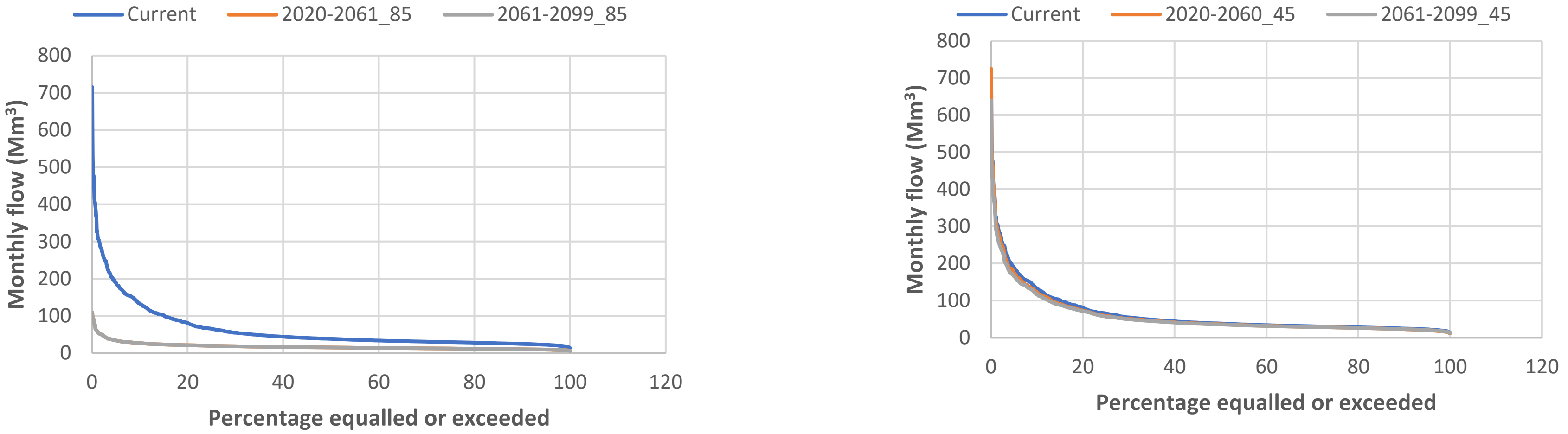


Figure C 9: Future water resources results for E72

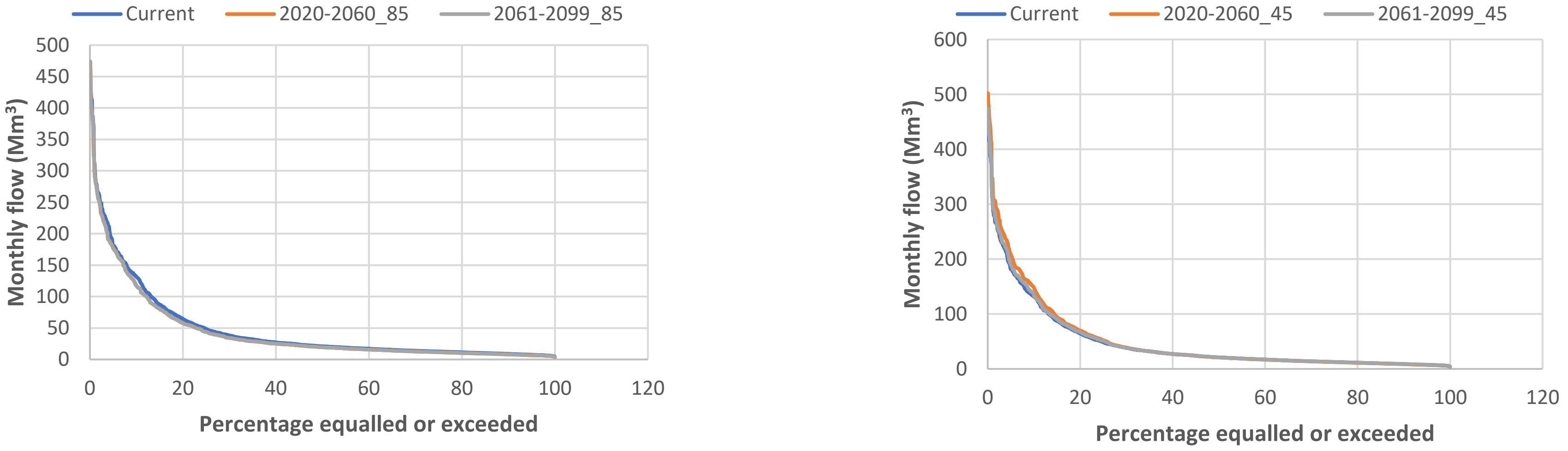


Figure C 10: Future water resources results for E73