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Development of a research approach to quantify temporal variations in baseflow in the developing world: Application to Malawi

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Declaration

This thesis is the result of the author's original research. It has been created by the author and has not been previously submitted, in part or whole, to any university or institution for any degree, diploma, or other qualification.

Signed:

Date:

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Abstract

Development of a research approach to quantify temporal variations in baseflow in the developing world: Application to Malawi

Laura Kelly

Quantification of temporal variations in baseflow is crucial for sustainable water resources management. Unfortunately, in the developing world, many countries struggle to quantify baseflow due to challenges such as lack of data, sporadic data, and limited financial resources. There is also no systematic approach to guide those on how to overcome these challenges. For this reason, this research aimed to develop an approach to quantify temporal variation in baseflow in the developing world context.

Malawi in Southern Africa was selected as the study area to develop the approach. Stakeholder engagement with the Government of Malawi was conducted to verify the need for the research and ensure the practical application of the research outputs. Existing data were collected and included climate data, river flows, lake levels and groundwater levels. Four case studies were used to demonstrate and test the selected methods and approach. First, Lake Malawi was used to demonstrate how to potentially analyse the recession limb of lake levels to provide a proxy indicator of changes in baseflow over time. Second, the Bua Catchment was used to demonstrate how sporadic river data and baseflow separation could be used to determine the annual and seasonal baseflow index (BFI). The BFI represents the baseflow component of river flow and is often used as a proxy indicator for groundwater discharge to a river. Third, the approach presented in the Bua Catchment was upscaled to a larger internationally strategic catchment, the Shire River Basin. Finally, the approach was upscaled to the national scale across Malawi.

The results of the Lake Malawi study showed variations occurred in the recession limb between 1900-2016 which were attributed to changes in baseflow in the lake catchment. The changes occurred in years which coincided with either extremely dry or wet conditions in Malawi (1916, 1942, 1948, 2012 and 2013). Whilst, the approach did not provide conclusive results, it highlighted the importance of baseflow to the lake in the context of sustainable water resources management for Malawi. Given the importance of the lake for water supply, further research was required outwith this thesis to quantify the volume of baseflow contribution to the lake from all inflow rivers and evaluate any variations over time.

The results from the Bua Catchment, the Shire River Basin and the Malawi studies conclusively showed that the approach was successful when used on the single catchment scale up to the national scale. The approach overcame the challenges typical of the developing world by utilizing sporadic river flow data and free open source tools. Specifically, the approach allowed the determination of annual and seasonal BFI and identification of long-term trends in the BFI data for a total of 68 river gauges across Malawi. This included 6 river gauges assessed as part of the Bua Catchment study and 15 gauges assessed as part of the Shire River Basin study. The results generated new knowledge on the important role of groundwater in sustaining rivers flows across Malawi.

This Malawi case study was the first national scale baseflow assessment for the country and data coverage ranged from 11-64 years. The results showed that baseflow in Malawi follows a seasonal pattern with minimal differences between the average annual and average wet season BFI (0.57 and 0.52 respectively). Generally, considerable increases were seen in the dry season BFI (0.97). This indicates that 57%, 52% and 97% of the total Malawi river flow is derived from groundwater in the annual, wet and dry season respectively. Long-term behavioural changes in BFI across all periods were also found. Annually, 10% showed an increasing trend and 16% showed a decreasing trend, which was comparable to the wet season results where 16% showed an increasing trend and 18% showed a decreasing trend. In contrast, in the dry season only 1% showed an increasing trend and 6% showed a decreasing trend. These distinct patterns were also reflected in results of the Bua Catchment and Shire River Basin studies.

This thesis has important implications on the sustainable management of water resources. The developed approach is practical, flexible and can be used as an independent assessment tool, or to complement an existing practice or framework. It fills an important gap in the literature by facilitating quantification of temporal variations in baseflow by environmental practitioners in a methodical manner using minimal data and resources. The research outputs also have specific implications for the management of Malawi's water resources. They offer crucial baseline data to support national policy and investment decisions, Integrated Water Resources Management (IWRM) and planning towards Sustainable Development Goal 6.

Preface

The results of this thesis were developed into a series of papers to be published in peer-review journals, three of which were peer-reviewed and are published and the fourth in draft form. Each results chapter has its own abstract, introduction, materials and methods, results and discussion and conclusion. A bridge text between these chapters was written to provide context, connection, and harmony between the chapters. The papers included in each results chapter are as follows:

Chapter 4

Kelly, L., Kalin, R.M., Bertram, D., Sibande, H., 2020. An Analysis of the recession limb of Lake Malawi to provide a Proxy Indicator of Temporal Variations in Baseflow [1st draft, further work is required for journal submission].

Chapter 5

Kelly, L., Kalin, R.M., Bertram, D., Kanjaye, M., Nkhata, M. and Sibande, H., 2019. Quantification of Temporal Variations in Baseflow Index Using Sporadic River Data: Application to the Bua Catchment, Malawi. Water, 11(5), p.901.

Chapter 6

Kelly, L., Bertram, D., Kalin, R.M., Ngongondo, C. 2019. Characterization of Groundwater Discharge to Rivers in the Shire River Basin, Malawi. American Journal of Water Science and Engineering, 5(4), p.127-137.

Chapter 7

Kelly, L., Bertram, D., Kalin, R.M., Ngongondo, C, Sibande, H. 2020. A National Assessment of Groundwater Discharge to Rivers: Malawi. American Journal of Water Science and Engineering. Special Issues: 21st Century Water Management, 6 (1), p.39-49.

The author of this thesis is the corresponding author of all papers and has produced the work guided by supervisors and key collaborators. Supervisors Prof. Robert Kalin and Dr Douglas Bertram of the University of Strathclyde guided the research. The research was underpinned by data provided by the Government of Malawi and enhanced through collaboration and discussion with Hyde Sibanda, Modesta Banda and Macpherson Nkhata (Ministry of Agriculture, Irrigation and Water Development) and Cosmo Ngongondo (University of Malawi).

Research Contribution

This thesis has made several contributions to knowledge. The global and local novelty of the research contributions are as follows:

Global novelty

- A simple assessment was presented to analyze the recession limb of a lake hydrograph to provide a proxy indicator of changes in baseflow over time.
- A new research approach was developed to quantify temporal variations in baseflow in the developing world context using spatial and temporal variable data.
- The research approach was designed by synthesizing several elements which have not previously been put together. Methods were selected based on predefined criteria which were required for the approach to overcome challenges typical of the developing world.

Local novelty

- A national dataset of river flow data and climate parameters has been obtained and organized and includes the creation of comprehensive station maps viewable via the mWater platform.
- New knowledge has been generated for Malawi. Annual and seasonal BFI and identification of long-term trends in BFI has been determined on a national scale for the first time. This also includes a more detailed catchment analysis of baseflow in the Bua Catchment and the Shire River Basin.
- Existing methods for investigation of baseflow (baseflow separation) and statistical trend identification (Mann-Kendall) were applied to new areas across Malawi.

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List of Abbreviations and Acronyms

BFI	Baseflow Index
CJF	Climate Justice Fund
CV	Coefficient of Variation
EFR	Environmental Flow Requirement
FORTRAN	Formula Translation
FRIEND	Flow Regimes from International Experiments and Network Data
GIS	Graphical Information System
FRA	Forest Resources Assessments
GFW	Global Forest Watch
GoM	Government of Malawi
GMI	Groundwater Management Institute
GRAPHIC	Groundwater Resources Assessment under the Pressures of Humanity and Climate Change
GRDC	Global Runoff Data Centre
IHP	International Hydrological Programme
IWRM	Integrated Water Resources Management
kHa	kilohectare
Km	Kilometers
Km^2	Kilometers squared
M	Meters
masl	Meters Above Sea Level
NGO	Non-Governmental Organization
MK	Mann-Kendall
MoAIWD	Ministry of Agriculture, Irrigation and Water Development
MIS	Management Information System
NWDP	National Water Development Programme
NWRMP	National Water Resources Master Plan

QGIS	Quantum Graphical Information System
RAP	River Analysis Package
RO	Research Objective
SAAS	Streamflow Analysis and Assessment Software
SADC	Southern African Development Community
SDG	Sustainable Development Goal
SRB	Shire River Basin
SWAT	Soil and Water Assessment Tool
USD	United States Doller
WASH	Water, Sanitation and Hygiene
WEST PRO	Water Engineering Time Series PROcessing Tool
WHAT	Web-based Hydrographic Analysis Tool
WMO	World Meteorological Organization
WRA	Water Resource Area
WRU	Water Resource Unit
WRIS	Water Resources Investment Strategy
<	Less than
>	Greater than
%	Percent

Chapter 1 Introduction

1.1 Background

Global water demand has been increasing worldwide by 1% since the 1980s and is expected to continue at the same rate until 2050 (WWAP (UNESCO World Water Assessment Programme), 2019). This increase in demand is driven by various factors including population growth, socio-economic development and changing consumption patterns. Complicating matters further, climate change and human activities are impacting the availability and distribution of water resources. For example, climate change such as altered weather patterns (including increased frequency and severity of floods and droughts), and human activities such as over-abstraction of water, inadequate management, pollution, and deforestation. As a result, many countries across the world are experiencing water stress, specifically arid and semi-arid environments, where the demand for water exceeds the available amount and the water which is available is unevenly distributed in space and time. This poses serious threats to human life, ecology, and economic stability.

To address the growing demand for water and ensure the water security of future generations, holistic management approaches such as Integrated Water Resources Management (IWRM) (Cardwell, Cole, Cartwright and Martin, 2006; Global Water Partnership, 2020) and conjunctive water (Brodie et al., 2007a) use are being promoted. At the heart of these approaches is the provision of reliable hydrological and hydrogeological data which is essential to support assessment and investment decisions (WWAP (UNESCO World Water Assessment Programme), 2019). Specifically, these approaches acknowledge the important role that groundwater plays in sustaining surface water and there is a significant need to provide quantitative data on groundwater discharge to rivers (also known as baseflow) (Lewandowski, Meinikmann and Krause, 2020). Such data helps to describe the complex relationship between groundwater and surface water and provides a holistic and integrated understanding of the water resources being managed. This is especially crucial in countries who experience long dry seasons with minimal rainfall and where dry season river flows can comprise >90% groundwater. Unfortunately, some countries remain challenged in their quantification of baseflow due to various challenges typical of the developing world. For example, lack of hydrological data and data which is sporadic, limited technical knowledge and a lack of financial resources to fund the appropriate investigations. One example of such a country is Malawi in Southern Africa which is the focus of this research.

1.2 Study area

Malawi is bordered by Zambia, Tanzania, and Mozambique (Figure 1). It is a semi-arid, low-income country with a population of 19 million (June 2020) (Worldometer, 2020) and approximately 71% of the population lives in poverty (World Bank, 2019). Malawi's climate and hydrological characteristics are considered like that of other African nations and it is therefore a good study area. For water resources management, Malawi is divided into 17 Water Resource Areas (WRAs) as per the National Water Resources Master Plan (NWRMP) (Government of Malawi, 2017b) (Figure 1). Each WRA is based on a river basin and is further divided into 78 Water Resources Units (WRU). Excluding the area of the country's largest lake, Lake Malawi, the catchment area for all WRAs is approximately 94,000km^2 (Government of Malawi, 2017a).

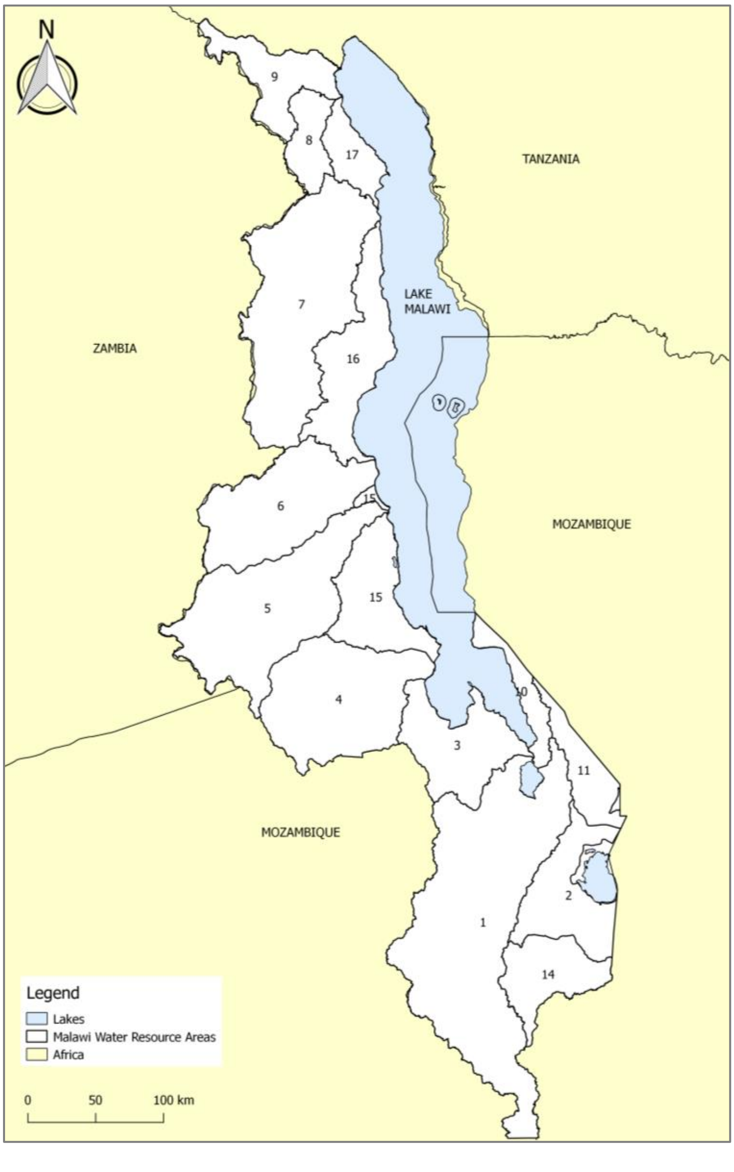

Figure 1 Location of Malawi in Africa, Malawi divided into Water Resource Areas

A digital elevation model of Malawi is shown in Figure 2 and presents the varied topography across the country. The topography is divided into four main zones of varying elevations; the highlands (1,500 to 3,000 masl), the plateau (900 to 1,500 masl) and the escarpment and the rift valley floor (500 masl at the Lakeshore to about 50masl in the Lower Shire Valley) (Government of Malawi, 2011e).

Malawi has a vast covering of surface water bodies including a dense network of rivers and lakes (Figure 2). There are four major lakes in Malawi (Lake Chilwa, Lake Chiuta, Lake Malombe and Lake Malawi). Lake Malawi is by far the largest lake with a catchment area of approximately 98,000km^2 comprising 64,000km^2 in Malawi, 27,000km^2 in Tanzania and the rest in Mozambique (Government of Malawi, 2017b). It is also the 9th largest freshwater lake on earth (Government of Malawi, 2017a). Lake Malawi plays an important role in tourism, transport, agriculture and the fishing industry, alongside supplying water to the lakeshore communities (Government of Malawi, 2011d). Major rivers in Malawi include the Shire, Bua, Linthipe, Songwe, North Rukuru, South Rukuru, Dwangwa and the Ruo. The Shire River (Figure 2) is one of Malawi's most important rivers and flows from its source at Lake Malawi, through the Southern Region of the country until it joins the Zambezi River in Mozambique. The Shire River supplies water to extensive areas of irrigation and it also houses three hydropower schemes which supply approximately 98% of the nation's electricity (Government of Malawi, 2011d). It is also of international significance transiting an annual average of 500-600m^3/s into Mozambique (Government of Malawi, 2017b). Malawi's rivers predominately drain into either Lake Malawi or the Shire River making them the country's key hydrological system.

The climate in Malawi is relatively dry with two distinct seasons; the wet season (1st November-31st April,) and the dry season (1st May-31st October) (Government of Malawi, 2011d). The country has an average annual rainfall of 1,095mm ranging from 700 to 2,400mm and is dependent upon topographic and climatic conditions (Government of Malawi, 2018a). Given the varied topography across the country, there are high spatial variations in climatic factors, for example, the south of the country receives less rain that the north and is generally hotter. The country receives very little rain during the dry season which results in significantly reduced river flows (Kumambala, 2010).

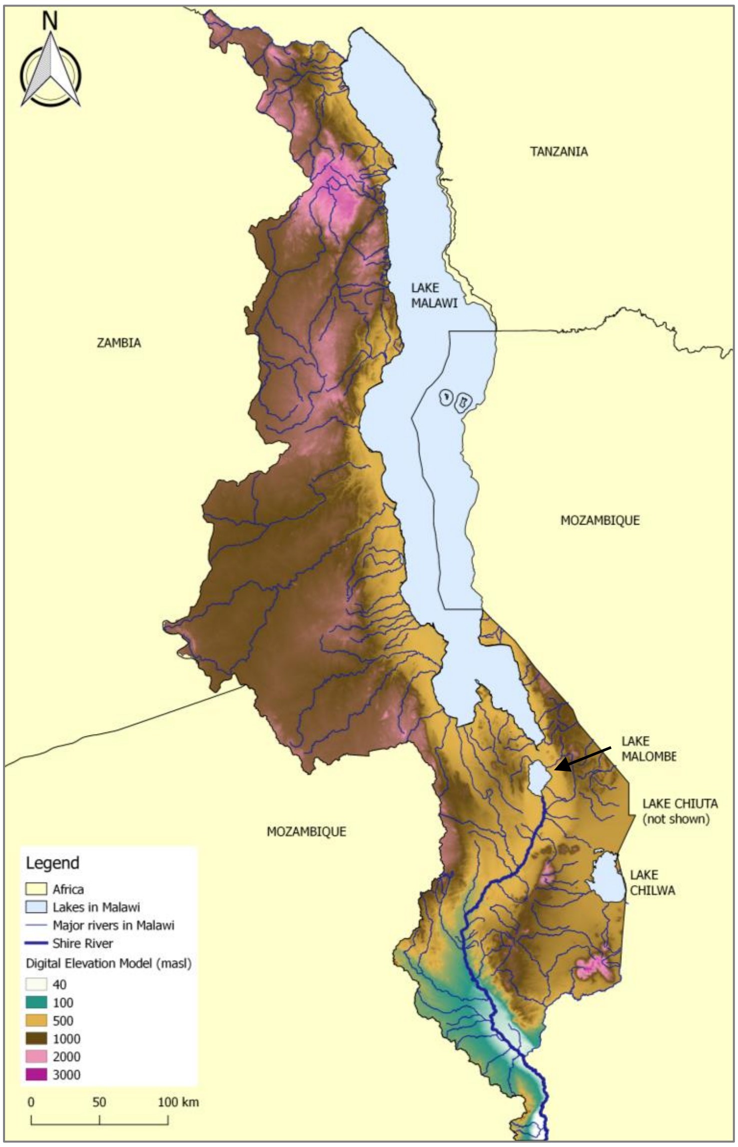

Figure 2 Digital elevation model of Malawi (obtained from the Government of Malawi) with major rivers and lakes.

The main groundwater occurrences (or aquifer types) which have been identified across Malawi are 1) the basement complex aquifers (weathered and fractured), 2) the consolidated and semi consolidated aquifers, and 3) the quaternary alluvium aquifers (Government of Malawi, 2018a). These have been identified within the Malawi Hydrogeological and Water Quality Atlas and are based on the origin of the surface geology, the groundwater flow regime and the water quality (Government of Malawi, 2018a). Figure 3, as extracted from this Atlas shows the spatial extent of the aquifers and they are summarized below.

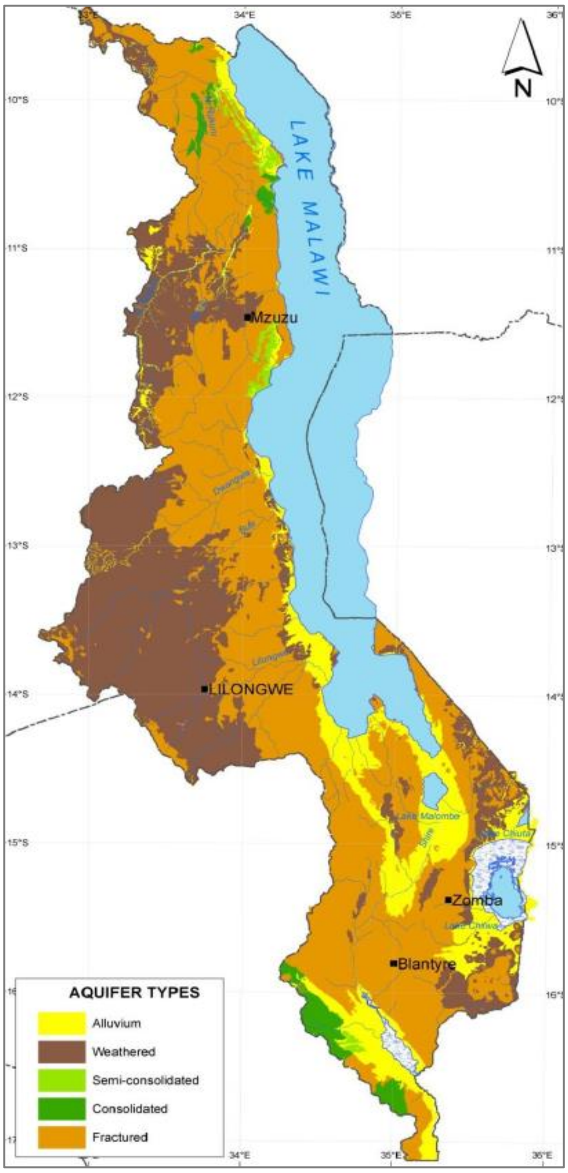

Figure 3 Aquifer map of Malawi (extracted from Government of Malawi (2018a))

The basement complex aquifers (weathered and fractured) comprise igneous and metamorphic rocks of varying lithology but are largely gneiss and granulite's (Fraser et al., 2018). They are of precambrian to lower palazonic status and have been subdivided into fractured and weathered basement aquifers. At least 80% of the country is underlain by the basement aquifers (Government of Malawi, 2018a). The 'weathered' basement rocks outcrop across the country and are considered Malawi's primary macro-scale aquifer unit with great potential for groundwater development. The 'fractured' metamorphic basement rocks typically underlie the weathered basement unit and are generally of poor groundwater potential, but this varies spatially and depends on the localized arrangement and condition of the fractures (Government of Malawi, 2018a). The consolidated and semi consolidated aquifers comprise the karoo and cretaceous sedimentary rocks which are situated north and south of the country. Both systems consist of conglomerates, sandstones, grits, siltstones, coal, mudstones and marl (Government of Malawi, 2018a). They are Permian to Triassic status and exhibit low porosity and permeability presumed due to calcite cementation (Fraser et al., 2018). The quaternary alluvium aquifers comprise gravel, sand, clay and silt. They are located along Lake Malawi shoreline and around lakes Chilwa, Malombe and Chiuta and in the lower Shire catchment. Generally, the alluvial aquifers are also found across the flood plains of rivers (Fraser et al., 2018). The geological unit is considered quaternary unconsolidated. They are small and discontinuous and very productive aquifer units which have a high potential storage capacity depending on the localized conditions (Government of Malawi, 2018a).

Groundwater is the main source of water supply for the country's rural populations which is estimated at 90% of the total population (Fraser et al., 2018). Groundwater also supplies water to several urban populations (Lilongwe and Blantyre) (Government of Malawi, 2017b). Further, groundwater discharges to feed the baseflow component of river flow year-round, playing a particularly important role in sustaining flows in the dry season, although there is a lack of scientific data to evidence this. Thus, the relationship between groundwater and surface waters in Malawi is particularly important within water resources management.

Due to these seasonal variations in river flow, access to water in some regions in Malawi has become increasingly scarce. Adding a further layer to this problem is the lack of infrastructure which can hold and regulate excess water in the wet season to ensure access to water in the dry season. Further, demands on water resources for domestic, agricultural, industrial, and power generation continue to grow as the population does. Since 2017, there have been reports across the country of declining river flows and disappearing rivers, alongside declining groundwater levels (Chitete, 2019). Thus, there has been a call by the Government of Malawi (GoM) for the promotion of research into understanding groundwater discharge to surface water (specifically baseflow) to improve sustainable water resources management.

This research forms part of an ongoing collaboration between the Scottish Government Climate Justice Fund (CFJ) Water Futures Programme and the GoM who are working in partnership towards sustainable groundwater development in Malawi.

1.3 Research questions, aim and objectives

The main research question was 'can a research approach be developed which will allow temporal variations in baseflow to be quantified in the developing world context?'. Based on this, the research aimed to 'develop a research approach that would allow the quantification of temporal variations in baseflow on a medium to long term basis in the context of the developing world'. The medium term is defined as seasons-years and the long term is defined as decades-centuries. The approach was developed and tested using Malawi as a study area.

There were several sub-research questions (SRQ) which guided the development of the research objectives (RO). The SRQs and RQs are presented in Table 1.

Table 1 Sub-research questions and research objectives

SRQ1 Can hydrology, hydrogeology, and climate data be collected for the study area?	**RO1** Collect existing hydrology, hydrogeology, and climate data for the study area.
SRQ2 Based on the collected data, are there investigation methods which could be used to quantify temporal variations in baseflow on the medium to long term basis?	**RO2** Based on the available data, review and evaluate investigation methods which can quantify temporal variations in baseflow on a medium to long term basis.
SRQ3 Can analysis of the recession limb of a lake using lake level data provide a proxy indicator of baseflow changes over time?	**RO3** Demonstrate, using Lake Malawi as a case study, how to potentially analyze the recession limb of lake level data to provide a proxy indicator of changes in baseflow in the lake catchment.
SRQ4 Can sporadic river data be successfully used with base flow separation to quantify temporal variations in baseflow?	**RO4** Demonstrate, using the Bua catchment as a case study, how sporadic river data and baseflow separation data can be used to quantify temporal variations in the baseflow index.
SRQ5 Can the research approach be successfully upscaled from the single catchment scale to the regional catchment scale and the national scale?	**RO5** Demonstrate, using the Shire River Basin as a case study, the application of the research approach presented for working with sporadic river data and baseflow separation to quantify temporal variations in the baseflow index on a larger regional catchment area. **RO6** Demonstrate, using Malawi as a case study, the application of the approach presented for working with sporadic river data and baseflow separation to quantify temporal variations in the baseflow index on a national scale in support of Integrated Water Resources Management and Sustainable Development Goal 6.

Through completion of the ROs, the SRQs were answered. As a result, the main research question was also answered, and the research aim was achieved.

The research has important implications for sustainable water resources management in the context of the developing world. It provides an approach to allow baseflow assessments to be carried out with minimal data requirements and free and easily accessible technology. The research outputs have important implications for the sustainable management of water resources in Malawi. They generate new knowledge on baseflow behaviour in the country and thus provide support to the GoM.

1.4 Thesis structure

Following this introductory chapter, the thesis comprises 7 chapters as described below. A flow chart of the thesis is presented in Figure 3.

- Chapter 2 provides a general overview of the research topic and context to the overall research. It also identifies research gaps in the literature
- Chapter 3 presents an overview of the research approach which was designed and adopted to address the research objectives
- Chapter 4 is the 1st of the results chapters and demonstrates, using Lake Malawi as a case study, how to analyze lake levels to provide a proxy indicator of temporal variations in baseflow over time
- Chapter 5 is the 2nd of the results chapters and demonstrates, using the Bua Catchment as a case study, how sporadic river data can be used with baseflow separation to quantify temporal variations in the baseflow index
- Chapter 6 is the 3rd of the results chapters and builds upon Chapter 5. Using the Shire River Basin in Southern Malawi, it demonstrates the application of the research approach presented in Chapter 5 on a larger regional catchment area
- Chapter 7 is the 4th results chapter and builds on Chapter 6. Using Malawi as a case study, it demonstrates the application of the research approach presented in Chapter 5 on a national scale
- Chapter 8 presents the discussion of the results chapters in the context of the aim of the research. It discusses the achievement of the research objectives and the strengths and limitations of the research. It also includes recommendations for future work and ends with a short conclusion.

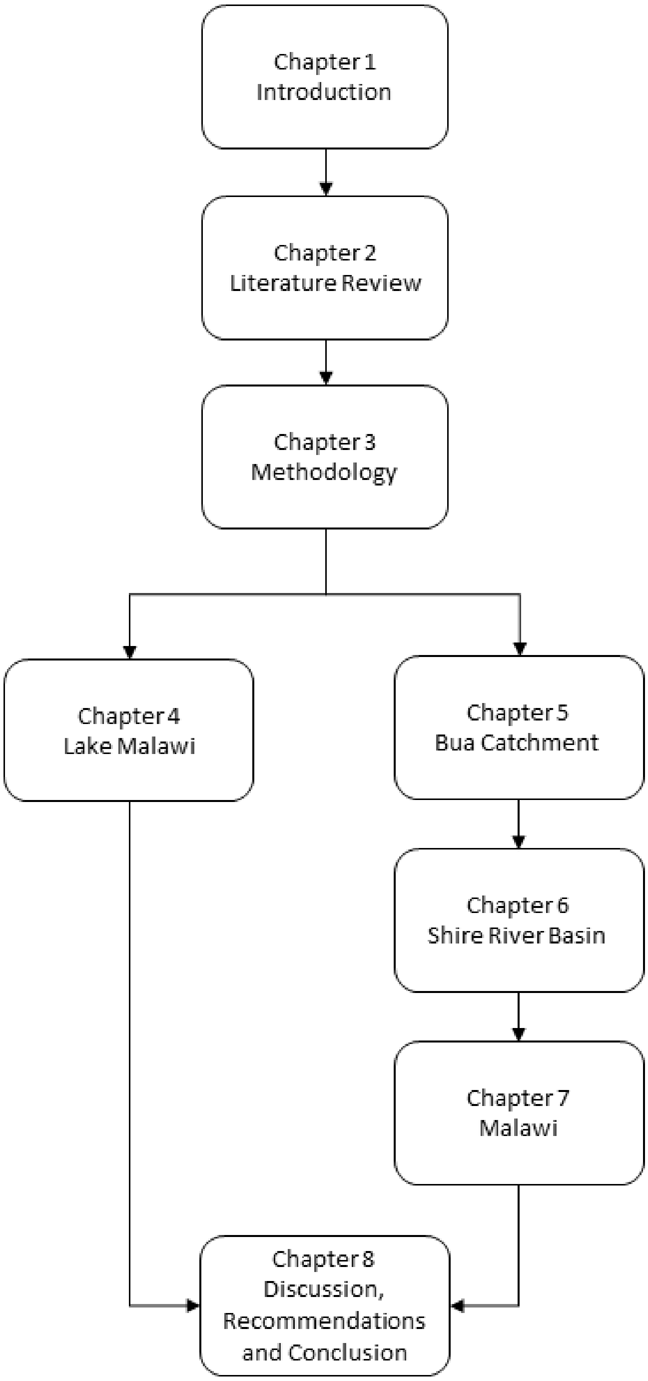

Figure 4 Flow chart of the thesis structure outlining chapters

Chapter 2 Literature Review

2.1 Introduction

The previous chapter provides a brief background to the research problem which this thesis aims to address, alongside the research aim and objectives. It also provides an overview of the study area, Malawi. As mentioned in the thesis preface, the results chapters of this thesis were developed as a series of papers to be published in peer-review journals. Each paper, therefore, comprises its own specific literature review within the introduction Section as necessary for the publication. This chapter, therefore, provides a general overview of the research topic and context to the overall research. Based on the review of the literature, knowledge gaps in the wider literature and the Malawian case study were determined and are presented.

2.2 Water cycle

The global hydrologic cycle or 'water' cycle (Figure 1) is a closed system where water moves on, above and through the earth in a continuous cycle (Winter, 1998). Along its journey, large quantities of water are held in 'storage' by reservoirs which include oceans, rivers, lakes, groundwater, ice, snow and the atmosphere itself. Water moves from one reservoir to another through the physical process (or transport mechanisms) of condensation, precipitation, surface runoff, infiltration, subsurface flow and evaporation (Browning and Gurney, 1999). As the water goes through these processes, it changes between its three forms: solid, liquid and vapor. The main input to the cycle is via precipitation. As precipitation falls on the earth's surface, it flows overland (above ground) as runoff to form streams, rivers ponds and lakes. It can also soak down through the ground via the process of infiltration and percolation to recharge the groundwater. Once below ground, water continues to flow through the soil profile via aquifers and eventually discharges back out to surface waters. The amount of water in the system is influenced by the type of precipitation (i.e. rain, drizzle, snow, sleet and hail etc.), its intensity, the duration of the event, and the frequency of occurrences (Browning and Gurney, 1999; Winter, 1998) and as such precipitation plays an important role in groundwater and surface water flows.

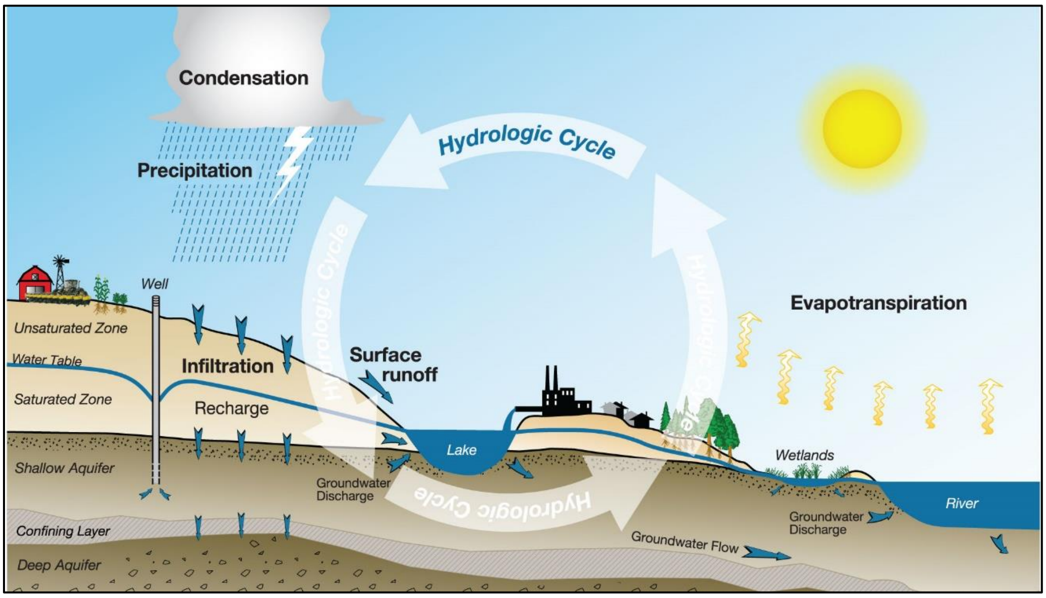

Figure 1 Water cycle (by Illinois State Water Survey, obtained from https://www.isws.illinois.edu/)

2.3 Groundwater-surface water interactions

Groundwater and surface water resources have historically been viewed and studied independently of each other. The resources were also managed as separate water resources, however, it has long been recognized that this is an unsustainable practice as both resources are connected in one continuous water cycle (UNESCO, 1980).

Groundwater and surface water interact in nearly all landscapes and the interaction is an important part of the hydrological cycle (Safeeq and Fares, 2016). In the context of rivers, there are three main ways in which the interaction takes place; rivers can gain water from the underlying aquifer 'groundwater discharge' (Figure 2), rivers can lose water to the underlying aquifer 'groundwater seepage' (Figure 3), or they can do both by gaining and losing water along different reaches of the river (Winter, 1998). The type of interaction depends on the position of the water table in relation to the river.

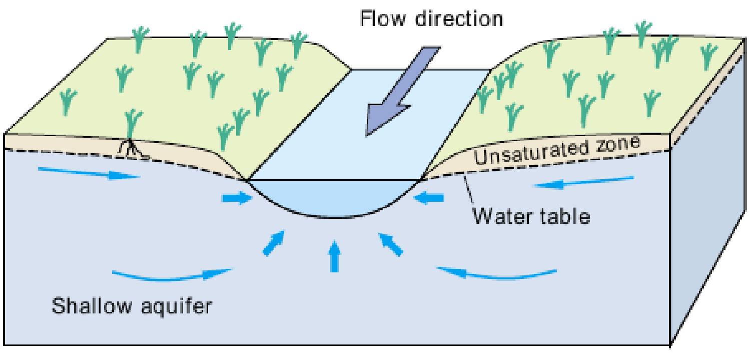

Figure 2 River gaining water from the underlying aquifer (extracted from Winter (1998))

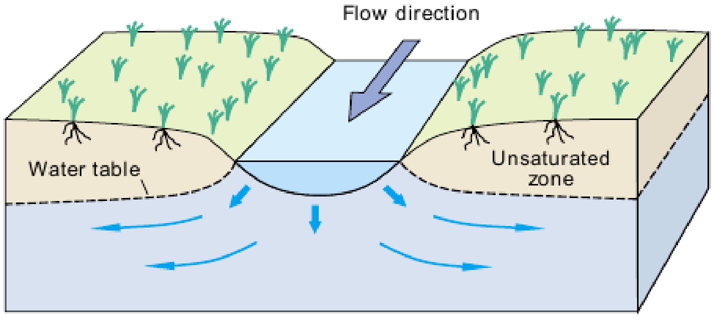

Figure 3 River losing water to the underlying aquifer (extracted from Winter (1998))

Where the water table drops below the riverbed for an extended period, it can become disconnected from the riverbed as shown in Figure 4.

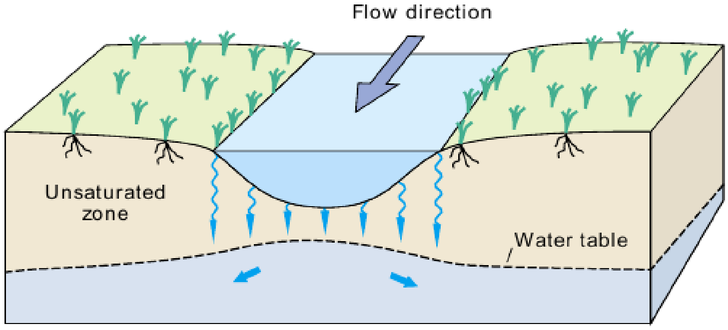

Figure 4 River disconnected from the underlying aquifer (extracted from Winter (1998))

Further, if river levels rise higher than the groundwater table, for example, due to flooding conditions, the river water can move into the banks of the river known as 'bank storage' (Figure 5).

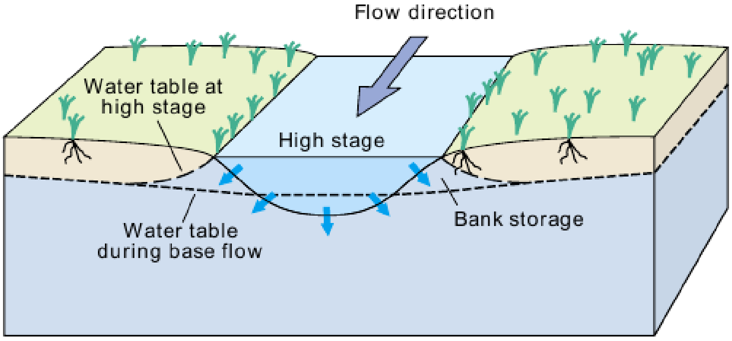

Figure 5 River levels rising higher than groundwater levels resulting in bank storage (extracted from Winter (1998))

The interaction between groundwater and surface water varies spatially and temporally influenced by several natural factors (Smakhtin, 2001). The influence of landscape setting, geology and climate are considered the most crucial natural influencing factors (Smakhtin, 2001). These factors are described below in the context of groundwater discharge to rivers which is the focus of this thesis (Figure 2).

Topographical controls the pathways in which water flows (Safeeq and Fares, 2016). Groundwater-surface water interactions vary across different landscapes due to the different rivers sizes and the different scales at which groundwater discharges to the rivers (Winter, 1998). Landscapes have been divided into five categories by Winter (1998); mountainous, riverine, coastal, glacial and dune and karst, each with individual characteristics. Geology controls permeability allowing water to pass from one medium to another and so controls how much groundwater discharges to rivers (UNESCO, 1980). For example, a river underlain by permeable sands and gravels will have a high groundwater component, whereas a river underlain by impermeable clays would have a low groundwater component (Winter, 1998). Climatic factors affect how groundwater interacts with rivers indirectly through altering recharge conditions (UNESCO, 1980). For example, if rainfall were to decline in an area, there would be less overland flow available for the rivers and less infiltration for groundwater recharge. Over time, this would result in reduced groundwater discharge to the rivers. Natural conditions are generally not considered significantly problematic when compared to anthropogenic activities which can have detrimental negative impacts on the water cycle. The over abstraction of groundwater and deforestation are widespread in Malawi and many other developing world countries and are discussed in Section 2.7.

Temporal variations in baseflow are important for several reasons. Short term seasonality variation is critical for understanding the water system and for allocation of water resources. Long-term changes are considered a valuable tool for sustainable water resources management as it indicates changes in the hydrological cycle. Transit time between the recharge of groundwater and the discharge from groundwater to surface waters can take decades or longer as responses to changes in catchment management (i.e. land use change, groundwater development) take a long time to develop (Winter, 1998).

In Malawi, groundwater and surface water are monitored and managed separately and there is a poor understanding of groundwater discharge to rivers. The Department of Water Resources is responsible for the management of water resources. Surface water is monitored by the Surface Water Division and Groundwater is monitored by the Groundwater Division. Although historically there was an extensive network of river gauging stations, since around 2010 this has been in deterioration due to various economic and political reasons (Government of Malawi, 2011a). The national groundwater monitoring network comprises 35 boreholes distributed across the country which were built around 2009 (Government of

Malawi, 2011a). Of the 35 boreholes, only 24 are considered reliable and this is not sufficient to properly depict the behavior of the country's aquifers. Based on a 2011 situation and needs assessment report, a significant improvement in the groundwater monitoring network was called for by the GoM (Government of Malawi, 2011a).

Knowledge gap 1 (local):

There is a need to understand groundwater discharge to rivers in Malawi and thus recognize the importance of monitoring groundwater and surface water together

2.4 Baseflow (a proxy for groundwater discharge to rivers)

River flow has two components of flow; the slow-moving component of river flow (slow flow) (UNESCO, 1980; Fetter, 2001) and the fast-moving component of river flow (quick flow). Quick flow is derived from direct and short term response to rainfall (i.e. flow over the land surface called overland flow or surface runoff), rapid lateral movement in the soil profile (interflow) and direct precipitation onto the river (Brodie et al., 2007a). The slow flow component is generally referred to as baseflow. Baseflow is generally presumed to be derived entirely from groundwater from the aquifer and as such it is widely used to understand the role that groundwater plays in rivers (Singh et al., 2019; UNESCO, 1980). Quantification of baseflow is especially useful in areas which lack groundwater data. Although mostly ignored, other stored sources can also contribute to baseflow. For example, water can be released slowly into rivers from connected lakes, wetlands, snow, temporary storage within the banks of the river channel and slow-moving interflow (Bosch et al., 2017). The true source of baseflow is impossible to identify from desktop study alone. Field investigations are required for example using hydrological isotopes to understand the source of water and travel times (Banda et al., 2019; Tetzlaff and Soulsby, 2008; Koeniger, Leibundgut and Stichler, 2009). Thus, baseflow is used as a proxy indicator of groundwater discharge to the river and to understand the groundwater-surface water interaction.

In many cases, when there are prolonged periods of low rainfall during dry seasons, groundwater often sustains river flows (Alley, Reilly and O, 1999). Although globally pertinent, this is particularly crucial for semi-arid countries who experience long dry seasons each year and rivers depend on groundwater to sustain flows, albeit reduced flows, as a result minimal surface runoff (Tallaksen and Van Lanen, 2004). Baseflow is of significant interest in water resources management which is discussed further in Section 2.5.

There is a vast body of literature available on baseflow with countless studies on the topic from around the world. Examples from country's include; Africa (Kouanda et al., 2018;

Ngongondo, 2006; Hughes, Parsons and Conrad, 2007), Australia (Zhang, Zhang, Song and Cheng, 2017), Canada (St. Jacques and Sauchyn, 2009), China (Liu et al., 2015; Frohlich, Frohlich and Wittenberg, 1994), New Zealand (Singh et al., 2019), South Korea (Lee et al., 2018) and the USA (Bosch et al., 2017; Ahiablame et al., 2013). Studies are varied in scope including global maps of baseflow (Beck, De Roo and van Dijk, 2015), national scale assessments; New Zealand (Singh et al., 2019) and Thailand (Techamahasaranont et al., 2017) and regional studies; Nebraska (Szilagyi, Harvey and Ayers, 2003), Mediterranean (Longobardi and Villani, 2009), North west territories in Canada (St. Jacques and Sauchyn, 2009) and New England USA (Hodgkins and Dudley, 2011).

To date, studies into groundwater discharge (baseflow) in Malawi appear scarce and are largely carried out independently of each other and there is no aggregated picture of the behaviour of baseflow available. The existing studies address baseflow to a limited spatial and temporal coverage of flow data and mainly focus on annual baseflows. As a result, most studies fail to recognize temporal changes in river baseflows and do not portray critical seasonality differences or longer-term decadal variations. A comprehensive assessment of seasonal and long-term trends in baseflow in Malawi is therefore lacking and jeopardizes the sustainable management of water resources in the country. A detailed review of the Malawian literature concerning baseflow is provided in Chapter 5 as part of the published paper.

As a proxy indicator of groundwater discharge, this national baseflow dataset can support Integrated Water Resources Management (IWRM) and Sustainable Development Goal (SDG) 6 as described in the next section.

Knowledge gap 2 (local):

There is a need to produce a comprehensive national dataset of temporal variations in baseflow in Malawi to underpin IWRM and SDG6

2.5 Significance in the context of sustainable water resources management

The concept of sustainable management of water resources has long been established (UNESCO, 1980). The concept means not altering the natural hydrological cycle to such an extent whereby negative impacts are visible. Further, it means making sure what we are doing today will not negatively impact on the water supply of future generations.

Quantification of temporal variations in groundwater discharge to rivers is a valuable tool for sustainable water resources management. For example, quantifying short term seasonality variation is critical for allocation of water resources. Identification of long-term changes can indicate behavioural changes in the hydrological cycle and unsustainable catchment management practices. This is because changes in groundwater discharge to rivers can take decades to occur due to the slow transit time of groundwater (UNESCO, 1980). As an aspect of the groundwater-surface water interaction, groundwater discharge underpins several sustainable water resources management approaches such as IWRM and Conjunctive Water Use (Brodie et al., 2007a; International Hydrological Programme of UNESCO, 2006).

IWRM is an interdisciplinary concept and has been promoted across the globe as a sustainable approach to the management of water resources. IWRM is defined as 'a process which promotes the coordinated development and management of water, land and related resources, to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems' (Snellen and Schrevel, 2004). The IWRM concept specifically requires an understanding of how groundwater interacts with rivers, however, to date, efforts in IWRM tend to focus on surface water and groundwater as separate entities and fail to address the interaction. IWRM acknowledges the importance of groundwater in such frameworks and works towards an integrated approach (Fraser et al., 2018).

Another requirement of IWRM being widely promoted around the world is conjunctive water use which promotes management of groundwater and surface water 'conjunctively' as a single resource (Brodie et al., 2007b). For example, in Australia a framework has been developed for managing connected resources as part of Australia's National Water Initiative (Brodie et al., 2007a). A key area within the conjunctive use management framework, which is also common to IWRM, is characterizing the connection between groundwater and surface water.

Sustainable water resources development and IWRM are both enshrined in the United Nations 2030 sustainable development agenda which outlines the 17 Sustainable Development Goals (SDG) (United Nation, 2018). The goals were designed to tackle the global challenges society faces today and all countries agreed to adopt and work towards the goals as a strategy to achieve a sustainable future for us all. Each goal has targets which are tracked by indicators. The water-specific goal is SDG6 'Ensure availability and sustainable management of water and sanitation for all' and is explicitly linked to other development goals (UNESCO, 2017). SDG6 has two key targets which are relevant to baseflow. First, target 6.6 'By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, river, aquifers and lakes' which is tracked by indicator 6.1.1 ' change in the extent of water-related ecosystems over time' which includes rivers, lakes and groundwater (United Nations, 2017). As it includes river, lakes and aquifers, indicator 6.1.1 is interpreted to also require the measurement of changes in the interconnected relationships over time (i.e. baseflow). Second, there is a target related to IWRM, target 6.5 'By 2030, implement IWRM at all levels, including through transboundary cooperation as appropriate' tracked by indicator 6.5.1 'Degree of integrated water resources management implementation (0-100)'. This indicator is focused on measuring the degree of implementation of IWRM at all levels and whilst it's not explicitly stated that this shall include understanding of how groundwater interacts with surface waters, it is fundamentally included as it's a requirement under IWRM. As such, the placement of groundwater-surface water interactions within sustainable water resources management and IWRM is considered to underpin progress towards SDG6.

In Malawi, sustainable water resources management is carried out by various institutions and ministries. This includes the Ministry for Water Development who manages national water resources, the National Water Resources Authority (NWRA) who regulates and promotes IWRM, and the regional water boards who deal with lower end duties (Government of Malawi, 2017b). Malawi is highly dependent on aid financing and because of this many other stakeholders also play a varied role in the management of water resources. For example, private consultancies are often employed on stand-alone projects, research institutions often work with the GoM to conduct research and finally Non-Governmental Organization (NGO)s are often involved in various projects. Unfortunately, to date, there has not always been a joined-up approach with many organizations and donor assistance not coordinated.

The Malawi Water Resources Act was passed in 2013 and promotes the rational management and use of water resources. Specifically, the Act implements IWRM (Government of Malawi, 2013a). Further, like many countries around the world, Malawi has committed to working towards the SDGs.

2.6 International research and policies

Recent developments in the water sector have seen a range of policies and legal frameworks specifically recognizing and addressing the importance of groundwater-surface water interactions. For example; California's Sustainable Groundwater Management Act 2014 (Cantor et al., 2018), Australia's Conjunctive Water Management Framework (Brodie et al., 2007a) and Europe's Water Framework Directive (Water Framework Directive, 2000).

Further, groundwater discharge to rivers is a major focus of many worldwide initiatives. For example, the United Nation Education Scientific and Cultural Organization promote understanding groundwater discharge to rivers through their International Hydrological Programme (IHP) (Donoso et al., 2012), and the Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC) (International Hydrological Programme of UNESCO, 2006) where groundwater discharge (more specifically reduced groundwater discharge to river baseflows) has been identified as a key issue. Other issues include measurement and quantification of discharge and aspects of temporal and spatial variability. Further, the Flow Regimes from International Experimental and Network Data (FRIEND) - Water project explores hydrological processes at regional and global scales and looks at how groundwater interacts with rivers (in pursuit of conjunctive water use) (UNESCO, 2011).

2.7 Anthropogenic impacts

This section describes how over-abstraction of groundwater and deforestation can impact upon baseflow behaviour and the presence of these factors in Malawi.

Over abstraction of groundwater

The effects of over-abstraction of groundwater by pumping are well documented in the literature (Alley, Reilly and O, 1999; Winter, 1998) and groundwater depletion caused by unsustainable abstractions is now a global problem (Bierkens and Wada, 2019; Gleeson and Richter, 2018). Over-abstraction of groundwater can result in the water table being drawn down as shown in Figure 5. The drawdown of the water table can range from the local scale (because of over-pumping of one borehole to a small cluster) to the regional scale (because of over-pumping from boreholes across a large area). When abstraction of groundwater occurs in the vicinity of a river which is hydraulically connected to the aquifer, this can result in decreased groundwater discharge to the river. Over time, with continued groundwater abstraction, the groundwater table is reduced to such an extent that is becomes disconnected from the river, and groundwater discharge to the river is reduced entirely. The river flow is now entirely dependent on precipitation, and where precipitation is limited, this results in a dry river.

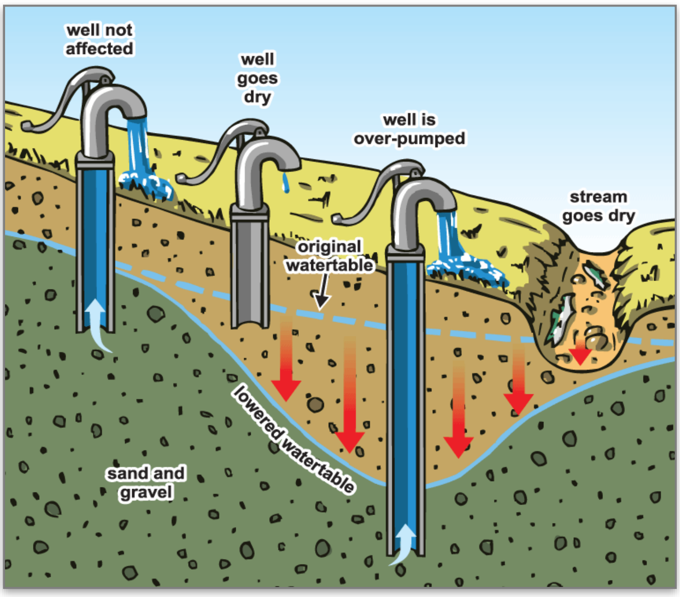

Figure 6 Diagram showing effects of over-abstraction of groundwater on connected rivers (Our Santa Fe River, 2020)

In Malawi, over-abstraction of groundwater has become a problem due to increased water demand to meet the needs of increasing populations especially in rural locations. A significant number of new boreholes have been drilled by the government, NGOs and the private sector to attempt to meet the demand (Pavelic et al., 2012). Whilst abstractions from one singular borehole may not impact severely on a local aquifer (and thus groundwater discharge), the cumulative effects of abstracting from several boreholes near a river may. There have been recent reports by Malawian villagers of rivers only flowing following significant rainfall events, with minimal flow in the dry season and some rivers where flow has completely ceased (Chitete, 2019). Historically, these rivers would have flowed year-round. These reports have been supported by internal assessments by the GoM showing a decline in groundwater levels and river flows in certain areas (Chitete, 2019). Unfortunately, to date, there appears no studies focused on the direct link between over-abstraction of groundwater and reduced baseflow in Malawi.

Deforestation

The effects of land-use change, in the form of deforestation, can also impact baseflow. Land use and land cover play a vital role in the hydrological cycle by distributing the amount of water which travels as surface runoff and infiltrates to recharge groundwater. Forests intercept rainfall, enhance soil moisture storage and infiltration, and reduce overland flows (Safeeq and Fares, 2016). Thus, forests aid recharge to groundwater, maintain groundwater discharge to surface waters and regulate peak flows in rivers during intense rainfall events (Safeeq and Fares, 2016). Deforestation of land areas comprises forests being cleared so that only bare land remains. This changes the land surface and results in reduced infiltration to groundwater and increases in surface runoff. As there is an increase in surface runoff, there is less water available for infiltration and groundwater recharge and storage of water in the underlying aquifers is reduced. Eventually, this can lead to declines in groundwater discharge to rivers which negatively impacts baseflow (Sandström, 1995).

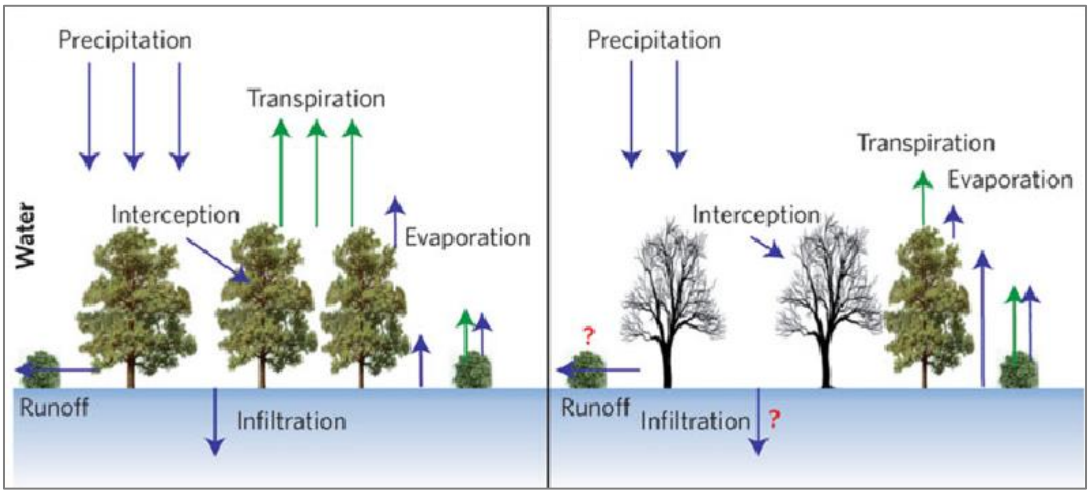

Figure 7 Fluxes of water before and after widespread deforestation (adopted from Anderegg et al, 2003 in Safeeq and Fares, 2016)

In Malawi, deforestation has been a problem since the 1970s, however, statistics to describe the magnitude of the impact are scarce and varied. For example, Global Forest Resources Assessments (FRA) are produced to monitor the world's forests. For Malawi's FRA, results have been based on extrapolations, deductions and forecasts since 1990 when the last Forest Resources Mapping and Biomass Assessment for Malawi was completed (Food and Agriculture Organisation, 2015). A recent study by the Shire River Basin Management Programme (SRBMP) evaluated forest data for over 20 years (1972-1992) and found that Malawi has lost approximately 3% of forest per year, a total decline of approximately 57% over the assessment period (Government of Malawi, 2017b). In recent years, data on deforestation has become more accessible with the launch of an open source online platform in 2014; Global Forest Watch (GFW) (Global Forest Watch, 2020). GFW uses landsat imagery and remote sensing algorithms to allow users to monitor forests and other parameters including tree cover which defined as all vegetation taller than 5 meters in height as of 2000 (Global Forest Watch, 2020). Various statistics are available for Malawi. For example, in 2019 Malawi lost 10.5 kha of natural forest, and from 2002-2019 it lost 274 ha of humid primary forest (Global Forest Watch, 2020). Further information can be found via the GFW interactive map at https://www.globalforestwatch.org/.

Population increases in Malawi have long resulted in forests being cleared for people to live and meet their agriculture requirements. People are also dependent on wood for fuel for energy and demands for charcoal continue (Food and Agriculture Organisation, 2015). Whilst alternatives to using wood have been promoted, there is little evidence that the culture will change with future forecasts indicating deforestation in Malawi will continue. To date, few studies present findings on how deforestation has impacted baseflows in Malawi. One PhD thesis used land-use records and hydraulic modelling to present changes in river flow and found a decrease in baseflows associated with deforestation trends in the upper Shire River catchment (1989-2002) (Palamuleni, 2009).

2.8 Methods for quantifying baseflow and identifying trends

Methods for quantify baseflow

There are multiple methods available to quantify baseflow. Methods can be categorized into desktop methods and field methods. Desktop methods include hydrograph analysis (baseflow separation, frequency analysis and recession analysis), hydrogeological mapping, water budgets and computer modelling (Brodie et al., 2007b). Field methods include temperature monitoring, seepage measurement, hydrochemistry and environmental tracers, artificial tracers, geophysics, remote sensing and ecological indicators (Brodie et al., 2007b). A comprehensive review of the various methods can be found in Brodie et al (2007b). The choice of method is largely dependent on the data and resources available. More information on methods are provided in Chapter 3.

Methods for identifying trends in hydrological data

There are various statistical tests available to identify trends in hydrological data. Methods can be categorized into parametric and non-parametric tests, however, non-parametric tests are recommended for use with hydrological data (Kundzewicz and Robson, 2004). This is because non parametric tests are not affected by the actual distribution of the data and are less sensitive to outliers, whereas parametric tests, although more powerful require the data to be normally distributed and are more sensitive to outliers (Hamed, 2008). As hydrological data tends to be skewed, often with missing values and seldom follows a normal distribution (Yue, Pilon and Cavadias, 2002) non-parametric tests are thus more suited for detecting trends in hydrological data. Trend tests include Spearman's Rho, Kendall's tau/Mann Kendall, Seasonal Mann Kendall, Linear regression and other regression tests (Kundzewicz and

Robson, 2004). A comprehensive review of the methodology for trend detection in hydrological data, alongside practical guidance for the use of the tests, can be found in Kundzewicz and Robson (2004). One of the most commonly used non-parametric tests used for detecting trends in hydrological data is the non-parametric Mann-Kendall (MK) (Yue, Pilon and Cavadias, 2002) which is discussed in Chapter 3, Section 3.4.4 .

2.9 Challenges to baseflow investigate

In the developing world, many countries are often challenged by various factors on their day to day assessment of water resources including baseflow. Such countries are usually those who experience long dry seasons each year and where baseflow knowledge is perhaps most pertinent. Challenges include:

- limited technical knowledge, lack of financial resources and technical staff to allocate to execute baseflow studies
- hydrology and hydrogeology data are lacking due to several social, economic, and political reasons. These include insufficient budgets, inability to attract, train and retain qualified staff and limited and declining hydrometeorological monitoring networks and data, and insufficient maintenance of hydrological infrastructure amongst others (World Bank, 2018)
- reliance on surface water data which is often limited in spatial and temporal scales and considered poor quality due to its sporadic nature (Houghton-Carr, Fry and Wallingford, 2006)

Although there is a significant body of literature on methods to quantify baseflow, there is no approach available which focuses on overcoming these challenges. As such, quantification of baseflow has received scant attention in many developing nations despite the day-to-day significance of water. There is a clear gap in the literature to develop a standardized approach which will guide practitioners in overcoming these challenges and allow the quantification of temporal variations in baseflow.

Knowledge gap 3 (global):

A research approach which quantifies temporal variations in baseflow in the developing world context is required

2.10 Summary

This chapter provides a general overview of the research topic and context to the overall research. It describes groundwater-surface water interactions and specifically defines and explains the characteristics of baseflow. It presents the importance of baseflow in the context of sustainable water resources management and discusses the human activities which can negatively impact on baseflows. The challenges to baseflow assessment which developing world countries face are outlined. From the review, the main gaps in the literature are as follows:

- Knowledge gap 1 (local): There is a need to understand groundwater discharge to rivers in Malawi and thus recognize the importance of monitoring groundwater and surface water together.
- Knowledge gap 2 (local): There is a need to produce a comprehensive national dataset of temporal variations in baseflow in Malawi to underpin IWRM and SDG6.
- Knowledge gap 3 (global): A research approach which quantifies temporal variations in baseflow in the developing world context is required.

The next chapter presents the research approach which was designed to achieve the objectives of the research.

Chapter 3 Methodology

3.1 Introduction

The previous chapter identified several knowledge gaps in the literature. One gap was the lack of a standardized approach to overcome challenges typical of the developing world and guide practitioners in quantifying baseflow. The challenges included limited data, lack of financial resources and technical staff. Thus, developing a research approach in this context was the focus of the thesis.

As mentioned in the thesis preface, the results chapters of this thesis were developed as a series of papers to be published in peer-review journals. Each paper, therefore, comprises its own research materials and methods section as adopted in the publication. In this chapter, the research approach for the thesis is described, including the research materials and methods, however, to avoid unnecessary repetition, reference is made to the specific papers where appropriate.

3.2 Stakeholder Engagement

Stakeholder engagement is increasingly important for ensuring that research is applicable in practice and of benefit to society. It is considered a research strategy which links research and practice. Stakeholders are those who have an interest in the research and some stakeholders can be called 'end-users', those who are specifically interested in the research outputs. End users are site-specific, however, generally, it involves those either directly involved (i.e. government bodies, industry professionals, academic institutes), or indirectly involved (i.e. farming, irrigation, hydropower companies) in water resources management. Stakeholder engagement also provides an important way in which to source data and information about the study area and in some cases source funding for investigations.

The stakeholder engagement conducted for this research, as described below, was underpinned by the key principles of best practice stakeholder engagement (Brodie et al., 2007b) as follows:

- communication (to communicate the aims and objectives of research)
- transparency (to inform that any outputs produced will be transparent and shared with those interested)

- collaboration (to offer collaboration opportunities where feasible to achieve outcomes which will be practical and beneficial to all parties)
- inclusiveness (to recognize and involve them in the overall project process) and
- integrity (to conduct engagement in a manner that fosters mutual respect and trust between parties).

Before the research began, stakeholder engagement between the CJF Water Futures Programme and the GoM identified the need for research into baseflow in Malawi. During the research, Malawi stakeholders were engaged to further clarify the need for the research and ensure the practical application and usability of the research outputs in Malawi. This engagement was initiated through email correspondence with several GoM officials which led to further engagement during a 7-week research trip to Malawi (May 10th to July 7th, 2017). The trip facilitated face-to-face meetings with the GoM and the University of Malawi and communication continued throughout the research with collaboration on the incremental research outputs (i.e. the papers). The GoM bodies involved included the Department of Climate Change and Meteorologist Services in Blantyre, the Department of Water Resources; Groundwater Division and Surface Water Division in Lilongwe, the Southern Regional Government Offices in Blantyre and the Shire River Basin Management Programme (SRBMP) Agency in Lilongwe. Further engagement comprised a visit to the University of Malawi, Chancellors College, in Zomba hosted by a leading Malawian academic and professor in water resources. Finally, attendance of an IWRM management conference in Malawi (22nd to 24th February 2017) allowed interaction with several industry professionals who were involved in water resources management in Malawi.

All stakeholders welcomed the investigation of baseflow in Malawi and stressed its importance in providing a key baseline dataset for the country. Specifically, the GoM expressed a need for baseflow data to inform sustainable water resources and catchment management. They echoed the findings of the literature review (Chapter 2) in that there were minimal data and understanding on baseflow currently available across the country. It was conveyed that whilst baseflow and BFI assessments were sometimes carried out by the GoM Department of Water Resources Surface Water Division, the focus was on annual and not seasonal values. It was confirmed that the specific challenges (e.g. lack of hydrological data and data which is sporadic, limited technical knowledge, lack of financial resources and experienced hydrology and hydrogeology staff) were generally applicable to Malawi. Further, it was noted that the country has a high reliance on external funding aid for water related projects which means that there can be a lack of holistic thinking across projects. Information on the availability and quality of the country's hydrological data, and who to contact regarding obtaining the data and the necessary protocols were also obtained through the communications. Finally, anticipated problems with data gathering were identified through stakeholder engagement and included encountering a general lack of data, sporadic and poor quality data, and prolonged waiting times in receiving requested data due to limited resourcing within the Government.

3.3 Research Materials

3.3.1 Data

The research focused on the collection of existing data and no fieldwork was conducted. Existing data should be evaluated in the first instance to allow the creation of a comprehensive view of the available data. In doing so, targeted fieldwork can be designed if required to address any gaps in the data or focus on areas of interest. Dependent on the scope and scale of the fieldwork, there can be significant costs in terms of time and resources. For example, resources and financing for feasibility studies, equipment purchases or rentals of equipment, installation and decommissioning of equipment, sample taking and lab processing, monitoring requirements and manual labour costs.

Existing data were collected for Malawi on a national scale as described in the following sections. It included climate (rainfall, temperature, wind speed, sunshine hours and pan evaporation), surface water (river flow and lake levels), groundwater levels. It also included Graphical Information System (GIS) files (rivers, topographical map, geological map, land use map etc.). When the data was received, it was clear that there was a wealth of existing data which had been collected by GoM departments.

3.3.1.1 Climate data

Climate data were obtained from the GoM Department of Climate Change and Meteorologist Services. The data included daily and monthly rainfall, temperature, wind speed, sunshine hours, and pan evaporation for a selection of stations across the country. The data was in Excel format and the periods covered varied across stations. An example of the raw rainfall daily and monthly data is presented in Figure 1 and Figure 2 respectively. The data appeared to be of good quality with minimal missing values.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	CHITIPA RAINFALL (mm)													
2		1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
3	01-Jan	17.8	0.0	4.1	1.3	5.6	10.2	8.1	0.0	18.3	25.4	0.0	10.9	26.4
4	02-Jan	0.0	0.0	6.1	7.6	0.0	28.2	23.6	5.3	0.0	21.6	3.3	10.2	0.8
5	03-Jan	0.0	38.1	12.2	6.9	0.0	1.3	0.0	5.1	8.1	9.4	0.0	0.0	14.7
6	04-Jan	0.0	25.4	41.1	1.0	12.7	27.9	0.0	8.1	29.5	3.3	6.4	26.9	0.3
7	05-Jan	6.9	1.0	38.1	26.2	14.0	4.6	28.4	0.0	0.0	22.4	8.9	9.4	0.5
8	06-Jan	0.8	5.8	8.9	29.2	5.1	0.0	0.0	0.0	29.0	24.9	0.0	4.3	0.0
9	07-Jan	1.3	0.0	33.0	0.0	35.3	0.0	37.1	2.8	0.0	0.0	10.4	31.5	0.0
10	08-Jan	8.9	1.3	7.6	7.6	0.0	0.0	3.3	0.0	31.8	0.0	0.0	11.4	0.0
11	09-Jan	0.8	9.4	12.7	12.7	1.8	2.3	0.8	0.0	4.3	0.0	52.6	0.0	0.0
12	10-Jan	2.5	0.0	1.3	0.0	2.3	26.9	0.5	18.0	0.0	0.0	27.2	19.6	0.0
13	11-Jan	2.3	6.9	29.2	46.5	7.9	25.4	2.3	5.3	0.0	12.7	11.2	0.0	13.2
14	12-Jan	0.0	11.4	4.1	0.0	123.2	10.9	0.0	30.5	0.0	0.0	2.0	3.0	28.4

Figure 1 An example of the raw daily rainfall data received from the GoM (Chitipa stations)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	CHITIPA: MONTHLY AND SEASONAL RAINFALL TOTALS (MM)													
2	SEASON	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	TOTAL
3	1999/00	0	5	5	0	19	151	72	161	194	19	0	0	625
4	2000/01	0	0	0	4	172	229	315	100	92	23	0	0	934
5	2001/02	2	0	0	0	10	179	283	162	100	57	0	0	792
6	2002/03	0	0	11	0	68	291	238	178	138	19	0	0	944
7	2003/04	0	0	0	21	18	252	179	144	194	74	0	0	883
8	2004/05	0	0	0	0	83	402	290	145	151	8	0	0	1079
9	2005/06	0	0	0	0	100	66	207	264	229	70	9	0	945
10	2006/07	0	0	0	0	91	343	268	233	122	3	7	0	1066
11	2007/08	0	0	0	13	43	221	198	179	132	5	0	0	789
12	2008/09	0	0	0	0	47	173	107	354	113	75	0	0	869

Figure 2 An example of the raw monthly rainfall data received from the GoM (Chitipa station)

Climate station map

A list of climate stations in Malawi alongside their co-ordinates and elevations was received with the climate data (267 in total). Quantum Graphical Information System (QGIS) was used to plot the stations for a visual check of their locations. It was found that there was several stations outwith Malawi. Follow up communication with the department clarified these locations. To encourage knowledge exchange with stakeholders, the climate station list was imported into the free open source digital Management Information System (MIS) platform 'mWater' (mWater, 2019). mWater is currently being promoted as Malawi's preferred online system for analyzing significant volumes of water and resources data (Miller et al., 2018). The CJF Water Futures Programme is working in partnership with the GoM to develop the MIS for the rural sector and long term strategic management of the water, sanitation and hygiene (WASH) sector infrastructure in Malawi (Kalin et al., 2019). The opportunity was taken to incorporate data from this thesis. The climate station map, as extracted from mWater is presented in Figure 3. Note that the clarity of the figure is limited due to the restricted map export options. The climate station map on mWater can be viewed at the following link https://share.mwater.co/v3/map_link/bc8e387eccf94baab3d9cd8c1d6fb1ef?share=aea85c5f5f834c21b144d7c485297178

Figure 3 mWater map of climate stations in Malawi

The climate station list was cross-compared with the data received and populated to record what data was available for which station. Figure 4 shows the data periods added for rainfall as an example. The complete excel worksheet is presented in Appendix A. Data is of good coverage from the 1960/1970s to around 2016.

	A	B	C	D	E	F	G	H
1	**Name**	**Latitude**	**Longitute**	**Elevation (m)**	**Rainfall (mm)**			
2					*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*
3	Alufandika	-17.08	35.08	480				
4	Alumenda	-16.38	34.93	61				
5	Amalika	-15.98	35.03	1097				
6	Baka	-9.93	33.92	488				
7	Balaka	-14.98	34.97		1976	2016	1999	2017
8	Bandanga	-16.08	35.12	960				
9	Bapani	-11.70	33.58	1425				
10	Bazale	-15.02	35.00	594				
11	Bilila	-14.80	34.88	716				
12	Blantyre	-15.78	35.03	1050				
13	Blind	-16.03	35.50	640				
14	Bolero	-11.02	33.78	1100	1962	2016	1999	2017

Figure 4 Extract from climate station list showing station names, latitude, longitude, elevation, and the associated data (daily or monthly) which was obtained for each station

3.3.1.2 Surface water data

Surface water data comprising river flow data and lake level data was obtained from several sources.

Lake level data for Lake Malawi was obtained from the University of Malawi (Chancellors College) and the Department of Water Resources (Surface Water Division). All data was in excel format and the periods covered varied across stations and sources. The data comprised daily and monthly averages for three monitoring stations along the Lake.

River flows were obtained from previous Strathclyde masters dissertations, University of Malawi, the Department of Water Resources (Surface Water Division), the Global Runoff Data Centre (GRDC) (https://www.bafg.de/GRDC/EN/Home/homepage_node.html) and the SRBMP online portal (http://shirebasinplanning.wris.info/). All data was in excel format and the periods covered varied across stations and sources. The data comprised daily measurements of flow and was sporadic.

As anticipated, there were delays in receiving data and the data was received at intermittent times from different sources. For example, Lake level data was received first from the University of Malawi, and from the Surface Water Division months later. Preliminary data for a select number of river gauges was received first from the Surface Water Division followed by more comprehensive data a few months later. Initially, all data were considered for analysis due to the intermittent times at which it was received and the lack of guarantee that it would be received. However, as the research progressed, a decision was required on which data would be progressed for analyzing. It would have been an inefficient use of time to proceed to analyze all datasets. It was expected that the data obtained from the Surface Water Division would be the most up to date source for both river flows and lake levels. As such, this data was used as a baseline and the various other datasets were evaluated against it by simple cross-comparisons and spot checks to identify any obvious similarities or differences. It was found that many of the data overlapped and was out-of-date when compared to the data provided by the Surface Water Division. Further, the data from the Surface Water Division was comprehensive and the coverage was significant compared to the other sources. As such, this data was selected for analysis.

The river and lake datasets selected for analysis

The dataset selected for lake level analysis of Lake Malawi (Figure 5) was a monthly average of the 3 stations which monitor the lake levels: 17C1 (Chilumba), 16G1 (Nkhabay) and 3A2 (Monkey Bay). The dataset was for the period 1900-2016 and appeared to be of good quality with minimal missing values. There is also a monitoring station located on the lake in Tanzania, however, this data could not be obtained.

The datasets selected for river flow analysis comprised data from 68 gauges in total with coverage varied across gauges. As an example, a graph of the river data for gauge 3E1 (1953-2014) is presented in Figure 6. Data does not extend past 2009 for any station.

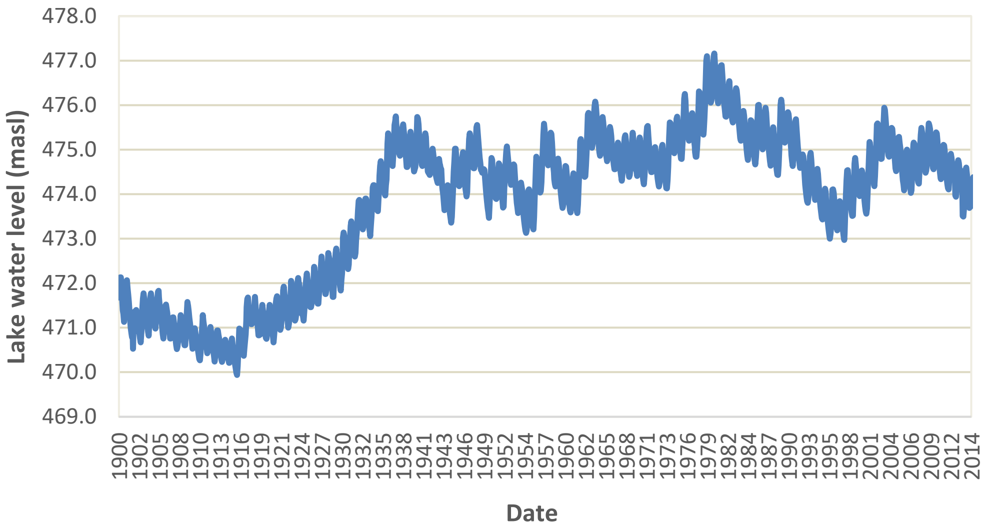

Figure 5 Monthly average Lake Level data for Lake Malawi (1900-2016)

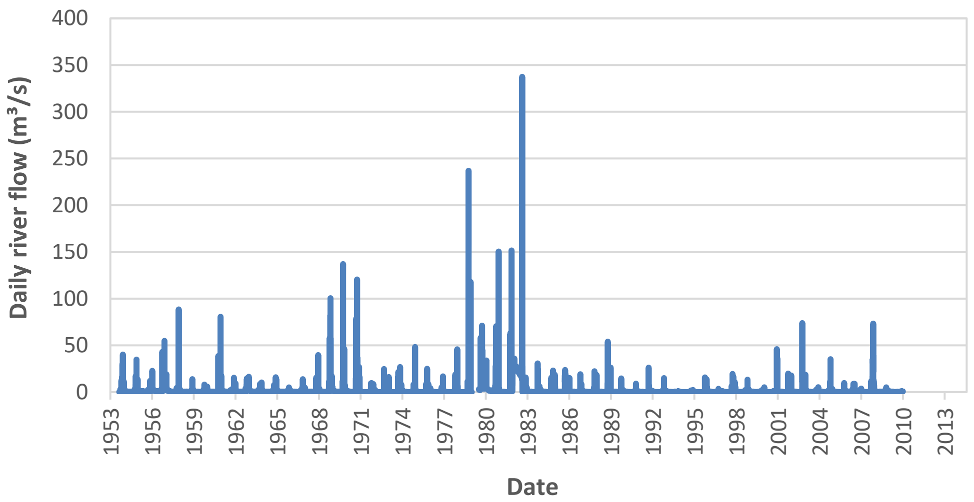

Figure 6 Daily river flow for gauge station 3E1 (1953-2014)

As expected from stakeholder engagement, on closer inspection of the river data, most of it was found to be sporadic with missing values throughout. As an example, Figure 7 below shows an extract of data from Jan-April 1976 from Gauge 3E1. As shown, the month of March is largely missing. This can be considered representative of all the river data where missing values range from a few days to a few months to years. Although this sporadic nature created was not ideal, it was envisaged that meaningful results could be extracted from analysis.

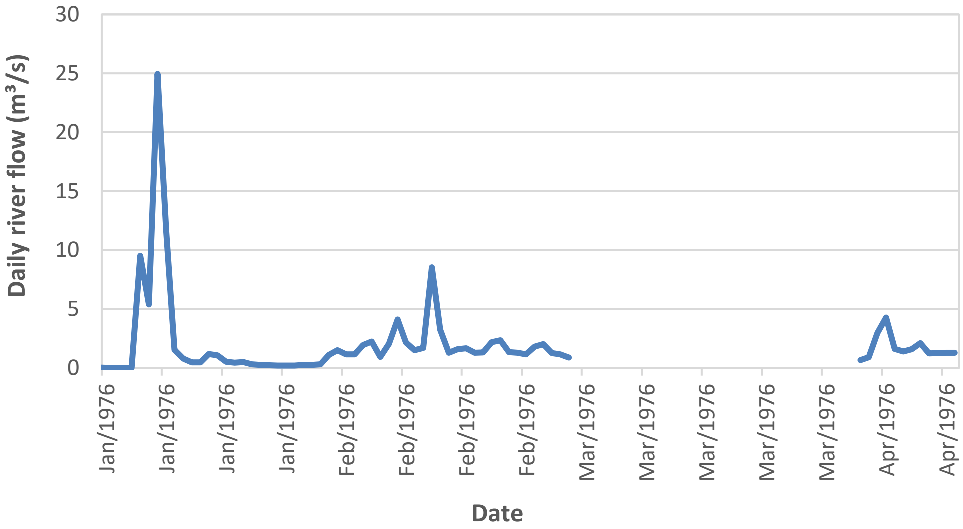

Figure 7 Daily river flow for gauge station 3E1 (Jan-April of 1976)

Surface water station map

A list of all surface water monitoring stations in Malawi was not provided by the Surface Water Division. A list of stations was therefore created in excel as shown in Figure 8. A total of 238 stations were identified. The total number of gauges represents the extensive operational surface water gauging network that Malawi once had, however, since around 2010 many stations have been shut down or vandalized. Station names and associated river/lake names, co-ordinates and station IDs were found in various sources including GoM reports, the SRBMP portal, a GRDC station list, previous master's dissertations, and a PhD thesis. Of the total 238 stations identified, co-ordinates were sourced for only 184. The complete excel worksheet is presented in Appendix A. To encourage knowledge exchange with stakeholders, this surface water station list was imported into the mWater platform as shown in Figure 9. Note that the clarity of the figure is limited due to the restricted map export options. The map can be viewed at the following link https://share.mwater.co/v3/map_link/3bd48380f0c04e8188b9563c342b95e7?share=b51762945af5407482cd3fba765a8c00

	A	B	C	D	E	F	G	H	I
1	**Name**	**River**	**Latitute**	**Longitude**	**mWater Unique ID**	**Station ID (National Gauge ID)**	**Station ID (National Code)**	**River flow (m3/s, mean)**	
2								*Daily (start)*	*Daily (end)*
3	Liwonde (HYCOS station)	Shire	-15.067	35.214	24296618	1B1	10201	16/11/1948	31/08/2012
4	Changalume Cement	Kaloti	-15.387	35.220	24296601	1B6	10206		
5	Liwonde (upstream)	Shire	-15.061	35.220	24296591	1B7			
6	Sitola Railway Bridge	Lukwenu	-15.060	35.265	24297509	1B9			
7	Lirangwe	Lirangwe	-15.531	35.018	24296773	1C1	10301	04/11/1951	31/08/2005
8	Whayo	Lunzu	-15.588	34.978	24296814	1C9	10309		
9	Tedzani	Shire	-15.555	34.783	24296924	1C11	10311		
10	Mpokonyola	Mwamphanzi	-16.048	34.862	24296883	1E1	10501	01/12/1951	24/03/2002
11	Namira	Likhubula	-16.003	34.831	24296890	1E2	10502	03/11/1980	31/10/1998
12	Stella Maris School	Naperi	-15.828	34.997	24296807	1E4			
13	Chimwankhunda	Nankhunda	-15.823	35.021	24296766	1E16			
14	Zingwangwa	Nankhunda	-15.817	35.017	24296797	1E17	10517	03/11/1990	31/08/1995
15	Sunnyside	Mudi	-15.792	34.824	24296900	1E19	10519	21/11/1961	30/04/1993
16	Mafumbi/at Maperera	Mapelera	-16.096	34.912	24296852	1F1	10601	20/06/1982	31/12/2005
17	Gooke	Thangadzi East	-16.404	35.163	24296670	1F2	10602	16/04/1953	31/12/2004
18	Masenjere	Milore	-16.342	35.075	24296728	1F3	10603		
19	Malata	Livunzu	-16.193	35.017	24296780	1F17	10617	03/07/1979	17/02/1997
20	Irrigation Headworks	Nkhate	-16.142	34.957	24296821	1F20			

Figure 8 Extract from surface water station list showing stations and the associated data which was obtained

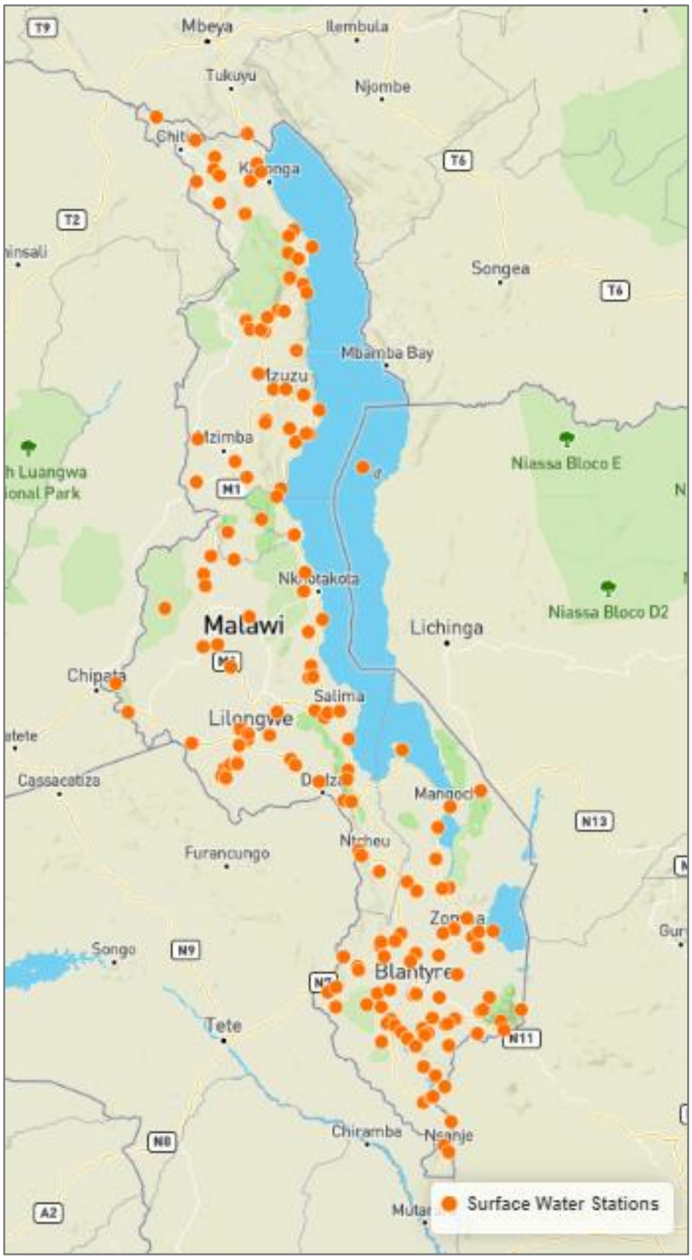

Figure 9 mWater map of surface water stations in Malawi

3.3.1.3 Groundwater data

Groundwater levels are monitored in Malawi via 35 monitoring boreholes constructed around 2009/2010. The locations of the monitoring boreholes are shown in Figure 10. The boreholes are managed by the Groundwater Division of the Department of Water Resources who provided the groundwater level data.

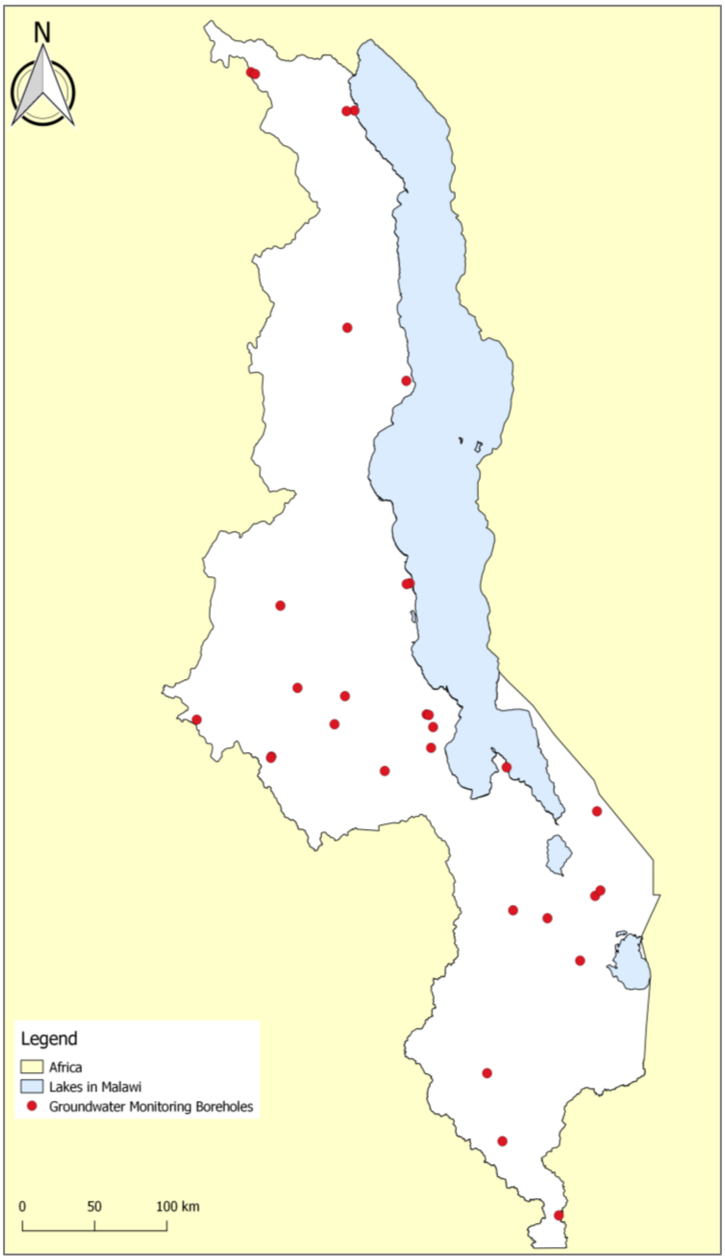

Figure 10 Map of groundwater monitoring boreholes in Malawi

All data was in excel format and the periods ranged from 2009-2015. Data was only available for a selection of the 35 boreholes and was sporadic. As an example, Figure 11 and Figure 12 show graphs of the groundwater level data from two of the monitoring boreholes in the Southern region of Malawi; Kaombe Dam (GN 205) and Ngabu Water Office (GN 166) respectively. Groundwater data is presented and discussed further in the Bua catchment case study in Chapter 5 and the Shire River Basin case study in Chapter 6.

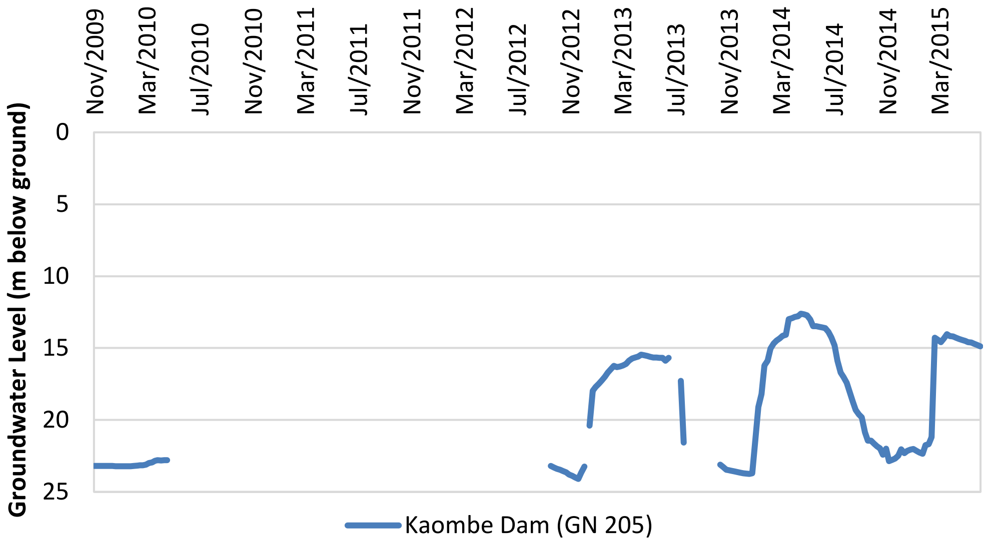

Figure 11 Groundwater levels from Kaombe Dam monitoring borehole in Malawi (2009-2015)

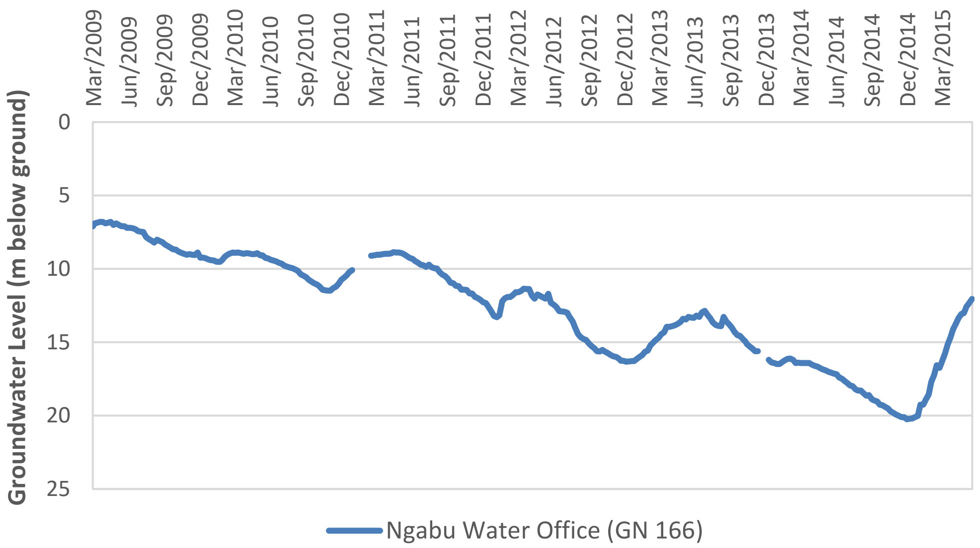

Figure 12 Groundwater levels from Ngabu Water Office monitoring borehole in Malawi (2009-2015)

3.3.1.4 Spatial data

Various GIS files were obtained from several sources including the SRBMP Portal and the CJF Water Futures Programme. Files included boundaries such as Malawi and WRAs, rivers, digital elevation model, topographical map and land use etc. Various GIS files were created during the research such as climate, surface water and groundwater locations. GIS Projects were created for each case study.

3.3.2 Software

The following software and programmes were used throughout the thesis:

- mWater for presenting and sharing data (mWater, 2019) [Chapter 3 and 7]
- Microsoft Excel for viewing, editing, analyzing data and creation of data [Chapter 3, 4, 5, 6 and 7]
- XLSTAT-Forecast for performing statistical trend analysis (Addinsoft, 2019) [Chapter 5, 6 and 7]
- QGIS for viewing, editing and visually presenting geospatial data [Chapter 3, 4, 5, 6 and 7]
- BFI programme for performing baseflow separation (Tallaksen and Van Lanen, 2004; Morawietz, 1997) [Chapter 5, 6 and 7]

3.4 Research Methods

3.4.1 Evaluation of principle methods available to the study

The choice of method for quantifying baseflow is significantly restricted by data and resources in the developing world context and has led to a dependency on the desktop methods, specifically, baseflow separation. Nonetheless, this section presents an evaluation of methods which were available to the study. To evaluate the methods in a structured way and to reveal their potential to overcome the challenges, three criteria were developed. The criteria were as follows:

Data: Availability of data

The choice of a method is largely dependent on the data available (Brodie et al., 2007b). As described in Section 3.3.1 the data available for this research comprised climate data, surface water data and groundwater data.

Scale: Capable of assessing baseflow on a medium to long term basis

The method was required to quantify temporal variations in baseflow on the medium to long term temporal basis. Baseflow exists at various spatial and temporal scales and before any investigation, the scale at which the study will focus should be defined.

Spatial scales and typical units have previously been defined as; the catchment scale (regional, >100km^2), the feature scale i.e. a river reach (intermediate, 1-100km) and the site scale i.e. hyporheic zone (local, <100m) (Brodie et al., 2007a). This research aimed to focus on the catchment and feature scale and did not consider the site scale. This was based on the available data and the relevance of the research outputs in water resources management. For example, site-scale considers small areas in detail which are useful for ecosystem and water quality protection studies. In comparison, feature scale and catchment scale consider the bigger picture. Feature scale studies can be useful for environmental planning and water management decisions and catchment scale can be useful for catchment monitoring and mapping water management areas (Brodie et al., 2007a). This research wanted to focus on the provision of 'big picture' baseline data which would entice interest from stakeholders and underpin future work on targeted research areas.

Temporal scales and typical units of baseflow has previously been defined as long term (decades-centuries), medium-term (seasons-years) and short term (days-months) (Brodie et al., 2007a). This research sought to quantify variations in the long term and medium term as many developing world countries are subject to distinct seasonal patterns and differentiation between the annual and seasonal baseflow is important. Additionally, many countries like Malawi will experience human activities such as over-abstraction of groundwater and deforestation which will impact baseflow in the longer term and may take years to decades to become apparent.

Practicability: Use must be practical and overcome challenges typical of the developing world

To recap, some of the challenges faced in the developing world context are limited technical knowledge, lack of financial resources and experienced hydrology and hydrogeology staff. To overcome these challenges, it was necessary to consider what the end users would want from a method. For example, first, the methods should be free at the point of use. Often, commercially licensed software is not free to use or share and it would be challenging for some departments to find and allocate funding. The use of free-open source tools promotes the shareability between stakeholders and repeatability of the research process. Second, methods should be easy to use, not overly complicated and not require significant amounts of time to perform. These requirements are reflected in the results of a Scottish study which investigated what stakeholders really needed in the development of software applications for supporting environmental decision making (Hewitt and Macleod, 2017). Workshop participants in the study identified 12 key principles for the development including ‘practicability-relates to users experience and needs’ and ‘accessible/easy to use’ (Hewitt and Macleod, 2017). Although not directly applicable to baseflow, it shows that there are common themes of stakeholder requirements within water resources management.

The methods evaluation is presented in Table 1 where the methods were evaluated against the above criteria.

Table 1 Evaluation of methods to quantify temporal variations in baseflow

Method	Description	Data	Scale	Practicality	Select (Yes/No)
Baseflow separation	Baseflow separation utilizes river flow data and provides estimates of baseflow without the need for complex modelling, detailed knowledge of soil characteristics or costly site investigations (UNESCO, 1997). It separates the river hydrograph into its slow flow component 'baseflow' and the quick flow component 'direct runoff' (UNESCO, 1980; Fetter, 2001). This approach assumes that the baseflow component is derived entirely from groundwater discharge from the aquifer, however, other stored sources can also contribute in some catchment. The true source of baseflow is impossible to distinguish from baseflow separations alone and would require detailed site investigations to map each flow path (UNESCO, 1980)	Yes: River data is available	Yes	Yes:	Yes: First, must demonstrate how to work with sporadic river data and select appropriate sub-methods
Analysis of recession limb	In the context of a lake hydrograph, the recession limb of the hydrograph represents the fall in lake levels during periods with little to no rainfall (Tallaksen and Van Lanen, 2004). The recession limb is controlled by several factors, one of which is surface runoff from the inflow rivers to the lake. In the dry season, surface runoff of most rivers is known to comprise mainly baseflow, therefore, baseflow will influence the recession limb	Yes: Good quality lake level is available	No	Further investigation required	Yes: Method has potential to provide a proxy indicator of baseflow changes if valid assumptions can be made about the influence of the other controlling factors

Method	Description	Data	Scale	Practicality	Select (Yes/No)
Water balance	Water Balance is a mathematical expression which is used to describe the inflows and outflows of water in a hydrological system (Kumambala and Ervine, 2010; Hayashi and Van Der Kamp, 2007). Typically used to solve unknown components in lake systems, where the inflows comprise runoff from rivers, precipitation falling directly over the Lake surface, groundwater discharge to the Lake, and the outflows from the Lake; groundwater seepage from the Lake, evaporation directly from the Lake surface, outflow to any rivers and consumption uses and diversions (Healy and Scanlon, 2010a).	No: Rainfall and evaporation data available. Direct groundwater discharge, outflow and consumption use and diversion not available	Yes	Further investigation required	No: Ruled out due to lack of data
Streamflow duration curves	Describe the relationship between magnitude and frequency of the occurrence of flow in a river (Healy and Scanlon, 2010c). Curves are developed using flow data and computer programmes. The curves can be visually examined to learn about baseflow conditions. For example, steep slopes in any section of the curve indicate high variability in flow most likely from rivers dominated by surface water flow. Whereas low slopes in the lower section of the curve generally indicate groundwater discharge (Healy and Scanlon, 2010).	Yes: River data is available	Further investigation required	No: The direct association of river flow duration with baseflow requires an independent estimation of baseflow (Healy and Scanlon, 2010c).	No: Ruled out as the independent estimation of baseflow would be required (i.e. baseflow separation)

Method	Description	Data	Scale	Practicality	Select (Yes/No)
Computer modelling	Hydrological and hydrological models can be used to investigate the various factors which function in a water system including baseflow (Brunner et al., 2017). Models are largely based on some form of water budget equation (Healy and Scanlon, 2010b) and involve simulation of water flow from groundwater to the river using mathematical equations. Models are dependent on good quality data and oversimplified models may not be robust and yield incorrect results.	Some: River flow data is available but limited groundwater data.	Yes	No: Requires modelling expertise and would be difficult to repeat	No: Ruled out due to lack of good quality data and as expected to be labour intensive and require expertise
Hydrogeological mapping	Hydrogeological mapping involves the mapping of groundwater systems including flow paths, properties, and the structure of the aquifer. It can provide a conceptual understanding of baseflow behaviour.	No: Borehole log data not available. Limited groundwater data.	No	No	No: Ruled out due to lack of data

As shown in Table 1, streamflow duration curves, hydrogeological modelling and computer modelling methods were not appropriate based on the criteria (data, scale and practicability). This was due to various reasons as outlined in Table 1. Its seen that the method of analysis of the recession limb of lake data may provide a proxy indicator of baseflow and baseflow separation was the most appropriate method overall for quantifying temporal variations in baseflow. As such, analysis of the recession limb of lake data and baseflow separation of river flow data were progressed for further investigation.

To progress the work and demonstrate the methods, several case studies from the study area of Malawi were selected as described in Section 3.4.2 and Section 3.4.3 below. Case studies are often used in the preliminary stages of an investigation to understand a specific topic within a single setting from which information is then used to inform the broader setting (Seale, Gobo, Gubrium and Silverman, 2004).

3.4.2 Analysis of the recession limb of lake data

Lake Malawi was used as a case study to demonstrate how to analyze the recession limb of lake level data to provide a proxy indicator of changes in baseflow. This is presented in Chapter 4 in the form of a paper drafted for journal submission and addresses RO3. To avoid repetition in the thesis, the ethos of the work is described in the Chapter introduction and specific details of the approach used are provided in the materials and methods section of the paper. The sub method of the moving average is also described, alongside the justification for its selection, in the materials and methods section of the paper. It's noted that the lake data which underpinned this method was considered good quality as described in Section 3.3.1 and no preliminary preparation was required.

3.4.3 Baseflow separation using sporadic river data

The Baseflow Index (BFI)

Whilst the baseflow volumes produced from the baseflow separation can be analyzed directly, it's popular to determine the Baseflow Index (BFI); a numerical expression of the baseflow component which has been adopted in this research (Singh et al., 2019; Esralew and Lewis, 2010; Gustard, Marshall and Sutcliffe, 1987; Beck et al., 2013). The BFI was originally developed during a study in the United Kingdom by the Institute of Hydrology as a parameter to index catchment geology and the ability of a catchment to store and release water (Gustard, Bullock and Dixon, 1992). Baseflow separation assumes that interflow is insignificant, and the baseflow component is derived entirely from groundwater discharge from the aquifer (UNESCO, 1980; Fetter, 2001). The BFI is therefore often used as a proxy indicator of groundwater discharge to rivers (Bosch et al., 2017; Gustard, Bullock and Dixon, 1992; Kelly et al., 2019b; Esralew and Lewis, 2010).

The BFI has many practical applications in hydrology and hydrogeology which further endorses its selection. For example, it is used within models to characterize and model flow in a catchment, as a catchment descriptor in low flow studies (Tallaksen and Van Lanen, 2004), as a parameter for Environmental Flow Requirements (EFR) which set a minimum flow required in a river to sustain its ecological health (Hughes and Hannart, 2003), and as a variable for estimating low flow-indices at an ungauged site (Singh et al., 2019).

Application using 3 case studies

The Bua catchment was used as a case study to demonstrate how to work with sporadic river data and baseflow separation to quantify temporal variations in BFI. This is presented in Chapter 5 in the form of a published paper and addresses RO4. To avoid repetition in the thesis, details of the specific approach used are provided in the materials and methods section of the paper. Sub methods (BFI, BFI programme, smoothed minima filtering technique, Mann-Kendall (MK) trend test and descriptive statistics of average, maximum and minimum) are also described, alongside justification for their selection, in the material and methods section of the paper. It is noted that the river data which underpins this method was sporadic and specific baseflow separation steps were developed to work with the data. Further, an appropriate implementation tool was required to be selected.

The approach used in the Bua Catchment was upscaled using another two case studies from the study area. The Shire River Basin was used as a case study to demonstrate the application of the approach on a larger regional catchment scale (Chapter 6). Finally, Malawi was used as a case study, to demonstrate the application of the approach to quantify temporal variations in BFI on a national scale (Chapter 7). The sub methods as used for the Bua catchment case study were also used within Chapter 6 and 7.

3.4.4 Statistical methods

Simple descriptive statistics were used to find the average, maximum and minimum of the BFI data in Chapter 5, 6 and 7. Beyond these simple statistics, the moving average was used to smooth lake level data in Chapter 4 and the Mann-Kendall (MK) trend test was used in Chapter 5 to identify trends in rainfall, river flow and BFI data. The MK was further used to identify trends in BFI data in Chapter 6 and 7. The following is a brief description of the statistical methods used in this research and further details are provided in their respective chapter (as part of the materials and methods section of the papers).

Moving Average

Statistical smoothing techniques are commonly used to remove irregularities or noise in data which allow trends to be more easily identified. The use of a moving average is popular in hydrological studies (Ferdowsian and Pannell, 2009; Tallaksen and Van Lanen, 2004; Neuland, 1984). The test was applied using a 3-month frequency and is described more in Chapter 4.

Mann-Kendall statistical test

The non-parametric MK test was introduced by Mann (1945) and later modified by Kendall (1975). The test is one of the most widely used tests for identifying trends in hydrological and climate data (Zhang et al., 2016; Bosch et al., 2017; Yue, Pilon and Cavadias, 2002; Kawala, 2020) and it is recommended by the World Meteorological Organization (WMO). As described in Chapter 2, Section 2.8, one of the main advantages of the MK test is that it is a non-parametric test meaning it does not make any assumptions about the distribution of the data which is particularly useful as hydrological data seldom follows a normal distribution (Yue, Pilon and Cavadias, 2002). Further, the MK test is insensitive to missing data which was a key limitation with the data collected in this research. As such, the MK test has been selected for analysis in the research.

To perform the MK test and describe what the test is investigating, the null and alternative hypothesis was defined. The null hypothesis, H0, was defined as ‘there is no trend in the data’, and the alternative hypothesis, Ha, was defined as ‘there is a trend in the data’. In statistical testing, the null hypothesis is assumed to be true and the test checks whether the data is consistent with this hypothesis. Where the data is not consistent, the null hypothesis is rejected. In the MK test, the H0 is rejected (and the alternative Ha accepted) where the calculated p-value is lower than the significance level. The significance level is the probability that the null hypothesis is incorrectly rejected and is known as a type I error (Kundzewicz and Robson, 2004; Yue, Pilon and Cavadias, 2002). The type II error is another error which can occur in statistical testing where the null hypothesis is accepted (i.e. no trend exists) but a trend does actually exist (Yue, Pilon and Cavadias, 2002). The smaller the significance value, the more confidence there is that the null hypothesis is really false.

A key limitation of the MK test is that it is not considered to be robust against serial correlation which can occur in time series data and can be statistically significant in some hydrological and climate time series (Tian et al., 2018). Serial correlation describes the relationship between observations of the same variable over specific periods and where a variable is serially correlated it means it has a pattern and is not random. Serial correlation in data can be removed before performing a trend test by a technique called ‘pre whitening’, or by modifying the original trend test to account for serial correlation in the data (Hamed, 2008). The advantage of pre whitening is that it can reduce the type I error (caused by the serial correlation), however, it also increases the risk of type II error because the power of the MK reduces after pre whitening (Yue, Pilon and Cavadias, 2002; Wang et al., 2020). In a recent review of the evaluation of the power of the MK test for detecting trends in hydrometeorological time series, Wang et al. (2020) expresses that the *‘debate around different approaches dealing with serial correlation and trend becomes a mathematical game and compromises the balance between the significance and power of the MK test, and that the only thing that matters is which error is more unacceptable in specific cases’.* To improve the situation, Wang et al. (2020) recommends that the significance level should be set to 5% or 10% which will present strong evidence against the null hypothesis and timeseries should extend as far as possible. Further, Bayazit and Önöz (2007) and Yue, Pilon and Cavadias (2002) both recommend that pre whitening is avoided when the time series is large. Based on these recommendations, and as the river datasets used in this research generally span minimum 10+ years, pre whitening has not been applied and the significance level has been set to 1%.

Details of the selection of the test parameters are described in their respective papers in Chapter 5 (Section 5.2) and to a lesser extent in Chapter 6 (Section 6.2) and Chapter 7 (Section 7.2). Specific details of the MK equations can be found in the literature (Mann, 1945; Kendall, 1975; Helsel and Hirsch, 1992).

3.5 Summary

This chapter presented the methodology used in the thesis to achieve the aim of the research. Stakeholder engagement was conducted with the GoM to clarify the need for the research and ensure the practical application of the research outputs. Existing data was collected for the study area which included climate data, surface water measurements and groundwater levels. Further, GIS files were gathered to present and visually evaluate the study area. Climate data and lake levels were found to be of good quality and considerable coverage, however, groundwater levels were extremely limited in both quality and coverage. The river flow data covered significant periods but was sporadic.

An evaluation of principle desktop methods to investigate baseflow was conducted based on the available data, the required scale of assessment and the practicability of using the method in the developing world context. From the evaluation, two methods were selected to be investigated further. First, analysis of the recession limb of lake levels was selected for its potential to provide a proxy indicator of changes in baseflow as demonstrated in Chapter 4. Second, baseflow separation to determine BFI was selected as the most appropriate method to achieve the aim of the thesis. An appropriate implementation tool was required to be selected and procedural steps for working with sporadic river data were required. The approach was first applied to a case study of the Bua Catchment in Chapter 5. This was followed by the upscaling of the approach to a larger regional catchment using the Shire River Basin as a case study (Chapter 6) and to the national scale using Malawi as a case study (Chapter 7).

The next chapter demonstrates the first selected method; an analysis of the recession limb of lake levels.

Chapter 4 Lake Malawi

4.1 Introduction

The previous chapter presented the methods to achieve the aim of the thesis. From the evaluation of methods available to the study, baseflow separation was anticipated to be the most applicable method to achieve the aim. However, the evaluation also revealed that analysis of the recession limb of lake levels may provide a proxy indicator of changes in baseflow over time. As good quality long-term lake level data were available for Lake Malawi, it was selected as a case study to conduct the analysis.

In the dry season in Malawi, there is very little rainfall for as many as 6 months and therefore a lack of overland flow available for surface runoff to the rivers. River flows are expected to be dominated by baseflow (i.e. groundwater discharge to rivers from the underlying aquifers). River flows are a major source of inflow to Lake Malawi in the dry season where the catchment area of the inflow rivers is approximately 100,000km^2 (Government of Malawi, 2011d). Baseflow is controlled by groundwater storage within the catchment and as such the river and lake hydrographs are dominated by groundwater storage in the dry season. In the lake hydrograph, decreasing lake levels are represented by the recession limb. Analysis of this limb can therefore provide a proxy indicator of changes in baseflow, and groundwater storage, across the Lake Malawi catchment. Changes in groundwater storage across the lake catchment will impact the rate of decline of the levels and ultimately the lake levels. For example, long term increases in groundwater storage will result in higher baseflow which results in a reduced rate of lake level decline in the dry season. This is opposed to long term decreases in groundwater storage which will result in lower river flows during the dry season which will result in an increasing rate of lake level decline.

Changes in groundwater storage occurs over long-term periods from years to decades. Therefore, changes in the hydrological cycle (e.g. climate change, extended periods of increased infiltration and groundwater recharge, or periods of decreased infiltration and recharge) will result in increases or decreases to baseflow but with a considerable time lag. Monitoring of these long-term changes is very important to ensure the lake can continue to supply water as it does. The lake is the main water supply to its only outlet, the Shire River. The Shire River is home to three hydropower stations which provide over 98% of the country’s electricity (Government of Malawi, 2016d). The river also provides for piped municipal surface water supplies, direct abstraction by local communities and water for irrigation for agriculture. Thus, the flow of water from the lake is of major importance to meet the water demands of the downstream users of the Shire River. In 1915, due to lake levels decreasing below the outlet, the Shire River became dry until the lake levels rose again in 1937 (Calder et al., 1995; Owen et al., 1990). This had a severe impact on the country and caused widespread water scarcity. Today, with even more water demands placed on the Shire River, if the lake levels were to drop and reduce flow to the Shire, an economic catastrophe could unfold for Malawi. The baseflow component of Lake Malawi must therefore be investigated to support sustainable water resources management of both the lake and the Shire River.

In this context, this chapter demonstrates, using Lake Malawi as a case study, how to potentially analyze the recession limb of lake level data to provide a proxy indicator of changes in baseflow. The investigation was accomplished by a draft paper intended for submission to a peer-review journal as follows:

Kelly, L., Kalin, R.M., Bertram, D., and Sibande, H., 2020. An analysis of the recession limb of Lake Malawi to provide a proxy indicator of variations in baseflow. TBC, TBC, TBC.

This paper is an initial first draft and further work will be required before submission to a journal. The draft paper is presented in the following section and to date, the author contributions were as follows: Conceptualization, L.K. and R.M.K.; Formal analysis, L.K.; Funding acquisition, R.M.K.; Methodology, L.K.; Resources, H.S.; Supervision, R.M.K. and D.B.; Validation, L.K., R.M.K.; Visualization, L.K.; Writing—original draft, L.K.; Writing—review & editing, L.K., and R.M.K.

4.2 Paper

An analysis of the recession limb of Lake Malawi to provide a proxy indicator of temporal variations in baseflow

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Abstract: This study demonstrates how to potentially analyze the recession limb of a lake hydrograph to provide a proxy indicator of temporal variations in the baseflow contribution to the lake from its inflow rivers. Lake Malawi in Southern Africa was used as a case study. The rate of decline (slope) of the lake levels was determined at 3-month intervals for 116 years of data (1900-2016). Statistical smoothing was applied to the slope data using a 3-month moving average. The negative slopes which correspond to the dry season in Malawi were visually examined. The results show several negative spikes in the non-smoothed slopes in 1916, 1942, 1948, 2012 and 2013 which indicated significant changes occurring in the recession limb. The results also show negative spikes in the smoothed slopes for the same years except for 1948. These changes in slope were attributed to baseflow from the inflow rivers. Several spikes (1916, 1942 and 1948) coincided with very dry conditions across Malawi, whereas, others (2012 and 2013) coincided with severe flooding conditions in Malawi. Both extreme conditions can result in changes to the baseflow component of river flow. This demonstration serves as a useful example to highlight the potential for baseflow to impact on lake levels during the dry season. To ensure the future sustainability of the lake, further research is recommended to quantify the total volume of baseflow contribution to the lake. This data is required to update existing and proposed development projects on the lake and further knowledge on the behaviour of the Lake.

Keywords: baseflow; lake; recession; groundwater; Malawi

1. Introduction

Baseflow is an important component in the sustainable management of lakes (Li and Zhang, 2018). Baseflow is defined as the proportion of river flow which is derived from groundwater and other stored sources with the lions share generally derived from groundwater (Singh et al., 2019). In a typical lake, water levels are maintained from several sources: runoff from rivers, rainfall falling directly on the lake surface and direct groundwater exchange with aquifers. In the context of the role which groundwater plays in a lake, it is recognized that the direct groundwater exchange plays a highly variable dependent on the lake characteristics. For example, in terms of the water budget, groundwater discharge to Lakes can range from 0-94% and groundwater seepage to the underlying aquifer can range from 0-91% (Hood, Roy and Hayashi, 2006; Vaheddoost and Aksoy, 2018; Rosenberry, Lewandowski, Meinikmann and Nützmann, 2015). However, less attention has been given to the importance of indirect groundwater discharge to a lake derived from the baseflow component of the inflow rivers (Vaheddoost and Aksoy, 2018).

Baseflow from rivers is a crucial water source to lakes during the dry season in semi-arid regions when there is minimal rainfall and rivers are largely sustained by baseflow which often comprises over 90% of the total river flow (Kelly et al., 2019b; Kelly, Bertram, Kalin and Ngongondo, 2019a). Despite this importance, the baseflow contribution is often neglected in lake studies and the focus remains on the total flow of the inflow rivers. However, as anthropogenic activities and climate change continue to influence the variability and availability of river flows, it is important to understand the baseflow component which sustains the rivers. For example, over-abstraction of local aquifers along the inflow rivers can cause a reduction in baseflow which in turn can negatively impact the water levels of the receiving lake resulting in detrimental implications for those who rely on the lake to supply water (Kumambala, 2010).

One example where the importance of river baseflow to a lake remains a relative mystery is Lake Malawi in Africa (Figure 1). The Lake catchment covers parts of Malawi, Tanzania, and Mozambique. The majority of the lake resides within the borders of Malawi, however, the lower east section of the lake is located within Mozambique and is known there as Lake Niassa (Yihdego and Paffard, 2016). Further, the north-west border of the lake meets Tanzania where it is known as Lake Nyasa. For this study, it will be referred to as Lake Malawi. The lake is the 3rd deepest and 9th largest freshwater lake on earth and is home to a greater diversity of fish species than any other lake (Bootsma and Jorgensen, 2013). It feeds its only outlet; the Shire River and together they act as Malawi's most important hydrological system, being a major source of water for lakeshore communities and playing an important role in the nations tourism, transport and fishery industries (Kelly et al., 2019a; Bhave et al., 2020). Pumping from the lake occurs mainly from the lakeshore villages and resorts (for irrigation, urban and rural water supplies). Further, over 90% of the country's electricity is generated by three hydropower plants on the Shire River and as such, Malawi's economic dependence on Lake Malawi to maintain outflows to the Shire River cannot be underestimated (Government of Malawi, 2016b; Bhave et al., 2020).

Historically, the water level in Lake Malawi has been relatively unstable and has fluctuated widely over the years (Delvaux, 1995). In 1915, the lake levels dropped below the bed of the outlet to the Shire River which resulted in flow stopping in the river. This caused widespread water scarcity until the lake levels rose again in 1937 and allowed/enabled the river to flow again (Calder et al., 1995; Owen et al., 1990). Studies in the 1980s mainly used water balances and focused on investigating the reason why lake levels fluctuated (Cochrane, 1957; Pike, 1968; Drayton, 1984) and predicting the future behaviour of the lake levels (Neuland, 1984; Jury and Gwazantini, 2002). Climate change modelling was also introduced to the water balance of the lake in attempts to project its future behaviour (Kumambala and Ervine, 2010). Studies in recent years continue to investigate the trend and variability in the lake levels (Sene et al., 2017). Generally, the changes are attributed to variations in rainfall and atmospheric conditions (Jury and Gwazantini, 2002; Calder et al., 1995; Drayton, 1984). All of these studies, except for 2 (Lyons, Kroll and Scholz, 2011; Government of Malawi, 1983), do not consider the role of direct groundwater exchange with the Lake, assuming it to be negligible based on either a lack of data or the limiting geological conditions of the lake. None of these studies considered the contribution of baseflow from rivers to the lake and the impacts that it and long-term changes in its behaviour may be having on the lake levels. The most recent model to be developed, a water evaluation and planning model specifically stated that the model showed limited ability to capture baseflow (Bhave et al., 2020). Given the importance of Lake Malawi within the context of national water resources management, an updated investigation to quantify the volume of baseflow contribution to the lake and identify any behavioural changes over time is considered critical.

In this context, this study aimed to utilize lake level data and demonstrate a simple approach of analyzing the recession limb of the lake hydrograph to deduce temporal variations in the river baseflow contribution over time. Specifically, the objectives were to 1) determine the rate of decline (slope) of lake levels and plot against time, 2) visually inspect the plot for any obvious spikes in the negative slope, 3) apply a statistical smoothing technique to the rate of decline (slope) data and plot against time and 4) visually inspect the plot of smoothed data for any obvious spikes in the negative slope and compare with the unsmoothed data. The approach demonstrated is considered a useful exercise to explore the role of baseflow in lakes in the absence of river flow data (which is typically used in the developing world context) or where there are long lead times in obtaining data.

This study forms part of on-going research in Malawi by the Climate Justice Fund Water Futures Programme, funded by the Scottish Government. The research focuses on the sustainable development of groundwater and offers support to the Government of Malawi as they work towards Sustainable Development Goal 6 (SDG6).

2. Materials and Methods

2.1 Study area

Lake Malawi (Figure 1) has a total surface area of approximately 28,750 km^2, reaches depths of 700 m and has a lake catchment of approximately 100,000 km^2 (Government of Malawi, 2011d). The main inflow rivers to the Lake are the Bua, South Rukuru, Dwanga and Linthipein (in Malawi), the Ruhuhu and Kiwira (in Tanzania), and the transboundary river the Songwe which forms the border between Malawi and Tanzania. Further, there are many smaller rivers which inflow to the Lake. The lakes only outflow is the Shire River in Malawi which is approximately 410 km long and houses 3 hydropower stations. Land use in the catchment is mixed-use comprising mainly subsistence and commercial farming. Further details of the specific characteristic of the lake can be found in the literature (Bhave et al., 2020).

2.2 Data

This study focused on monthly level data for Lake Malawi for the period 1900-2016. This dataset is an average of the 3 stations which monitor lake levels in Malawi: 17C1 (Chilumba), 16G1 (Nkhabay) and 3A2 (Monkey Bay) (Figure 1). The data were provided by the Surface Water Division of the Department of Water Resources of Malawi. The data was in excel format and appeared good quality on visual inspection with minimal data gaps throughout. There is also a monitoring station located on the lake in Tanzania, however, this data could not be obtained.

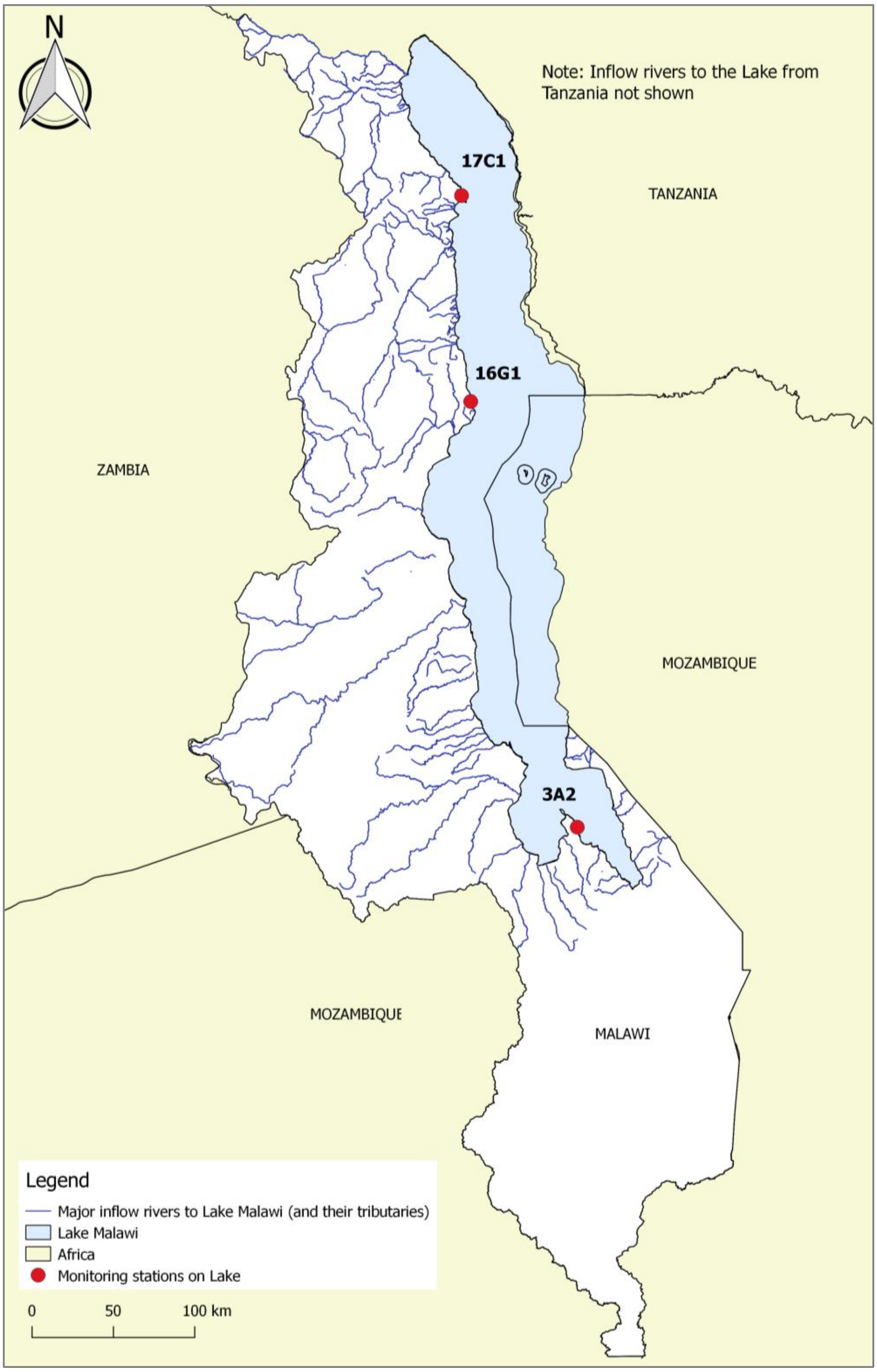


Figure 1 Location of Lake Malawi in Malawi and Africa, showing major inflow rivers to the Lake from Malawi and monitoring stations

2.3 Approach

Hydrographs are charts that display the change of a hydrologic variable over time and can be created for several bodies of water including rivers, lakes, water wells and springs. Generally, hydrographs comprise a series of peaks and valleys reflecting the physical processes that influence the hydrologic variable continuously (Tallaksen, 1995). Figure 2 shows a sketch of an extract from the Lake Malawi hydrograph for a hydrological year. It shows the rising limb (as the lake levels rise) and the recession limb (as the lake levels fall after rain). The rising limb coincides with the wet season and is mainly influenced by rainfall (+), river inflows (comprising surface runoff and baseflow components) (+) and direct groundwater exchange with the lake (+/-). The recession limb coincides with the dry season and has a relatively complex nature. It is mainly influenced by rainfall (+), river inflows (comprising surface runoff and baseflow components) (+), direct groundwater exchange (+/-), evaporation (-), outflow to the Shire River (-) and abstraction by local communities along the lakeshore.

Both the rising limb and the recession limb are influenced by inflow rivers which comprised a surface runoff component and a baseflow component. Thus, baseflow influences both the rising and recession limb. Baseflow influences the recession limb to a much larger extent than the rising limb as there are minimal rainfall and overland flow in the dry season contributing to the river flow. For example, rivers across Malawi have been shown to comprise >90% baseflow in the dry season (Kelly, Bertram, Kalin and Ngongondo, 2020; Kelly et al., 2019a; b). Therefore, this study focused on the analysis of the recession limb to attempt to deduce changes in baseflow over time.

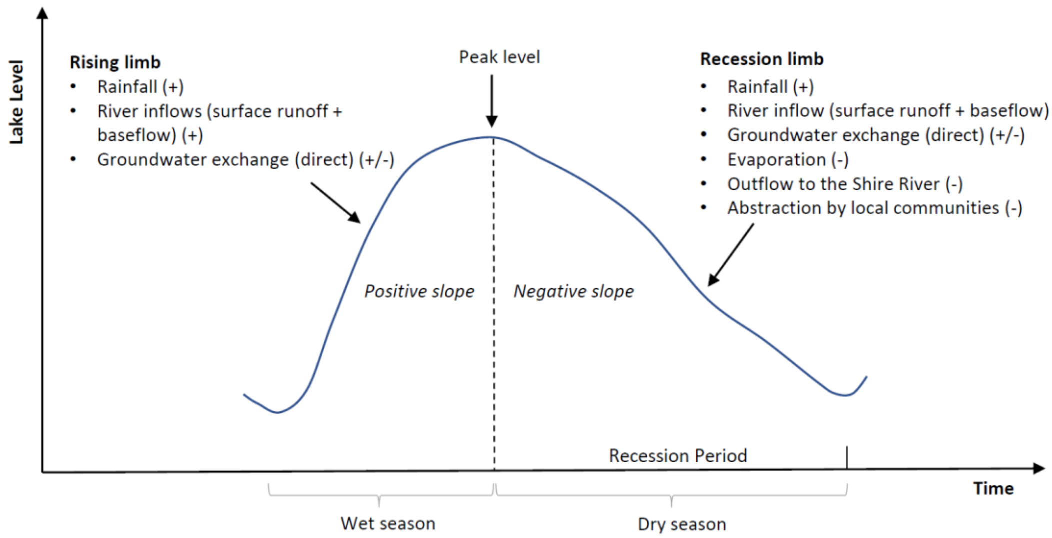


Figure 2 Hydrograph extract showing rising and recession limb with influencing factors

To explore the recession limb, the rate of decline of the lake levels was determined by calculating the slope of the lake levels (1900-2016) at 3-month intervals. The slope was calculated using the SLOPE function in excel. The slope is the ratio of the vertical change to the horizontal change between any two points on a line and is the equation of a line. It describes the direction of the line which is either increasing (i.e. slope is positive >0), decreasing (i.e. slope is negative <0) or vertical (i.e. slope =0). The determined slopes were plotted as a function of time and the negative slopes, which represent the recession limb, were visually examined to identify any significant changes in the slopes over time.

The slope data was also statistically processed using a smoothing technique to remove any irregularities or noise. Smoothing techniques separate the seasonal and long term trends from random fluctuations in the data which allows trends to be easily identified (Ferdowsian and Pannell, 2009; Tallaksen and Van Lanen, 2004). This study used the moving average technique which is popular in hydrological studies (Neuland, 1984) and the test was applied using a 3-month frequency. Like the examination of the slope data, this smoothed time-series was plotted as a function of time and the negative slopes were visually inspected for any significant changes. Microsoft Excel was used to analyze the data as described above.

For this study, any changes in the negative slope which were identified were attributed solely to changes in baseflow. This assumption was necessary to progress the study, however, in reality, the nature of the recession limb is complex, and the other influencing factors described will play a role in its behaviour. Although the other factors influence the recession limb, they are not expected to cause significant changes over time because they do not experience significant changes in the dry season. For example, in a study by Kumambala (2010) on the Lake Malawi water balance, although evaporation was found to be the largest component which withdraws water from the lake, it was found to vary the least among the water balance components over the study period (1976-1990). Additionally, the study analyzed the outflow from the Lake to the Shire River and found no marked variation throughout the study period (Kumambala, 2010). The outflow to the Shire River is artificial and controlled by the man-made Kamuzu Barrage. In theory, the outflows are to be managed by the barrage so that there is a consistent outflow over time (Government of Malawi, 2013b), however, this is not always the case. In drier years, for example, the release of water will be increased to meet demands and in wetter years it may be reduced to conserve water.

Further, in the dry season, there is minimal to no rainfall and the small amounts of rain that do fall are sporadic. A study by Ngongondo et al. (2011b) in Southern Malawi did not find any discernible upward or downward trends in dry season rainfall (1961-2006), and another study by Ngongondo, Xu, Tallaksen and Alemaw (2015) detected only a slightly decreasing trend in annual precipitation across Malawi. Direct groundwater exchange is likely to be immensely small due to the lakes geological conditions as described by previous studies on the water balance of the lake referred to in the introduction. Abstractions by the local communities along the lakeshore are also thought to be similar each year, although will likely have increased slightly over time given the rise in population in Malawi. Finally, it's recognized that Lake Malawi water levels are highly responsive to changes in river inflows, due to the small catchment areas of the rivers (Sene et al., 2017; Jury and Gwazantini, 2002; Jury, 2014; Shela, 2000). As such, it can be deduced that baseflow in the dry season will influence changes in the recession limb.

3. Results and Discussion

An understanding of the hydrological factors which determine Lake Malawi's water levels, specifically baseflow, is essential for future planning of water resource development in Malawi. The rate of decline of the lake levels (slope) was calculated based on a 3-monthly interval for the period 1900-2016. Before presenting the results of the entire period, it is useful to exam 1 year to understand what is happening annually. Figure 3 shows a plot of the lake levels and the calculated slope for the hydrological year 1904-1905. As expected, as the lake levels rise (over 4 months) positive slopes are seen, and as the levels begin to drop (over 7 months) negative slopes are seen. The peak level occurs between April to May which is representative of the average peak occurrence one month after the peak in rainfall as reported by the GoM (Government of Malawi, 2015c). In previous studies, this lag time between the peak level and peak rainfall has been attributed to the runoff response of the river basins to rainfall (Government of Malawi, 2015c).

Table 1 shows the calculation for the slopes presented in Figure 3. The slope was determined using the SLOPE function in excel based on 3-month intervals. For example, as highlighted in grey, the slope for 01/11/1904 was determined based on the slope of the lake levels from 01/10/1904-01/12/1904.

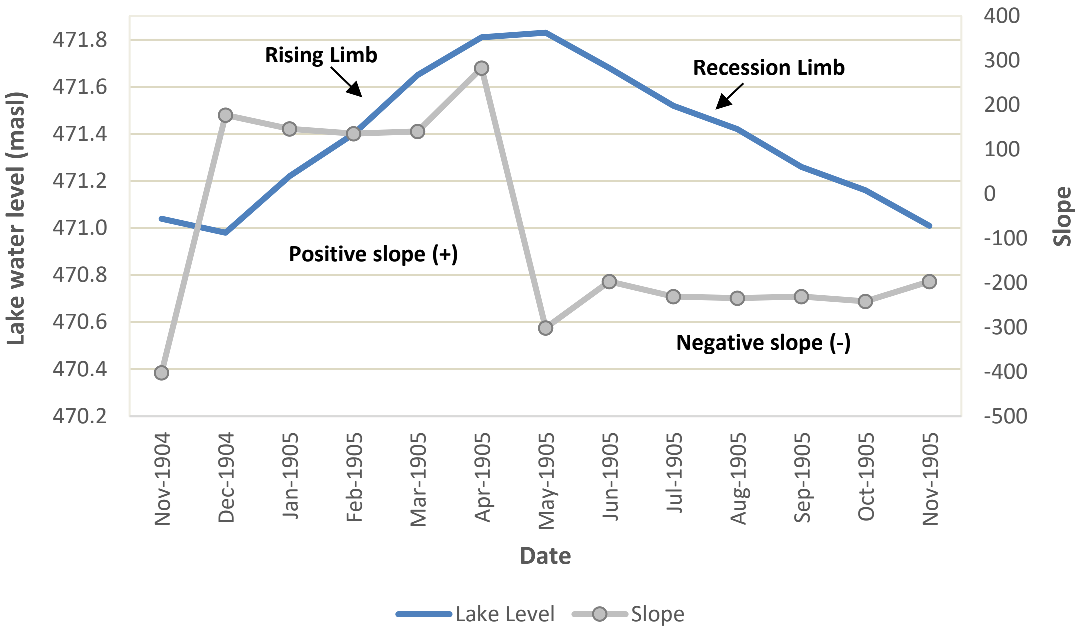


Figure 3 Lake Malawi monthly slopes and Lake levels (1904-1905)

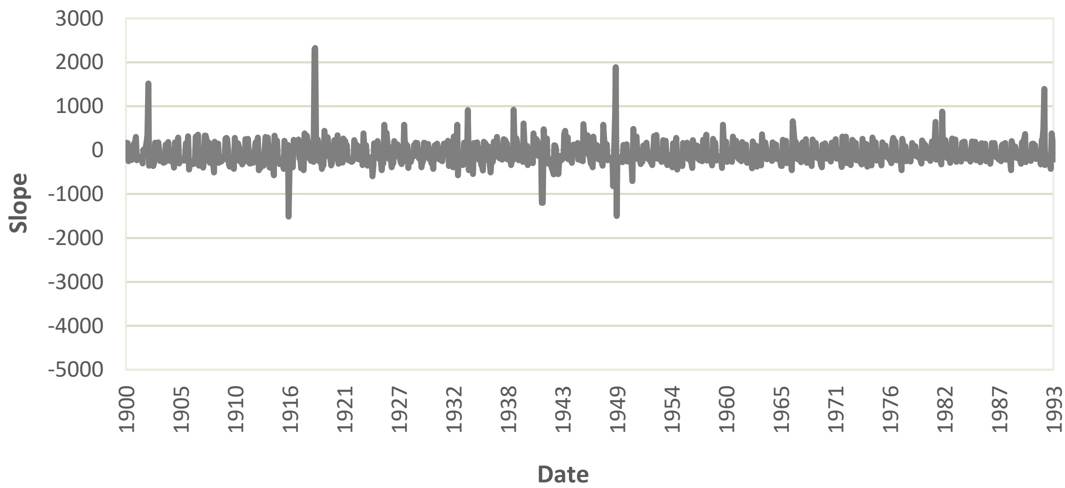
Table 1 Calculation for Lake Malawi monthly slopes and Lake levels (1904-1905) in Figure 3

Date	**Lake Level** (masl)	**Slope (3-month intervals)**
01/10/1904	471.13	-
01/11/1904	471.04	-401.75
01/12/1904	470.98	177.56
01/01/1905	471.22	146.62
01/02/1905	471.40	135.63
01/03/1905	471.65	141.10
01/04/1905	471.81	283.22
01/05/1905	471.83	-301.01
01/06/1905	471.68	-196.67
01/07/1905	471.52	-230.23
01/08/1905	471.42	-234.30
01/09/1905	471.26	-230.81
01/10/1905	471.16	-241.05
01/11/1905	471.01	-196.67
01/12/1905	470.85	-

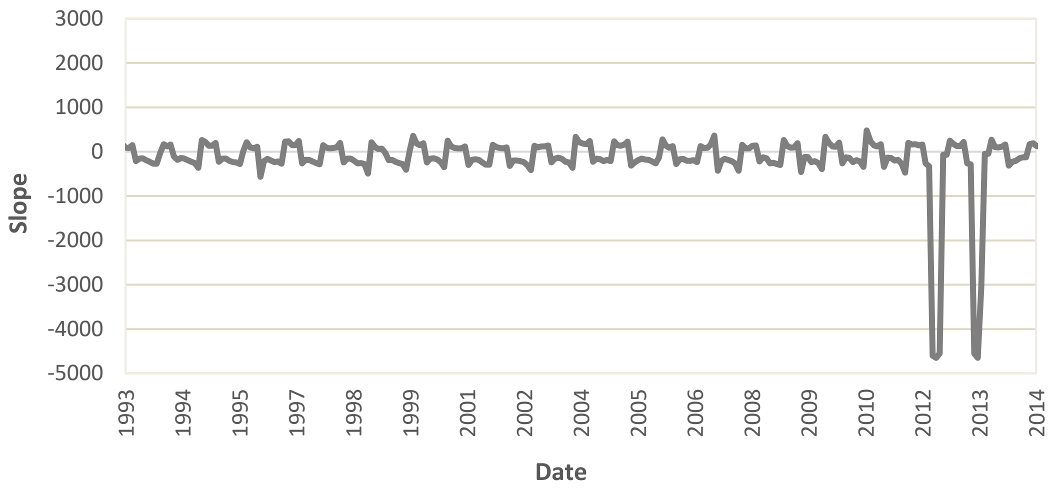
The slope of the lake levels for the complete period (1900-2016) are presented in Figure 4 (a) 1900-1993 and (b) 1993-2014. From visual inspection, several negative spikes were seen in 1916, 1942, 1948, 2012 and 2013, indicating significant changes in the recession limb attributed to baseflow from the inflow rivers.

Several of these spikes (1916, 1942, 1948) coincide with very dry conditions within Malawi. For example, 1916 sits within a period in which there was no outflow reported from the lake to the Shire River (1910-1919). Further, Lake Chilwa in the south of the country was reported to have dried up between 1913-1916. 1942 and 1948 sit within a period in which a countrywide drought occurred in Malawi (1940-1949) (Government of Malawi, 2011d). Further, warm dry weather was reported by the GoM for the years 1913-1916, and 1942-1949 (Government of Malawi, 2017b). Such dry conditions mean there were minimal rainfall and minimal surface runoff available for the rivers. Thus, during these periods, rivers would have experienced an increase in their reliance on baseflow.

Conversely, the remaining spikes (2012 and 2013) coincide with years in which Malawi experienced severe flooding in the country. Floods in Malawi were recorded where there was heavy rain from mid-December 2012 to mid-January 2013 resulting in severe flooding in several districts located at the southern end of Lake Malawi (IFRC, 2013). Flooding conditions result in increased surface water runoff available for the rivers, increased areal recharge for the aquifers and increased groundwater discharges to baseflow.



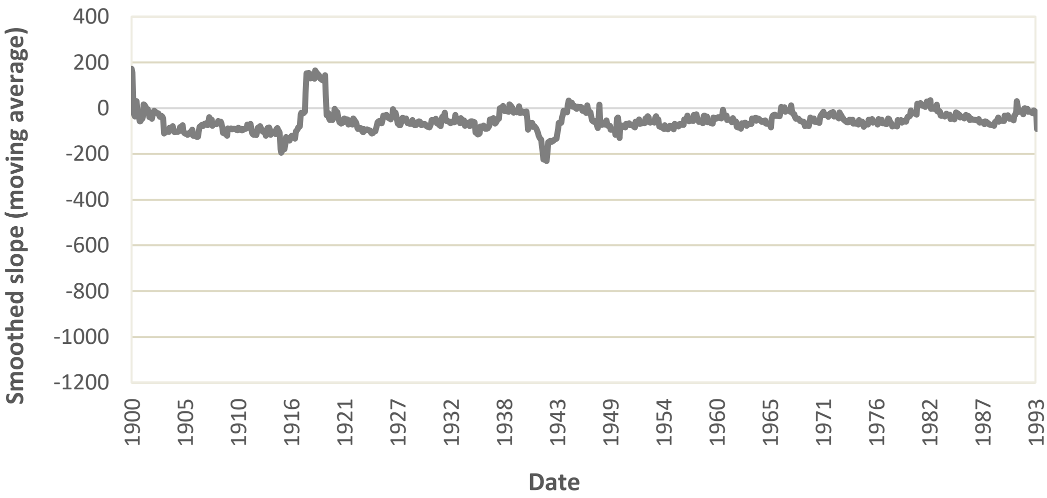
(a)



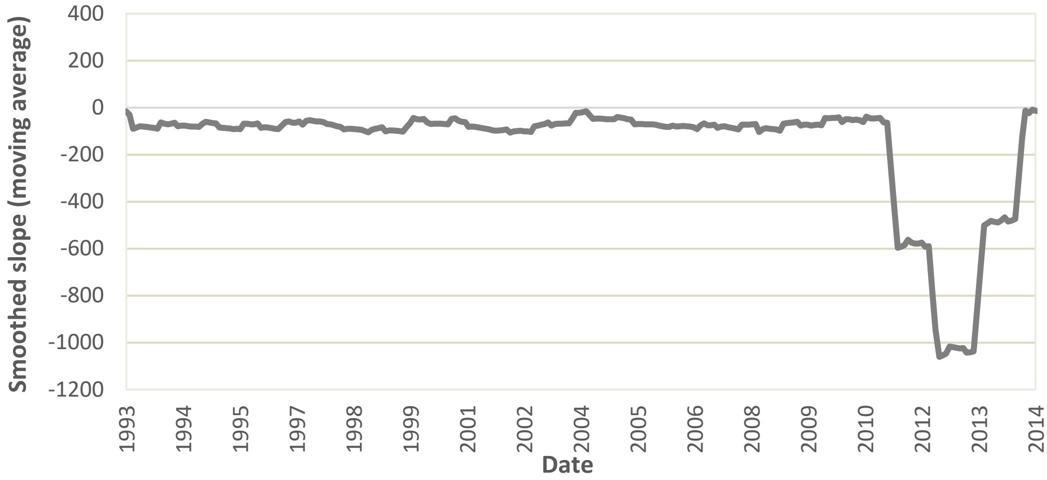
(b)

Figure 4 Lake Malawi monthly slopes, based on a 3-month slope (a) 1900-1993 and (b) 1993-2014

Further, the slope data (1900-2016) were smoothed using a 3-month moving average and the results are presented in Figure 5 (a) 1900-1993 and (b) 1993-2014. Comparing to the unsmoothed slopes in Figure 4, a lot of noise has been removed. Except for 1948, the same negative spikes are seen (1916, 1942, 2012 and 2013).



(a)



(b)

Figure 5 Lake Malawi monthly slopes, smoothed using a 3-month moving average (a) 1900-1993 and (b) 1993-2014

The results presented in this study have important implications for the management of Lake Malawi and its catchment area. The results provide a proxy indicator that baseflow in the Lake Malawi catchment have experienced significant changes over time. It can be deduced that the baseflow contributions to the lake (from the inflow rivers) are influencing lake levels during the dry season. This is important as to date, contributions to Lake Malawi from river baseflow have not been considered in any studies. They will be of interest to the GoM who continue to work towards the improvement of the management of their water resources. It is recommended that the volume of baseflow contribution to the lake from the inflow rivers is determined as a matter of urgency alongside an evaluation of temporal variations over time. This applies to the inflow rivers from Malawi but also those from Tanzania. Although Malawi contributes the majority of the land catchment to Lake Malawi, it is Tanzania that contributes the most in runoff inflow estimated around 60% including their shared river with Malawi, the Songwe (Kumambala and Ervine, 2010). Thus, a trans-national study is required to progress this work. Specifically, river flow data is required from both Malawi and Tanzania to determine baseflow.

Quantifying the volume of baseflow contribution to the lake and exploring changes over time is required to better understand the behaviour of the lake water balance. In the Malawian context, there are several projects which will benefit from being updated to reflect the baseflow contribution to the lake. For example, the structural stability of the Kamuzu barrage (which controls flow from the lake to the Shire) was in danger due to erosion problems affecting the foundations and underwent detailed design for an upgrade (World

Bank, 2019). The design states that the hydraulic model used in the design does not include baseflow influx to the lake through groundwater from river inflows (Government of Malawi, 2013b). Although it's noted that baseflow is included implicitly as part of the tributary inflow component, its stated that its 'generally believed that the baseflow is not of significant size' (Government of Malawi, 2013b). The construction barrage was completed in 2019 and is now operational (World Bank, 2019). As part of the barrage design, the hydrological investigations have focused on a concept of 'free water', previously promoted by Cochrane (1957) and recently used in a new rainfall-runoff model forming a component of the Shire River Basin Management Project (Phase 1) (Government of Malawi, 2016a). Free water, or lake storage, has been defined as the excess water in the lake which is available for sustainable use. It is calculated as land catchment runoff + lake precipitation - evaporation (Government of Malawi, 2016a) and doesn't appear to specifically consider baseflow. Finally, the newly proposed Lilongwe project which aims to pump water from the lake to supply the city of Lilongwe (Government of Malawi, 2016b).

Determining the volume of baseflow contribution to Lake Malawi entails determining the baseflow contribution to all inflow rivers. In addition to supporting the sustainable management of the lake as described above, this will also support the sustainable management of water resources within the river catchments. For example, baseflow variations which are identified in river baseflow through time will reflect changes in the overall catchment groundwater storage. This is because baseflow changes are caused by a change in the amount of water stored in the groundwater systems which feed the rivers.

4. Conclusion

The main aim of this study was to demonstrate, using Lake Malawi as a case study, how to analyze the recession limb of a lake hydrograph to provide a proxy indicator of temporal variations in the baseflow contribution over time. The rate of decline (slope) of the lake levels was calculated based on a 3-monthly interval for the period 1900-2016. The results show several negative spikes in the non-smoothed data (1916, 1942, 1948, 2012 and 2013) and the same spikes were seen in the smoothed data for all years except 1948. These negative spikes indicate significant changes occurring in the recession limb which are attributed to changes in the baseflow. The spikes coincide with either very dry conditions across Malawi (1916, 1942 and 1948) or periods where the country experienced severe flooding (1942, 2012 and 2013). This provides initial validation for the results as under such weather extremes baseflow will change due to changes in the water system. To ensure this valuable source of inflow to the lake is accounted for in future management decisions, it is recommended that future research quantifies the volume of baseflow contribution to Lake Malawi from the inflow rivers and evaluates temporal variations.

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4.3 Summary

In this chapter, Lake Malawi was used as a case study to demonstrate how to work with lake level data to provide a proxy indicator of temporal variations in baseflow. The results showed significant changes had occurred in the recession limb in several years which were attributed to changes in baseflow and imply long term changes in the groundwater storage of the lake catchment have occurred. It was recommended that future research quantify the baseflow contribution to the lake from all inflow rivers (i.e. Malawi and Tanzania) and evaluate temporal variations over time.

This future research will have important implications on the sustainable management of water resources in Malawi, specifically the management of Lake Malawi and its catchment area and its dependent Shire River which together form a significant resource system for the country. For example, the current water balances of the lake do not reflect the baseflow contribution to the lake. Neglecting the baseflow component means that water development projects may be working off inaccurate data which could result in unsustainable projects for water supply. For example, there are currently three hydropower stations located on the Shire River which supply over 98% of Malawi's electricity and depend upon sufficient water being released from the lake. There are 5 million people living in the Shire Catchment that depend upon the Shire River either directly through water supply or indirectly through irrigated agriculture and/or electricity. Further, there is a new project proposal for a water transfer scheme which will pump significant quantities of water from the lake to supply the city of Lilongwe and which will rely on accurate data to protect the lake from over-abstraction (Government of Malawi, 2016b).

This recommended research should be completed as a matter of urgency. To complete this research, river flow data for all the inflow rivers (Malawi and Tanzania) is required. Although river flow data from Malawi was obtained as part of this thesis, no data could be obtained from Tanzania. This research should progress outwith this thesis in the form of a trans-national study between Malawi and Tanzania. This work is partly progressed in the following chapters as baseflow is determined for Malawian rivers.

The next chapter demonstrates, using another case study from Malawi, how to work with baseflow separation and sporadic river data to quantify temporal variations in baseflow. This approach was identified in the methodology chapter (Chapter 3) as the method with the best potential to achieve the aim of the thesis.

Chapter 5 The Bua Catchment

5.1 Introduction

The previous chapter demonstrated, using Lake Malawi as a case study, how it might be possible to analyze the recession limb of lake level data to provide a proxy indicator of changes in baseflow on a large-scale catchment. It was considered a useful exercise and indicated changes in baseflow to the lake over time. However, the results were inconclusive as most of the water entering the lake is from Tanzania and no detailed data was available to further this research.

As identified in the methodology (Chapter 3), baseflow separation was identified as the most appropriate method to achieve the aim of the thesis and as such was the focus of the thesis. One challenge to the use of baseflow separation was the sporadic river data and a case study was required to demonstrate the usefulness of the data in extracting meaningful estimations on baseflow. This chapter used the Bua catchment in central Malawi to demonstrate how to work with sporadic river data and baseflow separation to quantify temporal variations in baseflow. This research output was accomplished through one paper published in the peer-review journal, Water, as follows:

Kelly, L., Kalin, R.M., Bertram, D., Kanjaye, M., Nkhata, M. and Sibande, H., 2019. Quantification of Temporal Variations in Baseflow Index Using Sporadic River Data: Application to the Bua Catchment, Malawi. Water, 11(5), p.901.

The published paper is presented in the following section and the author contributions were as follows: Conceptualization, L.K. and R.M.K.; Formal analysis, L.K.; Funding acquisition, R.M.K.; Methodology, L.K.; Resources, M.K., M.N. and H.S.; Supervision, R.M.K. and D.B.; Validation, L.K., R.M.K. and D.B.; Visualization, L.K.; Writing—original draft, L.K.; Writing—review & editing, L.K., R.M.K., D.B., M.K. and M.N.

5.2 Paper

Quantification of Temporal Variations in Baseflow Index Using Sporadic River Data: Application to the Bua Catchment, Malawi

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Abstract: This study investigated how sporadic river datasets could be used to quantify temporal variations in the baseflow index (BFI). The BFI represents the baseflow component of river flow which is often used as a proxy indicator for groundwater discharge to a river. The Bua catchment in Malawi was used as a case study, whereby the smoothed minima method was applied to river flow data from six gauges (ranging from 1953 to 2009) and the Mann-Kendall (MK) statistical test was used to identify trends in BFI. The results showed that baseflow plays an important role within the catchment. Average annual BFIs > 0.74 were found for gauges in the lower reaches of the catchment, in contrast to lower BFIs < 0.54 which were found for gauges in the higher reaches. Minimal difference between annual and wet season BFI was observed, however dry season BFI was >0.94 across all gauges indicating the importance of baseflow in maintaining any dry season flows. Long term trends were identified in the annual and wet season BFI, but no evidence of a trend was found in the dry season BFI. Sustainable management of the investigated catchment should, therefore, account for the temporal variations in baseflow, with special regard to water resources allocation within the region and consideration in future scheme appraisals aimed at developing water resources. Further, this demonstration of how to work with sporadic river data to investigate baseflow serves as an important example for other catchments faced with similar challenges.

Keywords: baseflow; baseflow index; hydrograph; groundwater; Malawi

1. Introduction

Understanding temporal variations in baseflow are crucial for sustainable water resources management (Brodie et al., 2007a). Baseflow is defined as the proportion of river flow derived from groundwater and other stored sources (UNESCO, 1980; Fetter, 2001). Other stored sources may include connected lakes, wetlands, melting snow, temporary storage in the banks of the river channel and slow-moving interflow (Bosch et al., 2017). Baseflow varies spatially and temporally influenced by several factors including geology, topography, climatic season and anthropogenic activities (Smakhtin, 2001). Baseflow can sustain river flows during prolonged periods of dry weather. Although dry season flows are significantly reduced and in some rivers approach zero flow, this water can be a vital life source for those who depend on it. Although globally pertinent, it is particularly crucial for semi-arid countries who experience long dry seasons each year (Tallaksen and Van Lanen, 2004). Long term changes in baseflow can indicate unsustainable catchment management practices. Baseflow is thus a key consideration in many sustainable management approaches such as integrated water resources management (IWRM) and conjunctive water use. They are also a major focus of many worldwide initiatives including the United Nation Education Scientific and Cultural Organization (UNESCO) International Hydrological Programme (International Hydrological Programme of UNESCO, 2006). Subsequently, it can be considered to underpin the United Nations Sustainable Development Goal (SDG) 6 'ensure availability and sustainable management of water and sanitation for all'.

There is a multitude of methods available to investigate baseflow which can be categorized into desk-based methods and field methods. Desk-based methods include hydrograph analysis (baseflow separation (Mei and Anagnostou, 2015), frequency analysis (Chimtengo, Ngongondo, Tumbare and Monjerezi, 2014) and recession analysis (Tallaksen, 1995), hydrogeological mapping (Bloomfield, Allen and Griffiths, 2009), modelling (Rassam and Werner, 2008) and mass balance (Capesius and Arnold, 2012). Field methods, as described in Turner (2009) include temperature profiling, seepage flux measurement, seepage meters, environmental tracers, artificial tracers, geophysics, remote sensing and ecological indicators. In some countries, however, investigation methods are limited to hydrograph analysis, specifically baseflow separation, which utilizes existing river flow data and provides estimates of baseflow without the need for complex modelling, detailed knowledge of soil characteristics or costly site investigations (UNESCO, 1997). Such countries are usually those who experience long dry seasons each year and where baseflow knowledge is perhaps most pertinent. These are also countries often challenged by limited technical knowledge, lack of financial resources and experienced hydrological and hydrogeological staff.

Baseflow index (BFI) is an important baseflow characteristic (Beck et al., 2013). Originally developed as a parameter to index catchment geology and the ability of a catchment to store and release water, BFI is a numerical representation of the baseflow component of river flow (UNESCO, 1980). BFI is calculated as the ratio of the flow under the baseflow hydrograph (the baseflow volume) to the flow under the river hydrograph (total flow volume) as presented in Equation 1 (Gustard, Bullock and Dixon, 1992). BFI is applied in hydrology and hydrogeology where it is used as a catchment descriptor in low flow studies (Tallaksen and Van Lanen, 2004), a groundwater availability indicator (Ngongondo, 2006) and as a key engineering parameter for environmental flow requirements (EFR), which set a minimum flow required in a river to sustain its ecological health (Hughes and Hannart, 2003). BFI is a popular means of providing a proxy indicator of groundwater discharge from the aquifer (Bosch et al., 2017; Esralew and Lewis, 2010; Gustard, Bullock and Dixon, 1992). A relative measure with no units, BFI ranges from near 0.0 to 1.0. A BFI close to 0.0 means a river has a low proportion of baseflow, an example would be a flashy river with relatively impermeable geology and little groundwater. A BFI close to 1.0 has a high proportion of baseflow, an example would be a stable river with relatively permeable geology and a lot of groundwater (Tallaksen and Van Lanen, 2004; Institute of Hydrology, 1980). In periods of dry weather, river flows can be significantly reduced, however, rivers with high BFI indicate that groundwater inflow is sustaining these reduced flows. Many countries and academics are now recognizing the importance of quantifying BFI including a global assessment based on over 3000 catchments worldwide (Beck et al., 2013), a national scale assessment in New Zealand (Singh et al., 2019), regional studies such as the Loss Plateau, China (Zhang et al., 2019) and an experimental watershed in the Gulf Atlantic Coastal Plain, USA (Bosch et al., 2017).

Equation 1 Baseflow index equation

$$\text{Baseflow Index (BFI)} = \frac{\text{Baseflow volume}}{\text{Total flow volume}}$$

Baseflow is particularly important in Malawi, a semi-arid country known as the warm heart of Africa (Figure 1a). Malawi is rich in both groundwater and surface water resources in comparison to other African countries, however, these are unevenly distributed in time and space. Malawi experiences a distinct dry season each year with minimal to no rainfall. Many rivers still have some flow in the dry season, and it is presumed that they are sustained by baseflow from the region's superficial aquifers. However, anthropogenic activities such as over-abstraction of groundwater and deforestation are threatening flows in Malawi by negatively impacting baseflows. For example, sustained over-abstraction of groundwater can draw down the water table and result in reduced groundwater discharge to any connected rivers. Similarly, deforestation increases overland flows and leaves less water for infiltration and groundwater recharge. This can ultimately lead to reduced water available for groundwater discharge to connected rivers. Although deforestation is widely reported in Malawi (Chimtengo et al., 2014; Hudak and Wessman, 2000), there are no published studies are confirming the over-abstraction of groundwater. The Ministry of Agriculture, Irrigation and Water Development has reported, based on internal assessments, a decline in groundwater levels and river flows which have resulted in the drying up of major rivers (Chitete, 2019).

To date, few studies have been published which investigate baseflow and quantify BFI in Malawi. Preliminary work done by the South Africa FRIEND (flow regimes from international experimental and network data) programme produced an annual BFI map for South Africa which included Malawi however, the project has been inactive for a long time and the data that were collected are largely out of date (UNESCO, 1997). More recently, a global BFI study reports estimates of annual BFI for Malawi (Beck et al., 2013) and the International Water Management Institute's tool; the Global Environmental Flow Information System also includes Malawi and provides estimates of annual baseflow (Sood et al., 2017). More site-specific studies, reporting annual BFI include Kumambala (2010) who examined four stations along the Shire River in Southern Malawi and Ngongondo (2006) who examined the Mulunguzi catchment. Only a few studies identify long term trends in baseflow; Ngongondo (2006) identifies a trend in baseflow in the Mulungzui river showing a decline of approximately 50% from 1954 to 1998. In contrast, Kambombe, Odongo, Mutua and Wambua (2018) identify an increase in baseflow in the Mulungzui catchment between 1970 and 1999. Kambombe et al. (2018) also found a significant decreasing trend in baseflow of the Domasi, Likangala and Thondwe catchments during that period. Further, baseflow is currently evaluated by the Surface Water Division of the Ministry of Agriculture, Irrigation and Water Development (MoAIWD) in Malawi, through use of their time series data management system 'HYDSTRA', however, focus appears to be mainly on annual baseflows. All these studies address BFI to a limited spatial and temporal coverage of flow data, with a focus on annual baseflow values. A gap in the research, therefore, exists to quantify seasonal and long-term trends in BFI for gauged catchments in Malawi.

This task is challenged by the lack of current data as river flow monitoring coverage has declined in Malawi since around 2010 and indeed is representative of sub-Saharan Africa (Houghton-Carr, Fry and Wallingford, 2006). Further, the data which is available is sporadic in nature, characterized by missing values.

This study demonstrates how to work with sporadic river flow data, using baseflow separation, to produce meaningful estimations on temporal variations in baseflow. We demonstrate this by using the Bua Catchment in Malawi as a case study, whereby the river data is considered representative of the wider Malawi. The objectives of this research were to 1) quantify the annual BFI; 2) quantify the seasonal BFI and 3) identify trends in the BFI. The results will provide important new insights on the behaviour of baseflow in the catchment. It will also serve as an example to other catchments challenged by sporadic river data.

This study forms part of on-going research on baseflow in Malawi and has important implications for the sustainable management of water resources in the country. It offers support to the Government of Malawi in their journey towards SDG6 and as such, the research was conducted in a manner that will permit the exchange of knowledge with the water sector.

In Section 2 below, the study area is described in addition to the data and analysis methods. Specifically, the decision procedure for selection of the baseflow separation method and the implementation tool is described and the baseflow separation steps followed are provided. The results and discussion are discussed in Section 3, while the conclusions are summarized in Section 4.

2. Materials and Methods

2.1 Study area

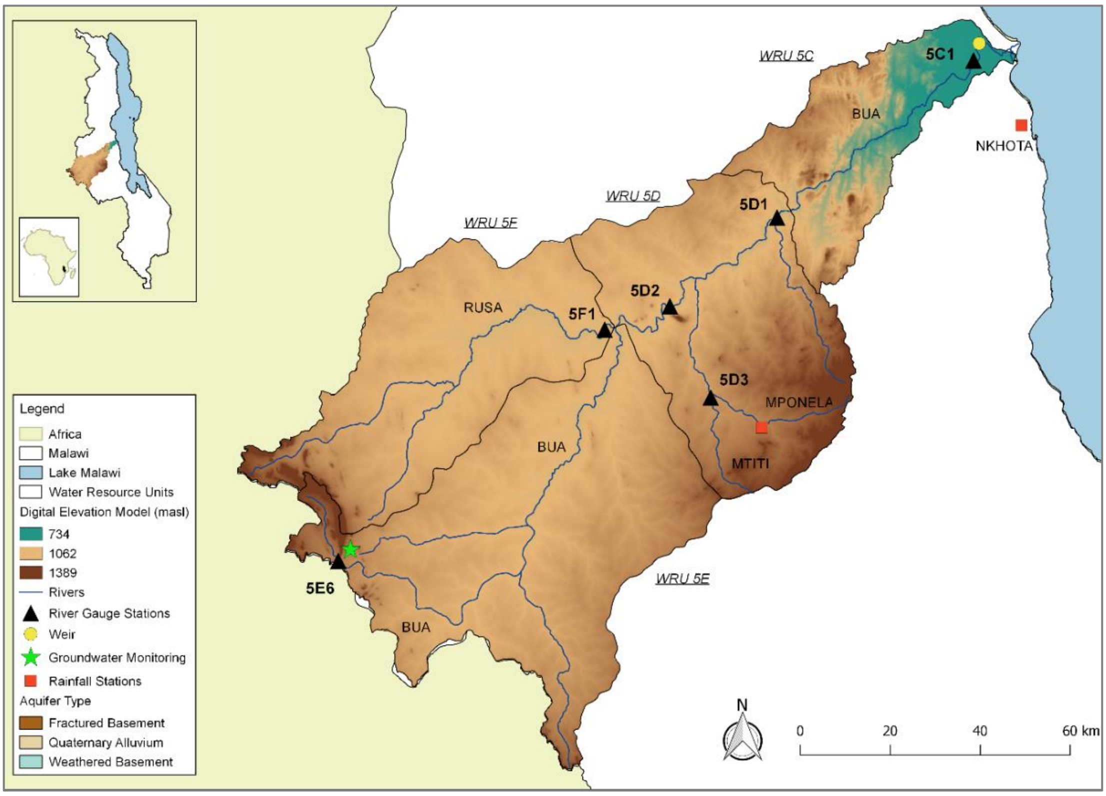
The Bua River originates on the western border of Malawi and flows in a northeasterly direction through Central Malawi to its outflow into Lake Malawi (Figure 1). The Bua is joined by five major tributaries (Mphelele, Kasangadzi, Rusa, Ludzi and Namitete) and has numerous minor tributaries. It has a catchment area of 10,658 km² which is approximately 186 km in length and its width varies from approximately 87 km in the west to approximately 16 km is the east.

The catchment comprises three distinct hydrological zones; the flat plateau, steep slopes on the highland which rise from the plateau and the rift valley escarpment, and the lakeshore plain (Smith-Carrington, 1983). The plateau is generally at 1000–1100 m above sea level (masl). Towards the southwest is the Mchinji mountains which rise to over 1750 masl. Towards the west, where the river meets the lakeshore plain, the catchment drops rapidly through a series of steep slopes. High levels of sedimentation occur at the lakeshore plain as the gradient becomes gentle.

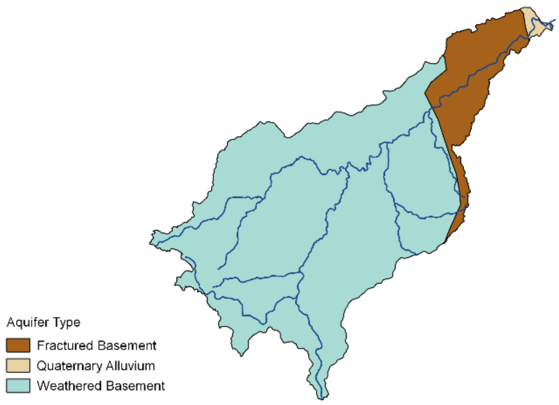
The Bua catchment is assigned Water Resource Area (WRA) 5 within the National Water Resources Master Plan (NWRMP) of Malawi (Government of Malawi, 2017b). WRA 5 is subdivided into four Water Resource Units (WRUs) named 5C, 5D, 5E and 5F (Figure 1a). Both WRAs and WRUs are based on river basin boundaries. WRA 5 lies within the administrative districts of Mchinji, Kasungu, Nkhotakota, Lilongwe, Dowa and Ntchisi.

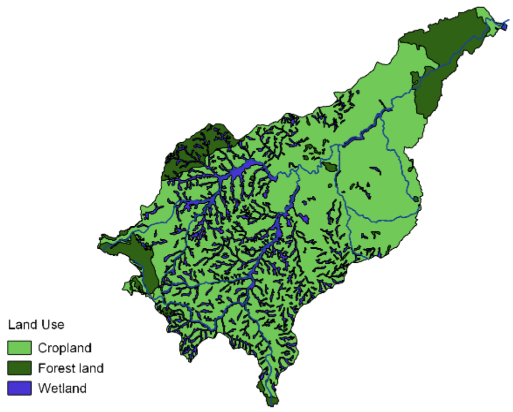
Land use in WRA 5, as shown in Figure 1c, mainly comprises cropland; arable agriculture of mainly maize crops and tobacco, and forest land; including Mchinji Forest Reserve and Kasungu National Park to the west, and Nkhotakota Game Reserve to the far east (Government of Malawi, 2018c). Wetlands or dambos are also scattered throughout the catchment. These wetlands become saturated in the wet season and provide a good source of water in the dry season (Government of Malawi, 2011c). The dambos are generally considered to drain the plateau area (Smith-Carrington, 1983).

The climate of WRA 5 can be generally represented as sub-tropical (Government of Malawi, 2017b). The climate is divided into three weather variations; the warm wet season (1 November–30 April); the cool dry season (1 May–31 August); and the hot dry season (1 September–31 October), however, it's generally accepted to be bimodal referring to the wet season and the dry season (Government of Malawi, 2017b). Over 95% of the annual rainfall falls in the warm wet season or rainy season. The exact length of the wet season varies depending on the location within Malawi, reported to end in March in the south of the country, and April/May in the north (Government of Malawi, 2013b). No average annual rainfall or temperature values were available for the wet and dry season. The average annual rainfall for WRA 5 is 897 mm, with a range of 800–1000 mm (Government of Malawi, 2011c). The average annual temperature in WRA 5 ranges from 20 to 24 °C (Government of Malawi, 2011c).



(a)





(b) (c)

Figure 1 (a) Location of Malawi in Africa (insert), location of the Bua catchment in Malawi (insert) and digital elevation model of the Bua catchment (WRA 5) with rivers, river gauges, weir, rainfall stations and groundwater monitoring; (b) aquifer type map (Government of Malawi, 2018b); (c) land use map (Government of Malawi, 2018c)

2.2 Data

This study focused on data from six river gauges within the Bua catchment (Table 2). Other gauges do exist, however, there was no data available for them. Four gauges monitor the main Bua river (5C1, 5D1, 5D2 and 5E6) which is a regulated river with a weir located downstream of gauge 5C1. Photos of the weir taken in January 2019 and are provided in Appendix 1 (Supplementary Material, Figure S1). The Rusa River, a major tributary of the Bua, is monitored by a fifth gauge, 5F1, and the Mtiti river (a tributary to the Kasangadzi river) is monitored by the final gauge, 5D3. Daily flow rate data were available for each gauge as follows; 5C1 (1957–2009), 5D1 (1958–2007), 5D2 (1953–2007), 5D3 (1958–2003), 5E6 (1970–2008) and 5F1 (1964–2005). Data coverage appears substantial ranging from 38-52 years, however, it is expected to have missing values throughout. Data were obtained from the Surface Water Division of the Department of Water Resources of Malawi.

Where possible, rainfall and groundwater data in the vicinity of the river gauges were also examined to provide support for the BFI analysis. Daily rainfall data for Nkhota station (18 km away from gauge 5C1 in a southeasterly direction) and Mponela station (13 km away from 5D3 in a southwesterly direction) was used. Stations are managed by the Department of Meteorological Services who provided the data. The rainfall data is of very good coverage with minimal missing values. Groundwater levels are monitored in WRA 5 via four monitoring boreholes, constructed around 2009/2010. The boreholes are managed by the Groundwater Division of the Department of Water Resources who provided the data. Only one of the monitoring boreholes, at Mchinji Water Office (GN196), had enough data coverage (2009–2013) to examine.

2.3 Decision procedure for the selection of baseflow separation method and implementation tool

Baseflow separation was selected to analyze the river data and determine BFI. Baseflow separation is categorized into graphical methods which are performed manually, and filtering methods which are automatically performed by a computer (Brodie et al., 2007b). There are a wide variety of filtering methods available, and a significant number of computer programs to implement the chosen method (Eckhardt, 2008). Although there is subjectivity involved in selecting an appropriate filtering method and an associated tool to implement it, merit holds in use of any of them as long as the use is consistent throughout the study (Tallaksen and Van Lanen, 2004; UNESCO, 1997; Eckhardt, 2008). The decision to select a filtering method and implementation tool is generally based on the criteria required for the study.

In this study, the selection of an appropriate implementation tool took precedence over the selection of a filtering method. The tool was required to meet certain criteria to allow the exchange of knowledge with the Government of Malawi. The tool needed to be automated, easily accessible, free to obtain and operate, require minimal training to use and capable of selecting seasonal periods from input data to quantify BFI. Several tools were evaluated against the required criteria including Flow Screen package for R (Dierauer, Whitfield and Allen, 2017), Formula Translation (FORTRAN) BFI program (Wahl and Wahl, 1995), Soil and Water Assessment Tool (SWAT) (Arnold et al., 2012), Water Engineering Time Series PROcessing Tool (WEST PRO) (Willems, 2009), Web-based BFlow (Younghun Jung and Lim, 2016), HYSEP (Sloto and Crouse, 1996), HydroClimATe: hydrologic and climate analysis toolkit (Dickinson, Hanson and Predmore, 2014), Streamflow Analysis and Assessment Software (SAAS) (Metcalfe and Schmidt, 2016), River Analysis Package (RAP) (CRC for Catchment Hydrology, 2003), Web-based Hydrograph Analysis Tool (WHAT) (Lim et al., 2005), BFI + 3.0 of Hydro Office (Gregor, 2010) and the BFI programme (Tallaksen and Van Lanen, 2004). The evaluation assessment is presented in Table 1. As the BFI Programme (Tallaksen and Van Lanen, 2004) met all of the criteria it was selected for analysis.

Table 1 Evaluation of baseflow separation tools against the required criteria

	Flow Screen R	**FORTRAN BFI**	**SWAT**	**WEST Pro**
Automated	Y	Y	Y	Y
Easily accessible	Y	N	Y	N
Free to obtain and operate	Y	-	Y	-
Requires minimal training to use	N	-	N	-
Can select seasonal periods	-	-	N	-
	Web-based BFlow	**HYSEP**	**Hydro ClimATe**	**SAAS**
Automated	Y	Y	Y	Y
Easily accessible	N	Y	Y	Y
Free to obtain and operate	-	Y	Y	Y
Requires minimal training to use	-	N	N	Y
Can select seasonal periods	-	-	-	N
	RAP	**WHAT**	**BFI+ 3.0**	**BFI Programme**
Automated	Y	Y	Y	Y
Easily accessible	Y	Y	Y	Y
Free to obtain and operate	Y	Y	Y	Y
Requires minimal training to use	N	Y	Y	Y
Can select seasonal periods	Y	N	N	Y

- Where: Y = yes; N = No.

The BFI programme is an excel based tool developed by Martin Morawietz at the Department of Geosciences in the University of Oslo, Norway. It was originally prepared for the textbook; Hydrological Drought-Processes and Estimation Methods for Streamflow and

Groundwater (Tallaksen and Van Lanen, 2004). It is free to download on the European Drought Centre website http://europeandroughtcentre.com/ The textbook provides working examples of how to use the tool. The tool implements the filtering method called the 'smoothed minima procedure' (Institute of Hydrology, 1980). It uses smoothing and separation techniques to process a river hydrograph. Daily river flow data is partitioned into 5-day increments and the minimum flow in each period is identified (Combalicer et al., 2008). Turning points are identified in the series of minimum flows and connected to draw the baseflow hydrograph. The precise details of the procedure are provided in the Low Flow Studies Report No 3 by the Institute of Hydrology (1980) and by Wahl and Wahl (1995).

2.4 Baseflow separation steps

The raw river data were screened before baseflow separation to identify the periods of missing data. Before proceeding to analysis, there were two options available to deal with the missing data; 1) infill the missing data or 2) ignore the missing data and analyze only the raw data. Although there are merits to infilling data (St. Jacques and Sauchyn, 2009; Harvey, Dixon and Hannaford, 2010) most studies agree with the recommendation by Ladson, Brown, Neal and Nathan (2013) that BFI should be determined from raw data only (Oki, 2004; Hodgkins and Dudley, 2011; Esralew and Lewis, 2010; Zhang et al., 2019). As such, this study did not infill data and analyzed the raw river flow data only. To do this, the flow data were prepared by dividing into periods of non-missing values (Ladson et al., 2013).

The assessment periods selected were annual and seasonal periods defined by months. The annual period was taken as the hydrological year in Malawi as used by the Government of Malawi Water Resources Department and coincides with the start of the wet season and runs to the end of the dry season (1 November–31 October). The seasonal periods selected were the wet season defined as 1 November–30 April, and the dry season defined as 1 May–31 October. These periods are based on the weather variations recognized in Malawi and used in water resources assessments by the Water Resources Department (Government of Malawi, 2011d) and the country's national irrigation master plan and investment framework (Government of Malawi, 2015b).

The following steps were taken to perform the baseflow separation using the BFI programme:

1) The baseflow separation was performed for each year of river data (1957–2009) producing a separate annual BFI value for each year where there was enough data in the period. It is commonly recommended in the literature to determine the long-

term BFI which uses all the data successively (Tallaksen and Van Lanen, 2004; UNESCO, 1997), however here, it was not possible due to missing data. The mean annual BFI was therefore determined based on the individual years

2) The baseflow separation was performed for each season of data (1957–2009) in the same manner as the annual period described above
3) The total flow, baseflow and surface runoff flow from each baseflow separation were summed for each period
4) Descriptive statistics (average, maximum and minimum, standard deviation, and coefficient of variation) were determined for the annual and seasonal periods.

2.5 Statistical trend analysis

The non-parametric Mann-Kendall (MK) statistical test (Kendall, 1975; Mann, 1945) was used to identify if the BFI results had statistically significant increasing or decreasing trends. The test is prominently used in hydrology studies. For example, it is popular when identifying trends in streamflow (St. Jacques and Sauchyn, 2009; Gumindoga, Makurira and Garedondo, 2018; Da Silva et al., 2015; Yue, Pilon and Cavadias, 2002) baseflow (St. Jacques and Sauchyn, 2009), BFI (Bosch et al., 2017; Techamahasaranont et al., 2017; Zhang et al., 2016) and the vertical exchange fluxes between streambeds and connected aquifers (Anibas et al,. 2016). It is also widely applied in identifying trends in rainfall (Da Silva et al., 2015; Gumindoga, Makurira and Garedondo, 2018). Application of non-parametric testing is appropriate due to hydrological data not being normally distributed (Yue, Pilon and Cavadias, 2002). One of the main advantages of the MK test is that it is insensitive to missing data, which was a key challenge with the data in this study.

The hypothesis for the test, H0, was defined as 'there is no trend in the data', and the alternative hypothesis, Ha, was defined as 'there is a trend in the data'. If the p-value calculated was lower than the significance level, the H0 was rejected and the alternative Ha accepted, and a trend was indicated. If the p-value was greater than the significance level, no trend was indicated. The significance level is referred to as a Type 1 error and is the probability of rejecting the null hypothesis when it is true (Yue, Pilon and Cavadias, 2002). The direction of the trend as indicated by the test statistic, S, where a negative S value indicates a declining trend and a positive S value indicates an increasing trend. Details of the MK equations can be found in the literature (Kendall, 1975).

The selection of the test parameters is important in statistical testing as they have a direct impact on the resulting trend. In this study, the following parameters were selected for the MK test; the 'exact p' method was used, the significance level was set to 0.01 (or 1%) and the equations were set to ignore missing data. Further, the 'normal' MK test was selected over the 'seasonal' MK test. Due to the decision not to infill data in this study, the BFI data was partitioned into annual and seasonal periods and as such the normal MK was applicable. If the data had been infilled, and there was no need to partition the data, the use of the seasonal MK test would have allowed comparison of the seasonal periods. The statistical programme XLSTAT, available at www.xlstat.com was used to perform the MK test (Addinsoft, 2019).

3. Results and Discussion

3.1 Annual and seasonal BFI analysis coverage

Annual and seasonal BFI was calculated for gauges 5C1, 5D1, 5D2, 5D3, 5E6 and 5F1. The results of the analysis for 5C1 are presented in Table 2 and the results of the other gauges are presented in Tables S1–S5.

As expected, the river data was characterized by missing values and this was seen across all datasets. This meant it was not possible to determine a BFI for all periods. To quantify the coverage of analysis, the number of periods for which a BFI was determined was counted and converted to a percentage based on the number of years of data (Table 3). For example, for 5C1, a BFI was determined for 30 full annual data periods, 39 wet seasons, and 37 dry seasons which equates to 58%, 75% and 71 % coverage for the respective periods. Data for each gauge ranged from 38 to 52 years and the percentage of coverage for each period (annual, wet and dry season) was consistently over 50%, with some periods as high as 80% coverage (Table 3). The results show, despite the sporadic nature of river flow data in Malawi, that such datasets can be analyzed to extract observations on baseflow. This is an important finding for Malawi and countries which hold similar datasets. They can begin to utilize such datasets and assess baseflow using minimal labour and financial resources.

Table 2 Results of the annual and seasonal BFI (baseflow index) analysis (tabular) for the Bua River, gauge station 5C1, 1957–2009 (52 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI	Period	Annual BFI	Wet Season BFI	Dry Season BFI
1957/1958	-	-	0.94	1983/1984	-	-	-
1958/1959	0.66	0.65	0.85	1984/1985	-	-	-
1959/1960	0.53	0.48	0.96	1985/1986	-	0.80	-
1960/1961	-	0.44	-	1986/1987	0.81	0.80	0.99
1961/1962	0.83	0.81	0.91	1987/1988	0.62	0.58	0.95
1962/1963	-	-	0.99	1988/1989	-	-	-
1963/1964	0.77	0.75	0.98	1989/1990	0.77	0.75	0.92
1964/1965	0.79	0.77	0.96	1990/1991	0.76	0.74	0.97
1965/1966	-	0.69	-	1991/1992	0.43	0.41	0.87
1966/1967	0.48	0.40	0.94	1992/1993	-	0.50	-
1967/1968	0.58	0.54	0.83	1993/1994	-	-	0.95
1968/1969	-	-	0.81	1994/1995	0.60	0.60	0.91
1969/1970	-	-	-	1995/1996	0.54	0.53	0.84
1970/1971	-	-	-	1996/1997	0.76	0.75	0.89
1971/1972	-	0.64	-	1997/1998	0.90	0.90	0.87
1972/1973	-	0.47	-	1998/1999	0.76	0.74	0.92
1973/1974	0.68	0.62	0.94	1999/2000	0.75	0.73	0.87
1974/1975	0.72	0.72	0.99	2000/2001	-	-	0.95
1975/1976	0.69	0.61	0.95	2001/2002	0.94	0.88	0.98
1976/1977	0.81	0.77	0.99	2002/2003	-	0.85	-
1977/1978	-	-	0.91	2003/2004	-	-	0.99
1978/1979	0.80	0.76	0.99	2004/2005	0.84	0.82	0.92
1979/1980	-	0.65	-	2005/2006	0.90	0.82	0.98
1980/1981	0.75	0.71	0.99	2006/2007	0.87	0.81	0.96
1981/1982	-	-	-	2007/2008	0.92	0.87	0.99
1982/1983	-	0.64	-	2008/2009	0.88	0.81	0.99

- denotes no BFI determined due to insufficient data in that period

Table 3 Percentage of data coverage in annual and seasonal BFI analysis for the gauges in WRA 5

Gauge ID	River Name	Period of Data Coverage	No of Years of Available Data; No of Annual, Wet Season, Dry Season Periods with Data	Annual	Wet Season	Dry Season
5C1	Bua	1957–2009	52; 30, 39, 37	58%	75%	71%
5D1	Bua	1958–2007	49; 25, 29, 31	51%	59%	63%
5D2	Bua	1953–2005	52; 34, 42, 35	65%	81%	67%
5D3	Mtiti	1958–2003	45;27, 30, 36	60%	67%	80%
5E6	Bua	1970–2008	38; 23, 27, 26	61%	61%	68%
5F1	Rusa	1964–2005	41; 24, 28, 27	59%	68%	66%

3.2 Average annual BFI

Average annual BFI for the gauges were determined based on the BFI analysis results in Section 3.1. The results are presented in Figure 2 and Table 4.

Traditionally BFI has been determined on an annual basis. This study found high average annual BFIs for the gauges located on the lower elevation reaches of the Bua; 0.74 for 5C1, 0.75 for 5D1 and 0.76 for 5D2. This indicates that the river has a moderately high baseflow component of approximately 74%–76% of the total annual river flow in the lower catchment. This finding is consistent with the annual BFI of 0.71 for 5C1 and 0.86 for 5D1 sourced from the HYDSTRA system in use by the Malawi Surface Water Division (Government of Malawi, 2011c). It also matches BFIs reported by Smith-Carrington (1983) of 0.85 (5D1) and 0.86 (5D2). Previous studies by UNESCO (1997) and Beck et al. (2013) reported similar annual BFI for Malawi in the range of 0.6 to 0.7 and 0.6 to 0.8 respectively. A moderately high baseflow was also found for 5F1 on the Rusa with a BFI of 0.80, or 80% of the total annual river flow which compares with a BFI of 0.81 from HYDSTRA.

In contrast, lower BFI values were found for the gauges located at higher elevations in the catchment. A BFI of 0.54 was found for 5E6, the highest gauged reach of the Bua. This doesn't match the BFI of 0.74 found from HYDSTRA. Finally, 5D3 on the Mtiti found a BFI of 0.48. There was no BFI available from HYDSTRA. Comparisons are provided for context only, it is important to bear in mind, that it's not generally recommended to compare BFIs across studies as different baseflow separation techniques and different data lengths will produce different baseflow volumes and this will affect the BFI (Ladson et al., 2013). Based on this study's annual average values, the Bua, the Rusa and the Mtiti rivers are considered perennial in nature with a stable flow regime.

3.3 Average seasonal BFI (wet and dry season)

Recent studies in BFI have sought to make seasonal adjustments, appreciating the variations that occur in baseflow both temporally and spatially and that annual BFI may not represent the true picture (Zhang et al., 2017). This study presents the first findings on seasonal BFI in the Bua catchment. Average seasonal BFI for the gauges was determined based on the BFI analysis results in Section 3.1. The results are presented in Figure 2 and Table 4.

For all gauges assessed, the results found minimal difference between the annual and the wet season BFI, however, in the dry season, all BFIs increased to over 0.80 (or 80% of the dry season flow was attributed to baseflow) as shown in Figure 2 and Table 4. For example, 5C1 had a BFI of 0.69 in the wet season increasing to 0.94 in the dry season. The increase in dry season BFI is indicative of the catchment geology. As mentioned in the literature, a high BFI indicates permeable catchment conditions whereby the catchment is storing water during the wet season and discharging it to the river during the dry season (Tallaksen and Van Lanen, 2004; Gustard, Bullock and Dixon, 1992). To support these BFI findings, it would have proved useful to compare river levels to groundwater levels near each gauging station. Unfortunately, however, of the groundwater data available there was none suitable for such a comparison.

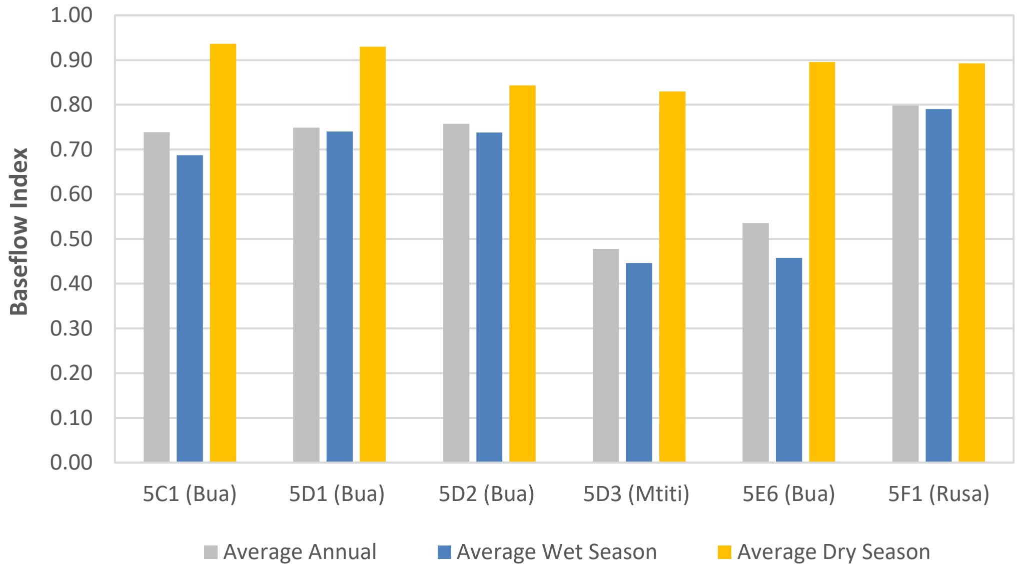


Figure 2 Results of annual and seasonal BFI analysis for the gauges in WRA 5 (graphical)

Table 4 Results of annual and seasonal BFI analysis for the gauges in WRA 5 (tabular)

Gauge ID (River)	**5C1 (Bua)**	**5D1 (Bua)**	**5D2 (Bua)**	**5D3 (Mtiti)**	**5E6 (Bua)**	**5F1 (Rusa)**
Data record	1957–2009	1958–2007	1953–2005	1958–2003	1970–2008	1964–2005
ANNUAL						
Average BFI	0.74	0.75	0.76	0.48	0.54	0.80
Minimum Average BFI	0.43	0.43	0.11	0.05	0.37	0.26
Maximum Average BFI	0.94	0.94	0.98	0.84	0.70	0.98
Standard Deviation	0.13	0.17	0.24	0.28	0.09	0.18
WET SEASON						
Average BFI	0.69	0.74	0.74	0.45	0.46	0.46
Minimum Average BFI	0.40	0.41	0.11	0.05	0.25	0.25
Maximum Average BFI	0.90	0.93	0.98	0.77	0.90	0.90
Standard Deviation	0.14	0.17	0.22	0.26	0.13	0.13
DRY SEASON						
Average BFI	0.94	0.93	0.84	0.83	0.90	0.89
Minimum Average BFI	0.83	0.55	0.55	0.00	0.47	0.61
Maximum Average BFI	0.99	1.00	1.00	1.00	0.98	1.00
Standard Deviation	0.05	0.11	0.11	0.23	0.12	0.10

Interestingly, from the wet season BFI results (Figure 2), there are two gauges which don't follow the high BFI seen in the other gauges; the 5D3 (Mtiti) and the 5E6 (Bua). The lower wet season BFI of these gauges can be attributed to the spatial variations in geology and topography which control baseflow. For example, both gauges are located at elevations of 1200 masl, compared to the much lower elevations of 550–1000 masl for the other gauges. 5E6 is located on the headwaters of the Bua and drains the entirety of the Mchinji Forest Reserve (Figure S3) and 5D3 drains part of the Dowa Hills (Figure S4).

There is considerable variability seen across all gauges in the BFI within the annual and wet season periods shown by the minimum and maximum BFIs (Table 4). The coefficient of variation (CV) of the dry season BFI was low, compared to the annual and wet season BFI which was, as expected, much larger. For example, at gauge 5C1, the dry season CV was 6%, compared to the annual CV of 18%, and the wet season of 20%. This difference in variability highlights the varying behaviour of baseflow. As mentioned in the literature, BFI is used in hydrology and hydrogeology in a range of applications (Tallaksen and Van Lanen, 2004; Ngongondo, 2006; Hughes and Hannart, 2003). Where there are variations between annual and seasonal values, as seen in these results, it is important to use the appropriate value as the use of an incorrect BFI could lead to inaccurate assessments. Several future scheme appraisals in Malawi would benefit from considering the seasonal BFI results of this study. For example, previous assessments for new investments in Malawi's water sector, which have taken account of EFRs and thus BFI values. The Water Resources Investment Strategy (WRIS) project, under the National Water development Program (NWDP), produced water resource assessments for the 17 WRAs in Malawi, including WRA 5 (Government of Malawi, 2011c). The project produced estimates for potential abstractable groundwater and sustainable surface water yield. Further, the National Irrigation Master Plan and Investment Framework (2014–2035), which sets out new investments for expansion of the irrigation sector in Malawi, is also centred around EFR, with one new dam proposed in the lower Bua catchment. It is presumed that these estimations have used annual BFI values which may lead to overestimation of available water resources. Seasonal variations are evidenced in this study and should be considered.

3.3.1 River flow, rainfall, and groundwater patterns

Examining rainfall, river and groundwater patterns support the variation in wet and dry season BFI found above. For example, river flow and rainfall patterns for gauge 5C1 are shown in Figure 3. The baseflow separation divided the daily river flow into its daily baseflow and daily surface runoff components for each annual and seasonal period. Average monthly values for each flow component were determined for the years with no missing data; 30 in total. Figure 3 shows the average monthly flow volumes for the Bua and the average monthly rainfall volumes for Nkhota station. The observed river flow and rainfall patterns highlight the distinct wet and dry season pattern recognized in Malawi. Rainfall is high during the wet season (November–April) and in response the total river flow volume and the direct runoff increases. The baseflow also increases but to a much lesser extent. River flows start to decrease after the peak river discharge in March. During the dry season (May–October), rainfall and direct runoff are reduced to a minimum. However, the baseflow remains relatively stable and sustains the river. The ratio of baseflow to total river flow is much higher in the dry season than in the wet season, thus resulting in a higher BFI. This pattern is considered generally representative of the other gauges in the catchment.

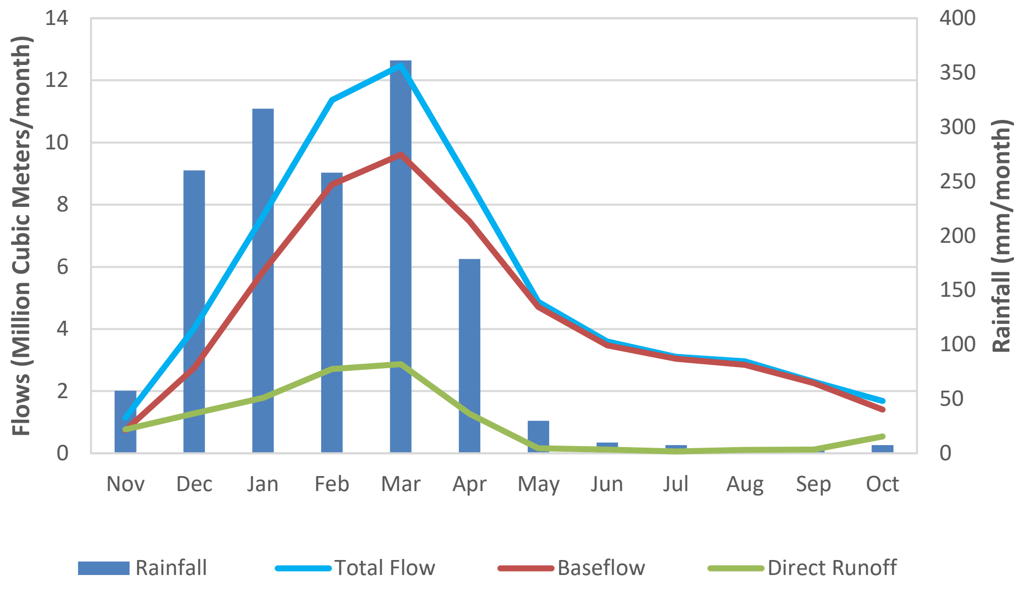


Figure 3 Average monthly flow volumes (total flow, baseflow, direct runoff), for the Bua River, Gauge 5C1, 1957–2009. Rainfall data for Nkhota station, 1960–2009

There was not enough groundwater monitoring data available in the vicinity of gauge 5C1 for analysis. However, groundwater monitoring data at Mchinji Water Office (2009–2013), located 2 km from gauge 5E6 and at the same topographical elevation did have enough data. The data shows seasonal fluctuations in groundwater levels in line with the rainfall and river patterns above (Figure 4).

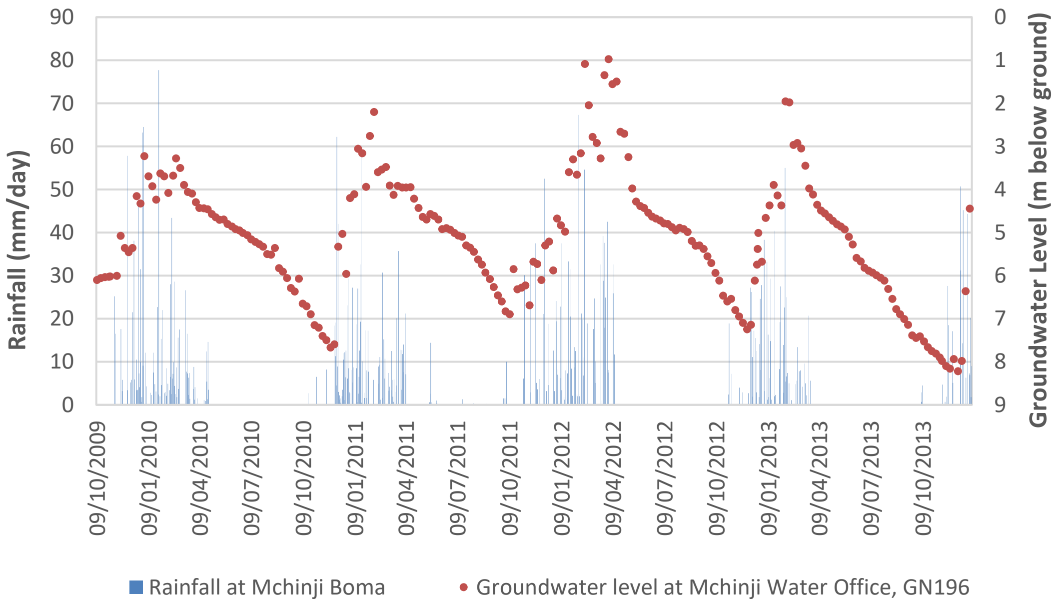


Figure 4 Daily rainfall (at Mchinji Boma) and sporadic groundwater levels (at Mchinji Water Office, GN196), located 2 km from the Bua River, Gauge 5E6, 2009–2013

3.3.2 Comments on the source of baseflow

The baseflow separation approach used in this study assumes that baseflow is derived entirely from groundwater discharge from the aquifer, however, other stored sources can also contribute. The true source of baseflow is impossible to distinguish from baseflow separations alone and would require detailed site investigations to map each flow path (UNESCO, 1980). It may be useful to provide some comments on the expected source of baseflow.

Based on the presence of aquifers identified through the literature and geological maps, we conceptualize that groundwater discharge from the local aquifers is the main contributor to baseflow during the wet and dry seasons. For example, an alluvium aquifer is present in the downstream reach of the Bua (5C1) and fractured basement dominates the entire upper catchment of the Bua (5E6) presenting good conditions for water to discharge to the river. Weathered basement aquifers underlay much of the middle reaches (5D1 and 5D2) and may contain pockets of perched aquifers. Further, interflow is expected to contribute to baseflow across all gauges during the wet season, though will not be a major source in the dry season. Finally, Dambos will also contribute to baseflow during the wet season and at the beginning of the dry season. Water is temporarily stored in the dambos and released slowly at the beginning of the dry season whereby it discharges to the river. Once the dambos have drained, the baseflow is maintained entirely from groundwater from the aquifers (Smith-Carrington, 1983). Dambos are present in much of the plateau area and the Rusa catchment (5F1) and have been previously identified as contributing to baseflow in the middle reaches of the Bua (5D1 and 5D2) (Smith-Carrington, 1983).

3.4 Long term behavioural changes in BFI (statistical trend results)

Detecting trends in BFI can help us understand the possible links between hydrological processes, anthropogenic activities and environmental changes. The MK test was used to identify increasing or decreasing statistically significant trends in the BFI results obtained in Section 3.1. The MK results are presented in Table 5. This study presents the first findings on detecting trends in BFI in the Bua catchment.

An increasing trend in BFI in the annual and wet season data was found at 5C1 (Bua) and 5D3 (Mtiti), however, no trend was found in the dry season data. Increases in baseflow have previously been linked to increases in groundwater levels because of prolonged increases in rainfall (Fetter, 2001). However, no trends in rainfall were detected in the annual, wet or dry season data from nearby rainfall stations; Nkhota station (close to 5C1) from 1960–2009, and

Mponela station (close to 5D3) from 1960–2003 (Appendix 1, Supplementary Material, Table S6). In contrast, a decreasing trend in BFI for the annual and wet season data was found for 5D1 (Bua) and 5D2 (Bua), however, no trend was found in dry season data. Decreases in BFI could be linked to prolonged over-abstraction of groundwater. Declining groundwater levels have been reported in Malawi; however, sparse monitoring of groundwater levels lends to lack of evidence of such trends. The natural vegetation of the plateau area was reported as Miombo woodland but had been cleared for cultivation in the 1980s which may have resulted in major changes to the hydrological cycle (Smith-Carrington, 1983).

Table 5 Mann Kendall statistical results for BFI for gauges in WRA 5

Gauge ID (River)	**5C1 (Bua)**	**5D1 (Bua)**	**5D2 (Bua)**	**5D3 (Mtiti)**	**5E6 (Bua)**	**5F1 (Rusa)**
Data record	1957–2009	1958–2007	1953–2005	1958–2003	1970–2008	1964–2005
ANNUAL						
MK Statistic 'S'	151	−166	−107	125	−90	−29
Trend (1% sig. level)	↑	↓	○	↑	○	○
WET SEASON						
MK Statistic 'S'	241	−214	−188	161	−102	−50
Trend (1% sig. level)	↑	↓	↓	↑	○	○
DRY SEASON						
MK Statistic 'S'	62	−142	−82	16	4	−17
Trend (1% sig. level)	○	○	○	○	○	○

- where ○ indicates no trend, ↑ indicates an increasing trend and ↓ indicates a decreasing trend

Interestingly, 5E6 (Bua) and 5F1 (Rusa) showed no trends in BFI for the annual, wet season or dry season data. The stability of the BFI here suggests that the systems are in balance, and the baseflow to the river has remained stable over the assessment period; 1970–2008 and 1964–2005 respectively. It may indicate the minimal impact to groundwater levels in the area and a well-managed catchment. This is perhaps also true of 5E6 which drains the Mchinji Forest Reserve and can be expected to have minimal impacts from human activities.

These findings suggest that long term behavioural changes have occurred in the annual and wet season baseflow at several gauges in the Bua catchment as described above. Based on the tests being conducted at a significance level of 1%, there is a 1% risk of being wrong or a confidence level of 99% in the results. The trend results should, however, be interpreted with caution as further work is recommended to quantify the magnitude of the trends and examine potential drivers for such changes in baseflow behaviour (Yue, Pilon and Cavadias, 2002).

The above results provide new evidence of temporal variations in baseflow in the Bua catchment. This will be of interest to the new National Water Resources Authority within the Malawi Government for catchment planning.

4. Conclusion

The main aim of this study was to demonstrate, using a case study, how to use sporadic river datasets to produce meaningful observations on temporal variations in baseflow. The findings can be summarized in terms of their contribution to knowledge.

4.1 Catchment originality

This is the first study to quantify temporal variations in baseflow in the Bua catchment. Annually, average BFIs > 0.74 were found for gauges in the lower reaches of the catchment, with lower BFIs < 0.54 found for gauges in higher reaches. Seasonally, minimal difference was found between the annual and wet season BFI, however, baseflow increased in the dry season across all gauges with BFI all found to be >0.80. Long term trends were found in the annual and wet season BFI indicating behavioural changes in baseflow have occurred within the catchment. No trend was found in the dry season BFI. The source of baseflow is expected to be mainly groundwater discharge from the aquifers underlain the rivers, however, interflow and dambo storage may also play a role. An implication of these findings is that temporal variations in baseflow should be considered in future scheme appraisals in the catchment such as the proposed irrigation infrastructure. Further, the results should be included in catchment management plans set by the new National Water Resources Authority within the Malawi Government, to inform the seasonal allocation of water resources in the catchment.

4.2 Generic relevance to the reader and the wider research community

Apart from the Bua catchment case study, this article serves as an important example for other gauged catchments in Malawi, and indeed other countries, which are required to assess variations in baseflow to underpin IWRM and SDG 6, but are faced with similar challenges of sporadic river data. Further research is now needed to quantify temporal variations in baseflow for all gauged catchments in Malawi. Our on-going baseflow research seeks to do this by using the approach demonstrated in this study.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1; Supplementary Material word document containing the following Figures and Tables. **Figure S1.** Pictures of the weir located on the Bua river downstream of gauge 5C1, taken January 2019 by Oliver Phiri; **Figure S2.** Results of the annual and seasonal BFI analysis (graphical) for the Bua River, gauge station 5C1, 1957–2009 (52 years); **Figure S3.** River gauge 5E6 on the Bua River, draining Mchinji Forest Reserve, Google Earth Image, February 2019; **Figure S4.** River gauge 5D3 on the Mtiti river, draining part of the Dowa Hills, Google Earth Image, February 2019; **Table S1**. Results of the annual and seasonal BFI analysis (tabular) for the Bua river, gauge station 5D1, 1958–2007 (49 years); **Table S2**. Results of the annual and seasonal BFI analysis (tabular) for the Bua river, gauge station 5D2, 1953–2005 (52 years); **Table S3.** Results of the annual and seasonal BFI analysis (tabular) for the Mtiti river, gauge station 5D3, 1958–2003 (45 years); **Table S4**. Results of the annual and seasonal BFI analysis (tabular) for the Bua river, gauge station 5E6, 1970–2008 (38 years); **Table S5**. Results of the annual and seasonal BFI analysis (tabular) for the Rusa river, gauge station 5F1, 1964–2005 (41 years); **Table S6.** Mann Kendall statistical results for rainfall stations in WRA 5; Nkhota (1960–2009) and Mponela (1960–2003).

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5.3 Supplementary Material

Supplementary Material for

Quantification of Temporal Variations in Baseflow Index Using Sporadic River Data: Application to the Bua Catchment, Malawi

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Contents

Figure S 1 Pictures of the weir located on the Bua river downstream of gauge 5C1, taken January 2019 by Oliver Phiri

Table S 1 Results of the annual and seasonal BFI analysis (tabular) for the Bua river, gauge station 5D1, 1958–2007 (49 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1958/1959	-	-	-
1959/1960	0.82	0.81	0.99
1960/1961	0.93	0.92	1.00
1961/1962	0.94	0.93	1.00
1962/1963	0.92	0.92	0.98
1963/1964	0.92	0.92	0.99
1964/1965	0.93	0.92	1.00
1965/1966	0.85	0.85	0.96
1966/1967	0.69	0.68	0.96
1967/1968	0.66	0.66	0.67
1968/1969	0.86	0.86	0.97
1969/1970	0.83	0.83	0.78
1970/1971	-	-	0.99
1971/1972	0.87	0.86	0.98
1972/1973	0.92	0.92	0.98
1973/1974	0.88	0.87	0.93
1974/1975	0.83	0.82	0.97
1975/1976	0.53	0.51	0.97
1976/1977	0.81	0.80	0.95
1977/1978	-	-	0.98
1978/1979	0.73	0.73	1.00
1979/1980	-	-	1.00
1980/1981	-	-	-
1981/1982	-	-	-
1982/1983	-	-	-
1983/1984	0.47	0.47	1.00
1984/1985	-	0.84	-
1985/1986	-	-	0.99
1986/1987	-	0.84	-
1987/1988	0.55	0.51	0.91
1988/1989	-	0.74	-
1989/1990	0.73	0.73	0.74
1990/1991	-	-	0.92
1991/1992	0.43	0.41	0.95
1992/1993	0.44	0.41	0.93
1993/1994	0.71	0.70	0.83
1994/1995	0.49	0.47	0.85
1996/1997	-	-	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	-	0.55	-
2006/2007	-	-	0.55

- denotes no BFI determined due to insufficient data in the period

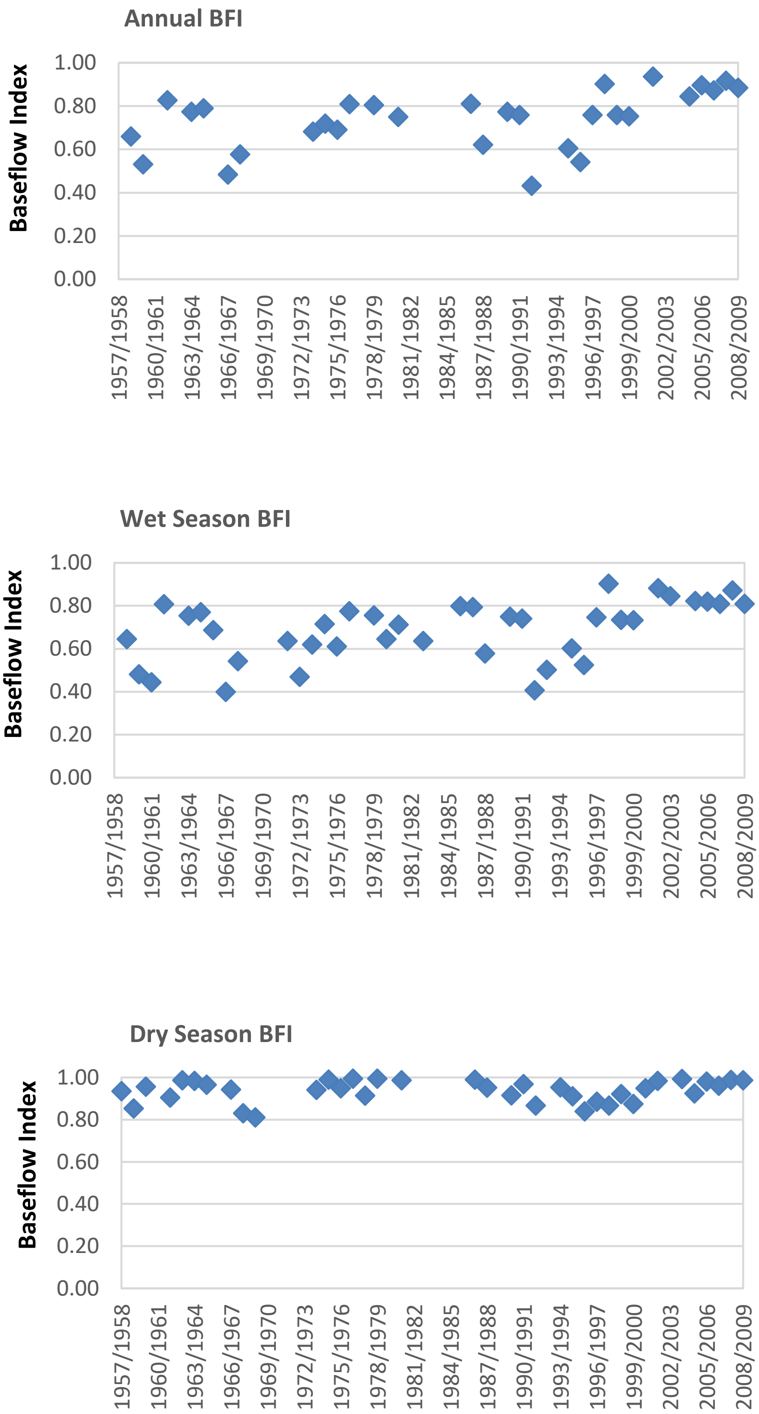

Figure S 2 Results of the annual and seasonal BFI analysis (graphical) for the Bua River, gauge station 5C1, 1957–2009 (52 years)

Table S 2 Results of the annual and seasonal BFI analysis (tabular) for the Bua river, gauge station 5D2, 1953–2005 (52 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1953/1954	-	-	0.95
1954/1955	0.96	0.98	0.79
1955/1956	0.96	0.95	1.00
1956/1957	0.95	0.95	0.96
1957/1958	0.98	0.98	0.93
1958/1959	0.89	0.89	0.93
1959/1960	0.74	0.71	0.99
1960/1961	0.92	0.92	0.94
1961/1962	0.88	0.87	0.91
1962/1963	0.97	0.97	0.99
1963/1964	0.86	0.85	0.98
1964/1965	0.72	0.70	0.96
1965/1966	0.80	0.79	0.96
1966/1967	0.48	0.46	0.54
1967/1968	0.88	0.86	0.98
1968/1969	0.36	0.32	0.70
1969/1970	0.14	0.12	0.94
1970/1971	0.69	0.69	0.91
1971/1972	0.67	0.68	0.59
1972/1973	0.73	0.74	0.69
1973/1974	0.87	0.86	0.94
1974/1975	0.88	0.88	0.90
1975/1976	0.89	0.87	1.00
1976/1977	-	0.72	-
1977/1978	-	-	-
1978/1979	-	-	-
1979/1980	0.54	0.49	0.83
1980/1981	-	0.63	-
1981/1982	0.74	0.77	0.47
1982/1983	-	0.72	-
1983/1984	-	-	-
1984/1985	-	-	-
1985/1986	0.96	0.96	-
1986/1987	0.90	0.89	1.00
1987/1988	-	-	-
1988/1989	-	-	-
1989/1990	-	-	0.86
1990/1991	-	0.62	-
1991/1992	-	-	0.00

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1992/1993	-	0.64	-
1993/1994	0.11	0.11	-
1994/1995	-	0.78	-
1995/1996	-	0.58	-
1996/1997	-	-	-
1997/1998	-	0.88	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-

- denotes no BFI determined due to insufficient data in the period

Table S 3 Results of the annual and seasonal BFI analysis (tabular) for the Mtiti river, gauge station 5D3, 1958–2003 (45 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1958/1959	-	-	0.88
1959/1960	0.20	0.19	0.90
1960/1961	0.18	0.13	0.89
1961/1962	0.13	0.09	0.91
1962/1963	0.37	0.36	0.91
1963/1964	0.25	0.23	0.88
1964/1965	0.20	0.18	0.88
1965/1966	0.13	0.13	0.39
1966/1967	0.18	0.15	0.82
1967/1968	0.18	0.17	0.56
1968/1969	0.21	0.21	0.81
1969/1970	0.05	0.05	0.19
1970/1971	0.77	0.67	0.97
1971/1972	0.81	0.74	0.95
1972/1973	0.70	0.60	0.96
1973/1974	0.82	0.67	0.98
1974/1975	-	-	0.98
1975/1976	-	-	0.90
1976/1977	0.80	0.73	0.96
1977/1978	-	-	-
1978/1979	-	-	0.86
1979/1980	0.76	0.64	0.97
1980/1981	-	0.72	-
1981/1982	-	-	0.98
1982/1983	0.84	0.77	0.98
1983/1984	0.75	0.65	0.98
1984/1985	-	0.69	-
1985/1986	0.83	0.77	0.96
1986/1987	0.79	0.73	0.96
1987/1988	-	0.27	-
1988/1989	0.30	0.28	0.71
1989/1990	0.33	0.34	0.00
1990/1991	-	-	0.90
1991/1992	0.49	0.49	0.88
1992/1993	0.60	0.60	0.72
1993/1994	-	-	0.85
1994/1995	0.79	0.77	1.00
1995/1996	0.44	0.37	0.81

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1996/1997	-	-	-
1997/1998	-	-	0.94
1998/1999	-	-	-
1999/2000	-	-	0.96
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-

- denotes no BFI determined due to insufficient data in the period

Table S 4 Results of the annual and seasonal BFI analysis (tabular) for the Bua river, gauge station 5E6, 1970–2008 (38 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1970/1971	-	-	0.93
1971/1972	0.70	0.61	0.90
1972/1973	0.57	0.53	0.88
1973/1974	0.64	0.55	0.90
1974/1975	0.54	0.47	0.86
1975/1976	0.58	0.50	0.94
1976/1977	0.54	0.45	0.95
1977/1978	0.54	0.41	0.98
1978/1979	0.60	0.51	0.95
1979/1980	0.54	0.41	0.98
1980/1981	0.56	0.41	0.97
1981/1982	-	-	0.90
1982/1983	0.44	0.36	0.92
1983/1984	0.38	0.32	0.94
1984/1985	-	0.36	-
1985/1986	0.61	0.50	0.97
1986/1987	0.59	0.47	0.97
1987/1988	0.50	0.40	0.87
1988/1989	0.63	0.50	0.96
1989/1990	0.61	0.50	0.91
1990/1991	0.53	0.50	0.91
1991/1992	0.41	0.41	0.47
1992/1993	-	0.33	-
1993/1994	-	0.90	-
1994/1995	-	-	-
1995/1996	0.37	0.35	0.53
1996/1997	0.45	0.38	0.87
1997/1998	-	-	-
1998/1999	0.56	0.25	0.93
1999/2000	0.44	0.30	0.94
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	0.70	-
2005/2006	-	-	-
2006/2007	-	-	0.98
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Table S 5 Results of the annual and seasonal BFI analysis (tabular) for the Rusa river, gauge station 5F1, 1964–2005 (41 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1964/1965	-	-	0.87
1965/1966	0.85	0.85	0.81
1966/1967	0.82	0.83	0.75
1967/1968	0.88	0.87	0.89
1968/1969	0.88	0.88	0.88
1969/1970	0.84	0.83	0.86
1970/1971	-	-	-
1971/1972	-	-	0.95
1972/1973	0.90	0.86	0.97
1973/1974	-	-	-
1974/1975	0.88	0.86	0.97
1975/1976	0.94	0.92	1.00
1976/1977	0.78	0.76	0.97
1977/1978	0.94	0.94	0.99
1978/1979	0.72	0.70	0.97
1979/1980	0.66	0.60	0.91
1980/1981	0.89	0.87	0.96
1981/1982	-	-	0.98
1982/1983	0.86	0.86	0.87
1983/1984	0.89	0.89	0.91
1984/1985	-	-	-
1985/1986	0.98	0.95	0.88
1986/1987	0.93	0.93	0.96
1987/1988	0.59	0.55	0.93
1988/1989	-	0.83	-
1989/1990	-	0.78	-
1990/1991	0.68	0.68	0.77
1991/1992	0.36	0.35	0.61
1992/1993	0.88	0.87	0.94
1993/1994	0.83	0.83	0.65
1994/1995	0.92	0.85	0.94
1995/1996	0.26	0.24	0.92
1996/1997	-	0.83	-
1997/1998	-	0.92	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-

- denotes no BFI determined due to insufficient data in the period

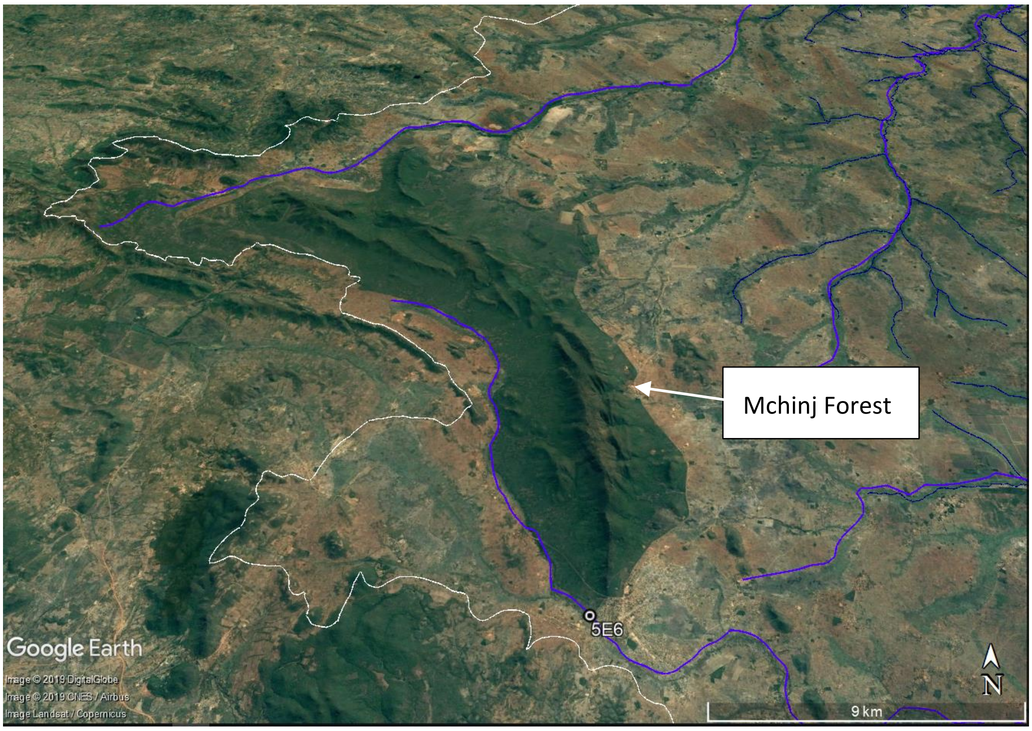

Figure S 3 River gauge 5E6 on the Bua river, draining Mchinji Forest Reserve, Google Earth Image, February 2019

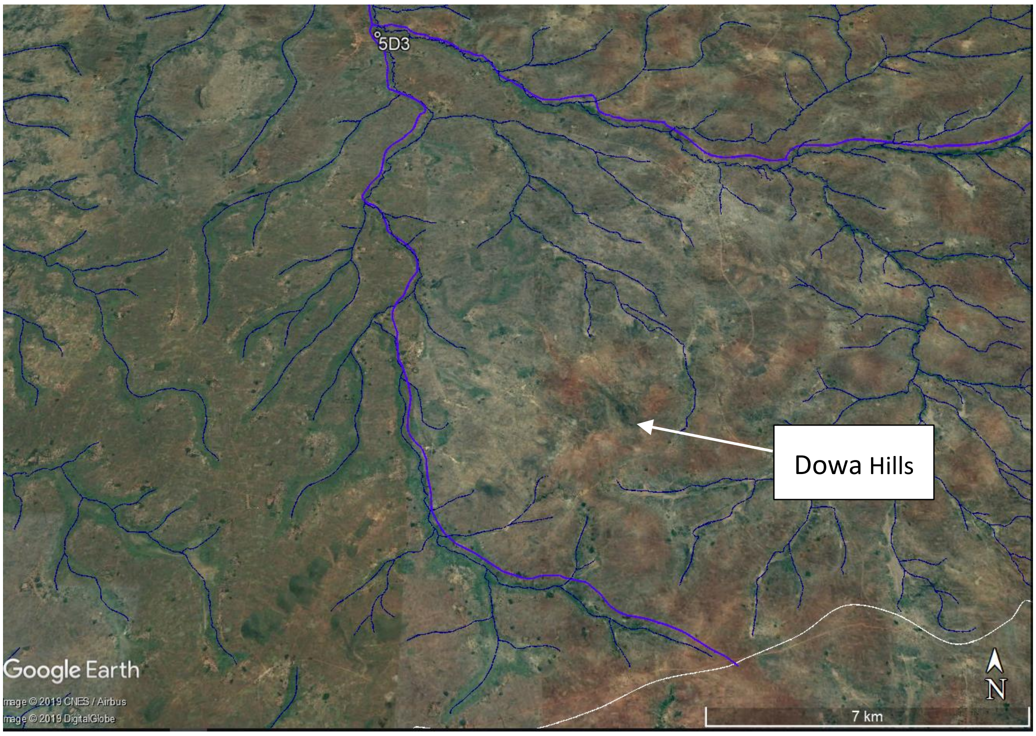

Figure S 4 River gauge 5D3 on the Mtiti river, draining part of the Dowa Hills, Google Earth Image, February 2019

Table S 6 Mann Kendall statistical results for rainfall stations in WRA 5; Nkhota (1960–2009) and Mponela (1960–2003)

	Nkhota			**Mponela**		
	Annual	Wet	Dry	Annual	Wet	Dry
MK Statistic ‘S’	−303	−293	−151	49	47	17
Trend (1% sig. level)	No trend	No trend	No trend	No trend	No trend	No trend

5.4 Further Discussion

As the BFI programme was repeatedly used to perform baseflow separation and generate BFI values, it became apparent that the programmes saving function was inefficient for the task. Therefore, a results template was created using excel so that the BFI Programme results could be saved consistently each time an assessment was performed. Each gauging station had its own 'BFI results spreadsheet' which was based on the results template. An example of the spreadsheet for gauge 5C1 is presented in Figure 5 and Figure 6. The spreadsheet comprised a raw results tab and a summary BFI tab.

The raw results tab is presented in Figure 5. The river flow data (m^3/day) which was entered into the BFI programme is seen in Column A and Column B. When the baseflow separation was performed, the programme separated the total flow into its baseflow component and surface runoff components and produced the baseflow data for Column C. Columns A, B and C were copied together from the BFI programme and pasted into this template. Following this, Column D (the surface runoff component) was manually calculated within the template as the difference between Column B (total river discharge) and Column C (baseflow component). Next, the assessment periods were entered into the programme for it to determine a BFI value. The periods were annual, wet and dry season as seen in Column G, H and I. The programme displays the BFI results under the following heading:

- Results: Whole series - This field gives the BFI for the whole river dataset entered
- Results: Annual - This field gives the mean of the annual BFIs. This is applicable when there are multiple years of river data input
- Lost days: Due to the calculation procedure, the baseflow separation cannot start on the first day of data and can't end on the last day of data. This results in several 'lost days'
- Season information - these fields show the season which was selected and whether the season contains a year shift or not
- Seasonal information - these fields display the first and last day of the input data, and the first and last day of the calculated baseflow line.

The above BFI results were also copied from the programme to the template. The annual BFI results were selected in this study. Its noted that the annual and whole series BFI values were the same because multiple years of data were not assessed together. Whilst, all these results described were not utilized, they may be useful for future analysis and interpretation.

The raw results tabs have not been included in the thesis but can be requested from the CJF Water Futures Programme.

	A	B	C	D
1	Date	Total River Flow	Baseflow component	Surface Runoff component
2	01/11/1959	6932		6932
3	02/11/1959	279		279
4	03/11/1959	279		279
5	04/11/1959	106		106
6	05/11/1959	13		13
7	06/11/1959	13	13	0
8	07/11/1959	13	13	0
9	08/11/1959	13	13	0
10	09/11/1959	13	13	0
11	10/11/1959	13	13	0
12	11/11/1959	13	13	0
13	12/11/1959	13	13	0
14	13/11/1959	13	13	0
15	14/11/1959	13	13	0
16	15/11/1959	13	13	0
17	16/11/1959	13	13	0
18	17/11/1959	13	13	0
19	18/11/1959	13	13	0
20	19/11/1959	13	13	0
21	20/11/1959	13	13	0
22	21/11/1959	13	13	0
23	22/11/1959	13	13	0
24	23/11/1959	13	13	0
25	24/11/1959	13	13	0
26	25/11/1959	13	13	0
27	26/11/1959	13	13	0
28	27/11/1959	13	13	0
29	28/11/1959	13	13	0
30	29/11/1959	13	13	0
31	30/11/1959	13	13	0
32	01/12/1959	13	13	0
33	02/12/1959	13	13	0
34	03/12/1959	13	13	0
35	04/12/1959	13	13	0
36	05/12/1959	13	13	0
37	06/12/1959	13	13	0
38	07/12/1959	13	13	0
39	08/12/1959	13	13	0
40	09/12/1959	12808	12808	0
41	10/12/1959	10907	10907	0
42	11/12/1959	9006	9006	0
43	12/12/1959	7019	7019	0

F	G	H	I
	Annual	Wet Season	Dry Season
Results: Whole series			
BFI	0.531	0.482	0.956
Mean of annual BFIs	0.531	0.482	0.956
Season Information			
Season start day	1	1	1
Season start month	11	11	5
Season end day	31	30	31
Season end month	10	4	10
Year shift during season	Yes	Yes	No
Series information			
Start of entire series	01/11/1959	01/11/1959	01/11/1959
Start of base flow line	06/11/1959	06/11/1959	06/11/1959
End of base flow line	18/09/1960	18/09/1960	18/09/1960
End of entire series	31/10/1960	31/10/1960	31/10/1960
Results: Annual values			
Year	1960	1960	1960
BFI	0.531	0.482	0.956
Lost Days	48	5	43

Summary BFI | 1957-1958 | 1958-1959 | 1959-1960 | 1960-1961 | 1961-1962 | 1962-1963 | 1963-1964 | 1964-1965

Figure 5 Example of BFI results spreadsheet, gauge 5C1 (1956-1960) - raw results tab (data within red boxes denotes data which is produced by and copied from the BFI programme

The summary BFI tab is presented in Figure 6. It was used to produce a summary of the BFI data for each year of assessment as shown. The summary results for each gauge in the Bua catchment are presented in the Supplementary Material of the published paper in this Chapter (Section 5.3). This tab was also used to calculate descriptive statistics such as the average, minimum, and maximum BFI over the assessment period.

	A	B	C	D
1	Period	Annual BFI	Wet Season BFI	Dry Season BFI
2	1957/1958	-	-	0.94
3	1958/1959	0.66	0.65	0.85
4	1959/1960	0.53	0.48	0.96
5	1960/1961	-	0.44	-
6	1961/1962	0.83	0.81	0.91
7	1962/1963	-	-	0.99
8	1963/1964	0.77	0.75	0.98
9	1964/1965	0.79	0.77	0.96
10	1965/1966	-	0.69	-
11	1966/1967	0.48	0.40	0.94
12	1967/1968	0.58	0.54	0.83
13	1968/1969	-	-	0.81
14	1969/1970	-	-	-
15	1970/1971	-	-	-
16	1971/1972	-	0.64	-
17	1972/1973	-	0.47	-
18	1973/1974	0.68	0.62	0.94
19	1974/1975	0.72	0.72	0.99
20	1975/1976	0.69	0.61	0.95
21	1976/1977	0.81	0.77	0.99
22	1977/1978	-	-	0.91
23	1978/1979	0.80	0.76	0.99
24	1979/1980	-	0.65	-
25	1980/1981	0.75	0.71	0.99
26	1981/1982	-	-	-
27	1982/1983	-	0.64	-
28	1983/1984	-	-	-
29	1984/1985	-	-	-
30	1985/1986	-	0.80	-
31	1986/1987	0.81	0.80	0.99
32	1987/1988	0.62	0.58	0.95
33	1988/1989	-	-	
34	1989/1990	0.77	0.75	0.92
35	1990/1991	0.76	0.74	0.97
36	1991/1992	0.43	0.41	0.87
37	1992/1993	-	0.50	-
38	1993/1994	-	-	0.95
39	1994/1995	0.60	0.60	0.91
40	1995/1996	0.54	0.53	0.84
41	1996/1997	0.76	0.75	0.89
42	1997/1998	0.90	0.90	0.87
43	1998/1999	0.76	0.74	0.92
44	1999/2000	0.75	0.73	0.87
45	2000/2001	-	-	0.95
54				
55	- denotes no result due to insufficent continuous data			
56				
57	Descriptive Statistics			
58	Period	Annual	Wet Season	Dry Season
59	Average BFI	0.74	0.69	0.94
60	Minimum Average BFI	0.43	0.40	0.81
61	Maximum Average BFI	0.94	0.90	0.99
62	Standard Deviation (SD)	0.13	0.14	0.05
63	Coefficient of Variation (CV) in %	18	20	6

Figure 6 Example of BFI results spreadsheet, gauge 5C1 (1956-1960) - summary BFI tab

5.5 Summary

In this chapter, the Bua Catchment was used to demonstrate how to work with sporadic river data and baseflow separation to quantify temporal variations in baseflow over time. The approach used allowed the determination of annual and seasonal BFI and identification of long-term trends in the BFI data for 6 river gauges in the catchment. It utilized sporadic river data and was easy to follow with a focus on free open source tools. It provides a research approach that allows scientists and practitioners to work with sporadic river data and baseflow separation to quantify temporal variations in BFI. The results of the study provide new knowledge on the seasonal and long term behaviour of baseflow in the Bua catchment. Previously, there was no data published on annual, seasonal, or long term baseflow behaviour in the catchment. The results showed that baseflow plays an important role on an annual basis with average annual BFIs >0.74, but even more so in the dry season where average BFIs increased to >0.80.

This research output has important implications on the sustainable management of water resources in the Bua catchment. For example, there are currently plans to invest in a new irrigation scheme in the Bua catchment as part of the National Irrigation Master Plan Investment Network (2014-2035) (Government of Malawi, 2015b). The scheme proposes the installation of one new dam with an investment cost of approximately 13 million USD. The design calculations for the proposed dam are based on maintaining an Environmental Flow (EF) in the river, where anything above this flow can be used for irrigation purposes without any deterioration to the health of the river. One parameter used in the determination of an EF is baseflow or the BFI. If the EF calculation does not use accurate BFI data, the sustainability of the catchment downstream of the proposed dam is at risk. This risk, in turn, applies to Lake Malawi as the Bua catchment is the largest inflow catchment to the lake (in Malawi) which means any negative changes to the hydrology on the Bua river could ultimately impact on the lake levels. Thus, it is recommended that this research output is used to update the proposed irrigation plan for the Bua Catchment.

The approach applied to the Bua catchment was considered a success. Next, further investigation is required to see if it can transfer across to another larger catchment of strategic water resource and economic value to Malawi. The next chapter demonstrates how the approach can be applied to the Shire River Basin in Southern Malawi.

Chapter 6 The Shire River Basin

6.1 Introduction

The previous chapter demonstrated, using the Bua Catchment as a case study, how sporadic river data can be used to quantify temporal variations in baseflow. The use of the approach was considered a success and further research was required to investigate if the approach could be scaled up and applied to another larger catchment of different characteristics.

This chapter applied the approach to another case study in Southern Malawi; the Shire River Basin (SRB). The basin has a catchment area of 22,430km^2 which is twice the size of the Bua catchment (10,658 km^2). The SRB is drained by the Shire River which flows for 520km from Lake Malawi (its only outlet) to its merge with the Zambezi River in Mozambique giving it international importance (Kawala, 2020) The Shire River is of significant value to the country's economy as it houses three hydropower stations which provide over 98% of the country's electricity. The river also supplies water for irrigation for agriculture, piped municipal surface water supplies, and for large areas of wetlands of major environmental importance (Government of Malawi, 2016d). The SRB experiences a dry climate in comparison to the central and northern regions of the country with less rainfall resulting in increased pressure on water resources. The basin also suffers from severe catchment degradation, for example, deforestation and siltation of riverbeds and it has also suffered from severe flooding in recent years. Hydropower stations are often unable to meet peak demands due to low flows and siltation of the Shire River (World Bank, 2019).

To support the GoM with the management of the basin, there has been a significant investment by the World Bank through the Shire River Basin Management Programme (World Bank, 2019). The project is expected to last 12-15 years and aims to 'increase sustainable social, economic and environmental benefits by effectively and collaboratively planning, developing and managing the Shire River Basins natural resources' (Government of Malawi, 2016d). The first phase of the project was completed in 2019 and consisted of major investments into water related infrastructure. The investment included an upgrade to the Kamuzu barrage which controls flows from Lake Malawi to the Shire River and flood management and mitigation measures in the lower Shire River. The first phase cost an estimated 142 million USD (World Bank, 2019) with the second phase expected to commence soon. Unfortunately, in the first phase there appeared to be a lack of focus on the relationship between groundwater and rivers. Therefore, this research output is needed to highlight the importance of groundwater discharge to rivers and ensure that baseflow is a topic to be included in the second phase of the project.

This research output was delivered through one paper published in a peer-reviewed journal, the American Journal of Water Science and Engineering, as follows:

Kelly, L., Bertram, D., Kalin, R.M., Ngongondo, C. 2019. Characterization of Groundwater Discharge to Rivers in the Shire River Basin, Malawi. American Journal of Water Science and Engineering, 5(4), p.127-137.

The published paper is presented in the following section and the author contributions were as follows: Conceptualization, L.K.; Formal analysis, L.K.; Funding acquisition, R.M.K.; Methodology, L.K.; Supervision, R.M.K. and D.B.; Validation, L.K. and C.N; Visualization, L.K.; Writing—original draft, L.K.; Writing—review & editing, L.K., D.B., R.M.K. and C.N.

6.2 Paper

Characterization of groundwater discharge to rivers in the Shire River Basin

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Abstract: This study investigates groundwater discharge to rivers in the Shire River Basin (SRB), Malawi, using the baseflow index (BFI) approach. The BFI represents the baseflow component of a river and is often used as a proxy indicator of groundwater discharge to a river. The smoothed minima method was applied to river flow data from 15 gauges in the Basin (ranging from 1948 to 2012) and the Mann-Kendall (MK) statistical test was used to identify trends in the BFI. The BFI results indicate that groundwater plays an important role in contributing to river flows in the SRB, especially in the dry season. Expressing the BFI as a percentage, these values indicate that annual groundwater discharge to the river's ranges from 19% in the Rivirivi River to 97% in the Shire River. Seasonally, minimal difference was found between the annual and the wet season BFI. Generally, the dry season BFI was higher than those of the wet season with most rivers increasing to >75%. Groundwater data supported the seasonal fluctuations identified in the BFI data, however, there was no groundwater monitoring boreholes in close proximity to any of the river gauges for in-depth analysis. The results also showed long term trends in the BFI data indicating behavioural changes in the river baseflow and groundwater discharge. In some areas, the declines in BFI indicate that groundwater discharge has been reducing over time due to declines in groundwater levels. This is a concern for the sustainable management of water resources in the Basin. The findings of this study provide important new knowledge on the seasonal and long-term behaviour of groundwater discharge to rivers in the Basin which will be crucial for supporting sustainable water resources management practices. The results will be

particularly useful to the new National Water Resources Authority within the Malawian Government, who will oversee catchment management plans.

Keywords: Baseflow, BFI, Groundwater Discharge, Malawi

1. Introduction

Groundwater depletion caused by unsustainable abstractions from our aquifers is a global problem (Bierkens and Wada, 2019; Gleeson and Richter, 2018). This depletion puts the future water security of life on earth at risk. Although pertinent to all countries, it is especially crucial to Africa which is heavily reliant upon groundwater with an estimated 75% of the population dependent on it as a water resource. Groundwater also has an important environmental use as baseflow to rivers. In connected groundwater-river systems, groundwater discharges from the aquifer year-round to contribute to river flow, with contributions varying dependent on geology, topography, climatic season and anthropogenic activities. In many semi-arid regions, groundwater can maintain river flows during the dry season contributing up to 90% of the total river flow in some rivers (Kelly et al., 2019b). Thus, when groundwater levels drop, so too does the groundwater discharge to the river, and if this drop is sustained ultimately the groundwater will become disconnected from the river and the river will cease to flow in sustained periods of no rainfall (Winter, 1998; UNESCO, 1980; Hendriks, Kuijper and Van Ek, 2014). This knock-on effect is also a global problem, with a recent study estimating that for 42-79% of the catchments where there is currently groundwater pumping, the environmental flow limits of the rivers, that is the level required for a healthy river, will be reached by 2050 (De Graaf et al., 2019). Depletion of one of the world's largest rivers, the Ganges, has also recently been attributed to reductions in groundwater baseflow (Mukherjee, Bhanja and Wada, 2018). As such, the groundwater-river connection is critical for sustainable water resources management and can be considered to underpin the Sustainable Development Goal (SDG 6) 'to ensure availability and sustainable management of water and sanitation for all' (International Hydrological Programme of UNESCO, 2006; Donoso et al., 2012).

Quantifying groundwater discharge to rivers is a difficult and challenging task given the complex nature of the interaction. There is a vast body of literature available with countless studies on the topic. Examples from the country's across the world include; China (Liu et al., 2015; Frohlich, Frohlich and Wittenberg, 1994); Africa (Kouanda et al., 2018; Ngongondo, 2006; Hughes, Parsons and Conrad, 2007), South Korea (Lee et al., 2018), Australia (Zhang et al., 2017), New Zealand (Singh et al., 2019), Canada (St. Jacques and Sauchyn, 2009) and the

USA (Bosch et al., 2017; Ahiablame et al., 2013). In many developing world countries, the task of quantifying groundwater discharge is challenged by a lack of data, financial resources and technical staff allocated to execute such studies (Government of Malawi, 2017a; Kelly et al., 2019b). Studies therefore often focus on quantifying river baseflow, or the baseflow index (BFI), which is often used as a proxy for groundwater discharge to rivers (Bosch et al., 2017; Gustard, Bullock and Dixon, 1992; Kelly et al., 2019b; Esralew and Lewis, 2010) due to the minimal data requirements. However, comprehensive baseline data on baseflow is still typically lacking in many countries. This baseline data is the prerequisite for sustainable water management approaches such as Integrated Water Resources Management (IWRM) and Conjunctive water use, and further the quantification of the impacts of human pressures and climate change on our water resources.

One example is Malawi in Southern Africa, where groundwater discharge to rivers plays a vital role in maintaining river flows (Kelly et al., 2019b). One of Malawi's most important hydrological systems is the 'Shire River Basin (SRB)' (Figure 1), which is located in the Southern Region and is the only outlet from the prominent Lake Malawi. The SRB is a sub-basin of the Zambezi River which cements its importance on an international scale. The SRB sustains the socio-economic livelihoods of over 5 million people through hydro-electric power generation, irrigated agriculture, aquaculture, transportation, tourism and, urban water supply and water use for the riparian communities (Zuzani, Ngongondo, Mwale and Willems, 2019). The Shire River is regulated at Liwonde, about 72 km downstream from Lake Malawi, by the Kamuzu Barrage for hydropower purposes (Jury, 2014). In recent years, high population density which is predicted to rise to over 8 million in the next 20 years (Government of Malawi, 2016d) and poverty has led to significant human pressure on its groundwater and river resources. To meet this increased demand for access to clean water, there has been a significant number of new boreholes drilled by the government, non-governmental organizations and the private sector (Pavelic et al., 2012). Further, increased climate variability has affected the SRB, with a lot of uncertainty in the timing and magnitudes of rainfall and river flows. There have been recent reports of declines in groundwater levels and rivers turning to dust, a topic which is being openly discussed (Government of Malawi, 2017b; Chitete, 2019). Unfortunately, groundwater monitoring has not been sufficiently monitored in the Basin to support such claims. It's presumed that low season river flows are sustained by baseflow from the underlying aquifers year-round. Specific studies are scarce, only one appears to focus exclusively on baseflow (Kelly et al., 2019b), whilst a handful of others consider it to a limited extent (Kumambala, 2010; Chimtengo et al., 2014). As such, quantitative data to describe the groundwater-river connection is lacking. This lack of baseline data is a key limitation to the sustainable management of water resources in the Basin.

Therefore, this study aims to characterize groundwater discharge to rivers in the SRB. Specifically, the objectives were to 91) quantify the annual and seasonal BFI and 2) to evaluate long term trends in the BFI. We use the baseflow index method as a proxy indicator of groundwater discharge to a river. The findings of this study are expected to provide important new insights on the behaviour of baseflow in the Basin and generate key baseline data which is required to integrate groundwater and surface water together in the management and development of water resources in the Basin.

This study is part of on-going research in the sustainable development of groundwater in Malawi to support the Government of Malawi in achieving SDG 6.

2. Material and Methods

2.1 Study area

The SRB (Figure 1) has a total catchment area of 22,430 km² and comprises the Shire river catchment (the area that is south of Lake Malawi, and from here defined as) and the Ruo river catchment. The Basin is part of the larger Lake Malawi which drains an area from Tanzania, Malawi and Mozambique. The Basin is not a true hydrological basin but intended as a planning unit as used in the World Bank Funded SRB Management Program (SRBMP) currently being executed by the Government of Malawi (Government of Malawi, 2016d). The SRBMP has been tasked with the sustainable planning, managing and development of the natural resources of the SRB through the implementation of Integrated Water Resources Management.

Within the National Water Resources Master Plan (NWRMP) of Malawi, the Shire river catchment is referred to as Water Resource Area (WRA) 1 and the Ruo river catchment is referred to as WRA 14 (Government of Malawi, 2017b).

The Shire River originates as the only outflow from Lake Malawi and flows south through Southern Malawi (520km) to its confluence with the Zambezi River in Mozambique (Figure 1) (Government of Malawi, 2016d). It is joined by five major tributaries (Rivirivi, Lisungwe, Wakulumadzi, Mwanza and the Ruo) and has numerous minor tributaries (including Nkasi, Lirangwe and Likhubula). The Ruo River is the largest tributary of the Shire River, originating in Mount Mulanje and flows south-west along the border with Mozambique until it joins the Shire river at Chiromo. Several tributaries join the Ruo including the Lichenya, Likabula, Mloza, Mombezi and Thuchila. The Ruo has a catchment area of 4,760 km², 1,266 km² of which lies in Mozambique (Government of Malawi, 2011b). The Ruo is thus a transboundary river of importance to both Malawi and Mozambique.

The topography of WRA 1 ranges from 0 masl to 1,700 masl (Figure 1). The south of the WRA 1 has some of the lowest-lying lands in Malawi with the floodplains adjacent the Shire River predominately less than 50 masl, making it susceptible to flooding. For example, the southern reach of the Shire burst its banks following torrential rains in 2015 and 2019, leaving 100s of people dead and 1000s homeless. The topography of WRA 14 (i.e. to the west of the Basin) is mainly low lying (typically 500-1000 masl) and drops consistently towards the south. Tributaries typically have steep upper reaches and low gradients further downstream. WRA 14 comprises most of the Mulanje mountains with a peak of approximately 3,000m (Government of Malawi, 2011b).

Land use in WRA 1 is shown in Figure 2a and mainly comprises cropland; arable agriculture of mainly maize crops, tobacco and sugarcane. There are many designated areas; Mwabvi Game Reserve and Namizimu Forest reserve in the south; Lengwe National Park and Majete Game Reserve in the south-west; Liwonde National Park, Zomba-Malosa Forest, Liwonde Forest Reserve and Liwonde National Park in the north. Outside the designated areas, the land is largely under arable agriculture. Wetlands in the south of the catchment include the Elephant marshes. Most of the land in WRA 14 is dominated by large areas for maize crops, and tea and coffee estates and smaller areas for tobacco. There is a small area of wetland in the north. On the Mulanje Mountains, there is forest land and grassland.

The climate of the SRB reflects that of wider Malawi, being sub-tropical and generally considered bimodal referring to the wet and dry season (1 November-31April, 1 May-31 October respectively) (Government of Malawi, 2017b). The average annual rainfall as shown in Figure 2b is 897 mm/year for WRA 1, and 1,331 mm/year for WRA 14 (Government of Malawi, 2011d). The highest rainfall in the Ruo catchment derives from the mountainous topography around Mount Mulanje 850 - >1,200mm/year (Government of Malawi, 2018a). The average annual temperature ranges from 19 to 26 °C in WRA 1 and 18 to 26 °C in WRA 14 (Government of Malawi, 2011d). Temperatures can drop to between 4 and 10°C for the months of May to August (the Malawi winter) and frost may even occur in isolated areas in June and July (Government of Malawi, 2016c). No average annual rainfall or temperature values were available for the wet and dry season.

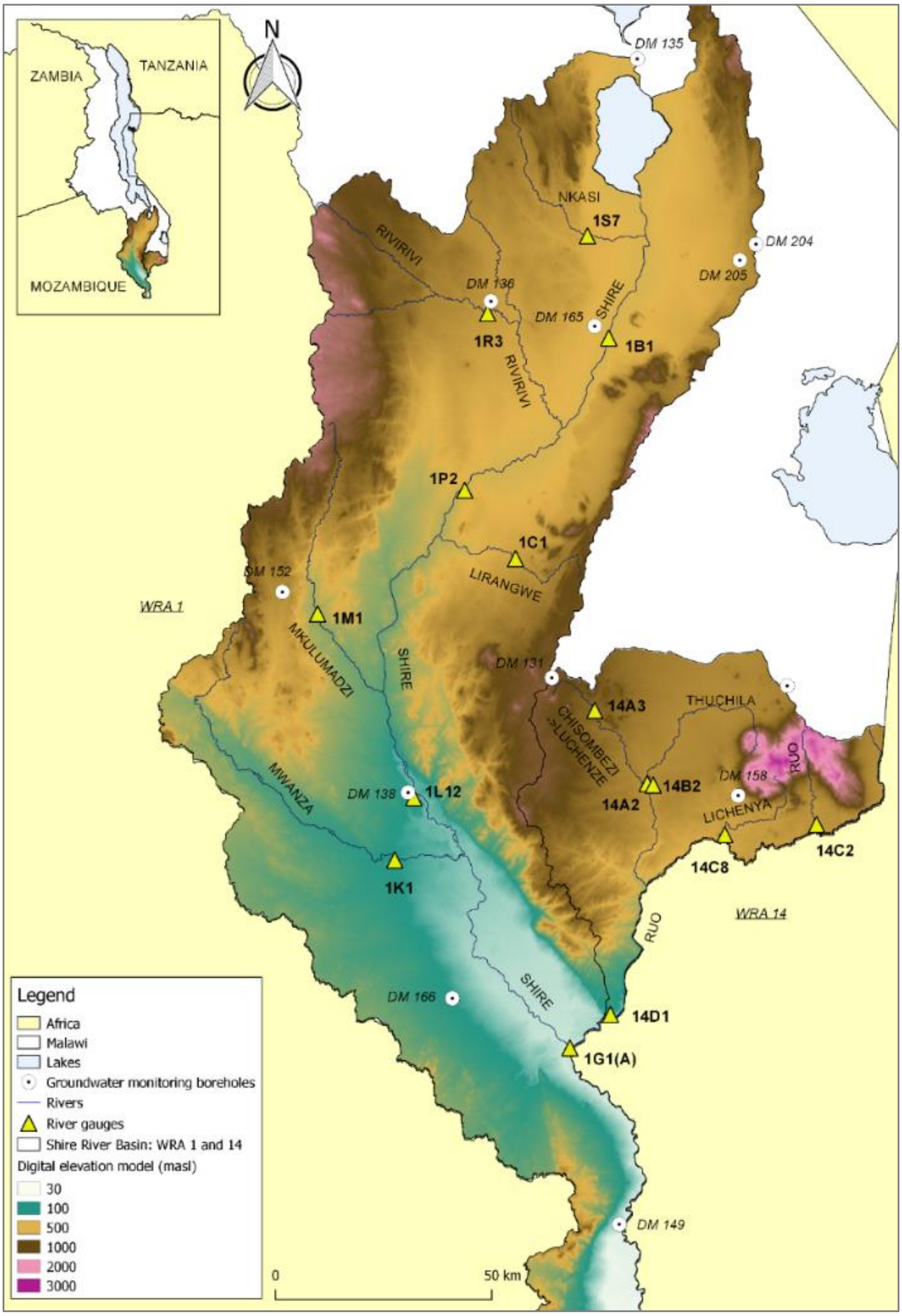
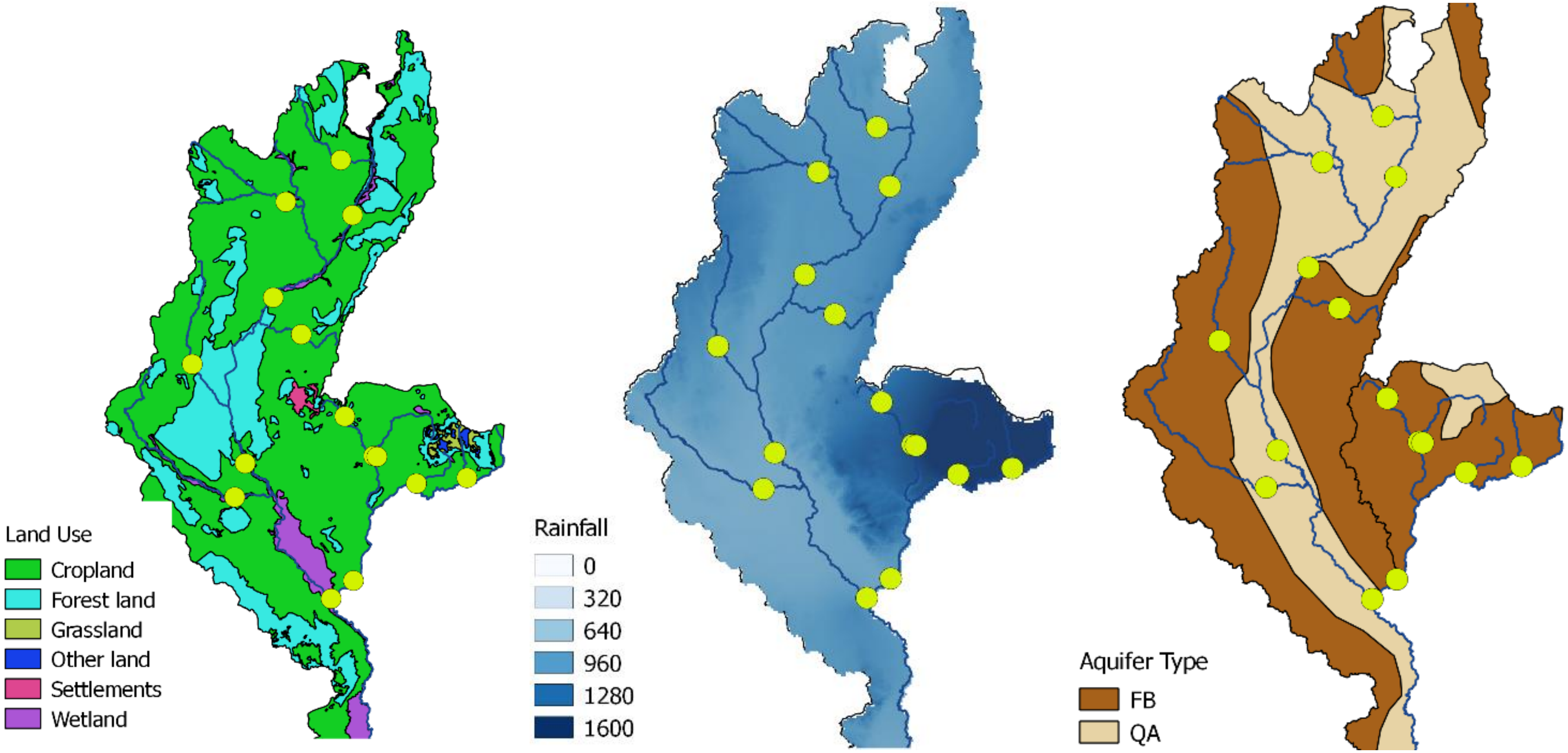


Figure 1 Location of the SRB (WRA 1; Shire catchment and WRA 14; Ruo catchment) in Malawi (insert) and digital elevation model of the SRB with rivers and river gauges in this study



(a) (b) (c)

Figure 2 (a) Land use map (Chimtengo et al., 2014), (b) Rainfall (mean annual), and (c) Aquifer types

[GIS files are freely available from the SRB Planning Portal (Government of Malawi, 2017c)

Aquifer types which have been identified in Malawi are alluvial aquifers, sedimentary aquifers and basement aquifers (fractured and weathered) (Government of Malawi, 2017b). Figure 2c shows the aquifer types in the SRB in a simplified format. The alluvium aquifer underlays the path of the Shire River, with additional coverage in the north and east. The fractured basement is present along the west of the basin, and to the east where it underlays most of the Ruo catchment (Government of Malawi, 2017c). More detailed hydrogeological maps of the area are available in the Malawi Hydrogeological and Water Quality Atlas 2018 (Government of Malawi, 2018a). Soil texture varies across the basin and includes clay, loam, sandy and several variations (Government of Malawi, 2017c). Recent studies outline that some of the aquifer units in the Shire River Basin are transboundary in nature as they are shared with Mozambique (Fraser et al., 2018).

Parameters in the basin are routinely monitored by Government bodies, however, with frequent flooding and budgetary constraints, the ability to collect comprehensive long-term continuous records has not been possible. Groundwater monitoring is carried out through a network of monitoring boreholes which were established by the Government of Malawi and managed by the Groundwater Division of the Department of Water Resource. Surface water is monitored by a network of river and lake gauges and managed by the Surface Water Division, and climate monitoring is carried out and managed by the Department of Meteorological Services. At present, there are 12 monitoring wells located in the Basin.

Further, a significant effort is currently being made by the Scottish Government Climate Justice Fund (CJF) Water Futures Programme, working in partnership with the Malawian Government, to locate all water points (and associated data) in the country using the Management Information System (MIS); mWater (Miller et al., 2018). Data is actively being used in several various research areas including the management of rural groundwater supply (Truslove et al., 2019), the impact of Stranded Assets for rural water supply (Kalin et al., 2019) and the design of groundwater-quality monitoring networks (Rivett et al., 2018). The most common occurring water points in the SRB appear to be boreholes, piped taps and dug wells, but can also include springs, rainwater, bottled water amongst others. To date (October 2019), 18,386 boreholes and 10,296 public taps have been mapped in the Basin.

2.2 Data

This study focused on data from a total of 15 river gauges within the SRB: comprising 9 gauges from WRA 1 and 6 gauges from WRA 14. Other gauges do exist; however, no data were obtained for them. Within WRA 1, the Shire river is monitored by four gauges; 1B1, 1G1 (A), 1L12 and 1P2. Several tributaries of the Shire are also monitored: the Rivirivi by 1R3, the

Nkasi by 1S7, the Mkurumadzi by 1M1, the Mwanza by 1K1 and the Lirangwe by 1C1. Within WRA 14, two gauges monitor the main Ruo river; 14C2 and 14D1. Two major tributaries of the Ruo are also monitored: the Lichenya by 14C8 and the Thuchila by 14B2. Further, the Luchenze (a tributary of the Thuchila) is monitored by 14A2, and the Chisombezi (a tributary of the Luchenze) is monitored by 14A3.

The Kamuzu Barrage is located on the upstream reach of the Shire and regulates the flow from the lake into the river (Government of Malawi, 2013b). The levels of Lake Malawi therefore highly influence the flows in the Shire River. For this reason, gauges on the Shire have been excluded from previous hydrological studies, for example during the development of a pilot water resources management software incorporating hydrological models in the area (UNESCO, 2004). However, for completeness and to explore all gauge data available, this study has chosen to include the gauges on the river Shire.

Daily flow rate data were available for each of the gauges as follows; 1B1 Shire (1948-2012), 1C1 Lirangwe (1951-2005), 1G1(A) Shire (1953-2009), 1K1 Mwanza (1951-1997), 1L12 Shire (1976-2010), 1M1 Mkurumadzi (1980-2008), 1P2 Shire (1952-2005), 1R3 Rivirivi (1952-2004), 1S7 Nkasi (1961-1997), 14A2 Luchenze (1954-2002), 14A3 Chisombezi (1962-2000), 14B2 Thuchila (1951-2003), 14C2 Ruo (1953-2008), 14C8 Lichenya (1959-2002) and 14D1 Ruo (1980-1991). Data coverage appears varied ranging from 11-65 years, however, it is expected to be sporadic and have missing values throughout. The data were obtained from the Surface Water Division of the Department of Water Resources of Malawi.

This study also examined groundwater levels in the Basin which are monitored via 11 monitoring boreholes at; Balaka Water Office (DM 136), Mtaja Water Office (GN 204), Ngabu Water Office (GN 166), Kaombe Dam (GN 205), Mwanza Prison (DM 152), Chikwawa Water Office (DM 138), M'manga School (GN 165), Mangochi Water Office (DM 135), Nansomba School (GN 158), Mulanje Water Office (DM 148) and Nsanje Water Office (DM 149). Data were available for each borehole from 2009-2015, however, the data is sporadic in nature. One of the original 12 boreholes constructed, one was vandalized shortly after completion in 2009/2010 and as such no data was available. Further, Nansomba School (GN 158) and Chikwawa Water Office (DM 138) did not have enough data for analysis. The Groundwater Division of the Department of Water Resources of Malawi provided the data.

2.3 Baseflow separation approach and statistical trend analysis

Baseflow separation was selected to analyze the river data and determine BFI. As the river data was sporadic, this study followed the approach set out in a recent study which demonstrated how to work with sporadic river data to quantify temporal variations in BFI

(Kelly et al., 2019b). The approach uses the BFI programme which implements the Institute of Hydrology's filtering method called the 'smoothed minima' procedure (Institute of Hydrology, 1980). Further information including the baseflow separation steps followed can be found in Kelly et al (2019b). The approach used in this study assumes that baseflow is derived entirely from groundwater discharge from the aquifer, however, it is appreciated that some flow may be also derived from interflow and other stored sources.

Three assessment periods selected for the baseflow separation were based on those used by the Malawi Water Resources Department: annual (1st November-31st October), the wet season (1st November-30th April), and the dry season (1st May-31st October).

The direction and significance of trends in the BFI series were determined by the non-parametric Mann-Kendal (MK) trend test (Mann, 1945; Kendall, 1975). The test is recommended for the analysis of trends in hydrometeorological variables by the World Meteorological Organisation (WMO) and is popular in the literature (MISSING:shu2012analysis, 2020; Zhang et al., 2016; Techamahasaranont et al., 2017). The test was applied using the statistical programme XLSTAT (Addinsoft, 2019). The following test parameters were adopted for the test: 'normal' MK test, 'exact p' method, ignore missing data' significance level of 1%. Further information on the selection of the test parameters can be found in Kelly et al. (2019b).

3. Results and Discussion

3.1 Seasonal behaviour of groundwater discharge to rivers

Average annual and seasonal BFI (wet and dry) for the gauges were determined and the results are presented in Table 1.

This study found average annual BFIs for the gauges as follows; 0.97, 0.95, 0.92 and 0.90 for Shire (1B1, 1G1(A), 1L12 and 1P2), 0.48 for Lirangwe (1C1), 0.38 for Mwanza (1K1), 0.64 or Mkurumadzi (1M1), 0.19 for Rivirivi (1R3), 0.32 for Nkasi (1S7), 0.43 for Chisombezi (14A2), 0.36 for Thuchila (14B2), 0.46 and 0.43 for Ruo (14C2 and 14D1), and 0.40 for Lichenya (14C8) (Table 1). Expressing the BFI as a percentage, these values indicate that annual groundwater discharge to the rivers ranges from approximately 19% (Rivirivi) to 97% (Shire). BFI is expected to vary across studies based on the difference in method and assessment periods used, however, its useful to consider the existing literature. For example, some of this study's findings are consistent with the average annual BFI sourced from the Malawian HYDATA system in use by the Malawi Surface Water Division, matching exactly or to the first decimal place. HYDATA reports an average annual BFI of 0.97 (1B1), 0.96 (1G1), 0.95 (1L12), 0.41

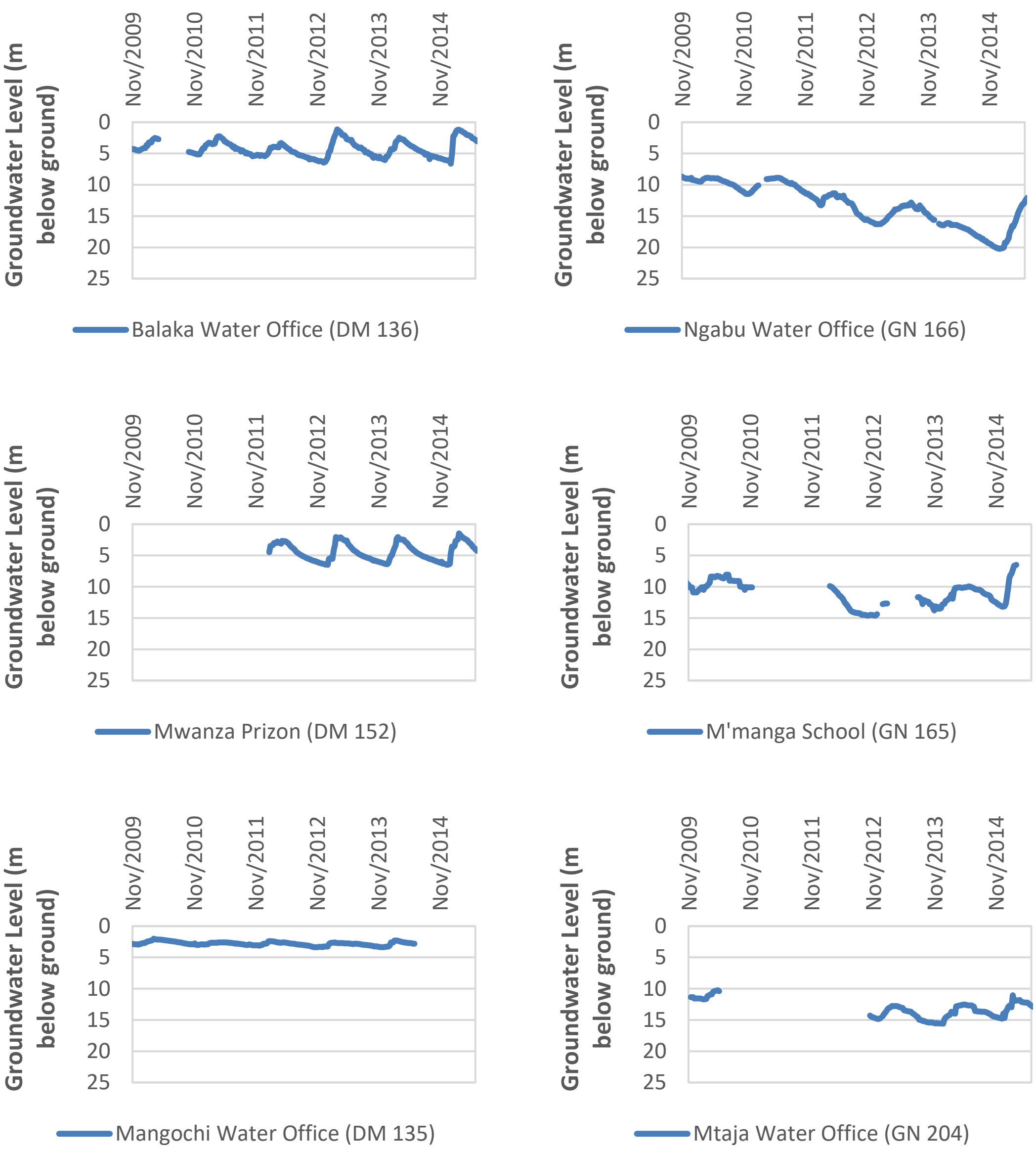
(14A2), 0.40 (14B2), 0.36 (14C2) and 0.51 (14D1). There was no BFI available from HYDATA for the other gauges. The results differ to global studies by UNESCO (2004) and Beck et al. (2013) who reported annual BFIs for Malawi in the range of 0.6 to 0.7 and 0.6 to 0.8 respectively. They also differ to a study by Chimtengo et al. (2014) who reported a BFI of 0.35 for 1R3 (Rivirivi) which is much higher than this studs BFI of 0.19. Based on this study's annual average BFI values, these rivers are considered perennial, that is, flowing year-round and as there is minimal rainfall in Malawi in the dry season, the dry season flow is expected to be sustained by groundwater discharge.

In addition to determining annual baseflow, it is now widely accepted and appreciated that baseflow should be determined on a seasonal basis (Kelly et al., 2019b; Bosch et al., 2017). This study presents the first findings on seasonal BFI in the SRB. For all gauges assessed, the results found minimal difference between the annual and the wet season BFI. In the dry season, except for 14C2 and 14C8 and the gauges on the Shire which are discussed below, all BFIs increased to over 0.75, or 75% of the dry season flow was attributed to groundwater discharge from the aquifer. For example, 14D1 had a BFI of 0.43 in the wet season increasing to 0.70 in the dry season. This increase in BFI in the dry season is indicative of permeable catchment geology, whereby the catchment stores water during the wet season with some discharge to the river, and the dry season, continues to discharge to the river to sustain flows when rainfall and surface runoff is reduced to a minimum (Kelly et al., 2019b). Under these conditions, we would expect to see increasing groundwater levels during the wet season as rainfall infiltrates the ground and recharges the groundwater table, and decreasing groundwater levels during the dry season, as rainfall declines to a minimum, and groundwater is used up. As such, evaluation of groundwater levels near the river gauges would help to provide support for the seasonal variations in BFI.

Table 1 Results of average annual and seasonal BFI analysis for the gauges in the SRB; Grouped into Shire River, Ruo River and tributaries

Gauge ID	**1B1**	**1P2**	**1L12**	**1G1(A)**	**14C2**	**14D1**	**14A3**	**14A2**	**14B2**	**1R3**	**1C1**	**14C8**	**1S7**	**1M1**	**1K1**
Data record	1948-2012	1952-2005	1976-2010	1953-2009	1953-2008	1980-1991	1962-2000	1954-2002	1951-2003	1952-2004	1951-2005	1959-2002	1961-1997	1980-2008	1951-1997
ANNUAL															
Average BFI	0.97	0.90	0.92	0.95	0.46	0.43	0.27	0.43	0.36	0.19	0.48	0.40	0.32	0.64	0.38
Minimum BFI	0.78	0.00	0.84	0.88	0.20	0.31	0.10	0.07	0.12	0.05	0.07	0.20	0.00	0.41	0.05
Maximum BFI	0.99	1.00	0.98	0.98	0.69	0.48	0.54	0.78	0.58	0.45	0.94	0.59	0.88	0.89	0.76
WET SEASON															
Average BFI	0.95	0.87	0.91	0.93	0.47	0.36	0.23	0.37	0.34	0.16	0.44	0.37	0.28	0.52	0.33
Minimum BFI	0.08	0.00	0.79	0.83	0.17	0.26	0.00	0.06	0.12	0.03	0.08	0.14	0.00	0.29	0.04
Maximum BFI	1.00	0.99	0.97	0.97	0.67	0.43	0.89	0.68	0.56	0.39	0.99	0.58	0.80	0.84	0.73
DRY SEASON															
Average BFI	0.98	0.93	0.96	0.98	0.49	0.70	0.81	0.87	0.74	0.87	0.85	0.53	0.76	0.87	0.76
Minimum BFI	0.85	0.00	0.88	0.90	0.15	0.51	0.13	0.62	0.00	0.51	0.00	0.12	0.00	0.49	0.24
Maximum BFI	1.00	1.00	1.00	1.00	0.75	0.79	0.97	0.97	0.97	0.96	0.99	0.79	0.98	0.99	1.00

Unfortunately, there was no groundwater monitoring boreholes near any of the gauges, all boreholes being located at least 2km away from any gauge. Groundwater level data at several monitoring boreholes did indicate seasonal fluctuations in line with the wet and dry season. The expected pattern is seen clearly over several hydrological years at Balaka Water Office (DM 136), Mtaja Water Office (GN 204), Ngabu Water Office (GN 166), Kaombe Dam (GN 205) and Mwanza Prison (DM 152), M'manga Water Office (GN 165) and Mulanje Water Office (DM 148) (Figure 3). Generally, at these boreholes, we see the groundwater levels increase during the wet season (November-April), and decrease during the dry season (May-October). In contrast, Nsanje Water Office (DM 149) showed no apparent seasonal fluctuations (Figure 4).



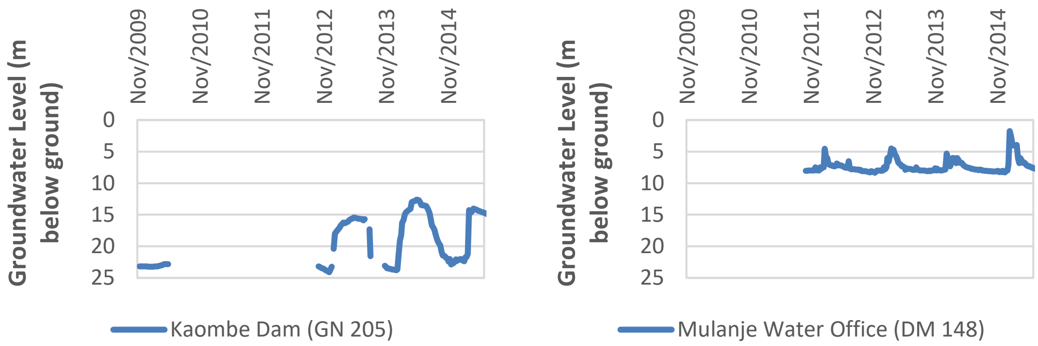


Figure 3 Groundwater monitoring boreholes in the SRB showing seasonal fluctuations in groundwater level between the wet season (1st November-30th April) and the dry season (1st May-31st October). Y-axis shows Groundwater Level (m below ground)

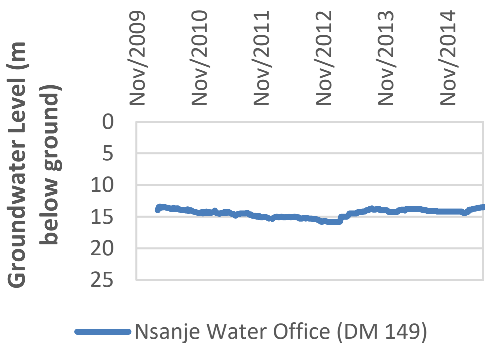


Figure 4 Groundwater monitoring borehole in the SRB with seasonal fluctuation between wet and dry season not apparent. Y-axis shows Groundwater Level (m below ground)

Gauges 14C2 and 14C8 do not see significant increases in the dry season BFI. The wet season BFI for 14C8; 0.37, increased to only 0.53 in the dry season. Similarly, the wet season BFI for 14C2; 0.47, increased marginally to 0.49. These results indicate that although water is being stored in the wet season, it's to a much lesser extent. The lower dry season BFI here, when compared to those over 0.75, can be attributed to spatial variations in the geology and rainfall which contribute to the control of baseflow. 14C8 drains a small part of the west side of Mount Mulanje and this area receives the highest rainfall in the Basin (>1,200mm/year) (Government of Malawi, 2018a) and 14C2 drains a large part of the eastern part of Mount Mulanje and also receives high rainfall.

Interestingly, all the gauges on the Shire river (1B1, 1G1(A), 1L12 and 1P2) show minimal variations in BFI between the annual, wet and dry season. This is attributed to the influence of Kamuzu Barrage which regulates the flow in the Shire river, and to a certain degree, the water levels of Lake Malawi (Government of Malawi, 2013b).

Overall, the BFI results display considerable variability within the annual and wet season BFI in all gauges, as shown by the minimum and maximum BFIs in Table 1.

3.2 Long term trends in groundwater discharge to rivers

This study presents the first comprehensive findings on detecting long term trends in BFI in the SRB. The MK test was used to identify statistically significant trends in the BFI and the results are presented in Table 2.

No trend in BFI was detected in the annual, wet or dry season data for gauge 1B1 (Shire), 1G1(A) (Shire), 1K1 (Mwanza), 1P2 (Shire), 1R3 (Rivirivi), 14A2 (Luchenze) and 14D1 (Ruo). The absence of a trend suggests that groundwater discharge to these rivers has remained stable over the assessment periods. A stable baseflow and feeding aquifer over a prolonged period suggest these catchments are well-managed catchment with minimal impacts from anthropogenic activities.

An increasing trend in BFI in the annual and wet season data was found at 1C1 (Lirangwe), 1S7 (Nkasi) and 14C8 (Lichenya), however, no trend was found in the dry season data. Further, an increasing trend in BFI in the annual and wet season data was found at 14C2 (Ruo), but interesting, a trend was also evident in the dry season data. These increases in BFI show that over the assessment period, the river has become more dependent on baseflow in the annual and wet season periods, which indicates that groundwater discharge to the river has increased. Such increases may be attributed to increases in groundwater levels arising from prolonged increases in rainfall (Ahiablame, Sheshukov, Rahmani and Moriasi, 2017), increases in forest cover or artificial recharge. Statistically, stationery trends in rainfall for the Southern Region of Malawi have been reported, however, it's noted that specific stations showed statistically significant increasing trends (Ngongondo et al., 2011b). An increase in baseflow associated with an increase in forest cover has also been reported in the Shire River catchment (1989-2002) when running land conversation scenarios, through use of a hydrological model and land cover mapping from satellite images (Palamuleni, 2009). It is unknown if there is any artificial recharge in the Basin.

In contrast, decreasing trends were seen in other gauges. For example, a decreasing trend in BFI for the annual and wet season data was found for 1L12 (Shire) and 14A3 (Chisombezi), and 1L12 also had a decreasing trend in the dry season data. 1M1 (Mukurumadzi) and 14B2 (Thuchila) had a decreasing trend in BFI for the wet season, however, no trend was found in the annual and dry season data. Decreasing trends in BFI shows a decrease in the proportion of the river which is baseflow. This can indicate an imbalance in the catchment system and indicates that groundwater discharge, and thus groundwater levels have been decreasing in these areas. Previous research has demonstrated that baseflow calculated from river data may be used as a proxy for changes in groundwater level elevation over time (Killian et al., 2019). Unfortunately, the quality and duration of the groundwater monitoring data as shown in Figure 3 and Figure 4 has been sporadic and sparse and as such it has not been possible to confirm these trends. Such decreases, especially in the dry season, are especially critical in the SRB where groundwater discharge to rivers is required to sustain dry season flows, albeit reduced flows.

Decreases in baseflow may be attributed to deforestation in the catchment (MISSING:shu2012analysis, 2020). For example, a decrease in mean annual baseflow associated with deforestation in the upper Shire River catchment from 1989-2002 has been previously reported (Palamuleni, Ndomba and Annegarn, 2011). There is also evidence of extensive deforestation in the SRB with the annual deforestation rate estimated at 2.7% (Government of Malawi, 2016c). Further studies, although not specifically targeting baseflow, investigated how deforestation has impacted on hydrological regimes in the SRB. For example, Chimtengo (Chimtengo et al., 2014) showed increases in high flows, decrease in low flows, and an increase in zero flow days in the Rivirivi catchment (1992-2008) and attributed much of these changes to deforestation in the area. Contrastingly, the study also showed that the Mpira River (a headwater stream of the Rivirivi River) had a more stable BFI regime due to more sustainable catchment practices. Over abstraction of groundwater can also cause declines in the groundwater table and thus groundwater discharge to the river (Fraser et al., 2018). This scenario is presumed in Malawi due to the tens of thousands of water points which now exist across the country (Fraser et al., 2018; Miller et al., 2018; Rivett et al., 2018) although little evidence could be found in the literature to support this claim.

Table 2 Mann Kendall statistical results for BFI for gauges in the SRB; Grouped into Shire River, Ruo River and all Tributaries

Gauge ID	**1B1**	**1P2**	**1L12**	**1G1(A)**	**14C2**	**14D1**	**14A3**	**14A2**	**14B2**	**1R3**	**1C1**	**14C8**	**1S7**	**1M1**	**1K1**
Data Record	1948-2012	1952-2005	1976-2010	1953-2009	1953-2008	1980-1991	1962-2000	1954-2002	1951-2003	1952-2004	1951-2005	1959-2002	1961-1997	1980-2008	1951-1997
ANNUAL															
MK Statistic 'S'	-276	-66	-26	196	414	-6	-120	10	-89	-39	138	191	168	-20	-79
Trend (1% sig. level)	○	○	↓	○	↑	○	↓	○	○	○	↑	↑	↑	○	○
WET SEASON															
MK Statistic 'S'	-209	-85	-63	196	338	-6	-153	1	-141	-63	171	283	174	-39	-131
Trend (1% sig. level)	○	○	↓	○	↑	○	↓	○	↓	○	↑	↑	↑	↓	○
DRY SEASON															
MK Statistic 'S'	-318	-102	-40	190	515	-3	54	150	-83	-47	135	195	133	-28	-159
Trend (1% sig. level)	○	○	↓	○	↑	○	○	○	○	○	○	○	○	○	○

- where ○ indicates no trend, ↑ indicates an increasing trend and ↓ indicates a decreasing trend

The above BFI results show how wet season and dry season BFI can vary significantly from annual values. They also provide evidence of long-term behavioural changes in groundwater discharge to rivers in the SRB over the assessment period. These findings in the seasonal and long-term behaviour of groundwater discharge to rivers have important implications for practice and in future scheme appraisals linked to water resources in the Basin. For example, BFI is a key engineering parameter used in environmental flow calculations, which are required to protect the ecological health of a river. Currently, there are multiple dams proposed in the Basin, as outlined in the National Irrigation Plan. Proposed designs appear to have been based on annual baseflows and would benefit from updating their calculations to consider the seasonal differences.

The long-term sustainability of the catchment should be evaluated in areas which have indicated a decrease in groundwater levels. The results should also be of interest to the Malawian energy sector, specifically the hydropower schemes of Kapachira I and II, located in close proximity to gauge 1L12 which showed a decreasing trend in BFI (Government of Malawi, 2016c). Finally, these results add to current knowledge and understanding of baseflow and groundwater discharge to rivers in the SRB. This will be particularly relevant to the new National Water Resources Authority and the SRB Management Programme who are both working in support of sustainable management and development of water resources.

4. Conclusion

This study characterizes groundwater discharge to rivers in the Shire River Basin, Malawi, and provides the first comprehensive study of baseflow in the Basin.

The results show that baseflow is an important component of river flow in the Basin which varies both spatially and temporally. For example, average annual BFI ranged from 0.19 (Rivirivi) to 0.97 (Shire), average wet season BFI ranged from 0.23 (Chisombezi) to 0.95 (Shire), and average dry season ranged from 0.49 (Ruo) to 0.98 (Shire). Baseflow in especially important to river flow in the dry season, as evidenced by dry season BFI found to be >0.75 for most gauges, indicating 75% of the total river flow is being derived from baseflow from groundwater. This highlights the importance of groundwater in sustaining dry season river flows, which are critical for water supply when rainfall and surface runoff are reduced to a minimum during these months. Several gauges, however, did not see an increase in dry season BFI when compared to the annual and wet season BFI. For example, the dry season BFI found for 14C2 (0.53) only showed a slight increase from the wet season BFI (0.37), and similarly, for 14C8, the dry season BFI (0.49) was only slightly higher than the wet season BFI (0.47). The similarity here between the wet season and the dry season BFI, and the lower dry season BFI when compared to the other gauges, emphasizes the dynamic behaviour of baseflow under the influence of natural and anthropogenic factors which vary from in time and space. Long term behavioural changes in the baseflow were evident across the annual, wet and dry season periods. Such changes in baseflow indicate changes to the water cycle and the decreasing trends found here (1L12, 14A3, 14B and 1M) may be considered a proxy indicator of decreasing groundwater levels in the area. This will be of interest to the Government of Malawi, specifically the National Water Resources Authority who is responsible for sustainable catchment management of both surface water and groundwater resources in the Basin.

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6.3 Further Discussion

The BFI results template presented at the end of Chapter 5 was also used in this study to record the BFI results. The raw results tabs have not been included in the thesis but can be requested from the CJF Water Futures Programme. However, for consistency with the supporting material contained within Chapter 5, the summary tab of the BFI results spreadsheets has been presented in Appendix C. It shows the results of the annual and seasonal BFI analysis (tabular) for the 15 river gauges in the study.

6.4 Summary

In this chapter, the SRB was used as a case study to test the usefulness of the research approach set out in Chapter 5 for quantifying temporal variations in BFI on a larger scale catchment. Like the Bua Catchment, the river data was sporadic, but the approach allowed the determination of annual and seasonal BFI and identification of long-term trends in the BFI data for 15 river gauges in the basin.

This research output has important implications for sustainable water resources management in the basin. The Shire River provides over 98% of Malawi's electricity and plays a major role in maintaining the economy of the country. Two of the two hydropower schemes (Kapachira I and II) are located close to river gauge L12 which showed a decreasing trend in annual and seasonal BFI over the assessment period (1976-2010). This indicates long term behavioural changes in the baseflow and thus the groundwater storage in the area. These results could provide new insight into the sustainability of the hydropower schemes. The Shire River also provides water for huge areas of irrigated land for agriculture and for piped municipal surface water supplies. This research output provides new quantifiable data on the role that groundwater plays in sustaining rivers flows in the catchment and how it has changed over time. This is particularly important to considerate in water supply studies to ensure projections for future water supplies are accurate. Its recommended that this research output is considered by the SRBMP which is focused on the sustainable management and development of water resources in the basin. The second phase of the project is due to commence soon and will represent a significant investment in the SRB. This research output can promote that groundwater and surface water resources must be considered together to ensure sustainability. The consequences of not considering the influence of temporal variations in baseflow could be devastating for the water supply for the estimated 5 million people which currently live in the catchment.

Further, this research output has important implications for sustainable water resources management of transboundary waters which Malawi shares with other countries. Transboundary waters are considered aquifers and lake and river basins which are shared by two or more countries (United Nations, 2020). A recent study by Fraser et al. (2018) identified multiple transboundary aquifer units along the Southern border of Malawi which are shared with Mozambique. As these units lie where the Shire River joins the Zambezi River, the river and groundwater are considered to have transboundary nature as they are inherently connected. Research work investigating the development and application of an approach for conjunctive water management in the Shire transboundary river-aquifer system is ongoing and could benefit from this research output (Southern Africa Groundwater Management Institute, 2017).

The application of the approach at a larger catchment scale was considered a success. Next, further investigation is required to demonstrate if the approach can be scaled up and applied to a national scale. This is accomplished in the next chapter using Malawi as a case study.

Chapter 7 Malawi

7.1 Introduction

The previous chapter demonstrated, using the Shire River Basin, the application of the research approach on a larger regional scale catchment. The results showed that the approach was successful and generated important new knowledge on the behaviour of baseflow in the basin.

This chapter scales the approach up to the National scale using Malawi as a case study. An understanding of baseflow at a national scale is needed given the dynamic and ever-changing variations in baseflow conditions across catchments. Malawi is considered a good representation of other African countries given the variability within its hydrological characteristics and so will be an important example for other countries aiming to conduct a similar assessment. Malawi has a subtropical climate which is relatively dry and strongly seasonal, and it has variations in topography ranging from high mountainous areas to low land floodplains. Generally, the north and south have different characteristics, for example, the south is drier than the north and receives less rainfall. The south is more densely populated than the north and central regions which has resulted in greater demands on water supply and water scarcity issues. The catchments in the south suffer more from anthropogenic impacts such as deforestation and over abstraction of groundwater. Further, Lake Malawi, one of the country's most economically valuable water resources, is positioned so that the catchments in the central and northern regions flow into the lake, whereas the south of Malawi is dominated by the Shire River which flows from the lakes only outlet.

This research output was accomplished through one paper published in a peer-reviewed journal, American Journal of Water Science and Engineering, as follows:

Kelly, L., Bertram, D., Kalin, R.M., Ngongondo, C, Sibande, H. 2020. A National Assessment of Groundwater Discharge to Rivers: Malawi. American Journal of Water Science and Engineering. Special Issues: 21st Century Water Management, 6 (1), p.39-49.

The published paper is presented in the following section and the author contributions were as follows: Conceptualization, L.K.; Formal analysis, L.K.; Funding acquisition, R.M.K.; Methodology, L.K.; Resources, H.S.; Supervision, R.M.K. and D.B.; Validation, L.K., R.M.K.; Visualization, L.K.; Writing—original draft, L.K.; Writing—review & editing, L.K., C. N, H.S. and R.M.K.

7.2 Paper

A National Scale Assessment of Temporal Variations in Groundwater Discharge to Rivers: Malawi

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Abstract: This study presents the first national-scale assessment of temporal variations in the Baseflow Index (BFI) for watercourses in Malawi. A proxy indicator of groundwater discharge to rivers, the BFI is a measure of the ratio of long term baseflow to total river flow and is a key parameter for sustainable water resources management. The smoothed minima technique was applied to river flow data from 68 river gauges across Malawi (data records ranging from 11-64 years). The long-term average annual BFI for each gauged site was determined, as well as seasonal values of BFI. The Mann Kendal (MK) statistical test was used to identify trends in the BFI. Average annual BFI was 0.57, average wet season BFI was 0.52 and average dry season BFI was 0.97. This indicates that 57%, 52% and 97% of the total river flow is derived from groundwater and other stored sources in the annual, wet and dry season periods respectively. These results show that baseflow in Malawi follows a seasonal pattern with minimal differences between the average annual and average wet season BFI; however, significant increases are generally seen in the dry season BFI. The results also found long-term behavioural changes in BFI across all periods. Annually, 74% showed no trend, 10% showed an increasing trend and 16% showed a decreasing trend. The wet season trends showed similar values with 66% showing no trend, 16% showing an increasing trend and 18% showing a decreasing trend. In contrast, for the dry season, 93% showed no trend, 1%

showed an increasing trend and 6% showed a decreasing trend. The dataset determined in this study can support sustainable water resources management in Malawi and contribute to measuring its progress towards Sustainable Development Goal 6.

Keywords: Baseflow, BFI, Groundwater Discharge, Malawi, SDG6

1. Introduction

The provision of reliable hydrological data continues to be a challenge for many countries across the globe (Singh et al., 2019; Kelly et al., 2019b). In the developing world context, this is attributed to several factors including insufficient budgets, inability to attract, train and retain qualified staff and declining maintenance of hydrological stations (World Bank, 2018). Where hydrological data does exist, it is often of poor quality, characterized by missing data and is generally sporadic (Kelly et al., 2019b; Houghton-Carr, Fry and Wallingford, 2006). Irrespective of the challenges, efforts continue to focus on providing reliable data to underpin sustainable water resources management.

One key parameter determined from hydrological data is baseflow. Baseflow is the component of river flow derived from groundwater and other stored sources which may include slow-moving interflow and connected wetlands and lakes (Tallaksen and Van Lanen, 2004; Bosch et al., 2017). Hydrograph analysis is frequently used to determine baseflow by separating the total river flow in a hydrograph into its fast-moving component (surface runoff) and its slow-moving component (baseflow). Baseflow is commonly expressed as the Baseflow Index (BFI) which is a unitless parameter, ranging from near 0.0; indicating a river with a relatively low proportion of baseflow, to close to 1.0; indicating a river with a high proportion of baseflow (Kelly et al., 2019b; Tallaksen and Van Lanen, 2004). Baseflow has been traditionally used as a proxy indicator of groundwater discharge (Kelly et al., 2019a; Bosch et al., 2017). The determination of baseflow, and in particular its temporal and spatial variations, is increasingly considered to underpin many holistic sustainable water management approaches such as integrated water resource management (IWRM) and conjunctive water use (Brodie et al., 2007a; International Hydrological Programme of UNESCO, 2006). Specifically, baseflow and BFI data are used in low flow studies (Tallaksen and Van Lanen, 2004), environmental flow calculations (Hughes and Hannart, 2003), hydropower generation (Beck et al., 2013) and as a groundwater availability indicator (Ngongondo, 2006). Although the provision of baseflow data is pertinent to all countries, it is especially crucial for countries which experience long dry seasons with limited rainfall and where rivers depend on groundwater to sustain flows as a result of the minimal surface runoff.

One example is Malawi in Southern Africa (Figure 1). To date, there have been few studies published on baseflow in the country and those that do exist are limited in their spatial and temporal coverage (Ngongondo, 2006; UNESCO, 1997; Kumambala, 2010). A summary of the existing work can be found in Kelly et al. (2019b). Recent studies have sought to promote the importance of baseflow research in Malawi and provide comprehensive coverage of several key catchments. For example, Kelly et al. (2019b) investigated baseflow in the Bua catchment in Central Malawi and quantified annual and seasonal BFI. Generally, the study found minimal difference between the average annual and wet season BFI, however, the dry season BFI was >0.94 across all gauges highlighting the importance of baseflow in maintaining dry season flows. This behavioural pattern was also mirrored in a study on baseflow in the Shire River Basin in Southern Malawi which found minimal difference between the annual and wet season BFI, but with the majority of dry season BFIs increasing to >0.75 (Kelly et al., 2019a). Further, both studies explored long term trends in the BFI and found mixed results. For example, some stations observed no statistically significant trends, some seen increasing trends and some seen decreasing trends. The variation in trends observed shows how the baseflow and groundwater discharge to the rivers is remaining stable in some catchments but changing over time under the influence of natural and anthropogenic factors in others. There remains a gap in the literature to quantify seasonal and long-term trends in BFI on a national scale in Malawi.

Therefore, the main goal of this study is to present a national-scale assessment of temporal variations in groundwater discharge in Malawi using the BFI approach. Specifically, the objectives were to 1) quantify the annual and seasonal BFI and 2) evaluate long term trends in the BFI across the country. The findings of this study are expected to provide crucial baseline data which will support sustainable water resources management in the country.

2. Materials and Methods

2.1 Study area

This study focused on Malawi; a country known as the warm heart of Africa (Figure 1). It is a landlocked country, bordered by Mozambique to the east, south and west, Zambia to the west, and Tanzania to the north and east. Malawi is divided into 17 Water Resource Areas (WRAs), where each WRA represents one hydrological basin as follows; WRA 1 (Shire), WRA 2 (Lake Chilwa), WRA 3 (South West Lakeshore), WRA 4 (Linthipe), WRA 5 (Bua), WRA 6

(Dwangwa), WRA 7 (South Rukuru/North Rumphi), WRA 8 (North Rukuru), WRA 9 (Songwe/Lufira), WRA 10 (South East Lakeshore), WRA 11 (Lake Chiuta), WRA 12 (Likoma Island), WRA 13 (Chizumulu Island), WRA 14 (Ruo), WRA 15 (Nkhota-Hota Lakeshore), WRA 16 (Nkhota-Bay Lakeshore) and WRA 17 (Karonga Lakeshore) (Figure 1). The catchment area for all WRAs combined is approximately 94,000km^2 which excludes the area of Lake Malawi (Government of Malawi, 2017a).

Malawi is covered extensively by surface water bodies. Major rivers in Malawi include the Shire, Bua, Linthipe, Songwe, North Rukuru, South Rukuru, Dwangwa and the Ruo. There are numerous minor tributaries associated with each river. There are four major lakes in Malawi (Lake Chilwa, Lake Chiuta, Lake Malombe and Lake Malawi) with a combined area of approximately 23,855km^2 within the Malawian territory (Government of Malawi, 2017a). The combined area of the lakes including the Mozambique territory is approximately 29,600 km^2 (Government of Malawi, 2017a). The most notable lake is Lake Malawi which is a major source of water for lakeshore communities and plays a crucial role in the national tourism, transport, agriculture and fisheries industries (Government of Malawi, 2011d). It is the biggest freshwater lake in Malawi, the 3rd biggest in Africa and the 8th biggest in the world. There is only one outflow from Lake Malawi, the Shire River, which is a tributary of the Zambezi in Mozambique. The Shire River supports extensive areas of irrigation together with the water supply to Malawi’s second-largest city, Blantyre, and three hydropower schemes which supply approximately 98% of the national electricity output (Government of Malawi, 2011d). Transboundary rivers in Malawi include the Songwe, Ruo and Shire (Fraser et al., 2018). Despite the number and widespread nature of surface water bodies, the availability and reliability of surface waters are highly variable due to climatology extremes between the wet and the dry season and from year to year (Government of Malawi, 2011e).

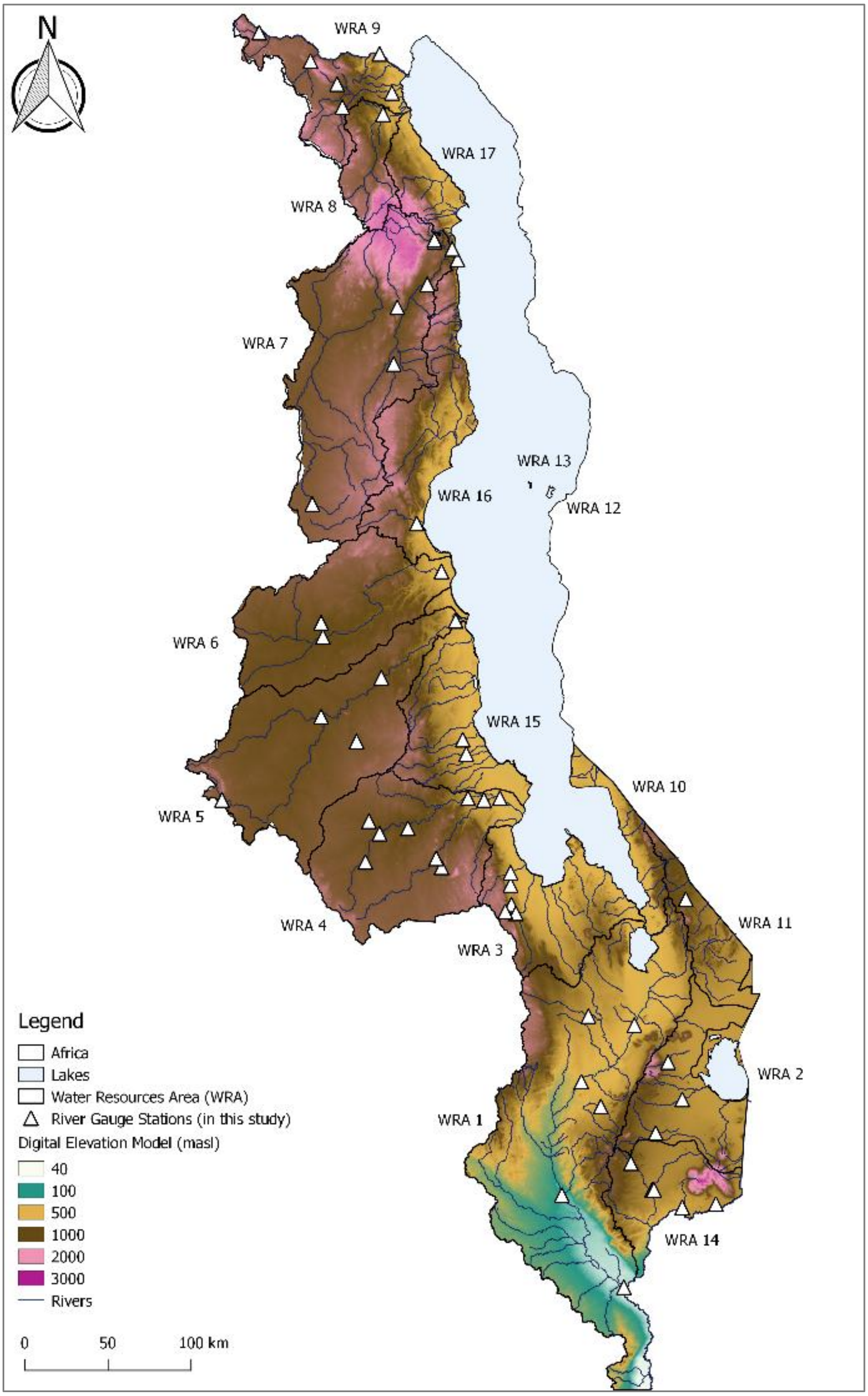

Figure 1 Digital elevation model of Malawi (obtained from the Government of Malawi) with Water Resource Areas, rivers, lakes, and river gauging stations used in this study

The topography of Malawi is shown in Figure 1. There are four main physiographic zones in the country with varying elevations; the highlands (1,500 to 3,000 masl), the plateau (900 to 1,500 masl), the escarpment and the rift valley floor (500masl at the Lakeshore to about 50masl in the Lower Shire Valley) (Government of Malawi, 2011e). The highlands comprise forest vegetation and grassland, the plateau has broad, undulating plains, and grass-covered swampy valleys, and the escarpment is the boundary between the plateau and the rift valley which is a major faulting area. The escarpment is largely protected forests and game reserves, and the rift valley is generally mixed woodland. Malawi is still predominately an agricultural-based society and as such agriculture dominates most of the land use (Government of Malawi, 2018c). There are also many designated areas in the form of game reserves, forest reserves and national parks. Wetlands also occur across the country with the most notable being the Elephant marshes in the South.

Malawi's climate is sub-tropical being relatively dry and strongly seasonal. There are two distinct seasons; the wet season and the dry season (1 November-31 April, 1 May-31 October respectively) (Government of Malawi, 2017a) with 95% of the annual rainfall occurring in the wet season. The average annual rainfall for Malawi depends on the topographic and climatic conditions and ranges from 700 to 2,400mm with a mean annual rainfall of 1,095mm (Government of Malawi, 2018a). Evaporation in the dry season is only slightly higher than in the wet season. Further information on the climatic characteristics of Malawi can be found in the literature (Zuzani et al., 2019; Ngongondo, Xu, Gottschalk and Alemaw, 2011a).

Groundwater is the main source of water supply for the rural populations in Malawi as well as several urban populations. Aquifer types which have been identified in Malawi are alluvial aquifers, sedimentary aquifers and basement aquifers (Government of Malawi, 2018a). The basement aquifers underlie at least 80% of the country and comprise both fractured and weathered aquifers. Detailed geological and hydrogeological maps of Malawi including groundwater occurrences and flow regimes and descriptive texts are available in the Malawi Hydrogeological and Water Quality Atlas 2018 (Government of Malawi, 2018a). The atlas was developed by the Ministry of Agriculture, Irrigation and Water Development through the National Water Development Programme and the Shire River Basin Management Programme funded by the World Bank and provide a vital data source.

Water resources management in Malawi is currently carried out by different ministries and institutions, for example, the Ministry for Water Development is primarily responsible for the management of national water resources and the newly formed National Water Resources Authority (NWRA) is responsible for the regulation and promotion of IWRM.

Further, regional water boards possess a lower level of responsibility and other stakeholders which also play a role include nonprofit organizations, research institutions and the private sector.

Parameters (i.e. groundwater, river flow) in Malawi are routinely monitored by Government bodies, however, long term continuous datasets are limited due to budgetary constraints (Kelly et al., 2019a). There is no known monitoring of baseflow currently carried out in Malawi, however, it is known to play an important role in several Malawian rivers with dry season flows reported to comprise 90% baseflow in some river reaches (Kelly et al., 2019a; b).

2.3 Data

This study focused on data from 68 river gauging stations in Malawi. More gauging stations do exist; however, data could not be obtained. The 68 stations comprised a varied number of stations within each WRA; WRA 1 (9), WRA 2 (3), WRA 3 (5), WRA 4 (9), WRA 5 (6), WRA 6 (3), WRA 7 (10), WRA 8 (1), WRA 9 (7), WRA 11 (2), WRA 14 (6), WRA 15 (2), WRA 16 (3) and WRA 17 (2). Currently, WRA 10, 12 and 13 do not have any river gauging stations.

Daily flow rate data were available for each station as shown in Table 1. Data coverage appears varied ranging from 11-64 years with an average of 42 years and it is expected to have missing values throughout. The data was provided by the Surface Water Division of the Department of Water Resources of Malawi.

Figure 1 shows the location of the river gauging stations. For clarity the associated gauge IDs have not been included on the map, instead, the gauges can be viewed via the mWater platform at

https://share.mwater.co/v3/console_link/02f661229dbc41ca9d038de79f668fd2?share=a7de4a5e48dc4245abb595f2d94b9b75 Co-ordinates could not be obtained for gauges 7E2, 9B5, 11A6, 16F1, 16F2, 17C6 and 17C10, and as such are not shown in Figure 1 or the mWater map, however, results are available.

Comprehensive baseflow assessments have previously been completed for the gauges in WRA 5 (Kelly et al., 2019b) and WRA 1 and 14 (Kelly et al., 2019a). Baseflow assessments for the gauges in WRA 3 and WRA 4 have been included in the work of Banda et al. (2019). As they form part of the overall national assessment these gauges have been included here for completeness.

Table 1 Daily flow rate data available for the 68 river gauging stations in Malawi

Gauge ID	River Name	Data Record
1B1	Shire	1948/1949-2011/2012
1C1	Lirangwe	1951/1952-2004/2005
1G1 (A)	Shire	1953/1954-2008/2009
1K1	Mwanza	1951/1952-1996/1997
1L12	Shire	1976/1977-2009/2010
1M1	Mkurumadzi	1980/1981-2007/2008
1P2	Shire	1952/1953-2004/2005
1R3	Rivirivi	1952/1953-2003/2004
1S7	Nkasi	1961/1962-1996/1997
2B22	Thondwe	1960/1961-2006/2007
2B33	Namadzi	1961/1962-2009/2010
2C3	Domasi	1958/1959-2009/2010
3E1	Nadzipokwe	1953/1954-2009/2010
3E2	Namikokwe	1957/1958-2002/2003
3E3	Livulezi	1956/1957-2007/2008
3E5	Namikokwe	1957/1958-2008/2009
3F3	Nadzipulu	1957/1958-2003/2004
4B1	Linthipe	1953/1954-2008/2009
4B3	Linthipe	1957/1958-2007/2008
4B4	Diamphwe	1957/1958-2009/2010
4B9	Linthipe	1974/1975-2009/2010
4C2	Lilongwe	1957/1958-2009/2010
4C11	Nanjiri	1985/1986-2009/2010
4D4	Lilongwe	1953/1954-2008/2009
4D24	Lilongwe	1990/1991-2004/2005
4E2	Lingadzi	1959/1960-2004/2005
5C1	Bua	1957/1958-2008/2009
5D1	Bua	1958/1959-2006/2007
5D2	Bua	1953/1954-2004/2005
5D3	Mtiti	1958/1959-2002/2003
5E6	Bua	1970/1971-2007/2008
5F1	Rusa	1964/1965-2004/2005
6C1	Dwangwa	1952/1953-2009/2010
6C5	Mpasadzi	1965/1966-2000/2001
6D10	Dwanga	1985/1986-2009/2010
7A3	South Rukura	1955/1956-2007/2008
7D8	Lunyangwa	1952/1953-2007/2008
7E2	South Rukuru	1956/1957-1997/1998
7F1	Runyina	1955/1956-1997/1998

Gauge ID	River Name	Data Record
7F2	South Rumphi	1956/1957-2007/2008
7G14	South Rukuru	1957/1958-2006/2007
7G18	South Rukuru	1985/1986-2008/2009
7H1	North Rumphi	1955/1956-2007/2008
7H2	Kaziwiziwi	1952/1953-2007/2008
7H3	North Rumphi	1971/1972-2006/2007
8A5	North Rukuru	1968/1969-2008/2009
9A2	Lufira	1953/1954-2009/2010
9A4	Lufira	1958/1959-2007/2008
9A5	Kalenje	1970/1971-2006/2007
9B3	Kaseye	1970/1971-2007/2008
9B5	Hanga	1979/1980-2003/2004
9B6	Songwe	1981/1982-2007/2008
9B7	Songwe	1985/1986-2011/2012
11A6	Lusangwisi	1976/1977-1997/1998
11A7	Masongola	1976/1977-1997/1998
14A2	Luchenza	1954/1955-2001/2002
14A3	Chisombezi	1962/1963-1999/2000
14B2	Thuchila	1951/1952-2002/2003
14C2	Ruo	1953/1954-2007/2008
14C8	Lichenya	1959/1960-2001/2002
14D1	Ruo	1980/1981-1990/1991
15A4	Chirua	1970/1971-1999/2000
15A8	Lingadzi	1960/1961-2009/2010
16E6	Dwambadzi	1972/1972-2008/2009
16F1	Limphasa	1970/1971-1990/1991
16F2	Luweya	1952/1953-1993/1994
17C6	Wovwe	1969/1970-1992/1993
17C10	Hara	1974/1975-1988/1989

2.3 Baseflow separation approach and statistical trend analysis

Baseflow separation, which is a type of hydrograph analysis, was used in this study to determine the BFI from the river data. Specifically, the technique used to perform the baseflow separation was the ‘smoothed minima’ filtering procedure developed by the Institute of Hydrology (Institute of Hydrology, 1980). The programme chosen to implement this procedure was the BFI programme (Tallaksen and Van Lanen, 2004; Morawietz, 1997) as recommended in Kelly et al. (2019b) based on various criteria which were chosen to facilitate the exchange of knowledge with the Government of Malawi. The tool is ‘automated, easily accessible, free to obtain and operate, requires minimal training to use and is capable of selecting seasonal periods from input data to quantify BFI' (Kelly et al., 2019b).

The river data in this study was characterized by missing data throughout and this study followed the steps recommended in Kelly et al. (2019b) to perform the baseflow separation using the BFI programme. The main assumption with baseflow separation is that it assumes that interflow is negligible and that baseflow is derived entirely from groundwater discharge from the aquifer.

The assessment periods selected were annual and seasonal periods defined by months; annual (1st November-31st October), the wet season (1st November-30th April), and the dry season (1st May-31st October). These periods are those used by the Government of Malawi and in recent baseflow studies for Malawi.

As recommended by the World Meteorological Organisation (WMO), the Mann-Kendal (MK) trend test (Mann, 1945; Kendall, 1975) was used to identify statistically significant trends in the BFI data. The statistical programme XLSTAT was used to apply the test (Addinsoft, 2019).

To promote the exchange of knowledge with the Government of Malawi and other stakeholders, the free data management platform 'mWater' was used in this study to share information where possible. Used in over 160 countries, the main goal of mWater is to make data 'sharable and actionable' by digital monitoring (mWater, 2019). It is currently being promoted as Malawi's preferred online Management Information System (MIS) for analyzing significant volumes of water and sanitation data in Malawi (Miller et al., 2018). The Climate Justice Fund (CJF) Water Futures Programme funded by the Scottish Government, is working in partnership with the Malawian Government to develop the MIS for the rural sector and long term strategic management of the water, sanitation and hygiene (WASH) sector infrastructure in Malawi (Kalin et al., 2019). The tool is building a complete assess register of water infrastructure to support the Government achieve Sustainable Development Goal 6 to 'ensure availability and sustainable management of water and sanitation for all. mWater data is actively being used in several ongoing research areas including the management of rural groundwater supply (Truslove et al., 2019), the impact of stranded assets for rural water supply (Kalin et al., 2019) and the design of groundwater-quality monitoring networks (Rivett et al., 2018). As such, an opportunity was seen to initiate the inclusion of baseflow. Further details on the design and development of the mWater MIS in Malawi are provided in Miller et al. (2018).

3. Results and Discussion

3.1 Average annual and seasonal BFI for river gauging stations across Malawi

The long-term average annual and seasonal (wet and dry) BFI values for the 68 gauging stations across Malawi are shown in Figure 2 and Table 2. The results have also been shared on the mWater platform and can be accessed at https://share.mwater.co/v3/console_link/02f661229dbc41ca9d038de79f668fd2?share=a7de4a5e48dc4245abb595f2d94b9b75 The results show that baseflow varies spatially and temporally across Malawi. For example, the results found an average annual BFI for Malawi of 0.57, an average wet season BFI of 0.52 and an average dry season BFI of 0.97. This indicates that on average, 57%, 52% and 97% of the total river flow across Malawi is derived from baseflow from groundwater for the annual, wet and dry season respectively. From this, we can generalize that baseflow behaviour across Malawi follows a distinct seasonal pattern characterized by minimal difference between the annual and wet season baseflow, but with a significant increase in the dry season.

Such a broad generalization of baseflow, although useful, is often limited in application. The BFI results display considerable variability within the annual and wet season BFI in all gauges, as shown by the minimum and maximum BFIs in Figure 2 and Table 2. The minimum and maximum averages found were 0.17-0.97 (annual), 0.16-0.95 (wet season) and 0.49-0.98 (dry season). These variations highlight the dynamic nature of baseflow and how it changes under the influence of natural and anthropogenic factors. As the baseflow is derived from groundwater discharge from the local aquifers, this dynamic behaviour is also reflected back to the groundwater pattern.

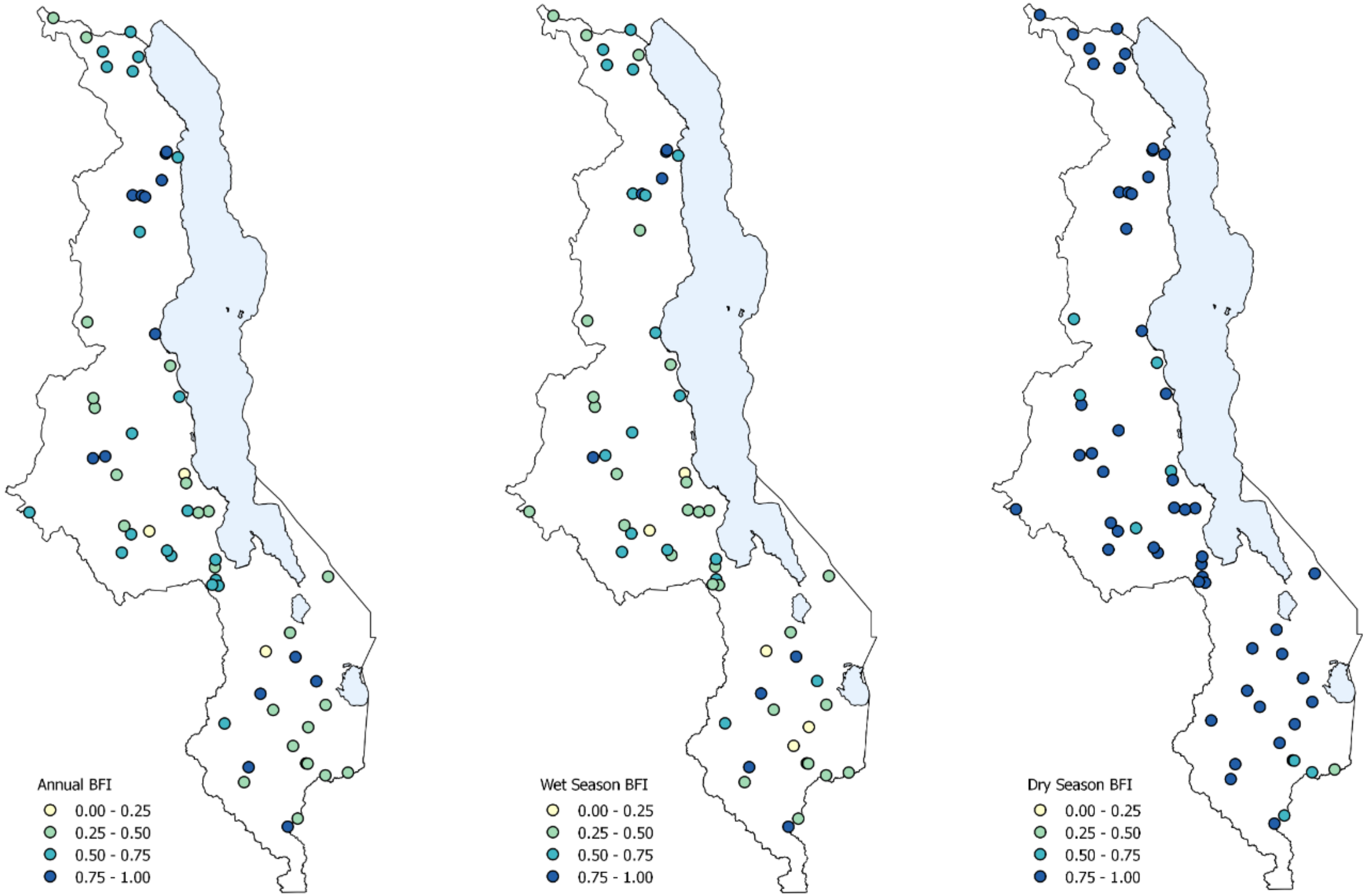

Figure 2 Long term average BFI values in Malawi derived for the annual, wet season and dry season period (graphical)

Table 2 Long term average BFI values in Malawi derived for the annual, wet season and dry season period (tabular)

		Annual			Wet season			Dry season		
Gauge ID	**River**	**Av.**	**Min**	**Max**	**Av.**	**Min**	**Max**	**Av.**	**Min**	**Max**
1B1	Shire	0.97	0.78	0.99	0.95	0.08	1.00	0.98	0.85	1.00
1C1	Lirangwe	0.48	0.07	0.94	0.44	0.07	0.99	0.85	0.00	0.99
1G1 (A)	Shire	0.95	0.88	0.98	0.93	0.83	0.97	0.98	0.90	1.00
1K1	Mwanza	0.38	0.05	0.76	0.33	0.04	0.73	0.76	0.24	1.00
1L12	Shire	0.92	0.84	0.98	0.91	0.79	0.97	0.96	0.88	1.00
1M1	Mkurumadzi	0.64	0.41	0.89	0.52	0.29	0.84	0.87	0.49	0.99
1P2	Shire	0.90	0.00	1.00	0.87	0.00	0.99	0.93	0.00	1.00
1R3	Rivirivi	0.19	0.05	0.45	0.16	0.03	0.39	0.87	0.51	0.96
1S7	Nkasi	0.32	0.00	0.88	0.28	0.00	0.80	0.76	0.00	0.98
2B22	Thondwe	0.36	0.17	0.64	0.31	0.14	0.53	0.79	0.00	0.95
2B33	Namadzi	0.27	0.04	0.63	0.22	0.03	0.53	0.79	0.00	0.98
2C3	Domasi	0.76	0.57	0.87	0.72	0.49	0.85	0.93	0.80	0.98
3E1	Nadzipokwe	0.49	0.15	0.78	0.42	0.00	0.72	0.94	0.59	0.98
3E2	Namikokwe	0.56	0.00	0.78	0.58	0.34	0.98	0.86	0.00	0.98
3E3	Livulezi	0.54	0.22	0.98	0.43	0.16	0.65	0.90	0.41	0.98
3E5	Namikokwe	0.55	0.00	0.85	0.50	0.00	0.88	0.95	0.88	0.99
3F3	Nadzipulu	0.72	0.55	0.84	0.64	0.33	0.79	0.93	0.64	0.99
4B1	Linthipe	0.43	0.16	0.65	0.39	0.10	0.64	0.78	0.10	0.99
4B3	Linthipe	0.52	0.03	0.90	0.48	0.03	0.91	0.89	0.62	0.98
4B4	Diamphwe	0.63	0.27	0.92	0.58	0.23	0.93	0.88	0.60	0.99
4B9	Linthipe	0.37	0.00	0.56	0.36	0.14	0.52	0.77	0.00	0.96
4C2	Lilongwe	0.51	0.00	0.77	0.42	0.00	0.65	0.91	0.65	0.99
4C11	Nanjiri	0.21	0.04	0.42	0.17	0.04	0.42	0.75	0.56	0.98
4D4	Lilongwe	0.65	0.47	0.76	0.59	0.41	0.71	0.92	0.72	0.98
4D24	Lilongwe	0.70	0.52	0.89	0.67	0.49	0.90	0.87	0.80	0.95
4E2	Lingadzi	0.37	0.06	0.93	0.37	0.05	0.93	0.80	0.21	0.99
5C1	Bua	0.74	0.43	0.94	0.69	0.40	0.90	0.94	0.81	0.99
5D1	Bua	0.75	0.43	0.94	0.74	0.41	0.93	0.93	0.55	1.00
5D2	Bua	0.76	0.11	0.98	0.74	0.11	0.98	0.84	0.00	1.00
5D3	Mtiti	0.48	0.05	0.84	0.45	0.05	0.77	0.84	0.00	1.00
5E6	Bua	0.54	0.37	0.70	0.46	0.25	0.90	0.90	0.47	0.98
5F1	Rusa	0.80	0.26	0.98	0.79	0.24	0.95	0.89	0.61	1.00
6C1	Dwangwa	0.28	0.07	1.00	0.28	0.06	1.00	0.82	0.10	1.00
6C5	Mpasadzi	0.47	0.20	0.87	0.43	0.17	0.87	0.74	0.04	1.00
6D10	Dwanga	0.35	0.00	0.68	0.38	0.00	0.64	0.71	0.00	0.98
7A3	South Rukura	0.35	0.00	0.84	0.35	0.00	0.79	0.73	0.00	1.00

		Annual			Wet season			Dry season		
Gauge ID	River	Av.	Min	Max	Av.	Min	Max	Av.	Min	Max
7D8	Lunyangwa	0.53	0.21	0.73	0.41	0.01	0.69	0.84	0.58	0.96
7E2	South Rukuru	0.71	0.31	0.86	0.71	0.29	0.94	0.87	0.67	0.99
7F1	Runyina	0.80	0.52	0.91	0.72	0.28	0.85	0.96	0.85	0.99
7F2	South Rumphi	0.85	0.71	0.90	0.77	0.61	0.86	0.97	0.88	0.99
7G14	South Rukuru	0.80	0.00	0.93	0.76	0.00	0.93	0.97	0.90	0.99
7G18	South Rukuru	0.84	0.73	0.92	0.75	0.00	0.90	0.97	0.87	0.99
7H1	North Rumphi	0.84	0.00	0.91	0.78	0.00	0.95	0.98	0.94	0.99
7H2	Kaziwiziwi	0.87	0.76	0.92	0.79	0.64	0.98	0.96	0.74	0.99
7H3	North Rumphi	0.71	0.29	0.83	0.60	0.20	0.75	0.93	0.79	0.98
8A5	North Rukuru	0.60	0.00	0.83	0.55	0.00	1.00	0.91	0.52	1.00
9A2	Lufira	0.54	0.00	0.75	0.48	0.00	0.73	0.92	0.54	0.99
9A4	Lufira	0.71	0.44	0.94	0.62	0.33	0.94	0.92	0.46	0.99
9A5	Kalenje	0.63	0.00	0.79	0.53	0.00	0.81	0.92	0.82	0.98
9B3	Kaseye	0.33	0.15	0.56	0.32	0.13	0.53	0.78	0.03	0.98
9B5	Hanga	0.25	0.07	0.53	0.21	0.00	0.43	0.70	0.00	0.95
9B6	Songwe	0.50	0.30	0.72	0.44	0.14	0.90	0.94	0.8	0.99
9B7	Songwe	0.64	0.53	0.77	0.56	0.45	0.71	0.86	0.53	0.98
11A6	Lusangwisi	0.44	0.21	0.74	0.36	0.12	0.66	0.87	0.33	0.98
11A7	Masongola	0.45	0.27	0.75	0.36	0.21	0.68	0.90	0.56	0.97
14A2	Luchenza	0.43	0.07	0.78	0.37	0.06	0.68	0.87	0.62	0.97
14A3	Chisombezi	0.27	0.10	0.54	0.23	0.00	0.89	0.81	0.13	0.97
14B2	Thuchila	0.36	0.12	0.58	0.34	0.12	0.56	0.74	0.00	0.97
14C2	Ruo	0.46	0.20	0.69	0.47	0.17	0.67	0.49	0.15	0.75
14C8	Lichenya	0.40	0.20	0.59	0.37	0.14	0.58	0.53	0.12	0.79
14D1	Ruo	0.43	0.31	0.48	0.36	0.26	0.43	0.70	0.51	0.79
15A4	Chirua	0.17	0.00	0.58	0.18	0.00	0.94	0.72	0.00	0.99
15A8	Lingadzi	0.49	0.07	0.94	0.42	0.06	0.91	0.95	0.70	0.99
16E6	Dwambadzi	0.78	0.30	0.93	0.71	0.22	0.98	0.91	0.12	0.99
16F1	Limphasa	0.67	0.57	0.82	0.56	0.42	0.75	0.86	0.67	0.97
16F2	Luweya	0.76	0.55	0.90	0.69	0.43	0.94	0.90	0.75	0.98
17C6	Wovwe	0.85	0.57	0.95	0.80	0.46	0.94	0.93	0.71	0.98
17C10	Hara	0.70	0.53	0.84	0.55	0.35	0.77	0.91	0.68	0.99

3.2 Long term trends in BFI for river gauging stations across Malawi

This study presents the first national dataset on detecting long term trends in BFI in Malawi. The MK test was used to identify statistically significant trends in the BFI results and the results are presented in Figure 3 and Table 3.

The results provide evidence of long-term behavioural changes in baseflow in Malawi over the assessment periods. The trends in BFI vary spatially across the country and temporarily through time. Annually, of the 68 gauging stations assessed, and in terms of statistically significant trends, 74% showed no trend, 10% showed an increasing trend and 16% showed a decreasing trend. The wet season trends showed similar values with 66% showing no trend, 16% showing an increasing trend and 18% showing a decreasing trend. In contrast, for the dry season, 93% showed no trend, 1% showed an increasing trend and 6% showed a decreasing trend (Figure 3).

No trend indicates that the baseflow component of these rivers has remained stable over time, and as suggested by Kelly et al. (2019a) that these catchments are well managed with minimal impacts from anthropogenic activities. Groundwater storage in the area is expected to be unaffected by over abstractions from boreholes. This is the case for most of the river gauging stations during the annual (74%), wet season (66%) and dry season (93%).

Increasing trends are evident across the annual (10%), the wet season (16%) and the dry season (1%). Increasing trends in BFI could be attributed to increases in the local groundwater table due to increased rainfall and recharge in the area which can be considered positive in terms of sustainable water resources management. On the other hand, increasing trends in BFI could also suggest a decreasing trend in rainfall intensity in the area which would result in reduced surface runoff available for the river. In addition, conservations efforts may also be having an impact in some areas. For example, the Ruo River (14C2) shows increasing BFI trends across all assessment periods. This catchment is occupied with numerous tea estates in the lower part and evergreen forests and few settlements in the upper part. There have been relentless efforts to conserve the Mulanje Mountain by various stakeholders especially the Mulanje Mountain Conservation Trust. These increasing trends in BFI suggest that these efforts are having a positive impact.

In contrast, decreasing trends in baseflow suggest that the local groundwater table is declining, perhaps under the impact of climate change or over-abstraction of groundwater. Decreasing trends are evident across the annual (16%), the wet season (18%) and the dry season (6%). Declines in baseflow and groundwater levels can serve as a warning sign that practices in the catchment may not be sustainable and should be investigated further. Where the decline in baseflow continues over time, ultimately the river will become disconnected from the feeding aquifer and the river will cease to flow in the dry season (De Graaf et al., 2019).

Interestingly, decreasing trends in BFI were found in the wet season when it is presumed that there is minimal threat to groundwater levels because rainfall generates surface runoff to the rivers. This indicates that groundwater is being unsustainably abstracted in these areas in the wet season and impacting the groundwater levels. Decreasing trends in the Northern and Central regions of Malawi is of concern as Lake Malawi depends greatly on the inflows from many of these river catchments, especially in the dry season where aquifers maintain baseflows to the main rivers. If the volume of baseflow in these rivers was reduced, it would negatively impact the lake levels and in turn, the flow available for the Shire river would also be impacted.

Establishing the relationship between groundwater and rivers is still in its infancy in Malawi; however, this study adds to existing knowledge and provides new insight into groundwater discharge as baseflow to rivers across the country. The results represent a comprehensive national dataset on baseflow for Malawi which will be of interest to the Malawian Government who continues to work towards sustainable management and development of their country's water resources. For example, they may include these results in catchment management plans, in hydrological assessment requiring BFI, as a guide for proposed new developments on a river and to identify new lines of research as mentioned in the previous paragraph. The BFI results show how wet season and dry season BFI can vary significantly from annual values. As such, the seasonal BFI results may be considered in the country's current National Irrigation Plan where design calculations appear to have focused on annual BFI values (Government of Malawi, 2015b). Identification and understanding of why these changes are occurring are fundamental in ensuring that further degradation of the rivers does not occur and providing protection for the rivers who currently exhibit no changes. It was outside the scope of this study to evaluate trends in factors which influence baseflow behaviour, for example, rainfall, over-abstraction of groundwater and deforestation. Further research should aim to quantify the magnitude of these trends and evaluate these influencing factors.

Finally, the Malawian Government may also use the results as a means of providing an initial dataset for Sustainable Development Goal, Target 6.6 'By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes' (United Nations, 2017). This target is tracked by indicator 6.1.1 which partly calls for data for quantifying ‘changes over time in the quantity of water in ecosystems (rivers, lakes and groundwater). With 2020 upon us, there is currently no data associated with this indicator on a global scale (United Nations, 2019), however, with the results of this study, Malawi can make its contribution and further evaluation of its progress towards the goal.

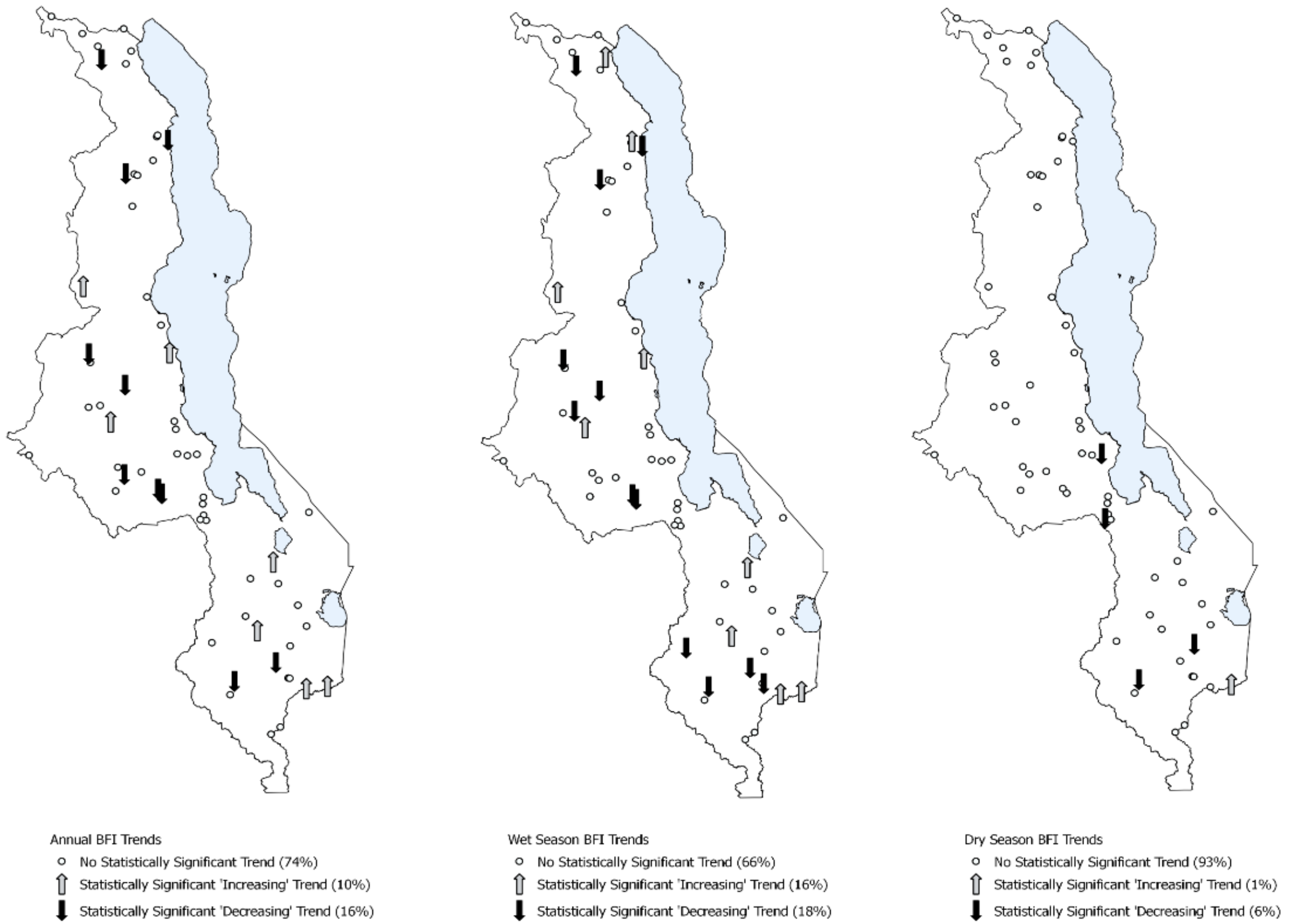

Figure 3 Mann Kendall statistical results for average annual and seasonal BFI for the 68 gauges in Malawi (the trend at 1% significance) (graphical)

Table 3 Mann Kendall statistical results for average annual and seasonal BFI for the 68 gauges in Malawi (the trend at 1% significance) (tabular)

Gauge ID	River Name	Data Record	Annual trend	Wet season trend	Dry season trend
1B1	Shire	1948/1949-2011/2012	○	○	○
1C1	Lirangwe	1951/1952-2004/2005	↑	↑	○
1G1 (A)	Shire	1953/1954-2008/2009	○	○	○
1K1	Mwanza	1951/1952-1996/1997	○	○	○
1L12	Shire	1976/1977-2009/2010	↓	↓	↓
1M1	Mkurumadzi	1980/1981-2007/2008	○	↓	○
1P2	Shire	1952/1953-2004/2005	○	○	○
1R3	Rivirivi	1952/1953-2003/2004	○	○	○
1S7	Nkasi	1961/1962-1996/1997	↑	↑	○
2B22	Thondwe	1960/1961-2006/2007	○	○	○
2B33	Namadzi	1961/1962-2009/2010	○	○	↓
2C3	Domasi	1958/1959-2009/2010	○	○	○
3E1	Nadzipokwe	1953/1954-2009/2010	○	○	○
3E2	Namikokwe	1957/1958-2002/2003	○	○	○
3E3	Livulezi	1956/1957-2007/2008	○	○	○
3E5	Namikokwe	1957/1958-2008/2009	○	○	↓
3F3	Nadzipulu	1957/1958-2003/2004	○	○	○
4B1	Linthipe	1953/1954-2008/2009	○	○	↓
4B3	Linthipe	1957/1958-2007/2008	↓	↓	○
4B4	Diamphwe	1957/1958-2009/2010	↓	↓	○
4B9	Linthipe	1974/1975-2009/2010	○	○	○
4C2	Lilongwe	1957/1958-2009/2010	○	○	○
4C11	Nanjiri	1985/1986-2009/2010	○	○	○
4D4	Lilongwe	1953/1954-2008/2009	↓	○	○
4D24	Lilongwe	1990/1991-2004/2005	○	○	○
4E2	Lingadzi	1959/1960-2004/2005	○	○	○
5C1	Bua	1957/1958-2008/2009	↑	↑	○
5D1	Bua	1958/1959-2006/2007	↓	↓	○
5D2	Bua	1953/1954-2004/2005	○	↓	○
5D3	Mtiti	1958/1959-2002/2003	↑	↑	○
5E6	Bua	1970/1971-2007/2008	○	○	○
5F1	Rusa	1964/1965-2004/2005	○	○	○
6C1	Dwangwa	1952/1953-2009/2010	○	○	○
6C5	Mpasadzi	1965/1966-2000/2001	↓	↓	○
6D10	Dwanga	1985/1986-2009/2010	○	○	○
7A3	South Rukura	1955/1956-2007/2008	↑	↑	○

Gauge ID	River Name	Data Record	Annual trend	Wet season trend	Dry season trend
7D8	Lunyangwa	1952/1953-2007/2008	○	○	○
7E2	South Rukuru	1956/1957-1997/1998	○	○	○
7F1	Runyina	1955/1956-1997/1998	↓	↓	○
7F2	South Rumphi	1956/1957-2007/2008	○	○	○
7G14	South Rukuru	1957/1958-2006/2007	○	○	○
7G18	South Rukuru	1985/1986-2008/2009	○	○	○
7H1	North Rumphi	1955/1956-2007/2008	○	○	○
7H2	Kaziwiziwi	1952/1953-2007/2008	○	↑	○
7H3	North Rumphi	1971/1972-2006/2007	↓	↓	○
8A5	North Rukuru	1968/1969-2008/2009	○	○	○
9A2	Lufira	1953/1954-2009/2010	○	↑	○
9A4	Lufira	1958/1959-2007/2008	↓	↓	○
9A5	Kalenje	1970/1971-2006/2007	○	○	○
9B3	Kaseye	1970/1971-2007/2008	○	○	○
9B5	Hanga	1979/1980-2003/2004	○	○	○
9B6	Songwe	1981/1982-2007/2008	○	○	○
9B7	Songwe	1985/1986-2011/2012	○	○	○
11A6	Lusangwisi	1976/1977-1997/1998	○	○	○
11A7	Masongola	1976/1977-1997/1998	○	○	○
14A2	Luchenza	1954/1955-2001/2002	○	○	○
14A3	Chisombezi	1962/1963-1999/2000	↓	↓	○
14B2	Thuchila	1951/1952-2002/2003	○	↓	○
14C2	Ruo	1953/1954-2007/2008	↑	↑	↑
14C8	Lichenya	1959/1960-2001/2002	↑	↑	○
14D1	Ruo	1980/1981-1990/1991	○	○	○
15A4	Chirua	1970/1971-1999/2000	○	○	○
15A8	Lingadzi	1960/1961-2009/2010	○	○	○
16E6	Dwambadzi	1972/1972-2008/2009	○	○	○
16F1	Limphasa	1970/1971-1990/1991	○	○	○
16F2	Luweya	1952/1953-1993/1994	○	↑	○
17C6	Wovwe	1969/1970-1992/1993	↓	↓	○
17C10	Hara	1974/1975-1988/1989	○	○	○

- where ○ indicates no trend, ↑ indicates an increasing trend and ↓ indicates a decreasing trend

4. Conclusion

The main aim of this study was to provide a comprehensive national assessment of temporal variations in groundwater discharge to rivers in Malawi using the Baseflow Index approach.

The study has shown that baseflow, a proxy indicator of groundwater discharge, in Malawi follows a seasonal pattern characterized by minimal difference between the annual and wet season baseflow, but with a significant increase in the dry season. This was evidenced through the average annual, wet season and dry season BFI found for Malawi, which was 0.57, 0.52 and 0.97 respectively. Considerable variability exists within the annual and wet season baseflow as shown by the minimum and maximum values, although minimal variability exists within the dry season BFI. Statistical trend analysis identified long-term behavioural changes in baseflow which varied spatially and temporally across the country over the assessment periods. Overall, most gauging stations showed no trend in the annual, wet and dry season BFI. However, decreasing trends were found in some BFI data indicating unsustainable catchment practices, for example, over-abstraction of groundwater. In contrast, increasing trends were also evident in some catchments possibly due to noted conservation efforts.

These results enhance our understanding of baseflow in Malawi on a national scale and as such results will be of interest to the Malawian Government for use in water resources planning and management. The results will be particularly useful for measuring progress towards Sustainable Development Goal 6 Target 6.6 which is related to measuring changes over time in rivers and groundwater and imposed a 2020 deadline.

Acknowledgements

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7.3 Further Discussion

The BFI results template presented at the end of Chapter 5 was also used in this study to record the BFI results. The raw results tabs have not been included in the thesis but can be requested from the CJF Water Futures Programme. However, for consistency with the supporting material contained within Chapter 5, the summary tab of the BFI results spreadsheets is presented in Appendix D. It shows the results of the annual and seasonal BFI analysis (tabular) for the gauges in this Chapter. This excludes those already presented in Chapter 5 and Chapter 6 meaning 47 of the total 68 gauges assessed are presented.

7.4 Summary

In this chapter, Malawi was used as a case study to demonstrate the application of the approach presented in Chapter 5 on a national scale. Like the Bua Catchment and Shire River Basin, the river data was sporadic, but the approach allowed the determination of annual and seasonal BFI and identification of long-term trends in the BFI data for a total of 68 river gauges across the country. This included the 6 river gauges previously assessed in Chapter 5 and the 15 gauges assessed in Chapter 6. The study provides evidence that the developed approach used can be successfully used up to the national scale overcoming the challenges faced and utilizing sporadic river flow data. This research output was the first national-scale assessment of baseflow in Malawi and generated knowledge on the seasonal and long term behaviour of baseflow across Malawi.

This research output has important implications on the sustainable management of water resources in Malawi in terms of an IWRM framework and SDG6 planning. For example, the National Irrigation Master Plan Investment Network (2014-2035) (Government of Malawi, 2015b) aims to install multiple dams across Malawi. As described in Section 5.5 of Chapter 5, the design of the dams is based on EF calculations which include BFI. It is recommended that this research output is used to update the proposed irrigation plan for Malawi. The plan represents a significant investment for Malawi and its crucial that it is based on accurate data before detailed design work and construction begins. Failure to do could result in irreversible damage to Malawi's water environment. Further, the GoM can use this research output to support its SDG6 planning. SDG Target 6.6 calls for 'By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes' (United Nations, 2017). This target is tracked by indicator 6.1.1 and specifically asks for countries to quantify changes over time in the quantity of water in ecosystems (rivers, lakes and groundwater). The GoM can therefore use this research output as an initial dataset for this target and begin to measure its progress towards the goal.

The next chapter presents the thesis discussion, recommendations, and conclusions. It summarises and critically discusses the main findings of the research based on the research objectives.

Chapter 8 Discussion, Recommendations and Conclusion

8.1 Introduction

Chapter 1 outlined the fundamental research issue and the aim and objectives of the research. The literature review in Chapter 2 provided the research context and identified research gaps in the literature. Chapter 3 presented the research approach which was used in the thesis and employed four case studies. Chapter 4 used Lake Malawi as a case study to demonstrate how analysis of the recession limb of a lake could potentially provide a proxy indicator of baseflow changes over time. Chapter 5 used the Bua Catchment as a case study to demonstrate how sporadic river data and baseflow separation can be used to quantify temporal variations in baseflow. Building upon Chapter 5, the approach was scaled for application to a larger regional catchment of international importance using the Shire River Basin. Finally, the approach was scaled to the national level using Malawi as the case study.

In this chapter, the overall research findings are discussed against the research aim and objectives. The research strengths, limitations and contribution are discussed, followed by how the gaps in the literature were filled. The implications of the research are discussed and recommendations for future research are stated. Finally, the thesis is summarized in Section 8.4.

8.2 Discussion

8.2.1 Restatement of research questions, aim and objectives

The study aimed to develop a research approach to quantify temporal variations in baseflow on a medium to long term basis in the context of the developing world. The thesis accomplished this aim through a series of ROs (developed based on SRQs). A recap of the SRQs and the ROs are presented in Table 1 below, alongside the objectives [associated chapters]:

Table 1 Sub-research questions, research objectives and associated chapters

SRQ1 Can hydrology, hydrogeology, and climate data be collected for the study area?	**RO1** Collect existing hydrology, hydrogeology, and climate data for the study area. *[chapter 3]*
SRQ2 Based on the collected data, are there investigation methods which could be used to quantify temporal variations in baseflow on the medium to long term basis?	**RO2** Based on the available data, review and evaluate investigation methods which can quantify temporal variations in baseflow on a medium to long term basis. *[chapter 3]*
SRQ3 Can analysis of the recession limb of a lake using lake level data provide a proxy indicator of baseflow changes over time?	**RO3** Demonstrate, using Lake Malawi as a case study, how to potentially analyze the recession limb of lake level data to provide a proxy indicator of changes in baseflow in the lake catchment. *[chapter 4]*
SRQ4 Can sporadic river data be successfully used with base flow separation to quantify temporal variations in baseflow?	**RO4** Demonstrate, using the Bua catchment as a case study, how sporadic river data and baseflow separation data can be used to quantify temporal variations in the baseflow index. *[chapter 5]*
SRQ5 Can the research approach be successfully upscaled from the single catchment scale to the regional catchment scale and the national scale?	**RO5** Demonstrate, using the Shire River Basin as a case study, the application of the research approach presented for working with sporadic river data and baseflow separation to quantify temporal variations in the baseflow index on a larger regional catchment area. *[chapter 6]* **RO6** Demonstrate, using Malawi as a case study, the application of the approach presented for working with sporadic river data and baseflow separation to quantify temporal variations in the baseflow index on a national scale in support of Integrated Water Resources Management and Sustainable Development Goal 6. *[chapter 7]*

8.2.2 Achievement of the research objectives/sub research questions

The achievement of each RO is discussed below followed by a summary of the key findings of each RO and answers to the sub research questions.

RO1 and RO2

The first and second research objectives were met through Chapter 3. Existing hydrology, hydrogeology and climate data for the study area Malawi was collected. The climate data and lake level data were continuous and of good quality, however, the river data was sporadic. Based on the available data, an evaluation of the principle methods available to the study which could achieve the aim of the research was conducted. It indicated that baseflow separation was the most appropriate method to use. Analysis of the recession limb of the lake hydrograph was also identified for its potential to provide a proxy indicator of changes in baseflow over time. These methods were demonstrated in Chapter 4 (analysis of recession limb of Lake Malawi) and Chapter 5 (baseflow separation with sporadic river data). The BFI, a numerical expression of the baseflow component of a river, was selected as the focus of the analysis in Chapter 5. This was selected given its many practical applications in the real world and its use as a proxy indicator of groundwater discharge to a river.

RO3

The third research objective was met through a drafted paper in Chapter 4 using Lake Malawi as a case study. It demonstrated how analysis of the recession limb of lake level data might provide a proxy indicator of changes in baseflow across the entire lake basin. Lake Malawi is one of Malawi's most important water resources in the region and the baseflow contribution in the water budget remains a mystery.

The study focused on monthly lake level data for approximately 116 years (1900-2016). The dataset was of good quality with minimal missing values. The rate of decline of the lake levels was determined by calculating the slope of the levels. The slope was plotted against time and visually inspected for any obvious spikes in the negative slope. Noise in the slope data was removed using the moving average smoothing technique. The smoothed slope data was plotted against time and visually inspected for obvious spikes in the negative slope. The results showed several spikes in the unsmoothed and smoothed slope data which were attributed to changes in the baseflow of the lake catchment.

In the context of the research aim, this demonstration was a useful exercise to provide a proxy indicator of baseflow variations. However, the results were not definitive and future research was recommended to quantify the total baseflow volume contributing to the Lake from the inflow rivers. This was to include both the Malawian and Tanzania inflow rivers, where Tanzania rivers contribute the most in runoff inflow estimated at around 60%. As no data were available for Tanzania, this research could not be completed within this thesis and a trans-national study was recommended. The research was partly progressed in the following objectives as baseflow was determined for Malawian rivers across the country including those in flowing into the lake.

RO4

The fourth research objective was met through a peer-reviewed publication in Chapter 5. The Bua Catchment was used as a case study and demonstrated how to work with sporadic river data and baseflow separation to quantify temporal variations in baseflow. The Bua catchment, situated in central Malawi, has a catchment area of 10,658 km^2 and is the largest inflow catchment to Lake Malawi. The catchment was considered a good representative of other African catchments in the context of the research aim. For example, before this study, there was no quantifiable data available on baseflow in the catchment and the river data was sporadic. The GoM Water Resources Department also faces many challenges in their day to day management of water resources. At times, largely due to understaffing and budget constraints, they may have limited technical knowledge, a lack of financial resources to dedicate to the investigation of baseflow, and only a few experienced hydrology and hydrogeology staff with limited available time.

The study focused on daily river flow data from 6 river gauges within the catchment with coverage ranging from 38-52 years. Rainfall and groundwater data in the vicinity of the river gauges were also examined, where possible, to provide support for the BFI analysis. The rainfall data was of good coverage with minimal missing values. Groundwater levels are monitored in the catchment via four monitoring boreholes, however, only one had enough data coverage to examine.

To overcome the challenges described above, the study used key criteria for the selection of a baseflow separation tool. The criteria required the tool to be automated, easily accessible, free to obtain and operate, require minimal training to use and capable of selecting seasonal periods from input data to quantify BFI. These criteria allowed the exchange of knowledge with the GoM and ensured the approach would be easy to follow, shareable and repeatable. Several baseflow separation tools were evaluated against the predefined criteria and the BFI programme (Tallaksen and Van Lanen, 2004) was selected as the most appropriate tool to use. The assessment periods selected were annual and seasonal periods defined by months, based on the hydrological year and the seasonal weather variations recognized in Malawi. Systematic steps for manually working with and preparing the sporadic river data were developed and shared here and with the GoM. The MK statistical trend test, alongside appropriate test parameters, were based on best practice to identify trends in the baseflow data.

Annual and seasonal BFI for the 6 river gauging stations in the study area was successfully quantified, alongside the identification of long-term trends in the BFI data. Rainfall and river data showed patterns which supported the seasonal fluctuations found in the BFI data. Some groundwater data also showed supporting patterns, however, generally, the groundwater data was very of poor quality and coverage.

In the context of the research aim, the research outcomes presented in this case study demonstrated the usefulness of utilizing the sporadic river data in quantifying temporal variations in BFI. The approach was a success and generated new knowledge and understanding of the behaviour of baseflow in the catchment.

RO5

The fifth research objective was met through a peer reviewed publication in Chapter 6 using the SRB as a case study. The study demonstrated that the research approach as used in the Chapter 5 could be scaled up to a larger regional catchment scale. The SRB, situated in Southern Malawi comprises the Shire river catchment (that which is south of Lake Malawi) and the Ruo river catchment making a total catchment area of 22,430 km^2. This area is approximately double that of the Bua catchment (10,658 km^2) and as such was considered a good representative of a larger catchment to test the applicability of the approach. Further, like the Bua catchment, there was limited quantifiable data available on baseflow and such data was urgently required by the GoM to support water resources management.

The study focused on daily river flow data from a total of 15 river gauges within the SRB. Data coverage was varied ranging from 11-65 years and was sporadic. Groundwater levels were examined for 11 boreholes to provide support for the BFI analysis. Generally, groundwater data was sporadic, being only available from 2009-2015.

Annual and seasonal BFI for the 15 river gauging stations in the study area was successfully quantified, alongside identification of long-term trends in the BFI data. Examination of the groundwater level data indicated seasonal fluctuations in line with the BFI results, however, none of the groundwater monitoring boreholes was located near any of the gauges and so was of limited use.

In the context of the research aim, the research outcomes showed that the application of the research approach to a larger catchment was successful. Key BFI data was generated where none previously existed and provided evidence of the robustness of the approach.

RO6

The sixth and final research objective was met through a peer reviewed publication in Chapter 7 using Malawi as a case study. It demonstrated that the application of the research approach presented in the Bua Catchment can be further ‘scaled-up’ to a national scale.

This study focused on data from 68 river gauging stations in Malawi. More gauging stations do exist; however, data could not be obtained for inclusion in the thesis. This included the 6 gauges from the Bua catchment case study and the 15 from the Shire Basin. River data was sporadic.

Annual and seasonal BFI for 68 river gauging stations across Malawi was quantified, alongside identification of long-term trends in the BFI data. Data ranged from 1948-2012 representing a significant snapshot of time. To promotes the exchange of knowledge with the GoM and other stakeholders, the BFI results were shared via the free data management platform 'mWater' (mWater, 2019) which is being adopted by the GoM as the National Management Information System (MIS) for water resources data in Malawi.

In the context of the research aim, the research outcomes show the successful applicability of the research approach to a national scale, providing confidence in the robustness of the approach.

Summary of key findings from the research objectives

Table 2 presents a summary of the key findings from the ROs in the context of the research.

Table 2 Summary of key findings from the research objectives

RO	Key findings
RO1 RO2	- Climate data, lake levels and river flow data were collected from the study area - Generally, river data was sporadic but lake levels and climate data was not - Baseflow separation is the most appropriate method to quantify temporal variations in baseflow based on the available data - Analysis of the recession limb of the lake hydrograph may provide a proxy indicator of changes in baseflow over time
RO3	- changes in the baseflow of the Lake Malawi catchment were evident over time - Analysis of the recession limb was a useful exercise to provide a proxy indicator of baseflow variations, however results were not definitive - future research was recommended to quantify the total baseflow volume contributing to Lake Malawi from the inflow rivers
RO4	- Sporadic river data and baseflow separation can be successfully used to quantify temporal variations in baseflow - Annual and seasonal BFI was determined for 6 river gauging stations in the Bua Catchment alongside the identification of long-term trends in the BFI data - The research approach presented was successful on a single catchment
RO5	- Annual and seasonal BFI was determined for 15 river gauging stations in the Shire River Basin, alongside the identification of long-term trends in the BFI data - The application of the research approach to a larger catchment was successful.
RO6	- Annual and seasonal BFI was determined for 68 river gauging stations across Malawi, alongside the identification of long-term trends in the BFI data. - The application of the research approach to a national scale was successful.

Answers to the sub-research questions

Achievement of the ROs as discussed in the previous section allowed the SRQs to be answered as follows:

- **SRQ1** Can hydrology, hydrogeology, and climate data be collected for the study area? Yes. [The completion of RO1 in Chapter 3 allowed this to be answered].
- **SRQ2** Based on the collected data, are there investigation methods which could be used to quantify temporal variations in baseflow on the medium to long term basis? Yes, there is one method available (baseflow separation). Another method (analysis of recession limb of lake levels) may be used to provide a proxy indicator. [The completion of RO2 in Chapter 3 allowed this to be answered].
- **SRQ3** Can analysis of the recession limb of a lake using lake level data provide a proxy indicator of baseflow changes over time? Yes, however, thew results were not definitive and as such only serves as a useful example. [The successful completion of RO3 in Chapter 4 allowed this to be answered].
- **SRQ4** Can sporadic river data be successfully used with base flow separation to quantify temporal variations in baseflow? Yes. [The successful completion of RO4 in Chapter 5 allowed to be answered].
- **SRQ5** Can the research approach be successfully upscaled from the single catchment scale to the regional catchment scale and the national scale? Yes. [The completion of RO5 and RO6 in Chapter 6 and Chapter 7 respectively allowed SRQ5 to be answered].

8.2.3 Strengths

Provision of a research approach for baseflow

This thesis presents the development of an approach which allows quantification of temporal variations in baseflow in the developing world context. The research approach is practical, and flexible. It is focused on making use of sporadic river data and use of free, open-source tools. Thus, one of the main strengths of the research is its provision of a research approach which enables the generation of new knowledge on baseflow where data and resources are scarce. This is important for practitioners who are currently faced with the task of producing data on baseflow but with no guidance to hand. The approach supports several water management approaches including IWRM and conjunctive water use which require data on the relationship between groundwater and surface water. The research approach was applied using three case studies which were put through structured and academic peer reviews for publication status.

Promotion of the use of sporadic river flow data

Another strength of the research is the promotion of sporadic river flow data. Previously, there was minimal coverage in the literature of the use of sporadic river flow data in hydrological assessments, and generally, it was perceived as poor quality and not appropriate for analysis. The research outputs have demonstrated the usefulness of using this time-limited data and extracting meaningful estimations of baseflow. This is an important example for other countries who hold sporadic river flow data and are unsure of its potential.

Research outputs to support better investment

The research outputs provide the first national-scale assessment of BFI in Malawi and generated a key baseline data set for the country. Another strength of the research is the ability of this research output to support water resources management and future investment designs and decisions. For example, a national irrigation master plan and investment framework (2014-2035) has been developed to install multiple new dams across the country (Government of Malawi, 2015a). This is a significant investment for Malawi representing millions of USD. As mentioned in Chapter 5 and Chapter 7, the design of the dams is based on maintaining an Environmental Flow (EF) after which the remaining water in the river is free to use in the irrigation schemes. The BFI is key parameters used within the EF calculations and if the EF calculation does not use accurate BFI data, then the sustainability of the catchment downstream of the proposed dams is at risk. To date, the design calculations of the proposed dams in Malawi don't appear to have considered baseflow (Government of Malawi, 2015a; b).

A platform to promote and secure funding for further baseflow research

Baseflow research in Malawi is still in its infancy. Certainly, the research outputs have generated a significant amount of new knowledge compared to what existed previously, however, this merely provides the foundation for future work in Malawi. The research outputs have strength as they provide the platform to secure funding for further, more detailed research into the topic. One of the main challenges faced by Malawi is the lack of funding available to government departments to allocate to this research. Where more river data is available outwith that obtained for this research, funding may be secured from senior government for junior staff members in the water resources division to be tasked with ongoing use of the approach. Alternatively, the Surface Water Division could outsource or delegate this task to local Universities with an interest in water resources. The research outputs could be directly used in funding applications to investigate baseflow and provide this approach as a systematic method for how they will generate the baseflow data. For example, the World Bank invests in various projects across the globe to help support countries in sustainable water resources management. Finally, where there is a Government led project on new developments involving water resources, government departments could stipulate that NGOs/consultants involved perform this assessment to form part of a holistic approach. All the above empowers the GoM to continue to generate baseflow data in support of water resources management.

Understanding of groundwater-surface water interactions

Another strength of the research is the research outputs ability to help us to begin to understand the relationship between groundwater and rivers in Malawi. As described throughout the thesis, baseflow represents the component of river flow derived from groundwater and other stored sources. As groundwater is considered to contribute the majority to baseflow, it can therefore be used as a proxy indicator of groundwater discharge. This is particularly useful in the absence of good quality long term groundwater monitoring data which is the case in Malawi.

8.2.4 Limitations

Limitations are defined as weaknesses directly related to decisions that were made in the research. The decisions made place restrictions and constraints on the research approach, and these factors impact the findings of the study. The limitations associated with this research are summarised as follows:

1) The first limitation concerns the decision to use sporadic river flow data and the underlying question on the quality of the data. Generally, hydrologic science avoids using data which is sporadic, however, in many developing world countries complete and continuous datasets are extremely rare. This limitation is important because the river flow data underpins the approach used to produce the BFI results. Sporadic river data implies that the data is of overall poor quality. For example, in the Malawian case studies, it has been reported that manual records by the gauge readers often contain errors and have long periods of missing data (Government of Malawi, 2017b). This is in part attributed to the fact that these employees are underpaid and there is no incentive to ensure all readings are always correctly

measured. There are also reports that the rating curves of the river gauges are not regularly updated which adds to the question over the quality of the data (Government of Malawi, 2017b). In terms of the specific impact this limitation had on the results, it means that the BFI values determined may be limited in representing the true baseflow behaviour. However, the choice to utilize sporadic river flow data is justified as it was the only data resource available to meet the aim of the thesis in combination with the available methods. The thesis therefore got the most out of the data which was available. Each case study specifically stated that the river flow was sporadic as a means of 'caveating' the results in this respect. To overcome this limitation in future studies, more investment in the Malawi gauging network is required starting with the gauge readers. To minimize the sporadic nature of the river flow data and ensure the quality of the data, more incentive should be given to the manual readers of the gauges. If this job is respected and well paid, the staff are more likely to carry out their duties more efficiently. This has been included in Section 8.3 as a recommendation for future research.

2) The second limitation concerns the decision to select a baseflow separation tool based on set criteria and not by comparing the results of several tools. This is important because different tools will determine slightly different baseflow and BFI values (Zhang et al., 2017; Rouhani and Malekian, 2013; Eckhardt, 2008). In terms of the impact this had on this research, it meant that the researcher's judgement played a role in the development of the approach, and this judgement may have been different to another researcher completing the same task. For example, another researcher may have selected slightly different criteria and as such the selected method may have been different. If another tool were used, the BFI results would be expected to be slightly different. However, decisions on the criteria were required to meet the aim of the study. The criteria were based on a comprehensive review of the literature and by stakeholder engagement with the GoM. Although a different tool would be expected to yield different baseflow results, the differences would not be expected to be significant as described in the literature (Tallaksen and Van Lanen, 2004). The BFIs would instead be slightly 'off set' dependent on which method was used. Thus, the use of any method is justified as long as there is consistency within the study (Tallaksen and Van Lanen, 2004).

3) The third limitation concerns the decision not to investigate runoff rates from each river catchment. The BFI programme uses the smoothed minima filtering technique by the Institute of Hydrology which assumes that the river responds to runoff events in hours or days. This is seen in the use of the 5-day minima blocks and a turning point factor of 0.9 when calculating the baseflow separation points (Tallaksen and Van Lanen, 2004). These parameters were not adjusted for any catchment in this research; however, each river will respond to runoff events at slightly different rates. The impact this has on the results is that where a river takes longer to respond to runoff events, for example for catchments with long-duration floods, this assumption could lead to the underestimation of the baseflow of the river. Like the second limitation, this means that the BFI values determined for some catchments may be underestimated. To overcome this limitation in the future, efforts could investigate the response runoff rates for each river and where varying to incorporate this into the programme. This would depend on time and resources available to the study. This has been included in Section 8.3 as a recommendation for further research.

8.2.5 Research contribution

This thesis has made several contributions to knowledge. The global and local novelty of the research contributions are as follows:

Global novelty

- A simple assessment was presented to analyze the recession limb of a lake hydrograph to provide a proxy indicator of changes in baseflow over time
- A new research approach was developed to quantify temporal variations in baseflow in the developing world context using spatial and temporal variable data
- The research approach was designed by synthesizing several elements which have not previously been put together. Methods were selected based on predefined criteria which were required for the approach to overcome challenges typical of the developing world

Local novelty

- A national dataset of river flow data and climate parameters has been obtained and organized and includes the creation of comprehensive station maps viewable via the mWater platform

- New knowledge has been generated for Malawi. Annual and seasonal BFI, and identification of long-term trends in BFI, has been determined on a national scale for the first time. This also includes a more detailed catchment analysis of baseflow in the Bua Catchment and the Shire River Basin
- Existing methods for investigation of baseflow (baseflow separation) and statistical trend identification (Mann Kendall) were applied to new areas across Malawi

8.2.6 Filling of the research knowledge gaps

The literature review (Chapter 2) identified four research gaps. The gaps are restated below (not in chronological order) followed by a statement of how they were addressed by this thesis.

Knowledge gap 3 (global): A research approach which quantifies temporal variations in baseflow in the developing world context is required

This thesis has filled knowledge gap 3 by demonstrating a research approach which quantifies temporal variations in baseflow in the developing world context. The methodology to create the approach was presented in Chapter 3. The approach was tested using three case studies in Malawi from the single catchment scale up to the national country scale. The research outputs show the success of the approach in overcoming challenges typical of the developing world. This approach will be useful to other countries hoping to complete a similar assessment.

Knowledge gap 2 (local): There is a need to produce a comprehensive national dataset of temporal variations in baseflow in to underpin IWRM and SDG6

This thesis has filled knowledge gap 2 through the research output in Chapter 8. A national-scale assessment quantified annual and seasonal BFI, alongside long term BFI trends, for 68 river gauging stations across Malawi. This was the 1st comprehensive assessment of baseflow for the country. The data can be used to underpin IWRM and SDG6 planning within the country.

Knowledge gap 1 (local): There is a need to understand groundwater discharge to rivers in Malawi and thus recognize the importance of monitoring groundwater and surface water together

This thesis has begun to fill knowledge gap 1 through the research outputs and discussion chapter. The baseflow component of a river is derived from groundwater and other stored sources. Generally, it assumed that groundwater is the major contributing factor and as such baseflow is used as a proxy indicator of groundwater discharge to rivers. Through the investigation of baseflow in Chapter 4-7, the research outputs have provided quantifiable data to describe how groundwater and rivers interact across the country and how this relationship has changed over the past 50 years. This chapter provides a useful discussion on the implications of these research outputs for Malawi, through which the importance of monitoring groundwater and surface water together is seen.

8.2.7 Research implications

This research has important implications for the sustainable management of water resources in Malawi in terms of an IWRM framework and planning for SDG6.

National Irrigation Master Plan and Investment framework

The research outputs can be used to support national policy and future water resources development decisions. As described in Section 8.2.3, the national irrigation master plan and investment framework (2014-2035) for Malawi aims to construct multiple new dams across the country representing a significant investment for the country (Government of Malawi, 2015a). Also described is the requirement for accurate BFI data to underpin the EF calculations. To date, these calculations do not appear to have catchment specific BFI data (Government of Malawi, 2015a; b). It is likely an average annual value has been used from an isolated study; however, this does not capture the important temporal variations in baseflow as seen in the research outputs. The seasonal variations are especially important to consider in Malawi where the results of this research have shown that BFI can vary significantly. The results outputs of this thesis therefore provide support to the designs within the irrigation plan and could ensure the proposed dams are a more sustainable investment for Malawi.

Research on conjunctive water management for the Shire transboundary river aquifer system

The research outputs can be used to support other research initiatives. For example, the Southern African Development Community (SADC), has received funding from the World Bank and delegated the implementation of one of their projects to the Southern African Development Community Groundwater Management Institute (SADC-GMI). The project entailed procurement of consultancy services to support the development and application of an approach for conjunctive water management in the Shire transboundary river-aquifer system in Malawi (Southern Africa Groundwater Management Institute, 2017). A key area in the conjunctive use management framework is characterizing the connection between groundwater and surface water, thus the results of this research (specifically those of the SRB study) would provide support to this project as it progresses.

Malawian energy sector

The research outputs can be used to support sustainability assessments for the Malawian energy sector. For example, there are two hydropower schemes (Kapachira I and II) located on the Shire River. Two of three total hydropower stations on the river, together they supply over 98% of Malawi's total electricity and are highly dependent on the flow in the river being sustained. Both Kapachira I and II are located close to river gauge 1L12 where the results showed a decreasing trend in the annual, wet and dry season BFI from 1976-2010. Decreases in BFI mean that the baseflow component of the river has declined which is likely due to declines in groundwater discharge to the river. As previously mentioned, the Southern region of Malawi suffers from increasing catchment degradation and there has been ongoing reports of rivers running dry and decreasing groundwater levels. The BFI trend data presented in Chapter 7 supports that there are unsustainable catchment practices affecting the water systems. Given that the river data ends in 2010, it can only be presumed that the declines have continued. The BFI data may be used as a baseline for the projection of future trends for this area.

Sustainable Development Goal 6 planning

The research outputs can support the GoM in planning for SDG6 'Ensure availability and sustainable management of water and sanitation for all' (United Nations, 2017). SDG6 has several targets which are tracked by indicators. Specifically, target 6.6 'By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes' is tracked by indicator 6.1.1 'Change in the extent of water-related ecosystems over time' which includes rivers, lakes and groundwater (United Nations, 2017). Thus, the research outputs of this thesis are directly applicable to support this target. Of further relevance is target 6.5 'By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate (United Nations, 2017). Although the indicators for this target are related to measuring the degree of IWRM implementation and operation, effective implementation is not possible without accurate data which includes data to describe the groundwater-surface water relationship. As baseflow provides a proxy indicator of groundwater discharge to rivers, the research outputs are indirectly providing support to this target.

The GoM may wish to use the research outputs as an initial dataset for these targets and build upon them to measure its progress towards the SDG6. For example, as the research has established a historical view of the behavior of baseflow in Malawi, a future aim could be to develop a national monitoring programme to continue to monitor temporal variations in baseflow across the country. This continued monitoring is important to underpin SDG6, IWRM and ultimately to ensure water resources are managed sustainably. Agenda 21 of the 1992 United Nation Earth Summit on Environment and Development called for new ways to measure and assess progress towards sustainable development and asked that we track what is happening to know whether policies are leading to sustainability (Smith and Zhang, 2004). Ensuring water security for future generations will have untold implications for the environment, society, and economy of Malawi.

8.3 Recommendations

Knowledge obtained and generated during the research process provided useful insights for future research direction which relates to Malawi and the applied approach. The recommended areas for future research are summarized as follows:

8.3.1 Specific recommendations Malawi

Quantify the volume of baseflow contribution to Lake Malawi and assess temporal variations over time

The baseflow contribution to Lake Malawi is an important consideration in the sustainable management of the Lake (Chapter 4). It is recommended that this component is determined on annual and seasonal basis and that trends over time are identified. This will include the assessment of baseflow from the inflow rivers from Malawi and Tanzania. Thus, a joint programme of research from Malawi with its Tanzanian counterparts is recommended. Specifically, river data from all inflow rivers (Malawi and Tanzania) is required to progress this research. Chapter 7 has partly started this by quantifying BFI for several of the Malawi inflow rivers. The raw results data includes BFI and baseflow volumes which can be used to estimate the total baseflow contribution from the Malawi rivers.

Update the National Irrigation Master Plan and Investment framework with respect to baseflow

As discussed in Section 8.2.7, the national irrigation plan for Malawi would benefit from being updated to reflect the findings of this research. Specifically, the annual and seasonal BFI values can be used to update the EF calculations.

Additional BFI assessments in Malawi

The GoM may wish to identify any river flow data in Malawi which has not been used to assess baseflow in this research. This may include historical data not obtained in the initial research requests, or data which has become available since the requests.

National Baseflow Monitoring Programme

As discussed in section 8.2.7, a national programme to monitor baseflow would be beneficial to Malawi. A historical view has already been established and ongoing monitoring would underpin IWRM and SDG6. Specifically, ongoing monitoring of baseflow would call for up to date river flow as river flow data appears to end around 2010 and further investment in the river gauging network would be required. A feasibility assessment could be first carried out to assess which gauges would be appropriate to be included in a long-term monitoring programme. Criteria to assess the stations may include status and condition of the gauge, location, additional investment required, stakeholders' requirements etc. This monitoring would cross over with long term monitoring of river flow in general. On a practical note, to help minimize the sporadic nature of the datasets in the future, more monetary incentive should be given to the manual readers of the gauges.

Detailed analysis and interpretation of each gauged catchment

To build upon the BFI results in the Malawi case study (Chapter 7) and provide a holistic understanding of the groundwater-river system in each catchment, detailed catchment analysis should be carried out. This would include analysis of supporting datasets to identify influencing factors on the baseflow and potential sources of significant increasing or decreasing trends. These supporting datasets could include the different river flow components (i.e. total river flow, baseflow and surface runoff), groundwater levels in boreholes within a certain radius of the river gauges, rainfall, land-use changes (i.e. deforestation) and historical water use (i.e. surface water diversions for irrigation). Where rivers have high baseflow components, further analysis may seek to map protection zones to protect the interconnected groundwater and river resources. Further, the magnitude of the BFI trends in the national assessment should be quantified, and trends should be projected into the future.

8.3.2 Specific recommendations for the approach

Worldwide national assessments of BFI

Its recommended that national assessments are completed for other countries using this approach. Feedback can be sought on their investigation and careful attention paid to any improvement suggested. The research approach could be revised to include any recommendations or lessons learned from other countries. When a research approach is used in a real-life context, often there may be trouble understanding steps that seem clear to those who developed it. Further, varying study area conditions can lend to different problems and experiences which can be learned from. Through sharing feedback and updating the approach, it can be further developed into a robust approach to be used across multiple catchments and countries. It will also allow for other counties to generate new knowledge on BFI where none previously existed, or additionally to support existing findings from other methods.

Research questions to further improve the approach

To build upon the approach, its recommended that the following research questions be the focus of future research. The questions should be placed in the developing world context.

- What is the best method to determine runoff rates for rivers?
- What is the best approach for quantifying the magnitude of the BFI trends?
- What is the best approach to project the BFI trends into the future? From these predictions, can we then identify the potential risks if these trends were to continue?
- What is the best way to investigate the cause of any significant increasing or decreasing trends? For example, should we examine groundwater levels in the vicinity of the rivers, rainfall patterns and or land-use changes? How can we integrate this with the BFI results?
- What would be the best approach to investigate ungauged catchments?

Further, its recommended that a small study aims to develop a macro to automate the process of selecting seasonal periods of data for input to the BFI programme. In this research, the assessment periods of raw data were manually selected and copied from the raw excel sheet to the BFI programme. This proved the most time laborious element of the assessment and although it was not significant for the 68 river gauges in total, it was not an efficient use of time.

8.4 Conclusion

In conclusion, the thesis achieved the aim of the research. A research approach was developed that allows the quantification of temporal variations in baseflow on a medium to long term basis in the context of the developing world. The developed approach overcomes challenges typical of the developing world and fills an important gap in the literature. It facilitates a systematic solution to generating knowledge in baseflow in developing world countries. Environmental practitioners may use the approach to conduct water resource assessment of baseflow in a methodical manner and with a degree of confidence, generating crucial baseline data to support sustainable water resources management.

The aim was achieved by the completion of several research objectives. Four of the research objectives were accomplished using real-world case studies in Malawi, three of which were published as papers. As such, the thesis is underpinned by peer-reviewed scientific research. Specifically, the thesis has produced the following outputs:

- Collected and organized a national dataset for Malawi in the form of climate data, river flow and lake levels
- Presented an evaluation of methods available to the study, based on set criteria, which could achieve the aim of the research
- Demonstrated how to analyze the recession limb of lake levels to provide a proxy indicator of changes in baseflow over time
- Demonstrated how to work with sporadic river data and baseflow separation to quantify temporal variations in BFI
- Produced detailed BFI investigations for the Bua Catchment and Shire River Basin including analysis of river flow, rainfall, and groundwater data
- Produced a national-scale assessment of BFI in Malawi comprising assessment of 68 river gauging stations across the country

The research outputs have important implications on the sustainable management of water resources in Malawi in terms of an IWRM framework and planning for SDG6.

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Appendix A Climate Station List

Climate station list showing station names, latitude, longitude, elevation, and the associated data (daily or monthly) which was obtained for each station

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**Name**	**Latitude**	**Longitute**	**Elevation (m)**	**Rainfall (mm)**				**Pan Evaporation (mm)**				**Temperature (max and min) (°c)**				**Sunshine Hours (hours/day)**				**Windspeed (meters/second)**			
2					*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*
3	Alufandika	-17.08	35.08	480																				
4	Alumenda	-16.38	34.93	61																				
5	Amalika	-15.98	35.03	1097																				
6	Baka	-9.93	33.92	488																				
7	Balaka	-14.98	34.97		1976	2016	1999	2017																
8	Bandanga	-16.08	35.12	960																				
9	Bapani	-11.70	33.58	1425																				
10	Bazale	-15.02	35.00	594																				
11	Bilila	-14.80	34.88	716																				
12	Blantyre	-15.78	35.03	1050																				
13	Blind	-16.03	35.50	640																				
14	Bolero	-11.02	33.78	1100	1962	2016	1999	2017					1982	2014	2000	2017					1982	2000		
15	Bowe	-13.30	34.40	1143																				
16	Bunda College	-14.15	33.78	1118			1999	2016																
17	Bvumbwe	-15.92	35.07	1146			1960	2017	1971	2000	1971	2000	1961	2005	2000	2017	1971	2000			1971	2000		
18	Bwengu	-11.07	33.92				1999	2017																
19	Chambe	-15.92	35.53	2829																				
20	Champhira	-12.40	33.63	1240																				
21	Champhoyo	-11.80	33.82	1798																				
22	Chancellor College	-15.38	35.35	886			1999	2016																
23	Changalume	-15.38	35.23	732																				
24	Chia	-13.17	34.35	457																				
25	Chibondwe	-12.20	33.55	1326																				
26	Chichiri	-15.78	35.03	1132	1965	2016	1999	2017	1972	2000	1972	2000	1971	2015	2000	2018	1971	2000			1971	2000		
27	Chididi	-16.92	35.17	670																				
28	Chigumula	-15.88	35.12	1067																				
29	Chikangawa Forest	-11.85	33.80	1728			1999	2017																
30	Chikwawa	-16.03	34.78	107	1970	2015	1999	2017																
31	Chikweo	-14.75	35.67	717			1999	2017									1987	2000			1985	2000		
32	Chikwina	-11.40	34.13	991																				
33	Chileka	-14.02	33.38	1158																				
34	Chileka Airport	-15.67	34.97	767	1949	2016	1999	2017	1971	2000	1971	2000	1961	2016	2000	2017	1971	2000			1971	2000		
35	Chingale	-15.37	35.25	610	1960	2016	1999	2017																
36	Chinunkha	-9.65	33.37	1219	1960	2016																		
37	Chintheche	-11.83	34.17				1999	2017																
38	Chinyama	-16.12	35.35	610																				
39	Chipunga	-11.38	34.17	1219																				
40	Chiradzulu	-15.70	35.18	1143																				

Climate station list showing station names, latitude, longitude, elevation, and the associated data (daily or monthly) which was obtained for each station (continued)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**Name**	**Latitude**	**Longitude**	**Elevation (m)**	**Rainfall (mm)**				**Pan Evaporation (mm)**				**Temperature (max and min) (°c)**				**Sunshine Hours (hours/day)**				**Windspeed (meters/second)**			
2					*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*
41	Chirimba	-15.73	35.02	991																				
42	Chisambo	-16.03	35.70	740																				
43	Chisenga	-9.97	33.40	1539																				
44	Chisepo	-13.63	33.43	1036																				
45	Chisunga	-16.00	35.03	1250																				
46	Chitakali	-16.02	35.50	645																				
47	Chitala	-13.68	34.25	606			1999	2014																
48	Chitedze	-13.97	33.63	1149	1960	2017	1999	2017	1971	2000	1971	2000	1961	2009	2000	2017					1971	2000		
49	Chitipa	-9.70	33.27	1285	1960	2016	1999	2017	1971	2000	1971	2000	1961	2014	2000	2017					1971	2000		
50	Chulu	-12.82	33.30	1052																				
51	Dedza	-14.32	34.25	1632	1961	2016	1999	2017	1974	2000	1974	2000	1961	2004	2000	2017	1971	2000			1971	2000		
52	Diwa	-15.83	34.38	533																				
53	Dolo	-16.55	34.92	137																				
54	Domasi	-15.28	35.43	747																				
55	Dowa	-13.65	33.93	1403			1999	2017																
56	Dwangwa Lllovo	-12.48	34.08	488	1972	2010	1999	2017																
57	Dzalanyama Forest	-14.22	33.60	1219			1999	2016																
58	Dzonzi	-14.98	34.68	1326																				
59	Edingeni	-12.02	33.33	1185																				
60	Ehehleni	-12.33	33.60	1245																				
61	Emfemi	-12.58	33.58	1097																				
62	Esperanza	-16.03	35.50	635																				
63	Euthini	-11.45	33.42				1999	2017																
64	Fort	-15.83	35.70	1128																				
65	Gaga	-15.82	34.33	564																				
66	Glenae	-16.07	35.20	839																				
67	Glengary	-16.08	35.12	1000																				
68	Glenorchy	-16.00	35.47	655																				
69	Gontha	-16.08	35.18	792																				
70	Jali	-15.48	35.47	686																				
71	Junju	-10.67	34.07	1250																				
72	Kachulu	-15.38	35.58	632																				
73	Kakoma	-16.10	34.62	137																				
74	Kalwera	-12.08	33.75	1750																				
75	Kambiri	-15.93	35.03	1097																				
76	Kamphonje	-15.92	35.18	991																				
77	Kampini	-14.30	33.78	914																				
78	Karonga	-9.95	33.88	529	1961	2015	1999	2017	1971	2000	1971	2000	1961	2014	2000	2017	1971	2000			1971	2000		
79	Kasamba	-15.35	34.80	411																				
80	Kasembereka	-16.12	35.08	884																				

Climate station list showing station names, latitude, longitude, elevation, and the associated data (daily or monthly) which was obtained for each station (continued)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**Name**	**Latitude**	**Longitude**	**Elevation (m)**	**Rainfall (mm)**				**Pan Evaporation (mm)**				**Temperature (max and min) (°C)**				**Sunshine Hours (hours/day)**				**Windspeed (meters/second)**			
2					*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*
81	Kasiya	-13.77	33.53	1036			1999	2017																
82	Kasungu	-13.02	33.47	1058	1961	2016	1999	2017					1983	2004	2000	2017					1983	2000		
83	Katowo	-10.85	33.52	1213																				
84	Kavuzi	-11.47	34.07	1274																				
85	Kawiya	-11.85	34.12	548																				
86	KIA	-13.78	33.78	1229	1961	2016	1999	2017	1971	2000	1971	2000	1961	2013	2000	2017	1987	2000			1986	2000		
87	Kochirira	-13.77	33.05	1158																				
88	Konzaalendo	-16.28	35.18	906																				
89	Lauderdale	-16.03	35.53	770																				
90	Lelembwe	-16.12	35.23	741																				
91	Lichenya	-15.97	35.55	1875																				
92	Lifupa	-13.05	33.12	1006																				
93	Lifuwu	-13.67	34.58				1999	2017																
94	Likanga	-16.08	35.58	627																				
95	Likhubula	-15.93	35.50	793																				
96	Likoma Island						1999	2015																
97	Lilongwe 1	-13.95	33.68	1134																				
98	Lilongwe 2	-13.95	33.80	1029																				
99	Lilongwe 3	-13.98	33.75	1102																				
100	Limphasa	-11.60	34.27	495																				
101	Lipinda	-14.27	35.42	678																				
102	Lipumula	-16.08	35.18	1000																				
103	Lisangadzi	-11.38	33.92	1311																				
104	Lisangadzi	-11.57	33.90	1554																				
105	Lisungwi	-15.43	34.77	351			1944	2000																
106	Liwonde Township	-15.05	35.22	457			1999	2016																
107	Luafwa	-11.60	33.80	1650																				
108	Luchenza	-16.00	35.30	678																				
109	Lujeri Tea Estate	-16.03	35.65	687			1999	2016																
110	Lulwe	-17.08	35.12	610																				
111	Lumbadzi	-13.78	33.82	1228																				
112	Lunyangwa	-11.42	34.03	1341																				
113	Lupaso	-11.40	33.98	1311																				
114	Lupembe	-10.07	33.97	488			1999	2017																
115	Luwawa	-12.12	33.73	1600																				
116	Madisi	-13.42	33.62	1097			1999	2017																
117	Mafisi	-16.07	35.25	747																				
118	Maganga	-15.92	34.58	100																				
119	Magombwa	-16.13	35.10	709																				
120	Mpilili/Makanjira	-13.72	35.05	488			1999	2017																

Climate station list showing station names, latitude, longitude, elevation, and the associated climate data (daily or monthly) which was obtained for each station (continued)

1	Name	Latitude	Longitude	Elevation (m)	Rainfall (mm)				Pan Evaporation (mm)				Temperature (max and min) (°C)				Sunshine Hours (hours/day)				Windspeed (meters/second)			
2					*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*
121	Mkanda	-13.52	32.95										1988	2001										
122	Makhanga	-16.52	35.15	52	1960	2015	1999	2016	1984	2000	1984	2000	1961	2001			1984	2000						
123	Makhuwira	-16.28	35.07	79																				
124	Makoka	-15.53	35.18	1029	1964	2016	1999	2017	1974	2000	1974	2000	1969	2005	2000	2017	1971	2000			1971	2000		
125	Makwasa	-16.20	35.08	335																				
126	Malomo	-13.13	33.83	1083																				
127	Malosa 1	-15.22	35.17	850																				
128	Malosa 3	-15.27	35.33	1570																				
129	Malosa 2	-15.22	35.35	1462																				
130	Mandimwi	-16.10	35.10	903																				
131	Mangochi	-14.47	35.25	482	1961	2016	1999	2017	1971	2000	1971	2000	1961	2004	2000	2017	1971	2000			1971	2000		
132	Mangunda	-16.05	35.25	731																				
133	Maone	-15.80	35.07	1189																				
134	Maonga	-16.07	35.07	1052																				
135	Masambanjati	-16.22	35.12	959			1999	2017																
136	Masanduko	-16.47	35.00	53																				
137	Masenjere	-16.37	35.12	76																				
138	Masuku	-14.48	35.58	838																				
139	Matapwata	-15.93	35.18	808																				
140	Matawale	-16.08	35.23	762																				
141	Matindi	-15.62	35.02	686																				
142	Matope	-15.35	34.95	472																				
143	Matope	-15.35	34.93	472																				
144	Mazamba	-11.72	33.92	1310																				
145	Mbawa	-12.12	33.40	1244			1999	2017																
146	Mboma	-16.05	35.13	950																				
147	Mbombo	-13.13	33.95	1098																				
148	Mbowe	-11.55	33.98	1250																				
149	Mchinji	-13.82	32.92	1350	1960	2016	1999	2017																
150	Mianga	-16.10	35.07	930																				
151	Mikundi	-16.07	35.30	1000																				
152	Mkanda	-13.52	32.95	1219			1999	2016																
153	Milango	-16.12	35.23	747																				
154	Milonde	-16.10	35.47	579																				
155	Mimosa	-16.08	35.58	652	1958	2016	1999	2017	1972	2000	1972	2000	1961	2003	2000	2017	1972	2000			1971	2000		
156	Mindimwi	-16.12	35.20	753																				
157	Mkonkhanthimpwa	-11.72	33.83	1554																				
158	Mloza	-16.07	35.73	655																				
159	Mlangeni/Njolomole	-14.68	34.53				1998	2017																
160	Mngwangwa	-13.82	33.67	1173																				

Climate station list showing station names, latitude, longitude, elevation, and the associated climate data (daily or monthly) which was obtained for each station (continued)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**Name**	**Latitude**	**Longitude**	**Elevation (m)**	**Rainfall (mm)**				**Pan Evaporation (mm)**				**Temperature (max and min) (°c)**				**Sunshine Hours (hours/day)**				**Windspeed (meters/second)**			
2					*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*
161	Mombezi	-15.73	35.12	884			1999	2017																
162	Monkey Bay	-14.08	34.92	482	1979	2016	1999	2017	1983	2000	1983	2000	1980	2004	2000	2017	1971	2000			1979	2000		
163	Mpemba Vet	-15.88	34.95	900	1960	2017	1999	2017																
164	Mpeni	-16.02	35.05	1183																				
165	Mponela	-13.53	33.75	1036	1960	2016	1970	2017																
166	Mpyupyu	-15.37	35.45	716																				
167	Msese	-12.38	33.72	1448																				
168	Mtangatanga	-11.90	33.70	1690																				
169	Mtakataka Airwing	-14.22	33.72				1999	2016																
170	Mua	-14.32	34.35	869																				
171	Mudi	-15.78	35.05	1094																				
172	Mulanje	-16.07	35.53	686			1999	2017																
173	Muonekera	-15.90	35.52	2890																				
174	Mvera	-13.45	33.93	1478																				
175	Mwalamphanda	-16.17	35.08	838																				
176	Mwalanthunzi	-16.05	35.12	1000																				
177	Mwalingo	-9.67	33.52	1285			1999	2017																
178	Mwangulukulu	-9.67	33.87	914																				
179	Mwansambo	-13.30	34.12	457																				
180	Mwanza Agric	-15.62	34.52	655	1965	2015	1999	2017																
181	Mwimba Research	-13.08	33.45				1999	2017																
182	Mzimba	-11.90	33.60	1349	1960	2016	1999	2017	1971	2000	1971	2000	1961	2014	2000	2017					1974	2000		
183	Mzokoto	-10.92	34.02	1065																				
184	Mzuzu	-11.43	34.02	1254	1961	2016	1999	2017	1974	2000	1974	2000	1961	2004	2000	2017	1971	2000			1971	2000		
185	Nabomba	-16.10	35.22	813																				
186	Nalipiri	-16.03	35.47	655																				
187	Namabinzi	-16.07	35.12	1051																				
188	Nambuma	-13.72	33.55	1067																				
189	Namiasi	-14.37	35.22				1999	2017																
190	Namilombwa	-13.93	33.75	1052																				
191	Naming`omba	-16.05	35.08	1067																				
192	Naminjiwa	-15.77	35.62	773	1968	2016	1999	2017																
193	Namulenga	-15.87	35.32	716																				
194	Namwera	-14.37	35.50	899			1999	2017																
195	Nankuma	-14.35	34.80	518			1999	2017																
196	Nasawa	-15.62	35.25	884																				
197	Nathenje	-14.08	33.92	1448			1999	2017																
198	Nchalo Lllovo	-16.23	34.93	64	1971	2015	1999	2017																
199	Nchenachena	-10.73	34.02	1289																				
200	Ndakwera	-16.22	34.70	102																				

Climate station list showing station names, latitude, longitude, elevation, and the associated climate data (daily or monthly) which was obtained for each station (continued)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**Name**	**Latitude**	**Longitute**	**Elevation (m)**	**Rainfall (mm)**				**Pan Evaporation (mm)**				**Temperature (max and min) (°c)**				**Sunshine Hours (hours/day)**				**Windspeed (meters/second)**			
2					*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*
201	Ndamera	-17.10	35.23	46																				
202	Ndokota	-15.88	35.08	1067																				
203	Neno	-15.40	34.65	899	1960	2015	1999	2017																
204	Ngabu	-16.50	34.95	102	1960	2016	1999	2017	1973	2000	1973	2000	1971	2004	2000	2017	1971	2000			1971	2000		
205	Nkhatabay	-11.60	34.30	500	1960	2016	1999	2017	1974	2000	1974	2000	1961	2003	2000	2017					1971	2000		
206	Nkhota	-12.92	34.28	500	1960	2015	1999	2017	1974	2000	1974	2000	1961	2005	2000	2017	1971	2000			1971	2000		
207	Nkhumano	-10.12	33.55	1372																				
208	Nkhwazi	-13.92	33.23	1105																				
209	Nsabwe	-16.33	35.25	458																				
210	Nsambi	-15.27	34.62	1295																				
211	Nsanje	-16.95	35.27	60	1973	2015	1999	3017																
212	Nsaru	-13.88	33.50	1097																				
213	Ntaja	-14.87	35.53	731	1970	2015	1999	2017					1985	2004	2000	2017								
214	Ntcheu	-14.82	34.62	1268	1960	2016	1999	2017																
215	Nkhande	-14.78	34.58	1158																				
216	Ntchisi	-13.03	34.02	1350	1960	2016	1999	2017																
217	Nyika	-10.58	33.82	2286																				
218	Nyungwe	-10.25	34.13	503																				
219	Nyungwe/Mbulum	-15.63	35.20	1036																				
220	Phalombe	-15.82	35.65	1500																				
221	Phalula	-15.27	34.95	579	1970	2015	1999	2017																
222	Phazi	-12.47	33.55	686																				
223	Rumphi	-11.03	33.87	1067			1999	2017																
224	Ruo	-16.10	35.67	609																				
225	Salima	-13.75	34.58	512	1960	2015	1999	2017	1974	2000	1974	2000	1961	2005	2000	2017	1971	2000			1971	2000		
226	Sambankhanga	-16.13	35.00	871																				
227	Santhe	-13.93	33.43	1067																				
228	Saopa	-16.47	34.87	168																				
229	Sapitwa	-16.02	35.52	3100																				
230	Satemwa	-16.05	35.10	1100																				
231	Satemwa	-16.07	35.10	975																				
232	Sayama	-16.05	35.52	641																				
233	Sharpevale	-14.57	34.77	624																				
234	Sinyala	-14.18	33.63	1067			1999	2016																
235	Sombani	-15.90	35.68	1981																				
236	Swazi	-16.08	35.67	625																				
237	Tembwe	-13.82	32.87	1097	1966	2016	1999	2017																
238	Tengani	-16.73	35.27	61																				
239	Thiwi	-14.32	34.12	1249			1999	2016																
240	Thornwood	-16.08	35.65	671																				

Climate station list showing station names, latitude, longitude, elevation, and the associated climate data (daily or monthly) which was obtained for each station (continued)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**Name**	**Latitude**	**Longitute**	**Elevation (m)**	**Rainfall (mm)**				**Pan Evaporation (mm)**				**Temperature (max and min) (°c)**				**Sunshine Hours (hours/day)**				**Windspeed (meters/second)**			
2					*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*	*Daily (start)*	*Daily (end)*	*Monthly (start)*	*Monthly (end)*
241	Thoza	-12.08	33.53	1417			1999	2017																
242	Thuchila	-15.95	35.25	701			1999	2017																
243	Thyolo 2	-16.07	35.13	914	1961	2016			1971	2000	1971	2000	1962	2014			1972	2000			1971	2000		
244	Thyolo Agric	-16.15	35.22	820			1999	2017																
245	Thyolomwani	-16.28	35.13	762																				
246	Toleza Farm	-14.93	35.00	689																				
247	Tsangano	-15.15	34.58	1615																				
248	Ulongwe	-14.85	35.18	518																				
249	Upper	-16.05	35.15	1000																				
250	Utale	-15.17	35.67	517																				
251	Uzumara	-10.83	34.13	1524																				
252	Vinthukutu	-10.42	34.20				1999	2017																
253	Vizara	-11.63	34.28	573																				
254	Walkers Ferry	-15.52	34.83	394	1965	2016																		
255	Zipanganani	-16.00	35.43	670																				
256	Zoa	-16.23	35.25	1021																				
257	Zomba RTC	-15.32	35.32	1817																				
258	Zombwe	-11.33	33.82	1143			1999	2017																
259	Zomba 1	-15.37	35.32	1442																				
260	Zomba 2	-15.33	35.32	1808																				
261	Zomba 3	-15.30	35.35	1785																				
262	Zomba 4	-15.33	35.28	1862																				
263	Zomba 5	-15.35	35.35	1722																				
264	Zomba 6	-15.33	35.18	7389																				
265	Zomba 7	-15.35	35.32	1570																				
266	Zomba Agric	-15.40	35.32	915	1960	2016	1999	2017																

Appendix B Surface Water Station List

Surface water station list showing gauging station names, river names, latitude, longitude, station IDs (national gauge ID and national code), and the river flow data (daily) which was obtained for each gauging station

	A	B	C	D	E	F	G	H	I
1	**Name**	**River**	**Latitute**	**Longitude**	**mWater Unique ID**	**Station ID (National Gauge ID)**	**Station ID (National Code)**	**River flow (m3/s, mean)**	
2								*Daily (start)*	*Daily (end)*
3	Liwonde (HYCOS station)	Shire	-15.067	35.214	24296618	1B1	10201	16/11/1948	31/08/2012
4	Changalume Cement	Kaloti	-15.387	35.220	24296601	1B6	10206		
5	Liwonde (upstream)	Shire	-15.061	35.220	24296591	1B7			
6	Sitola Railway Bridge	Lukwenu	-15.060	35.265	24297509	1B9			
7	Lirangwe	Lirangwe	-15.531	35.018	24296773	1C1	10301	04/11/1951	31/08/2005
8	Whayo	Lunzu	-15.588	34.978	24296814	1C9	10309		
9	Tedzani	Shire	-15.555	34.783	24296924	1C11	10311		
10	Mpokonyola	Mwamphanzi	-16.048	34.862	24296883	1E1	10501	01/12/1951	24/03/2002
11	Namira	Likhubula	-16.003	34.831	24296890	1E2	10502	03/11/1980	31/10/1998
12	Stella Maris School	Naperi	-15.828	34.997	24296807	1E4			
13	Chimwankhunda	Nankhunda	-15.823	35.021	24296766	1E16			
14	Zingwangwa	Nankhunda	-15.817	35.017	24296797	1E17	10517	03/11/1990	31/08/1995
15	Sunnyside	Mudi	-15.792	34.824	24296900	1E19	10519	21/11/1961	30/04/1993
16	Mafumbi/at Maperera	Mapelera	-16.096	34.912	24296852	1F1	10601	20/06/1982	31/12/2005
17	Gooke	Thangadzi East	-16.404	35.163	24296670	1F2	10602	16/04/1953	31/12/2004
18	Masenjere	Milore	-16.342	35.075	24296728	1F3	10603		
19	Malata	Livunzu	-16.193	35.017	24296780	1F17	10617	03/07/1979	17/02/1997
20	Irrigation Headworks	Nkhate	-16.142	34.957	24296821	1F20			
21	Chiromo (left bank channel)	Shire	-16.554	35.146	24296687	1G1(A)	10701	02/01/1953	31/12/2009
22	Chiromo (right bank channel)	Shire	-16.560	35.128	24295909	1G1(B)			
23	Nsangi	Shire	-16.949	35.263	24297516	1G2	10702		
24	Tengani (HYCOS station)	Shire	-16.733	35.280	24297482	1G3			
25	Nyanthana	Thangadzi West	-16.597	35.073	24296735	1G4	10704		
26	Mchacha Rest House	Nyamadzere	-16.903	35.228	24296584	1G10	10710		
27	Tomali	Mwanza	-16.164	34.763	24296931	1K1	11101	02/01/1952	27/02/1997
28	Kalanga	Ng'ona	-15.772	34.427	24296120	1K2	11102		
29	Old Customs Road	Mwanza	-15.555	34.481	24296106	1K3	11103	03/11/1970	31/08/2008
30	Gaga	Ng'ona	-15.808	34.365	24296144	1K8	11108		
31	Jasichindoko	Mwanza	-15.915	34.424	24296137	1K9	11109		
32	Chikwawa	Shire	-16.033	34.803	24296917	1L12	11212	07/05/1977	27/11/2009
33	Maganga (South)	Shire	-15.915	34.759	24296948	1L13	11213		
34	Mlongola	Mkurumadzi	-15.650	34.592	24297547	1M1	11301	03/11/1980	27/08/2008
35	Majete Camp	Mkurumadzi	-15.817	34.733	24296986	1M4	11304		
36	Nkulumadzi	Nkulumadzi	-15.626	34.585	24297554	1M5			
37	Moffat	Lisungwe	-15.450	34.758	24296955	1O1	11501	02/12/1951	01/11/1970
38	Railbridge	Lisungwe	-15.47644	34.751	24296962	1O2			
39	Matope	Shire	-15.389	34.907	24296869	1P2	11602	03/01/1953	31/10/2005
40	Zalewa	Shire	-15.442	34.864	24296876	1P6	11606	20/12/1987	01/10/2008

Surface water station list showing gauging station names, river names, latitude, longitude, station IDs (national gauge ID and national code), and the river flow data (daily) which was obtained for each gauging station (continued)

	A	B	C	D	E	F	G	H	I
1	**Name**	**River**	**Latitute**	**Longitude**	**mWater Unique ID**	**Station ID (National Gauge ID)**	**Station ID (National Code)**	**River flow (m3/s, mean)**	
2								*Daily (start)*	*Daily (end)*
41	Zalewa	Shire				1P7			
42	Balaka	Rivirivi	-15.018	34.953	24296838	1R3	11803	12/11/1952	31/08/2004
43	Gumbu	Mpamadzi	-14.833	34.623	24297011	1R18	11818	10/11/1963	03/07/2008
44	Gomeza	Mpira	-15.897	34.654	24296993	1R19	11819		
45	Manjawira	Rivi-Rivi	-14.944	34.746	24296979	1R20	11820		
46	Chitala	Rivi-Rivi	-15.08370	35.024	24296759	1R21			
47	Water Supply Intake	Marko	-14.829	34.613	24297028	1R22			
48	Mangochi	Shire	-14.479	35.273	24297499	1T1	12001	03/01/1951	31/05/2008
49	Mwalija	Lake Malombe	-14.62613	35.183	24296656	1T4			
50	Mvera Point-Malombe Out	Shire				1S2	11902		
51	Kalembo	Nkasi	-14.854	35.166	24296663	1S7	11907	03/10/1961	31/01/1997
52	Phaloni Hill	Sombani				2A2			
53	Ngangala	Lake Chilwa				2B1			
54	Namadzi	Namadzi	-15.546	35.188	24296649	2B6	20206		
55	Zomba Plateau	Mulunguzi	-15.359	35.309	24297420	2B8	20208		
56	Lambulira	Likangala				2B9			
57	Phlombe	Phalombe				2B10	20210		
58	Williams Falls	Mulunguzi	-15.344	35.301	24297475	2B11	20211		
59	Nkokanguwo	Likangala	-15.414	35.439	24297372	2B21	20221		
60	Jali	Thondwe	-15.487	35.478	24297358	2B22	20222	13/12/1959	28/02/2009
61	Upper Dambo	Mulunguzi				2B23			
62	No 6 Raingauge	Mulunguzi West				2B30			
63	Matiti	Namadzi	-15.682	35.325	24297396	2B33	20233	23/05/1962	31/03/2010
64	Irrigation Scheme	Likangala				2B35			
65	Zomba Plateau	Mulunguzi	-15.357	35.302	24297468	2B38			
66	Domasi T.T.C (Domasi MIE)	Domasi	-15.280	35.397	24297389	2C3	20303	08/11/1957	31/12/2009
67	Za-LL Road (by pass)	Domasi				2C4	20304		
68	Mwandama	Naisi	-15.376	35.486	24297341	2C8	20308		
69	Kachulu	Lake Chilwa	-15.372	35.592	24297293	2C10			
70	Monkey Bay (HYCOS station)	Lake Malawi	-14.069	34.917	24296845	3A2	30102		
71	Nkuchila	Mtemankhokwe				3D1	30401		
72	Mua Mission	Nadzipokwe	-14.280	34.507	24296089	3E1	30501	21/11/1953	31/03/2010
73	Mua Livulezi F.R	Namikokwe	-14.391	34.515	???	3E2	30502	03/12/1957	09/08/2003
74	Khwekhelele	Livulezi	-14.442	34.539	24296058	3E3	30503	19/10/1957	29/05/2008
75	Kampanikiza	Namikokwe	-14.434	34.484	24296096	3E5	30505	03/02/1958	05/09/2009
76	Thobola	Nkhande River	-14.793	34.594	24297530	3E7	30507		
77	Chipoka	Lake Malawi	-13.991	34.519	24296065	3F1			
78	Songwe	Nakaingqa				3F2			
79	Mtakatake	Nadzipulu	-14.214	34.513	24296072	3F3	30603	31/08/1957	13/12/2003
80	Eden Estate	Makonda	-14.298	34.300	24296199	4A4	40104		

Surface water station list showing gauging station names, river names, latitude, longitude, station IDs (national gauge ID and national code), and the river flow data (daily) which was obtained for each gauging station (continued)

	A	B	C	D	E	F	G	H	I
1	**Name**	**River**	**Latitute**	**Longitude**	**mWater Unique ID**	**Station ID (National Gauge ID)**	**Station ID (National Code)**	**River flow (m3/s, mean)**	
2								*Daily (start)*	*Daily (end)*
81	Salima Bridge	Linthipe	-13.790	34.452	24296113	4B1	40201	02/04/1953	16/06/2009
82	Linthipe Bridge	Linthipe	-14.180	34.124	24296364	4B3	40203	02/12/1957	31/12/2008
83	Chilowa New Bridge	Diamphwe	-14.134	34.088	24296405	4B4	40204	02/12/1957	31/01/2010
84	Malapa 2	Linthipe	-13.836	34.340	24296168	4B5			
85	Malapa	Linthipe	-13.802	34.363	24296151	4B9	40209	29/11/1974	31/01/2010
86	Chilowa New Bridge	Diamphwe	-14.136	34.088	24296395	4B10			
87	Knwenembela	Lilongwe	-13.785	34.268	24296209	4C2	40302	20/11/1957	30/04/2010
88	Chingira	Nanjiri				4C10			
89	Kadzizila	Nanjiri	-13.964	33.932	24297059	4C11	40311	15/09/1985	31/03/2010
90	Lilongwe Old Town	Lilongwe	-13.991	33.773	24295686	4D4	40404	03/07/1953	27/03/2009
91	Malingunde	Lilongwe	-14.169	33.693	4009443	4D6	40403		
92	Kaweche	Katete	-14.203	33.596	4009560	4D21	40421		
93	Malingunde	Kamuzu Dam	-14.174	33.642	4009508	4D23			
94	Masula	Lilongwe	-14.152	33.691	4009450	4D24	40424	03/02/1991	30/09/2005
95	Masula	Lisungwi	-14.163	33.690	4009467	4D25			
96	Chigwirizao	Likuni	-14.035	33.706	4009436	4D27	40427		
97	Mamina	Lilongwe	-14.272	33.608	4009553	4D28			
98	Mamina	Chaulongwe	-14.258	33.575	24295693	4D29	40429		
99	M1 Roadbridge	Lingadzi	-13.952	33.774	24295679	4E1	40501		
100	S11 Roadbridge	Lingadzi	-13.918	33.712	4009429	4E2	40502	23/12/1959	31/03/2005
101	Simakumi	Lumbadzi	-13.796	33.989	24296515	4F6	40606		
102	S53 Roadbridge	Bua	-12.786	34.196	24296292	5C1	50301	03/11/1957	31/01/2010
103	Mtunthama	Kamuzu Aca D				5C8			
104	Bua Drift	Bua	-13.107	33.780	24295662	5D1	50401	03/11/1959	31/07/2007
105	Old Bua Bridge	Bua	-13.308	33.546	24295734	5D2	50402	03/02/1954	28/02/2005
106	M1 Roadbridge	Bua	-13.308	33.546	24295727	5D2(B)			
107	Mtiti	Mtiti	-13.470	33.645	4009498	5D3	50403	14/12/1958	28/02/2003
108	Namitete Town	Namitete	-14.021	33.353	24295851	5E1	50501		
109	Tembwe	Bua				5E2			
110	Mchinji	Bua	-13.799	32.880	24295882	5E6	50506	03/11/1970	31/01/2008
111	Kasela	Rusa	-13.325	33.438	24295796	5F1	50601	02/12/1964	30/06/2005
112	Mkanda	Liwelezi				5F2	50602		
113	Matuwamba	Liwelezi	-13.588	32.790	24295899	5F3	50603		
114	Kasunga National Park	Lingadzi	-13.045	33.155	24295868	6B2			
115	Khwengwere	Dwangwa	-12.883	33.454	24295772	6C1	60301	21/02/1953	31/12/2009
116	S54 Roadbridge	Chitete				6C3			
117	M1 Roadbridge	Mpasadzi	-12.798	33.441	24295789	6C5	60305	01/12/1965	30/09/2001
118	Dam Water Works	Chitete				6C7			
119	M1 Roadbridhe	Milenje	-12.667	33.497	24295765	6D1	60401		
120	S53Roadbridge	Dwangwa				6D4			

Surface water station list showing gauging station names, river names, latitude, longitude, station IDs (national gauge ID and national code), and the river flow data (daily) which was obtained for each gauging station (continued)

	A	B	C	D	E	F	G	H	I
1	**Name**	**River**	**Latitute**	**Longitude**	**mWater Unique ID**	**Station ID (National Gauge ID)**	**Station ID (National Code)**	**River flow (m3/s, mean)**	
2								*Daily (start)*	*Daily (end)*
121	Matundu	Luwelezi	-12.493	33.621	4009515	6D5	60405		
122	Kamende	Rupache	-12.400	33.872	24295590	6D7	60407		
123	S53 Roadbridge D/S (Rupashe)	Dwanga	-12.514	34.116	24296371	6D10	60410	03/01/1986	31/01/2010
124	Entandweni	Milenje	-12.692	33.667	4009481	6D11			
125	Chimsewezo	South Rukura	-12.131	33.388	24295837	7A3	70103	17/05/1956	31/12/2008
126	Muweru Bulukutu	Mzinma	-11.980	33.675	4009474	7A4	70104		
127	Kamteteka	South Rukuru				7A9			
128	Mapanjira	South Rukuru				7A11	70111		
129	Kamangadzi (Mungoni)	South Rukuru	-11.817	33.398	24295813	7A12	70112		
130	Nthipa	Hara	-10.502	34.144	24296333	7C10			
131	Edundi	Kasitu				7D4	70404		
132	Mzuzu	Lunyangwa				7D5			
133	Njakwa	Kasitu				7D7	70407		
134	Zombwe (Ekwendeni - Mpherembe	Lunyangwa	-11.340	33.848	24295624	7D8	70408	02/08/1954	30/06/2008
135	Mzuzu Water Works (Mzuzu WW Int	Lunyangwa	-11.453	34.053	24296467	7D16	70416		
136	Kamweko (Mzuzu - Malivneji Road	Lusangazi	-11.454	33.959	24297042	7D17	70417		
137	Mopho Jere	Lunyangwa				7D18	70418		
138	Kazuni Bridge	South Rukuru				7E2	70502	03/11/1980	30/11/1997
139	Chikwawa	Runyina	-11.019	33.786	24295655	7F1	70601	03/11/1955	31/07/1998
140	Rumphi	South Rumphi	-11.022	33.866	24295617	7F2	70602	03/12/1959	31/07/2008
141	Mjuma	Runyina	-10.954	33.757	24296546	7F3	70603		
142	Muhuju	Muhuju	-10.878	33.996	24296508	7G3	70703		
143	Ng'onga (Roadbridge)	Luviri	-10.931	33.915	24295552	7G13	70703		
144	Phwezi	South Rukuru	-10.887	34.041	24296481	7G14	70714	29/11/1957	25/05/2007
145	Mlowe	South Rukuru	-10.752	34.208	24296278	7G18	70718	03/11/1985	31/08/2009
146	Phwezi	Chivungulu	-10.886	34.041	24296474	7G19			
147	Njakwa	South Rukuru	-11.034	33.895	24295583	7G18			
148	Phoka Court	North Rumphi	-10.653	34.077	24296436	7H1	70801	02/02/1956	30/04/2008
149	Kaziwizi	Kaziwiziwi	-10.638	34.084	24296412	7H2	70802	22/05/1953	30/05/2008
150	Chiweta	North Rumphi	-10.687	34.182	24296326	7H3	70803	12/09/1972	31/05/2007
151	Mwankenja	North Rukuru				8A2			
152	Mwakimeme (HYCOS station)	North Rukuru	-9.933	33.787	24295648	8A5	80105	20/11/1968	31/05/2009
153	Uledi	North Rukuru	-10.167	33.753	4009405	8A8	80108		
154	Uledi	Mibanga	-10.175	33.748	4009412	8A9	80109		
155	Ngerenge	Lufira	-9.807	33.837	24295631	9A2	90102	07/10/1953	30/09/2009
156	Chiwona	Chambo	-9.850	33.517	24295758	9A3	90103		
157	Chilanga	Lufira	-9.894	33.560	24295703	9A4	90104	02/06/1959	29/02/2008
158	Chilanga	Kalenje	-9.760	33.525	24295741	9A5	90105	11/12/1970	31/05/2007
159	Mwakasangila	Lufira	-9.867	33.867	24295600	9A7	90107		
160	Ngerenge Scheme	Lufira (canal)				9A8	90108		

Surface water station list showing gauging station names, river names, latitude, longitude, station IDs (national gauge ID and national code), and the river flow data (daily) which was obtained for each gauging station (continued)

	A	B	C	D	E	F	G	H	I
1	**Name**	**River**	**Latitute**	**Longitude**	**mWater Unique ID**	**Station ID (National Gauge ID)**	**Station ID (National Code)**	**River flow (m3/s, mean)**	
2								*Daily (start)*	*Daily (end)*
162	Chilanga	Mbalizi				9A10	90110		
163	Yotau Nyondo	Chambo	-9.938	33.388	24295820	9A13			
164	Mwangulukulu	Songwe				9B1	90201		
165	Chinkhopola	Nyungwe	-10.335	34.074	24296443	9B2			
166	Mwenebwiba	Kaseye	-9.635	33.380	24295844	9B3	90203	28/06/1971	31/01/2008
167	Ichinga	Songwe	-9.594	33.423	24295806	9B4	90204		
168	David Kameme	Hanga				9B5	90205	03/11/1979	30/04/2004
169	Ipenza	Songwe	-9.465	33.090	24295875	9B6	90206	03/11/1981	31/01/2008
170	Mwandenga (HYCOS Station)	Songwe	-9.587	33.767	24296522	9B7	90207	06/08/1985	29/02/2012
171	Mwenitende (NORPLAN)	Songwe				9D1			
172	Mpunguti (NORPLAN)	Songwe				9D2			
173	Mwamburi (NORPLAN)	Songwe				9D3			
174	Mbeya RoadBridge (NORPLAN)	Kiwira				9D5			
175	Mapwa (NORPLAN)	Songwe				9D6			
176	Mbako (NORPLAN)	Kiwira				9D7			
177	Nambande Estate	Lusangwisi				11A6	110106	02/09/1977	16/11/1997
178	Namwera	Masongola	-14.362	35.500	24297327	11A7	110107	04/09/1977	31/10/1998
179	Chisumullu Island	Lake Malawi	-12.022	34.623	24297004	13A1			
180	Henderson Estate	Namadzi	-15.994	35.141	24296694	14A1	140101	28/05/1971	31/03/1998
181	Luchenza	Luchenza	-15.999	35.307	24297444	14A2	140102	04/01/1955	31/10/2002
182	Midima Road	Chisombezi	-15.847	35.192	24296632	14A3	140103	12/05/1962	31/05/2000
183	M1 Roadbridge	Kwakwasi	-16.042	35.236	24296560	14B1	140201	14/12/1951	31/08/1986
184	Chonde	Thuchila	-16.002	35.320	24297406	14B2	140202	07/12/1951	30/12/2003
185	Chipungu	Nswadzi	-16.189	35.262	24297523	14B3	140203	02/01/1954	19/02/2002
186	Naming'omba	Nswadzi	-16.067	35.067	24296742	14B4	140204	03/11/1980	30/06/2002
187	Magombe Estate	Nswadzi	-16.117	35.083	24296711	14B5	140205	03/11/1980	29/04/1989
188	Kambenje	Thuchila	-15.846	35.564	24297303	14B6	140206		
189	Daudi	Likulezi				14B7	140207	16/09/1971	30/06/1997
190	Mangunda (Kwakwasi)	Kwakwasi	-16.035	35.254	24297561	14B8	140208		
191	Makwasa	Nsuwadzi	-16.102	35.110	24296704	14B9			
192	Lujeri Estate Weir	Lujeri	-16.017	35.650	24297286	14C1	140301		
193	M1 Roadbridge (Nsuwadzi)	Ruo	-16.080	35.674	24297262	14C2	140302	02/07/1953	31/10/2008
194	Mini Mini Estate	Lichenya	-15.847	35.192	24296625	14C3	140303	03/11/1980	31/07/1990
195	Chambe Plateau	Chapaluka	-15.933	35.517	24297310	14C4	140304	02/03/1954	01/11/1959
196	Ruo Estate	Ruo	-16.100	35.662	24297279	14C5			
197	Likabula Forestry (Likeabula Estate	Likabula	-15.942	35.496	24297334	14C6			
198	Mlelemba Drift	Muloza	-15.933	35.800	24297255	14C7	140307	03/01/1975	31/03/2002
199	Milonde	Lichenya	-16.104	35.476	24297365	14C8	140308	22/10/1960	31/10/2002
200	Sinoya (South)	Ruo	-16.483	35.233	24296577	14D1	140401	03/11/1980	27/01/1991

Appendix C Results of the annual and seasonal BFI analysis for Chapter 6

Results of the annual and seasonal BFI analysis (tabular) for gauge station 1B1, 1948–2012 (64 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1948/1949	-	-	0.99
1949/1950	0.98	0.97	0.99
1950/1951	0.98	0.96	0.99
1951/1952	0.99	0.97	1.00
1952/1953	0.99	0.99	0.99
1953/1954	0.99	0.99	0.99
1954/1955	0.98	0.96	0.99
1955/1956	0.98	0.97	0.99
1956/1957	0.95	0.08	0.96
1957/1958	0.99	0.98	1.00
1958/1959	0.99	0.99	0.99
1959/1960	0.99	0.99	0.99
1960/1961	0.98	0.97	0.99
1961/1962	0.99	0.99	1.00
1962/1963	0.99	0.99	1.00
1963/1964	0.99	0.99	1.00
1964/1965	0.96	0.99	0.92
1965/1966	0.78	0.68	0.85
1966/1967	0.96	0.95	0.97
1967/1968	0.99	0.99	1.00
1968/1969	0.94	0.94	0.94
1969/1970	0.98	0.98	0.99
1970/1971	0.96	0.93	0.98
1971/1972	0.98	0.99	0.96
1972/1973	0.98	0.99	0.96
1973/1974	0.96	0.98	0.95
1974/1975	0.97	0.98	0.96
1975/1976	0.96	0.91	0.99
1976/1977	0.97	0.98	0.97
1977/1978	0.98	0.98	0.99
1978/1979	0.99	1.00	0.99
1979/1980	0.99	0.99	1.00
1980/1981	0.99	0.99	0.99
1981/1982	0.98	0.97	1.00
1982/1983	0.99	0.99	0.99
1983/1984	0.97	0.98	0.97
1984/1985	0.96	0.95	0.97
1985/1986	0.97	0.94	0.99
1986/1987	0.97	0.95	0.98

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1987/1988	0.99	0.98	0.99
1988/1989	0.98	0.99	0.97
1989/1990	0.98	0.99	0.97
1990/1991	0.98	0.98	0.99
1991/1992	0.98	0.99	0.96
1992/1993	0.98	0.98	0.99
1993/1994	0.99	0.99	0.98
1994/1995	0.99	0.98	0.99
1995/1996	-	-	0.99
1996/1997	0.94	0.90	0.98
1997/1998	-	0.98	-
1998/1999	0.97	0.96	0.98
1999/2000	0.98	0.97	0.98
2000/2001	-	-	0.97
2001/2002	-	-	0.97
2002/2003	0.95	0.92	0.97
2003/2004	0.96	0.95	0.96
2004/2005	0.91	0.85	0.97
2005/2006	0.97	0.94	0.99
2006/2007	-	-	-
2007/2008	-	-	-
2008/2009	0.97	0.95	0.98
2009/2010	-	0.98	-
2010/2011	-	-	-
2011/2012	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 1C1, 1951-2005 (54 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1951/1952	-	-	0.99
1952/1953	0.57	0.52	0.92
1953/1954	0.08	0.07	0.91
1954/1955	0.28	0.22	0.88
1955/1956	0.25	0.15	0.97
1956/1957	0.48	0.43	0.97
1957/1958	0.35	0.30	0.93
1958/1959	0.13	0.12	0.64
1959/1960	0.07	0.08	0.02
1960/1961	0.17	0.15	0.82
1961/1962	0.19	0.14	0.96
1962/1963	-	-	0.98
1963/1964	0.21	0.19	0.85
1964/1965	-	-	0.74
1965/1966	-	-	-
1966/1967	-	-	0.68
1967/1968	-	-	0.69
1968/1969	-	-	0.77
1969/1970	-	-	0.74
1970/1971	-	-	
1971/1972	-	-	0.91
1972/1973	-	-	0.81
1973/1974	0.39	0.33	0.85
1974/1975	0.28	0.21	0.93
1975/1976	-	-	0.93
1976/1977	-	-	-
1977/1978	-	-	-
1978/1979	0.25	0.21	0.88
1979/1980	-	-	0.00
1980/1981	-	-	-
1981/1982	-	-	-
1982/1983	0.82	0.72	0.97
1983/1984	-	-	-
1984/1985	-	-	0.98
1985/1986	0.71	0.60	0.99
1986/1987	0.86	0.79	0.98
1987/1988	-	-	0.99
1988/1989	0.76	0.65	0.99
1989/1990	0.70	0.58	0.97

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1990/1991	0.78	0.67	0.97
1991/1992	-	-	-
1992/1993	-	-	0.96
1993/1994	0.72	0.64	0.95
1994/1995	0.43	0.37	0.86
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	0.94	0.91	0.94
1998/1999	-	-	-
1999/2000	0.81	0.72	0.94
2000/2001	0.68	0.58	0.95
2001/2002	-	-	-
2002/2003	-	0.99	-
2003/2004	-	-	-
2004/2005	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 1G1A, 1952-2010 (58 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1952/1953	-	-	0.99
1953/1954	0.95	0.93	0.98
1954/1955	0.93	0.91	0.97
1955/1956	0.92	0.87	0.99
1956/1957	-	-	0.95
1957/1958	0.96	0.94	0.98
1958/1959	0.94	0.90	0.99
1959/1960	0.94	0.91	0.98
1960/1961	0.97	0.95	0.98
1961/1962	0.97	0.94	0.99
1962/1963	0.95	0.91	1.00
1963/1964	0.98	0.97	0.98
1964/1965	0.98	0.97	0.98
1965/1966	0.93	0.90	0.96
1966/1967	0.94	0.90	0.98
1967/1968	0.97	0.95	0.99
1968/1969	0.90	0.83	0.98
1969/1970	0.94	0.90	0.90
1970/1971	0.94	0.90	0.99
1971/1972	-	-	0.94
1972/1973	0.89	0.83	0.96
1973/1974	0.93	0.90	0.96
1974/1975	-	0.97	-
1975/1976	0.97	0.94	0.99
1976/1977	0.98	0.97	0.99
1977/1978	0.98	0.97	0.99
1978/1979	0.96	0.93	0.99
1979/1980	-	-	1.00
1980/1981	0.98	0.97	0.99
1981/1982	0.97	0.94	0.99
1982/1983	0.95	0.92	0.99
1983/1984	-	0.92	-
1984/1985	0.88	0.85	0.99
1985/1986	0.97	0.95	0.99
1986/1987	0.95	0.91	0.99
1987/1988	0.96	0.94	0.98
1988/1989	-	-	-
1989/1990	0.97	0.97	0.97

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1990/1991	0.95	0.91	0.99
1991/1992	0.97	0.96	0.97
1992/1993	0.93	0.91	0.96
1993/1994	0.90	0.84	0.97
1994/1995	0.92	0.89	0.97
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	0.97	0.96	0.99
1998/1999	0.97	0.97	0.97
1999/2000	0.98	0.97	0.99
2000/2001	-	0.95	-
2001/2002	0.97	0.95	0.99
2002/2003	0.98	0.97	0.99
2003/2004	0.98	0.97	0.99
2004/2005	0.95	0.91	1.00
2005/2006	-	-	-
2006/2007	0.97	0.95	1.00
2007/2008	-	0.96	-
2008/2009	-	-	0.99
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 1K1, 1951-1997 (46 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1951/1952	-	-	0.89
1952/1953	0.55	0.50	0.81
1953/1954	0.35	0.35	1.00
1954/1955	0.52	0.47	0.80
1955/1956	0.53	0.41	0.79
1956/1957	0.39	0.36	0.86
1957/1958	0.29	0.26	0.89
1958/1959	0.54	0.54	1.00
1959/1960	0.07	0.07	0.34
1960/1961	0.53	0.52	1.00
1961/1962	0.47	0.38	0.90
1962/1963	0.38	0.33	0.93
1963/1964	0.21	0.20	0.99
1964/1965	0.57	0.53	0.98
1965/1966	0.21	0.18	0.65
1966/1967	0.31	0.20	0.54
1967/1968	-	-	-
1968/1969	0.59	0.57	0.88
1969/1970	0.22	0.22	0.31
1970/1971	0.22	0.22	-
1971/1972	0.46	0.45	0.70
1972/1973	0.15	0.12	0.77
1973/1974	0.37	0.30	0.87
1974/1975	0.60	0.60	0.66
1975/1976	0.51	0.42	0.86
1976/1977	0.40	0.36	0.90
1977/1978	0.45	0.39	0.86
1978/1979	0.76	0.73	0.84
1979/1980	0.05	0.04	0.86
1980/1981	0.39	0.36	0.94
1981/1982	0.37	0.36	0.59
1982/1983	0.10	0.10	-
1983/1984	-	-	-
1984/1985	-	-	-
1985/1986	-	-	-
1986/1987	-	0.29	-
1987/1988	-	-	-
1988/1989	-	-	0.44
1989/1990	-	0.12	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1990/1991	-	-	-
1991/1992	-	-	0.50
1992/1993	-	0.17	-
1993/1994	0.12	0.09	0.24
1994/1995	-	-	-
1995/1996	-	-	0.53
1996/1997	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for the gauge station 1L12, 1976-2010 (34 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1976/1977	-	-	-
1977/1978	-	-	0.99
1978/1979	-	0.97	-
1979/1980	0.98	0.97	1.00
1980/1981	-	-	-
1981/1982	-	0.95	-
1982/1983	-	0.96	-
1983/1984	-	-	-
1984/1985	-	-	-
1985/1986	0.94	0.90	0.99
1986/1987	0.97	0.96	0.98
1987/1988	0.95	0.93	0.98
1988/1989	0.95	0.91	0.99
1989/1990	-	0.95	-
1990/1991	0.93	0.89	0.97
1991/1992	-	-	0.89
1992/1993	0.84	0.79	0.91
1993/1994	0.89	0.86	0.92
1994/1995	-	-	-
1995/1996	0.85	0.82	0.88
1996/1997	-	-	-
1997/1998	-	0.90	-
1998/1999	-	-	0.96
1999/2000	-	0.92	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	-	-	-
2008/2009	-	-	-
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 1M1, 1980-2008 (28 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1980/1981	0.84	0.76	0.96
1981/1982	-	-	-
1982/1983	0.70	0.62	0.89
1983/1984	0.70	0.55	0.93
1984/1985	-	-	0.97
1985/1986	0.89	0.84	0.99
1986/1987	0.59	0.52	0.86
1987/1988	-	0.52	-
1988/1989	-	-	0.98
1989/1990	-	-	0.89
1990/1991	-	-	-
1991/1992	0.52	0.45	0.89
1992/1993	-	-	0.89
1993/1994	-	0.29	-
1994/1995	-	-	-
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	0.93
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	0.41	0.41	0.49
2005/2006	0.46	0.42	0.69
2006/2007	-	-	-
2007/2008	-	0.37	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 1P2, 1952-2005 (53 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1952/1953	-	-	-
1953/1954	-	-	-
1954/1955	-	-	-
1955/1956	0.00	-	0.00
1956/1957	0.96	0.00	0.98
1957/1958	0.97	0.94	0.99
1958/1959	0.97	0.96	0.98
1959/1960	0.97	0.95	0.99
1960/1961	0.94	0.90	0.99
1961/1962	0.97	0.93	0.99
1962/1963	-	-	1.00
1963/1964	0.99	0.99	1.00
1964/1965	-	0.98	-
1965/1966	0.69	0.54	0.81
1966/1967	0.92	0.89	0.95
1967/1968	0.99	0.98	0.99
1968/1969	0.86	0.82	0.88
1969/1970	0.95	0.93	0.99
1970/1971	0.93	0.86	0.98
1971/1972	0.96	0.97	0.92
1972/1973	0.91	0.92	0.90
1973/1974	0.89	0.75	0.94
1974/1975	0.96	0.95	0.95
1975/1976	0.95	0.88	0.99
1976/1977	0.98	0.98	0.98
1977/1978	-	-	0.99
1978/1979	1.00	0.99	1.00
1979/1980	0.99	0.99	1.00
1980/1981	0.98	0.96	1.00
1981/1982	-	-	1.00
1982/1983	0.99	0.98	1.00
1983/1984	-	0.98	-
1984/1985	-	-	1.00
1985/1986	0.97	0.93	1.00
1986/1987	0.98	0.97	0.99
1987/1988	0.97	0.96	0.99
1988/1989	0.96	0.97	0.96
1989/1990	0.96	0.97	0.96
1990/1991	0.96	0.92	0.99

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1991/1992	0.98	0.98	0.96
1992/1993	-	0.75	-
1993/1994	0.85	0.81	0.89
1994/1995	0.79	0.74	0.86
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	0.78	0.71	0.88
2000/2001	0.73	0.69	0.84
2001/2002	0.73	0.69	0.84
2002/2003	0.91	0.83	0.97
2003/2004	-	-	-
2004/2005	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 1R3, 1952-2004 (52 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1952/1953	-	-	0.87
1953/1954	-	-	-
1954/1955	-	-	0.93
1955/1956	-	-	0.92
1956/1957	-	-	0.96
1957/1958	-	-	0.95
1958/1959	0.26	0.21	0.81
1959/1960	-	0.22	-
1960/1961	0.05	0.03	0.76
1961/1962	0.11	0.08	0.89
1962/1963	0.24	0.20	0.95
1963/1964	-	-	0.91
1964/1965	0.21	0.20	0.93
1965/1966	0.05	0.04	0.72
1966/1967	-	0.12	-
1967/1968	-	-	0.87
1968/1969	0.21	0.20	0.89
1969/1970	0.09	0.09	0.84
1970/1971	0.18	0.16	0.92
1971/1972	0.24	0.22	0.77
1972/1973	0.08	0.07	0.51
1973/1974	0.45	0.39	0.79
1974/1975	0.26	0.24	0.91
1975/1976	0.24	0.21	0.94
1976/1977	0.29	0.25	0.96
1977/1978	0.24	0.22	0.95
1978/1979	0.29	0.25	0.96
1979/1980	-	-	0.93
1980/1981	0.24	0.20	0.94
1981/1982	0.26	0.22	0.77
1982/1983	0.22	0.20	0.83
1983/1984	0.25	0.21	0.83
1984/1985	-	-	0.94
1985/1986	0.30	0.25	0.96
1986/1987	0.21	0.18	0.91
1987/1988	0.06	0.06	0.86
1988/1989	0.21	0.17	0.95
1989/1990	0.08	0.07	0.63
1990/1991	0.07	0.06	0.75

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1991/1992	-	0.12	-
1992/1993	-	-	-
1993/1994	-	-	-
1994/1995	-	-	-
1995/1996	0.08	0.08	0.80
1996/1997	0.08	0.07	0.84
1997/1998	0.21	0.19	0.88
1998/1999	-	-	0.94
1999/2000	-	0.18	-
2000/2001	-	-	0.94
2001/2002	0.12	0.10	0.81
2002/2003	-	-	-
2003/2004	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for the gauge station 1S7, 1961–1997 (36 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1961/1962	0.27	0.26	0.85
1962/1963	0.15	0.14	0.92
1963/1964	0.24	0.24	0.51
1964/1965	0.18	0.16	0.86
1965/1966	-	-	0.51
1966/1967	0.11	0.11	0.31
1967/1968	0.16	0.16	0.35
1968/1969	-	-	0.89
1969/1970	-	0.02	0.00
1970/1971	-	-	0.76
1971/1972	-	-	0.90
1972/1973	0.07	0.06	0.81
1973/1974	0.20	0.16	0.89
1974/1975	0.26	0.22	0.88
1975/1976	0.00	0.00	0.83
1976/1977	0.41	0.36	0.80
1977/1978	0.00	0.00	0.96
1978/1979	0.55	0.51	0.94
1979/1980	0.28	0.24	0.89
1980/1981	0.30	0.27	0.94
1981/1982	0.30	0.28	0.94
1982/1983	0.16	0.14	0.79
1983/1984	0.20	0.17	0.44
1984/1985	0.15	0.13	0.98
1985/1986	0.44	0.42	0.93
1986/1987	0.23	0.20	0.96
1987/1988	0.12	0.10	0.92
1988/1989	0.26	0.25	0.93
1989/1990	0.53	0.49	0.84
1990/1991	0.63	0.61	0.84
1991/1992	0.22	0.23	0.00
1992/1993	0.88	0.80	0.96
1993/1994	0.77	0.77	-
1994/1995	0.72	0.72	-
1995/1996	0.66	0.50	0.89
1996/1997	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 14A2, 1954–2002 (48 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1954/1955	-	-	0.66
1955/1956	-	-	0.84
1956/1957	0.43	0.38	0.88
1957/1958	0.54	0.50	0.82
1958/1959	0.36	0.32	0.76
1959/1960	0.15	0.10	0.64
1960/1961	0.32	0.28	0.72
1961/1962	0.34	0.27	0.82
1962/1963	0.39	0.34	0.91
1963/1964	0.36	0.31	0.82
1964/1965	0.38	0.31	0.92
1965/1966	0.37	0.29	0.83
1966/1967	0.41	0.27	0.83
1967/1968	0.54	0.42	0.96
1968/1969	-	-	0.94
1969/1970	-	-	-
1970/1971	-	-	-
1971/1972	-	-	-
1972/1973	-	-	-
1973/1974	-	-	-
1974/1975	-	-	0.95
1975/1976	-	-	0.94
1976/1977	-	-	0.97
1977/1978	-	-	-
1978/1979	0.78	0.68	0.93
1979/1980	-	-	0.94
1980/1981	0.64	0.53	0.92
1981/1982	-	-	-
1982/1983	-	-	0.92
1983/1984	0.63	0.51	0.91
1984/1985	0.58	0.49	0.92
1985/1986	0.57	0.49	0.95
1986/1987	-	-	0.92
1987/1988	-	0.56	-
1988/1989	0.56	0.47	0.97
1989/1990	0.63	0.58	0.83
1990/1991	0.54	0.54	0.89
1991/1992	-	-	0.65

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1992/1993	0.20	0.18	0.81
1993/1994	-	0.41	-
1994/1995	-	-	0.92
1995/1996	0.27	0.18	0.94
1996/1997	-	-	0.93
1997/1998	0.23	0.18	0.97
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	0.07	0.06	0.62

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) gauge station 14A3, 1962–2000 (38 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1962/1963	0.39	0.35	0.92
1963/1964	-	-	-
1964/1965	-	0.27	-
1965/1966	0.36	0.28	0.71
1966/1967	0.35	0.18	0.89
1967/1968	0.35	0.30	0.71
1968/1969	0.17	0.13	0.85
1969/1970	0.27	0.23	0.84
1970/1971	0.35	0.31	0.87
1971/1972	0.21	0.25	0.13
1972/1973	0.17	0.12	0.87
1973/1974	0.47	0.38	0.90
1974/1975	-	0.10	-
1975/1976	0.37	0.27	0.88
1976/1977	-	0.00	-
1977/1978	0.30	0.89	0.89
1978/1979	0.54	0.49	0.49
1979/1980	0.37	0.30	0.88
1980/1981	0.48	0.42	0.88
1981/1982	-	-	-
1982/1983	0.30	0.25	0.75
1983/1984	0.14	0.10	0.63
1984/1985	-	-	0.95
1985/1986	-	-	0.92
1986/1987	0.12	0.09	0.85
1987/1988	0.18	0.14	0.78
1988/1989	0.19	0.14	0.95
1989/1990	0.17	0.13	0.80
1990/1991	0.17	0.13	0.86
1991/1992	-	-	0.71
1992/1993	0.16	0.12	0.80
1993/1994	0.10	0.08	0.86
1994/1995	-	0.04	-
1995/1996	-	-	-
1996/1997	-	-	0.97
1997/1998	0.20	0.14	0.95
1998/1999	-	0.10	-
1999/2000	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 14B2, 1951–2003 (52 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1951/1952	-	-	0.90
1952/1953	0.52	0.48	0.90
1953/1954	0.40	0.37	0.76
1954/1955	0.57	0.54	0.86
1955/1956	-	-	0.89
1956/1957	0.56	0.53	0.89
1957/1958	-	0.45	-
1958/1959	-	-	0.85
1959/1960	0.37	0.33	0.81
1960/1961	0.42	0.39	0.88
1961/1962	-	0.34	-
1962/1963	0.58	0.56	0.97
1963/1964	0.29	0.33	0.15
1964/1965	-	0.53	-
1965/1966	0.33	0.29	0.83
1966/1967	-	-	0.86
1967/1968	0.40	0.36	0.93
1968/1969	0.44	0.41	0.88
1969/1970	0.29	0.26	0.91
1970/1971	-	-	-
1971/1972	-	-	0.00
1972/1973	0.12	0.12	0.64
1973/1974	-	-	-
1974/1975	0.26	0.25	0.81
1975/1976	-	-	0.85
1976/1977	0.27	0.21	0.96
1977/1978	-	-	-
1978/1979	0.44	0.40	0.89
1979/1980	-	-	-
1980/1981	0.27	0.22	0.92
1981/1982	0.18	0.18	0.25
1982/1983	-	-	0.00
1983/1984	0.26	0.23	0.83
1984/1985	0.19	0.17	0.93
1985/1986	0.47	0.41	0.94
1986/1987	-	-	0.78
1987/1988	0.39	0.37	0.70
1988/1989	-	-	0.93

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1989/1990	-	-	-
1990/1991	-	-	0.63
1991/1992	-	-	-
1992/1993	-	-	-
1993/1994	-	-	-
1994/1995	-	-	0.76
1995/1996	-	0.23	-
1996/1997	-	-	-
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	0.00
2002/2003	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 14C2, 1953–2008 (55 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1953/1954	0.20	0.17	0.29
1954/1955	0.22	0.21	0.26
1955/1956	-	0.47	-
1956/1957	0.28	0.37	0.15
1957/1958	0.35	0.41	0.29
1958/1959	0.39	0.46	0.30
1959/1960	0.36	0.36	0.38
1960/1961	0.44	0.45	0.43
1961/1962	0.35	0.58	0.23
1962/1963	0.42	0.64	0.29
1963/1964	0.34	0.37	0.33
1964/1965	-	0.27	-
1965/1966	0.36	0.43	0.34
1966/1967	0.39	0.39	0.38
1967/1968	0.39	0.35	0.40
1968/1969	0.36	0.31	0.39
1969/1970	0.34	0.47	0.30
1970/1971	0.48	0.31	0.53
1971/1972	0.31	0.28	0.32
1972/1973	0.45	0.42	0.46
1973/1974	0.43	0.44	0.43
1974/1975	0.41	0.32	0.44
1975/1976	0.42	0.48	0.40
1976/1977	0.38	0.31	0.39
1977/1978	0.29	0.27	0.29
1978/1979	0.36	0.35	0.36
1979/1980	-	-	-
1980/1981	-	-	-
1981/1982	-	-	-
1982/1983	-	-	0.60
1983/1984	-	-	-
1984/1985	0.69	0.67	0.75
1985/1986	0.69	0.67	0.75
1986/1987	0.57	0.59	0.59
1987/1988	0.65	0.63	0.68
1988/1989	0.60	0.56	0.71
1989/1990	0.67	0.65	0.72
1990/1991	-	-	0.71

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1991/1992	0.65	0.64	0.66
1992/1993	0.66	0.65	0.68
1993/1994	0.54	0.53	0.57
1994/1995	0.52	0.50	0.59
1995/1996	-	0.60	-
1996/1997	0.54	0.52	0.61
1997/1998	0.59	0.57	0.67
1998/1999	-	0.50	-
1999/2000	-	-	0.60
2000/2001	0.67	0.66	0.68
2001/2002	0.58	0.55	0.66
2002/2003	0.55	0.55	0.57
2003/2004	0.61	0.54	0.66
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 14C8, 1959–2002 (43 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1959/1960	-	-	0.24
1960/1961	0.31	0.32	0.28
1961/1962	0.43	0.43	0.70
1962/1963	0.41	0.37	0.79
1963/1964	0.23	0.19	0.33
1964/1965	0.40	0.37	0.49
1965/1966	0.54	0.34	0.54
1966/1967	0.33	0.27	0.43
1967/1968	0.36	0.33	0.56
1968/1969	0.20	0.14	0.55
1969/1970	0.28	0.27	0.35
1970/1971	0.28	0.25	0.53
1971/1972	0.37	0.35	0.41
1972/1973	-	0.30	-
1973/1974	0.31	0.28	0.42
1974/1975	0.41	0.39	0.46
1975/1976	0.38	0.33	0.57
1976/1977	0.47	0.44	0.61
1977/1978	0.48	0.44	0.63
1978/1979	0.36	0.35	0.40
1979/1980	0.37	0.30	0.62
1980/1981	0.55	0.53	0.63
1981/1982	0.42	0.37	0.54
1982/1983	0.38	0.35	0.47
1983/1984	0.40	0.35	0.54
1984/1985	-	0.45	-
1985/1986	0.40	0.35	0.78
1986/1987	-	0.36	-
1987/1988	-	-	0.58
1988/1989	0.38	0.31	0.69
1989/1990	0.52	0.52	0.58
1990/1991	0.46	0.39	0.70
1991/1992	-	-	-
1992/1993	0.46	0.44	0.55
1993/1994	-	-	0.57
1994/1995	-	0.47	-
1995/1996	0.28	0.33	0.12
1996/1997	-	-	0.58

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1997/1998	0.54	0.53	0.60
1998/1999	0.44	0.41	0.58
1999/2000	0.45	0.42	0.49
2000/2001	0.59	0.58	0.63
2001/2002	0.45	0.41	0.63

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 14D1, 1980–1991 (11 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1980/1981	0.48	0.43	0.75
1981/1982	0.44	0.36	0.75
1982/1983	0.47	0.40	0.75
1983/1984	0.47	0.37	0.79
1984/1985	-	-	-
1985/1986	-	-	-
1987/1988	0.31	0.26	0.67
1987/1988	-	-	0.51
1988/1989	-	-	-
1989/1990	-	-	-
1990/1991	-	-	-

- denotes no BFI determined due to insufficient data in the period

Appendix D Results of the annual and seasonal BFI analysis for Chapter 7

Results of the annual and seasonal BFI analysis (tabular) for gauge station 2B22, 1960–2007 (47 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1960/1961	-	-	0.70
1961/1962	0.29	0.20	0.73
1962/1963	-	-	0.90
1963/1964	0.38	0.34	0.74
1964/1965	0.25	0.22	0.74
1965/1966	0.31	0.25	0.74
1966/1967	0.24	0.19	0.61
1967/1968	0.42	0.34	0.75
1968/1969	-	-	0.84
1969/1970	0.27	0.22	0.88
1970/1971	0.48	0.38	0.89
1971/1972	-	-	-
1972/1973	-	-	0.72
1973/1974	-	-	0.76
1974/1975	0.38	0.34	0.81
1975/1976	0.45	0.39	0.70
1976/1977	0.30	0.27	0.84
1977/1978	0.22	0.19	0.84
1978/1979	-	-	0.77
1979/1980	0.37	0.26	0.91
1980/1981	-	-	0.93
1981/1982	-	-	-
1982/1983	0.64	0.53	0.93
1983/1984	0.62	0.46	0.95
1984/1985	-	-	0.95
1985/1986	-	-	0.95
1986/1987	0.45	0.38	0.89
1987/1988	0.17	0.14	0.91
1988/1989	0.49	0.44	0.94
1989/1990	-	0.42	-
1990/1991	-	-	0.88
1991/1992	0.19	0.19	0.61
1992/1993	0.23	0.22	0.35
1993/1994	-	-	0.00
1994/1995	-	0.25	-
1995/1996	-	-	0.90
1996/1997	0.33	0.30	0.85
1997/1998	-	0.44	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	0.41	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	0.91

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 2B33, 1961–2010 (49 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1961/1962	-	-	-
1962/1963	0.13	0.09	0.97
1963/1964	0.28	0.18	0.91
1964/1965	0.55	0.46	0.92
1965/1966	-	-	-
1966/1967	0.27	0.17	0.91
1967/1968	0.44	0.32	0.94
1968/1969	0.19	0.16	0.87
1969/1970	0.34	0.27	0.94
1970/1971	0.22	0.19	0.76
1971/1972	-	-	0.93
1972/1973	0.40	0.26	0.96
1973/1974	-	-	0.96
1974/1975	0.55	0.43	0.98
1975/1976	0.57	0.44	0.98
1976/1977	0.53	0.44	0.98
1977/1978	0.35	0.27	0.95
1978/1979	0.63	0.53	0.95
1979/1980	-	-	-
1980/1981	-	-	0.92
1981/1982	-	-	-
1982/1983	0.06	0.06	0.19
1983/1984	-	0.09	-
1984/1985	-	-	0.93
1985/1986	0.18	0.16	0.92
1986/1987	0.22	0.18	0.87
1987/1988	0.14	0.11	0.66
1988/1989	0.13	0.11	0.92
1989/1990	0.12	0.11	0.58
1990/1991	0.15	0.13	0.91
1991/1992	-	-	0.28
1992/1993	0.15	0.14	0.77
1993/1994	0.05	0.05	0.63
1994/1995	0.12	0.12	-
1995/1996	-	0.22	-
1996/1997	0.24	0.21	0.86
1997/1998	-	0.19	-
1998/1999	-	-	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1999/2000	0.04	0.03	0.90
2000/2001	0.35	0.30	0.87
2001/2002	0.20	0.18	0.72
2002/2003	-	0.38	-
2003/2004	-	0.18	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	0.00
2007/2008	-	0.27	-
2008/2009	0.18	0.19	0.10
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 2C3, 1959–2002 (52 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1958/1959	0.73	0.68	0.94
1959/1960	0.57	0.49	0.92
1960/1961	0.82	0.79	0.92
1961/1962	0.76	0.71	0.92
1962/1963	0.80	0.76	0.97
1963/1964	0.72	0.69	0.93
1964/1965	0.77	0.71	0.97
1965/1966	0.73	0.70	0.86
1966/1967	0.68	0.60	0.85
1967/1968	0.66	0.57	0.91
1968/1969	0.80	0.76	0.97
1969/1970	0.71	0.68	0.88
1970/1971	0.87	0.85	0.96
1971/1972	0.84	0.84	0.85
1972/1973	0.84	0.80	0.98
1973/1974	0.84	0.79	0.96
1974/1975	0.71	0.66	0.93
1975/1976	0.83	0.79	0.95
1976/1977	0.82	0.79	0.96
1977/1978	-	-	0.96
1978/1979	-	-	0.80
1979/1980	-	-	0.95
1980/1981	-	-	0.98
1981/1982	-	-	0.93
1982/1983	0.80	0.78	0.94
1983/1984	0.77	0.72	0.95
1984/1985	0.80	0.76	0.95
1985/1986	0.84	0.81	0.96
1986/1987	0.79	0.76	0.96
1987/1988	-	-	-
1988/1989	-	0.74	-
1989/1990	0.76	0.72	0.93
1990/1991	0.82	0.78	0.97
1991/1992	-	-	0.92
1992/1993	-	-	0.96
1993/1994	0.66	0.63	0.88
1994/1995	0.68	0.65	0.92
1995/1996	0.65	0.58	0.86
1996/1997	0.72	0.68	0.90

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1997/1998	-	0.68	-
1998/1999	-	-	-
1999/2000	-	-	0.90
2000/2001	-	-	0.98
2001/2002	-	-	0.97
2002/2003	0.76	0.71	0.95
2003/2004	0.62	0.51	0.93
2004/2005	-	-	-
2005/2006	0.85	0.81	0.98
2006/2007	0.87	0.84	0.98
2007/2008	0.75	0.69	0.97
2008/2009	-	-	0.93
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 3E1, 1953–2010 (57 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1953/1954	-	-	0.93
1954/1955	0.58	0.48	0.91
1955/1956	0.61	0.46	0.94
1956/1957	0.54	0.45	0.95
1957/1958	0.45	0.36	0.92
1958/1959	0.73	0.66	0.95
1959/1960	0.66	0.55	0.94
1960/1961	0.44	0.35	0.96
1961/1962	0.67	0.56	0.97
1962/1963	0.61	0.53	0.98
1963/1964	0.69	0.62	0.97
1964/1965	0.64	0.54	0.97
1965/1966	0.78	0.72	0.97
1966/1967	0.59	0.46	0.92
1967/1968	0.45	0.31	0.95
1968/1969	0.34	0.26	0.95
1969/1970	0.30	0.25	0.95
1970/1971	0.15	0.14	0.94
1971/1972	0.20	0.17	0.89
1972/1973	0.18	0.14	0.93
1973/1974	0.36	0.32	0.91
1974/1975	0.19	0.18	0.89
1975/1976	-	-	0.96
1976/1977	-	0.24	-
1977/1978	-	-	-
1978/1979	-	0.00	-
1979/1980	0.56	0.48	0.97
1980/1981	0.20	0.18	0.95
1981/1982	-	0.72	-
1982/1983	0.26	0.24	0.94
1983/1984	0.45	0.38	0.88
1984/1985	0.45	0.35	0.95
1985/1986	0.30	0.21	0.96
1986/1987	0.60	0.52	0.96
1987/1988	0.46	0.37	0.95
1988/1989	0.35	0.29	0.96
1989/1990	0.54	0.48	0.92
1990/1991	0.57	0.51	0.94
1991/1992	-	-	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1992/1993	-	0.51	-
1993/1994	0.65	0.60	0.96
1994/1995	0.49	0.43	0.92
1995/1996	0.49	0.43	0.92
1996/1997	0.72	0.66	0.97
1997/1998	-	-	-
1998/1999	0.66	0.58	0.97
1999/2000	0.65	0.55	0.97
2000/2001	0.41	0.33	0.97
2001/2002	0.50	0.45	0.96
2002/2003	0.33	0.28	0.97
2003/2004	0.56	0.44	0.95
2004/2005	0.39	0.33	0.95
2005/2006	0.58	0.53	0.59
2006/2007	0.72	0.67	0.93
2007/2008	-	0.36	-
2008/2009	-	0.70	-
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 3E2, 1957–2003 (46 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1957/1958	-	-	0.94
1958/1959	-	-	0.95
1959/1960	0.59	0.51	0.96
1960/1961	-	-	0.95
1961/1962	-	0.61	-
1962/1963	-	-	0.98
1963/1964	-	-	0.94
1964/1965	0.74	0.69	0.96
1965/1966	0.78	0.74	0.96
1966/1967	0.68	0.58	0.94
1967/1968	0.67	0.58	0.96
1968/1969	0.67	0.59	0.97
1969/1970	0.00	0.56	0.00
1970/1971	-	-	0.97
1971/1972	-	-	0.92
1972/1973	-	-	-
1973/1974	-	-	0.92
1974/1975	-	-	0.92
1975/1976	-	-	-
1976/1977	-	-	-
1977/1978	-	-	-
1978/1979	-	-	-
1979/1980	-	-	-
1980/1981	-	-	-
1981/1982	-	-	-
1982/1983	-	-	0.95
1983/1984	-	-	0.95
1984/1985	-	-	-
1985/1986	-	-	0.98
1986/1987			0.96
1987/1988	0.45	0.39	0.95
1988/1989	-	-	0.94
1989/1990	0.49	0.49	0.88
1990/1991	-	-	0.96
1991/1992	0.57	0.54	0.73
1992/1993	-	-	0.88
1993/1994	0.51	0.44	0.92
1994/1995	0.29	0.34	0.94
1995/1996	0.67	0.63	0.98

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1996/1997	-	-	-
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	0.75	0.98	0.16
2000/2001	-	-	-
2001/2002	-	-	0.15
2002/2003	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 3E3, 1956–2008 (52 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1956/1957	-	-	-
1957/1958	-	-	0.94
1958/1959	-	-	0.85
1959/1960	-	-	0.88
1960/1961	0.46	0.40	0.92
1961/1962	-	-	-
1962/1963	-	-	0.96
1963/1964	0.58	0.50	0.88
1964/1965	-	-	-
1965/1966	-	-	0.84
1966/1967	0.51	0.37	0.94
1967/1968	0.28	0.19	0.95
1968/1969	0.98	0.65	0.98
1969/1970	-	-	-
1970/1971	-	-	-
1971/1972	-	-	-
1972/1973	-	-	0.90
1973/1974	-	-	-
1974/1975	-	-	-
1975/1976	-	-	-
1976/1977	-	-	0.94
1977/1978	-	-	-
1978/1979	-	-	0.95
1979/1980	0.48	0.39	0.95
1980/1981	-	-	0.97
1981/1982	-	-	-
1982/1983	0.22	0.16	0.89
1983/1984	-	-	-
1984/1985	-	-	0.96
1985/1986	-	-	0.41
1986/1987	-	-	0.92
1987/1988	0.61	0.53	0.94
1988/1989	0.68	0.61	0.96
1989/1990	-	-	0.77
1990/1991	-	-	-
1991/1992	-	-	-
1992/1993	-	-	-
1993/1994	-	-	-
1994/1995	-	-	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	0.58	0.50	0.98
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 3E5, 1957–2009 (52 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1957/1958	-	-	0.94
1985/1959	0.79	0.70	0.97
1959/1960	-	-	0.98
1960/1961	0.73	0.62	0.95
1961/1962	-	-	0.99
1962/1963	0.00	0.00	0.91
1963/1964	-	-	0.98
1964/1965	-	-	0.98
1965/1966	-	-	0.99
1966/1967	-	-	0.98
1967/1968	0.78	0.69	0.98
1968/1969	-	-	0.98
1969/1970	0.78	0.70	0.99
1970/1971	-	-	-
1971/1972	0.00	0.00	0.97
1972/1973	0.53	0.41	0.97
1973/1974	0.34	0.25	0.98
1974/1975	0.57	0.47	0.98
1975/1976	-	-	0.99
1976/1977	0.66	0.57	0.96
1977/1978	-	-	0.99
1978/1979	0.53	0.47	0.93
1979/1980	-	-	-
1980/1981	-	-	0.96
1981/1982	-	-	-
1982/1983	-	-	0.88
1983/1984	-	-	0.89
1984/1985	-	-	-
1985/1986	0.85	0.85	0.96
1986/1987	0.81	0.68	0.98
1987/1988	0.73	0.67	0.92
1988/1989	-	-	0.93
1989/1990	0.60	0.54	0.88
1990/1991	-	-	0.89
1991/1992	-	-	-
1992/1993	0.26	0.15	0.88
1993/1994	-	-	-
1994/1995	0.38	0.26	0.93
1995/1996	-	-	0.95

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1996/1997	-	-	-
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	0.88	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	-	-	
2008/2009	-	-	

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 3F3, 1957–2004 (47 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1957/1958	0.80	0.74	0.96
1958/1959	0.67	0.59	0.95
1959/1960	0.70	0.61	0.94
1960/1961	0.80	0.73	0.97
1961/1962	0.74	0.65	0.97
1962/1963	0.84	0.79	0.96
1963/1964	0.82	0.79	0.95
1964/1965	0.84	0.79	0.96
1965/1966	0.69	0.63	0.92
1966/1967	0.70	0.61	0.97
1967/1968	0.71	0.61	0.97
1968/1969	0.73	0.67	0.99
1969/1970	0.70	0.64	0.96
1970/1971	-	-	-
1971/1972	0.69	0.66	0.90
1972/1973	-		0.93
1973/1974	0.73	0.69	0.96
1974/1975	-	-	-
1975/1976	-	-	-
1976/1977	-	-	-
1977/1978	-	-	0.94
1978/1979	0.68	0.64	0.82
1979/1980	-	-	0.96
1980/1981	0.70	0.64	0.97
1981/1982	-	-	-
1982/1983	-	-	0.64
1983/1984	-	-	0.93
1984/1985	-	0.33	-
1985/1986	0.65	0.59	0.98
1986/1987	-	0.64	-
1987/1988	-	-	-
1988/1989	0.60	0.53	0.97
1989/1990	0.55	0.50	0.90
1990/1991	-	-	0.80
1991/1992	-	-	-
1992/1993	-	-	-
1993/1994	-	-	-
1994/1995	-	-	-
1995/1996	-	0.51	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1996/1997	0.74	0.68	0.96
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 4B1, 1953–2009 (56 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1953/1954	-	-	0.87
1954/1955	-	-	-
1955/1956	0.45	0.38	0.96
1956/1957	0.43	0.40	0.67
1957/1958	0.62	0.59	0.98
1958/1959	0.45	0.43	0.85
1959/1960	0.36	0.32	0.93
1960/1961	0.41	0.37	0.88
1961/1962	0.52	0.47	0.89
1962/1963	0.61	0.57	0.99
1963/1964	0.54	0.52	0.93
1964/1965	0.49	0.46	0.91
1965/1966	0.50	0.48	0.77
1966/1967	0.49	0.44	0.94
1967/1968	0.35	0.32	0.83
1968/1969	0.45	0.41	0.87
1969/1970	0.49	0.48	0.89
1970/1971	0.53	0.49	0.86
1971/1972	0.31	0.29	0.65
1972/1973	0.26	0.25	0.49
1973/1974	-	-	0.73
1974/1975	-	0.56	-
1975/1976	-	-	-
1976/1977	-	0.56	-
1977/1978	-	-	-
1978/1979	-	-	-
1979/1980	-	-	-
1980/1981	-	-	-
1981/1982	-	-	-
1982/1983	-	-	-
1983/1984	-	-	-
1984/1985	-	-	-
1985/1986	-	-	-
1986/1987	0.43	0.39	0.90
1987/1988	0.54	0.50	0.88
1988/1989	-	-	0.76
1989/1990	-	-	-
1990/1991	0.53	0.51	0.91
1991/1992	0.35	0.34	0.76

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1992/1993	0.42	0.40	0.73
1993/1994	-	0.27	-
1994/1995	0.22	0.22	0.81
1995/1996	-	0.10	-
1996/1997	-	-	0.94
1997/1998	0.37	0.36	0.91
1998/1999	-	0.32	-
1999/2000	0.39	0.35	0.86
2000/2001	0.39	0.36	0.91
2001/2002	0.65	0.64	0.96
2002/2003	-	-	0.44
2003/2004	-	-	-
2004/2005	0.33	0.10	0.72
2005/2006	-	-	0.17
2006/2007	-	-	0.10
2007/2008	0.16	0.16	0.36
2008/2009	-	0.17	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 4B3, 1957–2008 (51 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1957/1958	-	-	0.88
1958/1959	0.89	0.89	0.90
1959/1960	0.84	0.84	0.89
1960/1961	0.88	0.89	0.82
1961/1962	0.90	0.91	0.84
1962/1963	0.89	0.88	0.89
1963/1964	0.85	0.85	0.93
1964/1965	0.86	0.86	0.92
1965/1966	0.88	0.88	0.89
1966/1967	0.88	0.88	0.86
1967/1968	0.89	0.89	0.91
1968/1969	0.87	0.87	0.82
1969/1970	0.88	0.88	0.88
1970/1971	0.19	0.18	0.94
1971/1972	0.27	0.22	0.82
1972/1973	0.33	0.28	0.94
1973/1974	0.41	0.37	0.79
1974/1975	0.30	0.27	0.86
1975/1976	0.25	0.20	0.94
1976/1977	-	-	0.88
1977/1978	0.45	0.42	0.91
1978/1979	-	0.37	-
1979/1980	0.35	0.31	0.96
1980/1981	0.03	0.03	0.93
1981/1982	0.34	0.27	0.81
1982/1983	-	-	0.93
1983/1984	0.42	0.40	0.92
1984/1985	0.37	0.34	0.95
1985/1986	0.36	0.34	0.90
1986/1987	-	0.26	-
1987/1988	0.30	0.27	0.84
1988/1989	0.43	0.42	0.98
1989/1990	0.24	0.21	0.62
1990/1991	0.27	0.24	0.95
1991/1992	0.33	0.32	0.86
1992/1993	0.17	0.15	0.82
1993/1994	0.45	0.43	0.95
1994/1995	0.33	0.32	0.94
1995/1996	-	-	0.97

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1996/1997	-	-	-
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	-	-	0.98
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	0.17	-
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 4B4, 1957–2010 (53 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1957/1958	-	-	0.88
1958/1959	0.88	0.88	0.91
1959/1960	0.89	0.89	0.92
1960/1961	0.86	0.86	0.84
1961/1962	0.91	0.91	0.86
1962/1963	0.90	0.90	0.89
1963/1964	0.84	0.84	0.94
1964/1965	0.87	0.87	0.89
1965/1966	0.90	0.90	0.90
1966/1967	0.87	0.87	0.89
1967/1968	0.87	0.87	0.90
1968/1969	0.85	0.85	0.84
1969/1970	0.85	0.85	0.92
1970/1971	0.87	0.87	0.90
1971/1972	0.92	0.93	0.87
1972/1973	0.84	0.85	0.69
1973/1974	0.91	0.92	0.84
1974/1975	0.57	0.53	0.91
1975/1976	0.58	0.51	0.91
1976/1977	0.52	0.46	0.94
1977/1978	0.58	0.53	0.94
1978/1979	0.46	0.41	0.84
1979/1980	0.42	0.36	0.96
1980/1981	0.36	0.30	0.90
1981/1982	0.45	0.41	0.76
1982/1983	0.29	0.23	0.82
1983/1984	0.53	0.49	0.80
1984/1985	-	-	-
1985/1986	-	0.36	-
1986/1987	-	-	0.82
1987/1988	-	-	0.81
1988/1989	0.37	0.34	0.78
1989/1990	0.27	0.25	0.60
1990/1991	0.30	0.27	0.89
1991/1992	-	-	-
1992/1993	-	0.43	-
1993/1994	0.49	0.47	0.91
1994/1995	0.37	0.35	0.98
1995/1996	0.34	0.32	0.73

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1996/1997	-	-	-
1997/1998	-	-	0.96
1998/1999	-	-	-
1999/2000	0.31	0.24	0.86
2000/2001	0.48	0.44	0.96
2001/2002	0.41	0.37	0.96
2002/2003	-	-	0.89
2003/2004	-	-	0.97
2004/2005	0.45	0.43	0.92
2005/2006	-	-	0.99
2006/2007	-	-	-
2007/2008	-	0.24	-
2008/2009	-	0.33	-
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 4B9, 1974–2010 (36 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1974/1975	-	-	0.77
1975/1976	0.33	0.29	0.90
1976/1977	-	-	0.94
1977/1978	-	-	-
1978/1979	-	-	0.96
1979/1980	-	0.20	-
1980/1981	-	-	-
1981/1982	-	-	-
1982/1983	-	-	0.53
1983/1984	-	-	0.86
1984/1985	-	-	-
1985/1986	-	-	-
1986/1987	0.45	0.39	0.95
1987/1988	0.56	0.51	0.88
1988/1989	-	-	-
1989/1990	0.47	0.43	0.72
1990/1991	-	-	0.93
1991/1992	0.33	0.31	0.79
1992/1993	-	-	0.84
1993/1994	0.31	0.29	0.94
1994/1995	-	0.31	-
1995/1996	0.19	0.14	0.83
1996/1997	0.51	0.48	0.91
1997/1998	0.00	0.49	0.00
1998/1999	-	-	-
1999/2000	0.39	0.35	0.58
2000/2001	0.56	0.52	0.92
2001/2002	-	0.21	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	0.41	0.41	0.53
2005/2006	-	-	0.57
2006/2007	-	-	-
2007/2008	-	-	-
2008/2009	-	-	-
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 4C2, 1957–2010 (53 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1957/1958	-	-	0.96
1958/1959	-	-	-
1959/1960	-	-	0.98
1960/1961	-	-	0.90
1961/1962	-	-	0.76
1962/1963	-	0.50	-
1963/1964	0.60	0.54	0.99
1964/1965	-	-	0.91
1965/1966	0.62	0.57	0.90
1966/1967	0.55	0.48	0.98
1967/1968	0.51	0.48	0.92
1968/1969	0.48	0.41	0.96
1969/1970	0.52	0.48	0.96
1970/1971	-	-	-
1971/1972	0.00	0.00	0.95
1972/1973	0.51	0.47	0.96
1973/1974	0.59	0.50	0.92
1974/1975	-	-	0.98
1975/1976	-	-	-
1976/1977	-	-	0.99
1977/1978	-	-	-
1978/1979	0.66	0.61	0.93
1979/1980	-	-	0.98
1980/1981	-	-	-
1981/1982	-	-	-
1982/1983	-	-	-
1983/1984	-	-	-
1984/1985	-	-	-
1985/1986	-	-	0.91
1986/1987	-	-	0.90
1987/1988	0.41	0.39	0.66
1988/1989	-	-	-
1989/1990	-	-	0.65
1990/1991	-	0.34	-
1991/1992	-	-	0.91
1992/1993	-	0.31	-
1993/1994	-	0.08	-
1994/1995	-	0.19	-
1995/1996	-	-	0.84

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1996/1997	-	-	0.94
1997/1998	0.41	0.38	0.87
1998/1999	0.77	0.65	0.98
1999/2000	-	0.63	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	-	-	-
2008/2009	-	-	-
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 4C11, 1985–2010 (25 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1985/1986	0.20	0.17	0.82
1986/1987	0.19	0.13	0.98
1987/1988	0.36	0.32	0.80
1988/1989	0.20	0.15	0.96
1989/1990	0.35	0.28	0.85
1990/1991	-	-	0.66
1991/1992	0.15	0.05	0.79
1992/1993	0.16	0.14	0.67
1993/1994	0.10	0.09	0.63
1994/1995	-	-	0.70
1995/1996	0.04	0.04	0.56
1996/1997	0.19	0.18	0.77
1997/1998	-	-	0.56
1998/1999	0.15	0.14	0.76
1999/2000	-	-	0.82
2000/2001	-	-	0.59
2001/2002	-	0.11	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	0.42	0.42	0.76
2006/2007	-	-	-
2007/2008	-	-	-
2008/2009	-	-	-
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 4D4, 1953–2009 (56 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1953/1954	-	-	-
1954/1955	0.55	0.52	0.72
1955/1956	0.76	0.69	0.96
1956/1957	0.73	0.67	0.98
1957/1958	0.75	0.71	0.97
1958/1959	0.71	0.68	0.94
1959/1960	-	0.54	-
1960/1961	-	-	-
1961/1962	-	-	-
1962/1963	0.67	0.59	0.98
1963/1964	0.70	0.65	0.96
1964/1965	0.69	0.63	0.97
1965/1966	0.74	0.69	0.91
1966/1967	0.68	0.60	0.93
1967/1968	0.69	0.64	0.90
1968/1969	0.65	0.58	0.96
1969/1970	0.56	0.52	0.93
1970/1971	0.65	0.61	0.96
1971/1972	0.74	0.69	0.91
1972/1973	0.59	0.50	0.97
1973/1974	0.68	0.61	0.92
1974/1975	0.70	0.64	0.97
1975/1976	0.63	0.53	0.95
1976/1977	0.67	0.60	0.96
1977/1978	0.52	0.43	0.98
1978/1979	-	-	0.92
1979/1980	0.60	0.54	0.97
1980/1981	0.51	0.43	0.92
1981/1982	0.54	0.45	0.93
1982/1983	0.60	0.53	0.93
1983/1984	-	-	-
1984/1985	0.74	0.69	0.93
1985/1986	0.64	0.58	0.95
1986/1987	0.70	0.69	0.76
1987/1988	-	-	0.86
1988/1989	-	-	0.87
1989/1990	0.63	0.60	0.72
1990/1991	0.70	0.69	0.76
1991/1992	-	-	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1992/1993	0.48	0.41	0.83
1993/1994	-	-	-
1994/1995	-	-	-
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	0.47	0.46	0.95
1998/1999	-	0.66	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	-	-	-
2008/2009	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 4D24, 1990–2005 (15 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1990/1991	-	-	0.83
1991/1992	0.62	0.54	0.84
1992/1993	-	-	-
1993/1994	-	-	-
1994/1995	0.77	0.69	0.94
1995/1996	0.73	0.70	0.80
1996/1997	0.74	0.70	0.91
1997/1998	0.52	0.49	0.85
1998/1999	0.56	0.53	0.81
1999/2000	-	-	-
2000/2001	-	-	0.95
2001/2002	0.77	0.76	0.92
2002/2003	0.69	0.66	0.80
2003/2004	0.89	0.90	0.87
2004/2005	-	0.73	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 4E2, 1959–2005 (46 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1959/1960	-	-	0.92
1960/1961	0.27	0.24	0.82
1961/1962	0.43	0.40	0.77
1962/1963	-	-	0.95
1963/1964	-	-	0.60
1964/1965	-	-	-
1965/1966	-	-	0.33
1966/1967	-	-	0.94
1967/1968	0.06	0.05	0.45
1968/1969	-	-	-
1969/1970	-	-	0.81
1970/1971	-	-	0.71
1971/1972	-	-	-
1972/1973	-	-	0.88
1973/1974	0.34	0.30	0.71
1974/1975	0.32	0.32	0.96
1975/1976	0.32	0.27	0.94
1976/1977	-	-	0.91
1977/1978	-	-	0.93
1978/1979	-	-	-
1979/1980	0.19	0.15	0.94
1980/1981	0.43	0.40	0.97
1981/1982	0.36	0.31	0.94
1982/1983	0.23	0.21	0.21
1983/1984	0.35	0.34	0.91
1984/1985	-	-	0.91
1985/1986	-	-	0.90
1986/1987	-	-	-
1987/1988	-	-	0.88
1988/1989	0.56	0.53	0.89
1989/1990	-	-	0.42
1990/1991	-	-	-
1991/1992	-	-	0.75
1992/1993	0.61	0.58	0.92
1993/1994	-	0.73	-
1994/1995	0.93	0.93	0.99
1995/1996	-	0.67	-
1996/1997	0.21	0.20	0.62
1997/1998	0.25	0.24	0.78

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1998/1999	-	0.23	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 6C1, 1952–2010 (58 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1952/1953	-	-	0.99
1953/1954	1.00	1.00	1.00
1954/1955	0.43	0.64	0.23
1955/1956	-	-	-
1956/1957	-	-	-
1957/1958	-	-	-
1958/1959	-	-	-
1959/1960	-	-	1.00
1960/1961	0.12	0.11	0.99
1961/1962	-	0.21	-
1962/1963	-	-	-
1963/1964	-	-	-
1964/1965	-	-	-
1965/1966	-	-	-
1966/1967	-	-	-
1967/1968	-	-	-
1968/1969	-	-	-
1969/1970	-	-	-
1970/1971	-	-	0.80
1971/1972	0.07	0.06	0.21
1972/1973	0.12	0.12	1.00
1973/1974	0.14	0.12	0.46
1974/1975	0.10	0.10	0.36
1975/1976	0.11	0.09	0.77
1976/1977	0.18	0.18	1.00
1977/1978	-	-	0.94
1978/1979	0.20	0.20	0.94
1979/1980	-	0.37	-
1980/1981	-	-	1.00
1981/1982	0.32	0.33	0.10
1982/1983	0.14	0.14	1.00
1983/1984	0.41	0.41	1.00
1984/1985	0.23	0.22	0.87
1985/1986	0.47	0.46	0.80
1986/1987	0.22	0.22	0.95
1987/1988	0.16	0.15	0.92
1988/1989	0.30	0.28	0.86
1989/1990	-	-	0.44
1990/1991	0.32	0.31	1.00

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1991/1992	0.25	0.24	0.91
1992/1993	0.48	0.47	0.99
1993/1994	-	0.49	-
1994/1995	0.30	0.30	1.00
1995/1996	0.19	0.19	0.90
1996/1997	-	-	0.89
1997/1998	-	0.23	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	0.40	0.37	0.97
2008/2009	0.27	0.23	0.94
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 6C5, 1965–2001 (36 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1965/1966	-	-	0.09
1966/1967	0.79	0.79	0.56
1967/1968	0.75	0.75	0.08
1968/1969	0.79	0.79	0.08
1969/1970	0.87	0.87	-
1970/1971	0.51	0.49	0.89
1971/1972	0.34	0.32	0.85
1972/1973	-	-	0.35
1973/1974	0.47	0.41	0.80
1974/1975	0.45	0.39	0.96
1975/1976	0.40	0.31	0.95
1976/1977	0.40	0.39	0.94
1977/1978	-	0.17	-
1978/1979	-	-	
1979/1980	-	-	0.98
1980/1981	-	-	-
1981/1982	0.51	0.47	0.85
1982/1983	0.37	0.34	0.89
1983/1984	-	-	-
1984/1985	-	-	0.90
1985/1986	-	0.46	-
1986/1987	0.49	0.45	0.90
1987/1988	0.31	0.27	0.85
1988/1989	0.45	0.39	0.91
1989/1990	0.35	0.33	0.70
1990/1991	0.40	0.39	1.00
1991/1992	0.20	0.20	1.00
1992/1993	-	-	-
1993/1994	0.30	0.30	0.85
1994/1995	0.27	0.27	1.00
1995/1996	0.36	0.36	1.00
1996/1997	-	-	0.04
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 6D10, 1985–2010 (25 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1985/1986	-	-	0.88
1986/1987	0.43	0.42	0.67
1987/1988	0.00	0.00	0.31
1988/1989	-	-	-
1989/1990	0.49	0.47	0.75
1990/1991	0.00	0.43	0.00
1991/1992	-	-	-
1992/1993	-	-	0.87
1993/1994	0.00	0.00	0.70
1994/1995	0.00	0.43	0.00
1995/1996	0.42	0.41	0.63
1996/1997	0.28	0.26	0.92
1997/1998	0.47	0.45	0.84
1998/1999	0.00	0.00	0.93
1999/2000	0.59	0.57	0.73
2000/2001	0.68	0.64	0.95
2001/2002	0.56	0.46	0.98
2002/2003	0.57	0.52	0.96
2003/2004	0.39	0.35	0.88
2004/2005	0.45	0.45	0.47
2005/2006	-	-	-
2006/2007	0.57	0.56	0.91
2007/2008	-	-	0.88
2008/2009	-	-	-
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7A3, 1955–2008 (53 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1955/1956	-	-	-
1956/1957	-	-	0.28
1957/1958	0.07	0.07	-
1958/1959	0.12	0.12	0.00
1959/1960	0.11	0.11	1.00
1960/1961	0.02	0.02	0.02
1961/1962	0.71	0.07	0.82
1962/1963	0.52	0.49	0.96
1963/1964	0.59	0.57	0.98
1964/1965	-	0.58	-
1965/1966	0.23	0.22	0.73
1966/1967	0.59	0.59	0.71
1967/1968	0.28	0.27	0.77
1968/1969	0.18	0.18	0.84
1969/1970	0.04	0.04	0.97
1970/1971	0.37	0.37	0.40
1971/1972	0.02	0.02	0.00
1972/1973	0.17	0.17	0.00
1973/1974	0.19	0.19	0.11
1974/1975	0.22	0.21	0.69
1975/1976	0.29	0.28	0.83
1976/1977	0.07	0.07	-
1977/1978	0.50	0.50	0.89
1978/1979	-	-	0.92
1979/1980	0.28	0.22	0.89
1980/1981	0.31	0.30	0.82
1981/1982	0.21	0.21	0.45
1982/1983	0.43	0.43	0.78
1983/1984	-	-	-
1984/1985	-	-	0.92
1985/1986	0.60	0.58	0.91
1986/1987	0.51	0.49	0.93
1987/1988	0.00	0.00	0.90
1988/1989	0.54	0.44	0.96
1989/1990	-	-	-
1990/1991	0.41	0.39	0.95
1991/1992	0.22	0.68	0.68
1992/1993	0.42	0.40	0.94
1993/1994	0.41	0.37	0.92

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1994/1995	0.37	0.35	0.97
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	0.65	0.65	0.81
1998/1999	-	0.60	-
1999/2000	-	-	0.89
2000/2001	0.77	0.73	0.95
2001/2002	0.84	0.79	0.98
2002/2003	0.65	0.62	0.74
2003/2004	-	0.63	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7D8, 1952–2008 (56 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1952/1953	-	-	-
1953/1954	-	-	-
1954/1955	-	-	0.80
1955/1956	0.58	0.46	0.86
1956/1957	0.58	0.49	0.80
1957/1958	0.37	0.31	0.74
1958/1959	0.58	0.12	0.76
1959/1960	0.34	0.24	0.80
1960/1961	0.43	0.32	0.58
1961/1962	0.58	0.48	0.89
1962/1963	0.63	0.47	0.90
1963/1964	0.67	0.60	0.89
1964/1965	0.51	0.40	0.93
1965/1966	0.56	0.42	0.86
1966/1967	0.40	0.29	0.62
1967/1968	0.38	0.27	0.78
1968/1969	0.38	0.24	0.81
1969/1970	-	-	0.77
1970/1971	-	-	0.80
1971/1972	-	-	0.80
1972/1973	0.52	0.44	0.68
1973/1974	0.54	0.38	0.83
1974/1975	-	-	0.93
1975/1976	0.45	0.32	0.82
1976/1977	0.51	0.37	0.90
1977/1978	0.51	0.34	0.89
1978/1979	0.54	0.42	0.94
1979/1980	0.43	0.28	0.85
1980/1981	-	0.01	-
1981/1982	0.64	0.53	0.81
1982/1983	0.71	0.64	0.90
1983/1984	0.71	0.59	0.88
1984/1985	0.53	0.40	0.88
1985/1986	0.58	0.48	0.93
1986/1987	0.60	0.49	0.94
1987/1988	0.53	0.37	0.78
1988/1989	0.73	0.63	0.92
1989/1990	0.66	0.56	0.87
1990/1991	0.55	0.39	0.86

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1991/1992	0.54	0.45	0.87
1992/1993	0.52	0.44	0.92
1993/1994	-	-	-
1994/1995	-	-	0.85
1995/1996	-	-	-
1996/1997	-	-	0.85
1997/1998	-	0.62	-
1998/1999	-	-	0.96
1999/2000		0.53	
2000/2001	-	-	-
2001/2002	0.21	0.13	0.72
2002/2003	-	-	-
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	0.69	-
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7E2, 1956–1998 (42 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1956/1957	-	-	-
1957/1958	-	-	-
1958/1959	-	-	-
1959/1960	-	-	-
1960/1961	-	-	-
1961/1962	-	-	-
1962/1963	-	-	-
1963/1964	-	-	-
1964/1965	-	-	-
1965/1966	-	-	-
1966/1967	-	-	-
1967/1968	-	-	-
1968/1969	-	-	-
1969/1970	-	-	-
1970/1971	-	-	-
1971/1972	-	-	-
1972/1973	-	-	-
1973/1974	-	-	-
1974/1975	-	-	-
1975/1976	-	-	-
1976/1977	-	-	-
1977/1978	-	-	-
1978/1979	-	-	-
1979/1980	-	-	-
1980/1981	-	-	0.77
1981/1982	-	-	-
1982/1983	-	0.68	-
1983/1984	-	-	-
1984/1985	-	0.94	-
1985/1986	0.86	0.85	0.93
1986/1987	-	-	0.84
1987/1988	-	-	0.90
1988/1989	-	-	0.96
1989/1990	-	-	0.84
1990/1991	0.31	0.29	0.71
1991/1992	-	-	0.67
1992/1993	0.74	0.73	0.99
1993/1994	0.78	0.77	0.97
1994/1995	-	0.63	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1995/1996	-	-	-
1996/1997	0.84	0.80	0.99
1997/1998	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7F1, 1955–1998 (43 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1955/1956	0.87	0.83	0.94
1956/1957	0.87	0.82	0.96
1957/1958	-	-	0.96
1958/1959	0.78	0.68	0.96
1959/1960	0.86	0.82	0.96
1960/1961	0.89	0.80	0.98
1961/1962	0.87	0.83	0.97
1962/1963	0.88	0.83	0.98
1963/1964	0.82	0.75	0.98
1964/1965	0.86	0.81	0.98
1965/1966	0.78	0.67	0.94
1966/1967	0.83	0.73	0.96
1967/1968	0.82	0.73	0.98
1968/1969	0.85	0.78	0.98
1969/1970	0.89	0.85	0.97
1970/1971	0.77	0.69	0.99
1971/1972	0.89	0.84	0.98
1972/1973	0.83	0.75	0.99
1973/1974	-	0.75	-
1974/1975	0.76	0.68	0.98
1975/1976	-	0.65	-
1976/1977	0.91	0.85	0.99
1977/1978	-	0.51	-
1978/1979	-	-	-
1979/1980	0.52	0.28	0.88
1980/1981	-	-	0.97
1981/1982	0.84	0.76	0.96
1982/1983	0.82	0.78	0.97
1983/1984	-	-	0.90
1984/1985	0.72	0.66	0.96
1985/1986	0.75	0.71	0.97
1986/1987	0.80	0.74	0.96
1987/1988	0.65	0.54	0.97
1988/1989	-	-	0.99
1989/1990	0.87	0.81	0.98
1990/1991	-	-	0.97
1991/1992	-	0.84	-
1992/1993	0.77	0.69	0.97
1993/1994	0.80	0.72	0.97

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1994/1995	0.71	0.63	0.98
1995/1996	0.64	0.55	0.93
1996/1997	0.66	0.59	0.85
1997/1998	-	0.69	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7F2, 1956–2008 (52 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1956/1957	-	-	-
1957/1958	-	-	-
1958/1959	-	-	-
1959/1960	-	-	0.96
1960/1961	0.84	0.76	0.94
1961/1962	0.80	0.73	0.95
1962/1963	0.81	0.71	0.97
1963/1964	0.84	0.78	0.98
1964/1965	0.84	0.76	0.98
1965/1966	0.86	0.80	0.96
1966/1967	0.80	0.69	0.96
1967/1968	0.82	0.74	0.97
1968/1969	-	0.80	-
1969/1970	0.86	0.77	0.99
1970/1971	0.75	0.61	0.98
1971/1972	-	0.62	-
1972/1973	-	-	-
1973/1974	-	-	-
1974/1975	0.80	0.70	0.93
1975/1976	0.71	0.61	0.98
1976/1977	0.89	0.83	0.98
1977/1978	0.90	0.84	0.99
1978/1979	0.89	0.83	0.99
1979/1980	0.87	0.79	0.98
1980/1981	0.89	0.85	0.96
1981/1982	0.86	0.77	0.97
1982/1983	0.89	0.85	0.96
1983/1984	0.89	0.82	0.98
1984/1985	0.90	0.86	0.99
1985/1986	0.90	0.85	0.98
1986/1987	0.89	0.84	0.96
1987/1988	0.85	0.77	0.98
1988/1989	0.88	0.81	0.98
1989/1990	0.87	0.81	0.98
1990/1991	0.84	0.75	0.98
1991/1992	0.85	0.79	0.96
1992/1993	-	0.75	-
1993/1994	0.83	0.75	0.97
1994/1995	0.81	0.75	0.88

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1995/1996	0.81	0.71	0.97
1996/1997	0.81	0.73	0.96
1997/1998	0.89	0.84	0.98
1998/1999	0.88	0.81	0.98
1999/2000	-	-	0.97
2000/2001	0.87	0.82	0.96
2001/2002	0.85	0.77	0.98
2002/2003	0.85	0.77	0.98
2003/2004	0.85	0.77	0.99
2004/2005	-	-	-
2005/2006	0.80	0.73	0.92
2006/2007	-	-	-
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7G14, 1957–2007 (43 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1957/1958	-	-	0.96
1958/1959	0.83	0.80	0.96
1959/1960	0.87	0.84	0.96
1960/1961	0.86	0.93	0.93
1961/1962	0.85	0.83	0.96
1962/1963	0.81	0.74	0.98
1963/1964	-	-	0.98
1964/1965	0.89	0.87	0.97
1965/1966	0.85	0.84	0.90
1966/1967	0.87	0.84	0.94
1967/1968	0.83	0.79	0.97
1968/1969	0.82	0.76	0.99
1969/1970	0.86	0.82	0.99
1970/1971	0.85	0.82	0.99
1971/1972	0.85	0.80	0.98
1972/1973	0.87	0.83	0.97
1973/1974	-	-	-
1974/1975	-	-	0.99
1975/1976	0.88	0.85	0.98
1976/1977	0.91	0.83	0.96
1977/1978	0.91	0.89	0.99
1978/1979	0.87	0.83	0.99
1979/1980	0.77	0.71	0.97
1980/1981	0.77	0.72	0.95
1981/1982	0.88	0.87	0.91
1982/1983	0.93	0.92	0.97
1983/1984	0.84	0.81	0.98
1984/1985	-	0.66	-
1985/1986	-	-	0.99
1986/1987	0.89	0.87	0.97
1987/1988	0.74	0.68	0.97
1988/1989	0.85	0.81	0.99
1989/1990	0.61	0.52	0.98
1990/1991	0.76	0.69	0.98
1991/1992	0.00	0.00	0.95
1992/1993	-	-	-
1993/1994	0.77	0.73	0.98
1994/1995	0.76	0.73	0.98

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1995/1996	-	-	-
1996/1997	0.67	0.61	0.94
1997/1998	-	0.86	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	0.99
2001/2002	0.66	0.60	0.94
2002/2003	-	-	0.97
2003/2004	-	-	0.99
2004/2005	-	-	-
2005/2006	-	-	0.95
2006/2007	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7G18, 1985–2009 (24 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1985/1986	0.90	0.87	0.98
1986/1987	0.91	0.90	0.98
1987/1988	0.73	0.67	0.96
1988/1989	0.90	0.87	0.98
1989/1990	-	0.71	-
1990/1991	-	-	-
1991/1992	0.76	0.73	0.87
1992/1993	0.82	0.80	0.94
1993/1994	0.79	0.76	0.98
1994/1995	-	-	-
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	0.85	0.82	0.99
1998/1999	0.74	0.68	0.96
1999/2000	-	0.74	-
2000/2001	0.88	0.86	0.98
2001/2002	0.85	0.85	0.97
2002/2003	-	-	0.97
2003/2004	0.89	0.86	0.99
2004/2005	0.92	0.90	0.99
2005/2006	-	0.82	-
2006/2007	-	0.73	-
2007/2008	-	0.00	-
2008/2009	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7H1, 1955–2008 (53 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1955/1956	-	-	0.98
1956/1957	0.82	0.72	0.97
1957/1958	0.85	0.79	0.96
1958/1959	0.81	0.71	0.97
1959/1960	-	-	0.98
1960/1961	0.87	0.79	0.96
1961/1962	0.91	0.87	0.98
1962/1963	0.86	0.78	0.98
1963/1964	0.89	0.84	0.99
1964/1965	0.85	0.77	0.98
1965/1966	0.81	0.72	0.97
1966/1967	0.85	0.74	0.96
1967/1968	0.89	0.95	0.98
1968/1969	0.90	0.84	0.98
1969/1970	0.86	0.79	0.98
1970/1971	0.86	0.78	0.98
1971/1972	0.87	0.80	0.97
1972/1973	0.84	0.75	0.98
1973/1974	-	-	-
1974/1975	-	-	-
1975/1976	0.86	0.78	0.98
1976/1977	0.86	0.79	0.97
1977/1978	0.87	0.78	0.98
1978/1979	0.87	0.81	0.98
1979/1980	0.87	0.80	0.98
1980/1981	0.90	0.86	0.98
1981/1982	0.88	0.81	0.96
1982/1983	0.88	0.82	0.97
1983/1984	0.86	0.79	0.97
1984/1985	0.84	0.77	0.98
1985/1986	0.87	0.80	0.96
1986/1987	0.88	0.82	0.98
1987/1988	0.85	0.78	0.98
1988/1989	0.88	0.80	0.97
1989/1990	0.88	0.81	0.97
1990/1991	0.83	0.73	0.98
1991/1992	0.85	0.77	0.96
1992/1993	0.87	0.79	0.98

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1993/1994	0.90	0.85	0.97
1994/1995	0.88	0.83	0.98
1995/1996	0.85	0.78	0.95
1996/1997	0.88	0.82	0.97
1997/1998	0.87	0.95	0.99
1998/1999	-	-	0.98
1999/2000	0.78	0.78	0.99
2000/2001	0.86	0.78	0.99
2001/2002	0.81	0.70	0.97
2002/2003	-	-	-
2003/2004	0.00	0.00	0.99
2004/2005	0.73	0.61	0.94
2005/2006	-	-	-
2006/2007	0.90	0.85	0.99
2007/2008	-	0.80	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7H2, 1952–2008 (56 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1952/1953	-	-	-
1953/1954	0.88	0.82	0.98
1954/1955	0.86	0.75	0.96
1955/1956	0.88	0.81	0.97
1956/1957	0.83	0.72	0.96
1957/1958	0.87	0.98	0.98
1958/1959	0.83	0.76	0.92
1959/1960	0.82	0.70	0.95
1960/1961	0.89	0.81	0.95
1961/1962	0.90	0.83	0.99
1962/1963	-	-	-
1963/1964	-	-	0.99
1964/1965	0.80	0.68	0.99
1965/1966	0.85	0.75	0.99
1966/1967	-	-	0.95
1967/1968	0.88	0.79	0.99
1968/1969	-	-	-
1969/1970	-	0.75	-
1970/1971	0.82	0.72	0.97
1971/1972	0.85	0.74	0.96
1972/1973	0.84	0.74	0.97
1973/1974	-	0.65	
1974/1975	-	-	0.92
1975/1976	-	-	0.98
1976/1977	-	-	-
1977/1978	0.88	0.80	0.98
1978/1979	0.81	0.69	0.98
1979/1980	0.85	0.76	0.96
1980/1981	0.81	0.64	0.94
1981/1982	0.92	0.84	0.98
1982/1983	0.92	0.88	0.98
1983/1984	0.91	0.85	0.98
1984/1985	0.76	0.78	0.74
1985/1986	-	-	0.86
1986/1987	0.85	0.77	0.98
1987/1988	0.89	0.82	0.99
1988/1989	0.87	0.78	0.97
1989/1990	0.87	0.79	0.98

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1990/1991	0.86	0.76	0.99
1991/1992	0.89	0.83	0.95
1992/1993	-	-	0.97
1993/1994	0.92	0.88	0.98
1994/1995	-	-	-
1995/1996	0.83	0.74	0.96
1996/1997	0.87	0.80	0.96
1997/1998	0.91	0.84	0.99
1998/1999	-	-	0.94
1999/2000	0.88	0.81	0.96
2000/2001	0.92	0.86	0.97
2001/2002	0.91	0.83	0.98
2002/2003	-	-	0.98
2003/2004	0.87	0.78	0.98
2004/2005	0.89	0.83	0.98
2005/2006	0.91	0.86	0.97
2006/2007	0.91	0.85	0.98
2007/2008	-	0.86	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 7H3, 1971–2007 (36 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1971/1972	-	-	-
1972/1973	0.79	0.68	0.97
1973/1974	-	-	0.91
1974/1975	-	-	-
1975/1976	-	-	0.97
1976/1977	0.81	0.72	0.94
1977/1978	0.83	0.74	0.98
1978/1979	0.81	0.73	0.95
1979/1980	0.80	0.70	0.97
1980/1981	0.76	0.68	0.94
1981/1982	0.58	0.58	0.84
1982/1983	0.80	0.73	0.96
1983/1984	0.72	0.62	0.91
1984/1985	0.73	0.64	0.97
1985/1986	0.78	0.70	0.95
1986/1987	0.78	0.71	0.96
1987/1988	0.66	0.55	0.95
1988/1989	0.67	0.49	0.93
1989/1990	0.76	0.68	0.90
1990/1991	0.70	0.58	0.97
1991/1992	0.29	0.20	0.79
1992/1993	0.62	0.51	0.82
1993/1994	-	-	-
1994/1995	0.71	0.62	0.95
1995/1996	0.66	0.58	0.80
1996/1997	0.70	0.59	0.97
1997/1998	0.74	0.65	0.98
1998/1999	0.59	0.42	0.95
1999/2000	-	0.41	-
2000/2001	0.64	0.50	0.98
2001/2002	0.70	0.55	0.95
2002/2003	-	0.63	-
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	0.75	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 8A5, 1968–2009 (41 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1968/1969	-	-	0.96
1969/1970	0.48	0.39	0.98
1970/1971	-	0.57	-
1971/1972	0.57	0.48	0.95
1972/1973	0.69	0.60	0.98
1973/1974	0.64	0.55	0.87
1974/1975	0.66	0.55	0.98
1975/1976	0.64	0.53	0.99
1976/1977	0.65	0.55	0.94
1977/1978	0.62	0.53	0.99
1978/1979	0.64	0.54	0.99
1979/1980	0.65	0.54	0.96
1980/1981	-	-	0.75
1981/1982	-	-	0.83
1982/1983	-	-	0.86
1983/1984	0.52	0.49	0.98
1984/1985	-	-	0.96
1985/1986	0.33	0.27	0.80
1986/1987	-	-	-
1987/1988	-	-	-
1988/1989	0.56	0.46	0.97
1989/1990	0.47	0.37	0.96
1990/1991	-	0.37	-
1991/1992	0.55	0.49	0.92
1992/1993	0.47	0.40	0.92
1993/1994	-	-	0.98
1994/1995	0.70	0.66	0.99
1995/1996	-	0.71	-
1996/1997	0.00	0.00	0.98
1997/1998	0.73	0.62	0.99
1998/1999	-	0.83	-
1999/2000	0.72	0.58	0.98
2000/2001	0.83	0.76	1.00
2001/2002	-	-	-
2002/2003	-	-	0.52
2003/2004	0.80	1.00	0.72
2004/2005	0.77	0.97	0.67
2005/2006	-	-	-
2006/2007	-	-	-

Period	Annual BFI	Wet Season BFI	Dry Season BFI
2007/2008	-	-	-
2008/2009	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 9A2, 1953–2010 (57 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1953/1954	-	-	-
1953/1954	0.75	0.69	0.94
1954/1955	0.63	0.57	0.86
1955/1956	0.00	0.00	0.89
1956/1957	0.57	0.58	0.54
1957/1958	0.33	0.28	0.78
1958/1959	0.60	0.48	0.95
1959/1960	0.46	0.32	0.98
1960/1961	-	-	-
1961/1962	-	-	-
1962/1963	0.00	0.00	0.99
1963/1964	0.53	0.43	0.99
1964/1965	0.46	0.39	0.99
1965/1966	-	-	-
1966/1967	-	-	-
1967/1968	-	-	-
1968/1969	-	-	-
1969/1970	0.46	0.37	0.99
1970/1971	-	-	-
1971/1972	0.60	0.49	0.99
1972/1973	0.53	0.42	0.99
1973/1974	0.60	0.47	0.88
1974/1975	-	0.54	-
1975/1976	-	-	-
1976/1977	-	-	-
1977/1978	0.67	0.60	0.91
1978/1979	0.57	0.46	0.96
1979/1980	0.53	0.41	0.93
1980/1981	0.59	0.51	0.79
1981/1982	0.58	0.47	0.96
1982/1983	0.69	0.62	0.91
1983/1984	0.51	0.44	0.96
1984/1985	0.49	0.40	0.98
1985/1986	-	0.57	-
1986/1987	-	-	0.96
1987/1988	-	-	0.97
1988/1989	0.62	0.52	0.93
1989/1990	0.50	0.42	0.88
1990/1991	0.33	0.26	0.88

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1991/1992	0.34	0.27	0.87
1992/1993	0.53	0.47	0.84
1993/1994	-	-	-
1994/1995	0.67	0.63	0.96
1995/1996	0.50	0.45	0.92
1996/1997	-	0.44	-
1997/1998	-	-	0.92
1998/1999	-	-	-
1999/2000	-	0.56	-
2000/2001	0.72	0.60	0.98
2001/2002	-	0.67	-
2002/2003	0.74	0.64	0.96
2003/2004	0.70	0.63	0.92
2004/2005	0.74	0.68	0.97
2005/2006	0.74	0.66	0.98
2006/2007	-	-	0.96
2007/2008	-	0.73	-
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 9A4, 1958–2008 (50 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1958/1959	-	-	-
1959/1960	-	-	-
1960/1961	-	-	-
1961/1962	-	-	-
1962/1963	-	-	-
1963/1964	-	-	-
1964/1965	-	-	-
1965/1966	-	-	-
1966/1967	-	-	-
1967/1968	-	-	-
1968/1969	-	-	-
1969/1970	-	-	-
1970/1971	-	-	0.96
1971/1972	-	-	-
1972/1973	-	-	-
1973/1974	-	-	-
1974/1975	0.91	0.91	0.95
1975/1976	0.94	0.94	0.94
1976/1977	0.94	0.94	0.92
1977/1978	0.91	0.90	0.94
1978/1979	0.94	0.94	0.93
1979/1980	-	-	0.84
1980/1981	-	0.53	-
1981/1982	0.68	0.61	0.91
1982/1983	0.71	0.63	0.97
1983/1984	-	-	0.97
1984/1985	0.67	0.56	0.99
1985/1986	0.44	0.34	0.89
1986/1987	0.91	0.91	0.95
1987/1988	-	-	0.97
1988/1989	0.55	0.45	0.97
1989/1990	0.52	0.43	0.46
1990/1991	0.58	0.45	0.98
1991/1992	0.59	0.52	0.92
1992/1993	-	-	-
1993/1994	-	-	-
1994/1995	-	-	0.96
1995/1996	-	-	-
1996/1997	0.74	0.64	0.96

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1997/1998	-	-	-
1998/1999	-	-	-
1999/2000	-	-	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	0.56	0.45	0.98
2004/2005	0.48	0.35	0.99
2005/2006	-	0.33	-
2006/2007	-	-	-
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 9A5, 1970–2007 (37 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1970/1971	-	-	0.94
1971/1972	-	-	0.95
1972/1973	-	-	0.92
1973/1974	-	-	0.87
1974/1975	0.57	0.40	0.94
1975/1976	0.50	0.34	0.93
1976/1977	0.78	0.69	0.91
1977/1978	0.74	0.60	0.94
1978/1979	0.70	0.56	0.88
1979/1980	0.66	0.53	0.84
1980/1981	0.00	0.00	0.82
1981/1982	0.51	0.38	0.92
1982/1983	0.74	0.63	0.90
1983/1984	0.73	0.62	0.94
1984/1985	0.69	0.58	0.94
1985/1986	0.70	0.60	0.91
1986/1987	0.74	0.66	0.95
1987/1988	0.71	0.60	0.94
1988/1989	0.53	0.38	0.92
1989/1990	0.70	0.60	0.94
1990/1991	0.60	0.42	0.97
1991/1992	0.64	0.51	0.93
1992/1993	0.49	0.34	0.94
1993/1994	-	-	-
1994/1995	0.61	0.50	0.95
1995/1996	0.64	0.50	0.89
1996/1997	-	-	-
1997/1998	-	0.74	-
1998/1999	-	-	-
1999/2000	-	-	0.98
2000/2001	0.79	0.72	0.94
2001/2002	-	0.58	-
2002/2003	-	-	-
2003/2004	-	0.81	-
2004/2005	-	-	-
2005/2006	-	-	-
2006/2007	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 9B3, 1970–2008 (38 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1970/1971	-	-	-
1971/1972	0.30	0.52	0.26
1972/1973	0.22	0.18	0.93
1973/1974	0.17	0.13	0.92
1974/1975	0.46	0.37	0.92
1975/1976	0.56	0.47	0.89
1976/1977	-	0.53	-
1977/1978	0.30	0.22	0.98
1978/1979	-	-	0.93
1979/1980	-	-	-
1980/1981	-	-	-
1981/1982	-	-	0.77
1982/1983	-	-	-
1983/1984	0.19	0.17	0.92
1984/1985	0.29	0.25	0.96
1985/1986	0.35	0.28	0.93
1986/1987	0.37	0.33	0.94
1987/1988	0.33	0.29	0.93
1988/1989	0.41	0.34	0.86
1989/1990	-	0.34	-
1990/1991	-	-	0.24
1991/1992	0.15	0.23	0.03
1992/1993	0.34	0.30	0.89
1993/1994	0.31	0.28	0.74
1994/1995	0.28	0.25	0.84
1995/1996	0.38	0.36	0.88
1996/1997	0.42	0.39	0.75
1997/1998	0.30	0.26	0.98
1998/1999	0.50	0.44	0.91
1999/2000	0.31	0.28	0.89
2000/2001	-	-	-
2001/2002	0.43	0.38	0.94
2002/2003	0.36	0.31	0.95
2003/2004	0.26	0.20	0.94
2004/2005	0.45	0.44	0.45
2005/2006	0.25	0.26	0.21
2006/2007	-	0.40	-
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 9B5, 1979–2004 (25 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1979/1980	0.28	0.25	0.91
1980/1981	0.28	0.24	0.85
1981/1982	0.18	0.15	0.61
1982/1983	0.26	0.25	0.73
1983/1984	0.14	0.13	0.85
1984/1985	0.30	0.31	0.23
1985/1986	0.30	0.31	0.23
1986/1987	0.33	0.30	0.94
1987/1988	0.26	0.24	0.91
1988/1989	-	0.28	-
1989/1990	0.24	0.22	0.90
1990/1991	-	-	-
1991/1992	0.24	0.23	0.58
1992/1993	0.15	0.14	0.71
1993/1994	0.07	0.06	0.81
1994/1995	-	0.09	-
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	-	-	-
1998/1999	0.24	0.16	0.94
1999/2000	0.53	0.43	0.95
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-		0.00
2003/2004	-	0.00	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 9B6, 1981–2008 (27 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1981/1982	0.683	0.589	0.964
1982/1983	0.676	0.600	0.987
1983/1984	-	-	0.985
1984/1985	-	-	0.984
1985/1986	0.453	0.388	0.983
1986/1987	-	0.313	-
1987/1988	0.347	0.286	0.970
1988/1989	0.338	0.273	0.981
1989/1990	0.317	0.250	0.857
1990/1991	-	0.904	-
1991/1992	-	-	0.929
1992/1993	-	-	-
1993/1994	0.360	0.314	0.892
1994/1995	-	0.139	-
1995/1996	0.303	0.271	0.871
1996/1997	-	-	-
1997/1998	-	-	-
1998/1999	0.643	0.572	0.960
1999/2000	0.581	0.513	0.980
2000/2001	-	-	0.798
2001/2002	0.540	0.507	0.953
2002/2003	-	-	0.856
2003/2004	-	0.444	-
2004/2005	0.724	0.709	0.977
2005/2006	-	-	-
2006/2007	-	-	-
2007/2008	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 9B7, 1985–2012 (27 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1985/1986	-	-	-
1986/1987	0.65	0.59	0.83
1987/1988	-	-	0.94
1988/1989	-	-	0.83
1989/1990	0.67	0.58	0.87
1990/1991	0.61	0.48	0.94
1991/1992	0.66	0.57	0.86
1992/1993	0.67	0.56	0.95
1993/1994	-	0.63	-
1994/1995	-	-	-
1995/1996	0.60	0.57	0.67
1996/1997	0.63	0.55	0.97
1997/1998	-	0.55	-
1998/1999	0.77	0.70	0.98
1999/2000	-	-	-
2000/2001	0.54	0.45	0.87
2001/2002	0.77	0.71	0.96
2002/2003	-	0.56	-
2003/2004	-	-	0.53
2004/2005	0.69	0.53	0.94
2005/2006	0.66	0.55	0.81
2006/2007	-	0.59	-
2007/2008	-	-	0.90
2008/2009	0.53	0.46	0.82
2009/2010	-	-	0.80
2010/2011	0.57	0.49	0.86
2011/2012	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 11A6, 1976–1998 (22 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1976/1977	-	-	-
1977/1978	0.58	0.54	0.98
1978/1979	0.49	0.27	0.77
1979/1980	0.21	0.12	0.94
1980/1981	-	-	-
1981/1982	0.74	0.66	0.88
1982/1983	0.29	0.21	0.97
1983/1984	-	-	-
1984/1985	-	-	0.96
1985/1986	0.53	0.46	0.97
1986/1987	0.46	0.40	0.96
1987/1988	0.36	0.31	0.93
1988/1989	0.51	0.42	0.87
1989/1990	0.34	0.27	0.85
1990/1991	-	-	0.90
1991/1992	0.34	0.31	0.88
1992/1993	-	-	0.92
1993/1994	-	-	-
1994/1995	-	-	0.33
1995/1996	-	-	-
1996/1997	-	-	-
1997/1998	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 11A7, 1976–1998 (22 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1976/1977	-	-	-
1977/1978	-	-	0.95
1978/1979	0.43	0.32	0.86
1979/1980	0.40	0.30	0.96
1980/1981	0.44	0.37	0.86
1981/1982	-	-	-
1982/1983	-	-	0.97
1983/1984	0.30	0.24	0.95
1984/1985	-	-	0.96
1985/1986	0.75	0.68	0.93
1986/1987	0.55	0.45	0.92
1987/1988	0.58	0.50	0.95
1988/1989	0.45	0.32	0.87
1989/1990	0.32	0.29	0.56
1990/1991	0.48	0.37	0.91
1991/1992	0.27	0.21	0.94
1992/1993	-'	-	-
1993/1994	-	0.27	-
1994/1995	-	-	-
1995/1996	-	-	
1996/1997	-	-	0.83
1997/1998	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 15A4, 1970–2000 (30 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1970/1971	0.00	0.00	-
1971/1972	0.00	0.00	-
1972/1973	0.00	0.00	-
1973/1974	0.49	0.94	0.94
1974/1975	0.58	0.40	0.99
1975/1976	-	-	-
1976/1977	-	-	-
1977/1978	-	-	-
1978/1979	-	-	-
1979/1980	-	-	-
1980/1981	-	-	-
1981/1982	-	-	-
1982/1983	-	-	-
1983/1984	-	-	-
1984/1985	0.00	0.00	0.00
1985/1986	-	-	-
1986/1987	0.17	0.17	0.79
1987/1988	-	-	0.93
1988/1989	-	-	-
1989/1990	-	-	0.96
1990/1991	0.22	0.18	0.97
1991/1992	0.11	0.12	0.06
1992/1993	0.18	0.17	0.77
1993/1994	0.11	0.11	0.62
1994/1995	-	-	-
1995/1996	-	-	-
1996/1997	0.04	0.04	0.89
1997/1998	0.10	0.10	0.59
1998/1999	0.37	0.25	0.91
1999/2000	0.19	0.16	0.67

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 15A8, 1960–2010 (50 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1960/1961	-	-	-
1961/1962	0.61	0.50	0.90
1962/1963	0.67	0.58	0.95
1963/1964	0.72	0.66	0.97
1964/1965	0.61	0.51	0.96
1965/1966	0.51	0.45	0.92
1966/1967	0.31	0.22	0.93
1967/1968	0.34	0.29	0.70
1968/1969	-	-	-
1969/1970	0.26	0.23	0.91
1970/1971	-	-	-
1971/1972	-	-	-
1972/1973	-	-	-
1973/1974	-	-	-
1974/1975	0.64	0.54	0.97
1975/1976	0.60	0.50	0.96
1976/1977	-	-	-
1977/1978	-	-	0.96
1978/1979	0.65	0.55	0.97
1979/1980	0.33	0.22	0.98
1980/1981	-	-	0.98
1981/1982	-	-	-
1982/1983	-	-	-
1983/1984	-	-	-
1984/1985	-	-	-
1985/1986	0.31	0.23	0.94
1986/1987	-	-	0.92
1987/1988	0.43	0.32	0.95
1988/1989	-	-	0.96
1989/1990	0.52	0.42	0.97
1990/1991	0.30	0.22	0.96
1991/1992	0.24	0.19	0.94
1992/1993	-	-	0.96
1993/1994	0.28	0.25	0.94
1994/1995	0.07	0.06	0.88
1995/1996	-	0.42	-
1996/1997	-	-	0.95
1997/1998	0.35	0.28	0.98

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1998/1999	0.37	0.28	0.96
1999/2000	0.61	0.59	0.97
2000/2001	0.42	0.34	0.99
2001/2002	0.42	0.33	0.96
2002/2003	0.57	0.41	0.99
2003/2004	-	-	-
2004/2005	-	-	-
2005/2006	-	-	0.96
2006/2007	0.94	0.91	0.96
2007/2008	0.86	0.85	0.97
2008/2009	0.82	0.80	0.90
2009/2010	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 16E6, 1972–2009 (37 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1972/1973	0.76	0.61	0.98
1973/1974	0.79	0.69	0.92
1974/1975	0.77	0.61	0.97
1975/1976	0.81	0.98	0.98
1976/1977	0.74	0.60	0.96
1977/1978	0.72	0.58	0.96
1978/1979	0.79	0.69	0.99
1979/1980	0.79	0.98	0.98
1980/1981	0.84	0.76	0.98
1981/1982	0.75	0.65	0.88
1982/1983	-	-	0.98
1983/1984	0.75	0.64	0.92
1984/1985	0.73	0.94	0.94
1985/1986	-	-	-
1986/1987	0.79	0.71	0.98
1987/1988	0.78	0.66	0.90
1988/1989	-	-	-
1989/1990	0.93	0.90	0.99
1990/1991	0.87	0.79	0.99
1991/1992	0.88	0.82	0.96
1992/1993	-	-	-
1993/1994	0.81	0.71	0.99
1994/1995	0.92	0.87	0.99
1995/1996	-	0.78	-
1996/1997	0.80	0.69	0.98
1997/1998	0.76	0.67	0.98
1998/1999	-	-	0.96
1999/2000	-	0.94	-
2000/2001	-	-	-
2001/2002	-	-	-
2002/2003	-	-	-
2003/2004	-	-	0.12
2004/2005	0.30	0.24	0.43
2005/2006	-	-	-
2006/2007	-	0.62	-
2007/2008	-	0.74	-
2008/2009	-	0.22	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 16F1, 1970–1991 (21 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1970/1971	0.70	0.56	0.97
1971/1972	0.82	0.72	0.95
1972/1973	-	-	-
1973/1974	-	-	-
1974/1975	-	-	-
1975/1976	-	-	-
1976/1977	-	-	-
1977/1978	-	-	-
1978/1979	-	-	-
1979/1980	-	-	-
1980/1981	0.82	0.75	0.93
1981/1982	0.58	0.42	0.77
1982/1983	0.67	0.57	0.83
1983/1984	0.57	0.44	0.81
1984/1985	0.65	0.51	0.88
1985/1986	0.65	0.55	0.85
1986/1987	0.66	0.57	0.91
1987/1988	-	0.48	-
1988/1989	-	-	-
1989/1990	0.60	0.54	0.67
1990/1991	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 16F2, 1952–1994 (42 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1952/1953	-	-	0.88
1953/1954	0.75	0.66	0.98
1954/1955	0.71	0.62	0.82
1955/1956	0.75	0.68	0.83
1956/1957	-	-	-
1957/1958	0.61	0.47	0.92
1958/1959	0.65	0.54	0.87
1959/1960	0.55	0.43	0.81
1960/1961	-	-	-
1961/1962	0.80	0.71	0.94
1962/1963	0.76	0.62	0.97
1963/1964	0.82	0.77	0.89
1964/1965	0.79	0.69	0.97
1965/1966	-	0.62	-
1966/1967	0.79	0.74	0.86
1967/1968	0.69	0.59	0.93
1968/1969	0.77	0.67	0.92
1969/1970	0.69	0.60	0.89
1970/1971	0.74	0.59	0.98
1971/1972	-	0.65	-
1972/1973	-	-	-
1973/1974	-	-	-
1974/1975	0.76	0.65	0.92
1975/1976	0.77	0.69	0.85
1976/1977	0.75	0.65	0.93
1977/1978	0.78	0.94	0.94
1978/1979	0.86	0.76	0.98
1979/1980	0.90	0.84	0.97
1980/1981	0.89	0.83	0.96
1981/1982	0.78	0.71	0.85
1982/1983	0.88	0.83	0.96
1983/1984	0.76	0.68	0.87
1984/1985	-	0.78	-
1985/1986	0.80	0.71	0.96
1986/1987	0.83	0.77	0.95
1987/1988	0.72	0.69	0.75
1988/1989	0.81	0.73	0.91
1989/1990	0.81	0.77	0.86

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1990/1991	-	-	-
1991/1992	-	-	-
1992/1993	0.69	0.62	0.80
1993/1994	-	-	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 17C6, 1969–1993 (24 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1969/1970	-	-	-
1970/1971	0.80	0.69	0.98
1971/1972	0.93	0.93	0.94
1972/1973	0.93	0.93	0.93
1973/1974	0.91	0.90	0.93
1974/1975	0.95	0.94	0.96
1975/1976	0.93	0.92	0.94
1976/1977	0.94	0.93	0.95
1977/1978	0.91	0.89	0.96
1978/1979	0.94	0.94	0.93
1979/1980	0.89	0.87	0.93
1980/1981	0.80	0.80	0.95
1981/1982	0.78	0.63	0.94
1982/1983	0.86	0.79	0.97
1983/1984	0.84	0.79	0.95
1984/1985	0.81	0.72	0.96
1985/1986	0.83	0.76	0.95
1986/1987	0.89	0.84	0.97
1987/1988	0.77	0.72	0.93
1988/1989	0.80	0.74	0.92
1989/1990	0.81	0.78	0.86
1990/1991	0.57	0.46	0.85
1991/1992	-	-	0.71
1992/1993	-	0.51	-

- denotes no BFI determined due to insufficient data in the period

Results of the annual and seasonal BFI analysis (tabular) for gauge station 17C10, 1974–1989 (15 years)

Period	Annual BFI	Wet Season BFI	Dry Season BFI
1974/1975	-	-	-
1975/1976	0.55	0.37	0.96
1976/1977	0.53	0.42	0.72
1977/1978	0.65	0.47	0.96
1978/1979	0.80	0.71	0.98
1979/1980	0.70	0.63	0.86
1980/1981	-	-	-
1981/1982	-	-	-
1982/1983	0.58	0.35	0.68
1983/1984	0.78	0.57	0.96
1984/1985	0.84	0.70	0.97
1985/1986	-	-	0.93
1986/1987	0.84	0.77	0.99
1987/1988	-	-	0.98
1988/1989	-	-	-

- denotes no BFI determined due to insufficient data in the period

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