The Characterisation of Water Scarcity: Developing a Storage-based Indicator Framework for the Great Ruaha River Catchment, Tanzania

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A thesis presented in partial fulfilment
of the requirements for the degree of

Doctor of Philosophy
in
Sustainable Water Resources and Policy

University College London
Institute for Sustainable Resources
Bartlett School of Environment, Energy and Resources

12th April 2019

For Flo

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We never knew you in this life,

but you remain loved, always;

in this life and the next.

Declaration of ownership

I, **SIMON SPARSOE DAMKJAER** confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Acknowledgements

This thesis was proudly produced and submitted in the European Union

I am grateful to a handful of people who have made this research possible and supported me throughout the process.

Firstly, I would like to thank my entire supervisory team, Professor Raimund Bleischwitz, Professor Richard Taylor, and Professor Paul Ekins. To Raimund for his insights, continuous support and ability to challenge me to take a broader view of my research. To Richard, for his continuous support, encouragement and patience with all of my enquiries as well as mutual passion for Water and Human Ecology in sub-Saharan Africa. Paul, for always being able to provide intellectual insight and an alternative views into my research. The entire team was also an incredible source of moral support throughout my endeavours. My gratitude furthermore goes to UCL-ISR for the generous scholarship and institutional support. I am further indebted to my Tanzanian colleagues at Sokoine University of Agriculture for making my fieldwork possible. To Professor Kashaigili and Professor Tarimo for their assistance with everything related to my stay in Tanzania: logistics, water expertise and for welcoming me to SUA and the Great Ruaha Catchment. Furthermore, I also am grateful for the insights into the social sciences of water use in Tanzania provided by Dr. Mosha-Kilave, and to Johnson and Doris for assisting me during the many days of data acquisition, acting as interpreters and for providing me with company during the countless hours I spent behind the wheel on Tanzania's dusty rural roads. Also, many thanks to all institutional and administrative staff at SUA for giving me access to their facilities, offices and library resources, as well as to *Grofutures* colleagues, especially Shams, John, Declan and everyone based in Ethiopia and Niger.

More personally, an incredible thanks is owed to my supportive family who have always believed in me. To my partner Allison, for your endless motivation, support and understanding of how consuming my research has been, physically, emotionally, mentally and spiritually - I am grateful for your ability to put up with me in times of stress. To my parents, who have always motivated me even when I have not been able to articulate my work properly. I am grateful for everything in life that has led to the fulfilment of this thesis. A special thanks also to auntie Kathy and Uncle David for having been like second parents in Tanzania, and for the days and nights spent camping and on safari. And last but not least, thanks to all the amazing people in Central House, old and new, who have not just been amazing colleagues but also become great friends, always helpful on all matters academic and non-academic alike.

Abstract

This thesis addresses a fundamental lack of critical research investigating the meaning and practical application of widely used water scarcity metrics that include the Falkenmark Water Stress Index (WSI) and the Water Withdrawal to Availability (WTA) ratio. Recognising that current indicators do not account for the significant inter- and intra-annual variability in freshwater resources, this research proposes a new methodology to characterise water scarcity that explicitly considers the contribution of water storage to freshwater availability. This approach also specifically addresses common assumptions of domestic water demands (i.e. ~100 litres capita day (LCPD)) and adaptive strategies that people employ to maintain access to freshwater.

Central to the arguments presented in this thesis is a case-study from the semi-arid Great Ruaha River Catchment (GRRC) in Tanzania. Application of the two metrics to the GRRC provide contrasting results, despite an absence of river discharge for an increasing period of the year. Investigating the strong inter-annual variability of freshwater availability suggests that naturally-occurring shifts in upstream hydrology may have a greater impact on downstream zero-flows than previously suggested, bringing into question the predominant narrative that livestock keepers and irrigation has constituted the primary cause for the experienced water shortages.

Fieldwork, informed by a mixed-methods approach, quantifies domestic water demand in three villages to show that domestic water use is significantly lower than the assumed ~100 LCPD embedded in the WSI. Analysing the pathways to accessing the varying water available in the same villages show that development interventions which did not follow participatory approaches, failed. As a response to the resulting lack of clarity over water infrastructure ownership, informal pathways emerge through self-supply water storage systems such as hand-dug wells. Such systems are not uncommon in sub-Saharan Africa but remain inadequately represented in water scarcity metrics.

Finally, the research considers what an indicator approach that is informed by inter- and intra-annual contributions of storage to freshwater availability could look like and evaluates the current limitations to its implementation.

Impact Statement

The research presented in this doctoral thesis has a two-fold impact, relevant both to areas of methodology and policymaking. The former concerns the contribution to advancing methods for measuring and characterising water scarcity. This thesis challenges the current ways that the water sector, both within and outside of academia, frame the narrative surrounding water scarce conditions. Bringing to light the importance of the inter- and intra-annual variability of freshwater availability, as well as the role that surface- and sub-surface storage play in facilitating adaptive capacity and resilience in less economically developed countries, the research advancement impact is demonstrated through the elaboration and evaluation of what an indicator approach that is informed by storage could look like in order to more accurately and realistically relate to the disequilibrium in hydrological characteristics common in this part of the world (arid- and semi-arid areas) where most of the world's future population are expected to live.

The research was informed through fieldwork in rural Tanzania in collaboration with local researchers at the Sokoine University of Agriculture and civil servants working with water resources. The thesis was part of the UCL-led Groundwater Futures project, funded through the DfID programme Unlocking Potential for Groundwater in Africa, a consortium-wide effort to scale-up knowledge on both the physical- and social-science knowledge-base of groundwater use in one of the world's fastest-growing sub-continental economies.

The practical nature of this thesis brings out a real-world understanding of experiences and perceptions of water scarcity and freshwater resources availability that are not adequately captured in current water scarcity- and stress indicators, despite their continued application for over three decades. It is in this context that the second contribution related to policy-making emerges. The Millennium- and Sustainable Development Goals (MDG & SDG) are heavily metric-dependent in their effort to measure progress towards reaching their respective targets. As this research shows, despite achieving the MDG on halving the proportion of people with access to water several years before the 'deadline', the adopted indicator failed to recognise informal pathways of accessing water for domestic purposes, such as using hand-dug and shallow wells. Consequently, the declaration of having halved the number of people without access to safe drinking water, still left a significant proportion of the global population that are not connected and, primarily in Less Economically Developed Countries, unaccounted for. The more recent SDG indicator for measuring progress towards halving the proportion of people that suffer from water scarcity further fails to adequately reflect much of the criticism in this thesis. The resulting was the adoption of an indicator that is not adequately informed by the hydrological realities of the human- and physical environment. Indeed, relying on numerical outputs by indicator is convenient to inform policy-makers about a range of decision-making options, but they can be far from adequate if their application are to be used to inform policies that are truly sustainable.

The research critically reflects the shortcomings identified, with the thesis unpacking assumptions regarding the hydrological environment and its water users and subsequently elaborates on one approach that could address these deficiencies. The approach however is evaluated to not be fully operational but has the potential to be used as a starting point to not only provide information about the magnitude and periodicity of water supply deficits relative to demand, but also provide decision-makers with information on best options for developing storage-based water supply options. These options are derived from insights into local-scale preferences and uses of water, and thereby could be more likely to improve the quality of infrastructure resilience and sustainability, adapting it to local scale conditions and maintenance capacities.

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List of Acronyms

AWRI	**Arctic Water Resources Vulnerability Index**
BFI	**Baseflow Index**
BRBVI	**Bagmati River Basin Vulnerability Index**
CVI	**Climate Vulnerability Index**
CWSI	**Canadian Water Sustainability Index**
DANIDA	**Danish International Development Agency**
DfID	**Department for International Development**
DHS	**Demographic and Health Survey**
DIA	**Domestic Industrial Agricultural Withdrawals**
DoW	**Drawers of Waters**
EIA	**Environmental Impact Assessment**
ER	**External Respondent**
EU	**European Union**
EWR	**Environmental Water Requirements**
FAO	**Food and Agricultural Organisation (United Nations)**
FGD	**Focus Group Discussions**
FoRS	**Friends of Ruaha Society**
GCMs	**General Circulation Models**
GCVI	**Governance and Climate Vulnerability Index**
GDP	**Gross Domestic Product**
GNP	**Gross National Product**
Grofutures	**Groundwater Futures**
GRR	**Great Ruaha River**
GRRC	**Great Ruaha River Catchment**
GURT	**Government of the United Republic of Tanzania**
GWS	**Groundwater Storage**
GWUA	**Groundwater Users Association**
HDI	**Human Development Index**
HELP	**Hydrology Environment Life and Policy Platform**
HEP	**Hydroelectric Power**
HWSI	**Hydrological Water Stress Index (i.e Inverted Falkenmark WSI)**
IPCC	**Intergovernmental Panel on Climate Change**
IR	**Internal Respondent**
ITCZ	**Inter-Tropical Convergence Zone**
IWMI	**International Water Management Institute**
IWRM	**Integrated Water Resources Management**
JMP	**Joint Monitoring Programme**
L	**Litres**
LCA	**Life Cycle Assessment**
LCIA	**Life Cycle Impact Assessment**
LCPD	**Litres per capita per day**
LECD	**Less Economically Developed Countries**
MARR	**Mean Annual River Runoff**
MDG	**Millennium Development Goal**

MEDC	**More Economically Development Countries**
MEDEA	**Measurements of Earth Data for Environmental Analysis**
MW	**Mega Watts**
NAFCO	**National Agriculture and Food Company**
NAWAPO	**National Water Policy**
NERC	**Natural Environmental Research Council**
NGO	**Non-governmental Organisations**
NWSDS	**National Water Sector Development Strategy**
mamsl	**Metres above mean sea level**
PB	**Planetary Boundaries**
PI	**Primary Investigator**
PRI	**Policy Research Institute**
Q	**River Discharge**
RBMSIIP	**River Basin Management and Smallholder Irrigation Improvement**
RBWB	**Rufiji Basin Water Board**
RBWO	**Rufiji Basin Water Office**
RDF	**Recursive Digital Filter**
RIPARWIN	**Raising Irrigation Productivity and Releasing Water for Inter-sectoral Needs project**
RNP	**Ruaha National Park**
SAGCOT	**Southern Growth Corridor of Tanzania**
SDG	**Sustainable Development Goal(s)**
SGAP	**Sustainability Gap**
SMS	**Soil Moisture Storag**
SMUWC	**Sustainable Management of the Usangu Wetlands and its Catchment project**
SSA	**Sub-Saharan Africa**
SUA	**Sokoine University of Agriculture**
SUANAL	**SUA National Library of Agriculture**
SWSI	**Social Water Stress Index**
TANAPA	**Tanzania National Park Authority**
TANESCO	**Tanzania Electric Supply Company**
TANZAM	**Tanzania - Zambia Highway**
TAWICO	**Tanzania Wildlife Corporation**
TAZARA	**Tanzania - Zambia Railway Authority**
TLU	**Tropical Livestock Units**
TRWR	**Total Renewable Water Resources**
UBAMPA	**Ubaruku Mpakani**
UNDP	**United Nations Development Programme**
UNICEF	**United Nations International Children's Emergency Fund**
UPGro	**Unlocking the Potential of Groundwater**
USAID	**The United States Agency for International Development**
WHO	**World Health Organisation**
WII	**Water Impact Index**
WJWSI	**West Java Water Sustainability Index**
WPI	**Water Poverty Index**
WRM [Act]	**Water Resources Management [Act]**
WSI	**Water Stress Index**

WSI_{EWR}	**Water Stress Index Environmental Water Requirements**
WTA	**Water to Withdrawal**
WUA	**Water Users Associations**
WVI	**Water Vulnerability Index**
WWAP	**World Water Assessment Programme**
WWF-RWP	**World Wildlife Fund Ruaha Water Programme**
WWF-UK	**World Wildlife Fund United Kingdom**

Chapter 1 Introduction

"*Sustainable Development Goal 6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all*"

"Sustainable Development Goal 6.4: By 2030, substantially reduce the number of people suffering from water scarcity";

(United Nations Sustainable Development Summit, New York, 2015)

1.1 Background and context

Ensuring adequate quantities of freshwater available to sustain the health and well-being of humans and the ecosystems in which they live, remains one of the world's most pressing challenges (Jiménez-Cisneros *et al.*, 2014; Rockström and Falkenmark, 2015). Water covers over two-thirds of the global surface, but only ~2.5% is in freshwater stocks, with an even smaller proportion accessible for human consumption (Shiklomanov, 1991). The world's freshwater resources base has increasingly been subject to pressures from population growth and rising food demand during the last century. Over the 20th century, the global population has grown by over four times while global water withdrawals increased nearly six times in the same period (Hanasaki *et al.*, 2013; Wada *et al.*, 2016). Food demand alone has required global cropland area to double and the total area under irrigation to grow six-fold. Expectations are that there will have been a 5.5% increase in water withdrawals for irrigation between 2008 – 2050 (FAO, 2011) and Burek *et al.* (2016) project increases in global crop irrigation water requirements for 2050 to be between 23% - 42% based on 2010 levels. Overall demand for water for industry is also expected to increase in most regions of the world by 2050. This rise is predicted to be up to eight times in Western, Middle, Eastern and Southern

Africa and up to two and a half times in Southern, Central and Eastern Asia from 2010 levels (Burek *et al.*, 2016). The greatest increases in domestic water demands over the same period could be three-fold in African and Asian sub-regions and more than double in Central and South America (Burek *et al.*, 2016).

Low-income countries in the tropics, where most of the global population are projected to live in the future (Gerland *et al.*, 2014), are expected to feel the increased pressures on water resources more severely, particularly in global cities (Bell, 2017). The effects of climate change on both the magnitude and frequency of extreme drought and flood events will become greater and significantly impact the way in which people use and access water, as the gap between supply and demand grows. Adequately communicating and characterising where and when freshwater availability may become insufficient to meet human and environmental demands requires an understanding of how people use water and adapt to changing circumstances of accessible freshwater. The conventional method of characterising water shortages through metrics tends to be limited to providing just a snapshot of the situation against a proscribed threshold of estimated 'sufficiency'.

This thesis interrogates conventional approaches to the measurement of water scarcity and the development of early-warning signals to identify where and when water shortages occur, in order to inform successful water management strategies. The challenge to conventional water scarcity further comes through the assessment of their limits in relation to assumptions about fixed levels of water demand and disregard for real-life consumption patterns as well as overseeing relevant parts of water supply. Arguments developed in this thesis are rooted in a case-study from semi-arid Tanzania.

1.2 The importance of researching water scarcity in semi-arid areas

Arid- and semi-arid areas, along with sub-humid and hyper-arid geographies, constitute environments within the definition of the drylands biome. Drylands cover ~50% of the earth's terrestrial surface and are characterised by limited by soil moisture resulting from both low rainfall and high evapotranspiration rates (Safriel and Adeel, 2008). The drylands biome supports ~40% of the global population, providing multiple ecosystem services, as well as playing a major role in global biophysical processes (Koohafkan & Stewart, 2008). Over time, such regions have played a central role in the development of human societies, including the domestication of animals and plants and the growth of at least three major religions (Middleton *et al.*, 2011). Arid- and semi-arid areas consist primarily of low-income countries and have one of the highest infant mortality rates in the world (Kwon *et al.*, 2016). The primary source of livelihood in these areas is agriculture, making up ~50% of global farmland and support nearly half of the world's livestock (UNDP, 2013). Drylands experience extreme variations in the magnitude and frequency of rainfall which General Circulation Models (GCMs) suggest will be exacerbated under future climate change (IPCC, 2014a; 2014b).

The several billion people who live in drylands share a common attribute of possessing high levels of adaptive capacity, which have commonly fuelled their resilience and survival (Adams, 1992). However, in light of globally increasing pressures on the environment, the attention given to addressing such challenges by scientific enquiries lack focus specifically on the impacts on arid- and semi-arid regions compared to other biome sub-systems. Between 2000 and 2011, a majority of scientific publications in the field of ecology focussed on the forest biome (67%) (Durant *et al.*, 2014). The 2015 Paris Agreement, that aims to limit the average increase in anthropogenic-induced global warming to less than 2^{o} does not take into consideration the differences in unevenly distributed terrestrial warming which can be as much as 20 – 40% higher in dryland areas compared to temperate latitudes (Huang *et al.*, 2017).

1.3 The case for researching water scarcity metrics in semi-arid Great Ruaha River Catchment, Tanzania

Formal quantification of water scarcity originated with the development of the Water Stress Index (WSI) (Falkenmark, 1986; 1989) to explore links between food security and freshwater availability in the context of famines that occurred in Sub-Saharan Africa (SSA) during the early 1980s. The simplicity of the WSI led to its widespread application and growth in the development of more holistic and complex methods to measure water scarcity. Such metrics also emerged to inform international development policy in measuring progress towards achieving Sustainable Development Goal (SDG) target 6.4, which aims to halve the number of people that suffer from water scarcity by 2030. Given their vast application at both local (Sullivan *et al.*, 2003; Alessa *et al.*, 2008; Juwana, 2012) and global (Arnell 2004, Wada, 2013; Vorosmarty *et al.*, 2000) scales, this adoption has occurred with limited critical examination of the assumptions that inform the characterisation of measuring water scarcity. Consequently, the convenience of easily applying such metrics also carries with it multiple simplifications regarding global water supply and demand, and examining the validity of these assumptions is a core objective of this thesis.

First, the supply side of water scarcity indicators has historically been subject to a methodology, which only relies on the estimation of mean annual surface water discharge to compute freshwater availability. As a result, the approach does not account for the contribution of surface- and sub-surface water storage to freshwater availability nor does it adequately represent the high inter- and intra-annual variability of freshwater availability that is prominent in semi-arid areas. Second, conventional water scarcity metrics apply a uniform assumption about adequate quantities of water required to meet domestic water demands, masking adaptive capacity and management of water users' demands in highly dynamic hydrological regimes. Furthermore, by considering the contribution of surface- and sub-surface water storage to freshwater availability as negligible, the metrics tell little about the role that these components of the hydrological cycle play in meeting water demands. Rectifying the lack of attention to 1) storage, 2) inter- and intra- annual variability and demand, and 3) an enhanced understanding of adaptive capacity, is highly important for long-term sustainable management and planning of resilient water resources infrastructure.

The lack of attention to surface- and sub-surface water storage in semi-arid sub-Saharan Africa (SSA) drove this research, which was conducted as part of the consortium Groundwater Futures (*GroFutures*), led by University College London, under the Natural Environmental Research Council (NERC) programme 'Unlocking the Potential of Groundwater' (UPGro) in SSA. Informing arguments made in this thesis is a case study, conducted in collaboration with the Sokoine University of Agriculture (SUA), of the semi-arid Great Ruaha River Catchment (GRRC) located in south-western Tanzania. This site is similar to areas of SSA that the WSI was developed for during the 1980s, which makes it a highly appropriate location to examine the assumptions about water supply and demand that inform widely applied water scarcity metrics. Interest in the GRRC was triggered by an observed decline in surface water resources and recurrent drying up of the main channel of the Great Ruaha River (GRR) in the heart of the Ruaha National Park (RNP). Little attention has been paid to the role of surface- and sub-surface water storage in adapting to this condition. Such oversight is of concern as the Government of the United Republic of Tanzania (GURT) undertakes a large-scale agricultural development initiative known as the Southern Growth Corridor of Tanzania (SAGCOT). SAGCOT is planned to run through the GRRC and will focus on increasing the use of groundwater- and basin-storage for irrigated agriculture.

1.4 The significance of the research

The significance of this thesis lies in its contribution to advancing the methodological basis for characterising and quantifying water scarcity. The issue of whether there are adequate amounts of water to meet everyone's needs is of age-old concern and central to informing international development policy through global-scale initiatives such as the SDGs. However, explicit attention is rarely given to how water scarcity is characterised and the assumptions informing such characterisations.

Thus, the contribution of this research is multi-fold. On the one hand, this thesis aims to influence and advance global debate on the characterisation of water scarcity by re-evaluating the basis for current approaches. Measuring progress towards achieving the SDGs on water and sanitation requires more than just reporting on whether a target is met or not. The outcomes need to be evaluated on the background of the process behind the assumptions entailed in the assessment itself and whether such assumptions are relevant for the specific context and account for strategies such as adaptive capacity. On the other hand, the thesis further aims to advance critical debate around the methodologies for measuring and characterising water scarcity. The investigation highlights previously limited addressed shortcomings of water scarcity metrics in-depth and moves beyond simple critique to suggest how a future approach to characterising may look. Such an approach should address shortcomings related to assumptions about freshwater availability and demand, the role of storage and, the inter- and intra-annual variable nature of freshwater resources.

1.5 Research Questions

This thesis aims to contribute to the discussion surrounding the characterisation of water scarcity, examine its measurement both theoretically and practically and use the resulting insights to provide an alternative framing of the characterisation of water scarcity. There exists a dearth of studies that interrogate the meaning and usefulness of current metrics for measuring water scarcity and even fewer studies that interrogate the assumptions that inform such indicator. Resulting, the overall question that the thesis aims to address:

"To what extent are current methods for characterising water scarcity useful, especially when applied in semi-arid zones?"

This research question is guided by three sub-questions:

a) *What are the deficits in current characterisations of water scarcity?*
b) *what are the implications for semi-arid zones and;*
c) *what could a more meaningful approach to measuring water scarcity look like?"*

The following four research objectives were central to answering the overarching research question and sub-questions each addressed in separate empirical chapters:

1. To apply the WSI and WTA ratio indicator, two widely accepted measurements of water scarcity, to the Great Ruaha River Catchment, to assess change in characterisations of water scarcity over time.
2. To examine how assumptions of domestic water demand embedded in the WSI relate to field observations.
3. To investigate how water users characterise 'water scarcity' and how freshwater storage informs adaptive capacity.
4. To explore a future approach for measuring water scarcity and evaluate the limits to its current development based on available field data.

1.6 Thesis outline

Chapter 1 introduced the background to the study, its significance and importance and presented the overarching research question that the thesis aims to address, guided by four research objectives. The overall aim is to address the conventional way of characterising and measuring water scarcity, examine the assumptions that inform such indicators and, explore a different approach to measuring water scarcity that addresses the identified limits to current methods of characterising water scarcity. The overall focus of the investigation is on a low-income semi-arid and hydrologically vulnerable catchment in Tanzania, that is subject to potential large-scale water irrigation development in the future.

Chapter 2 provides a critical review of the broad literature that exists on water scarcity indicators in providing an answer to the first sub-research question: "What are the deficits in current characterisations of water scarcity?". First, the review examines the evolution of water scarcity metrics and the assumptions about the data that have informed such indicators until now. The review exposes limitations in current metrics and proposes three points of critique to inform a more robust approach to measuring water scarcity. Each point of critique is addressed in practice in three separate chapters (Chapters 5-7) that together aim address the second sub-research question "what are the implications [of the deficits of the characterisation of water scarcity] for semi-arid zones" which inform the final sub-research question which is the evaluation of a proposed approach for measuring water scarcity in the future, in Chapter 8. Prior to presenting the four empirical chapters, the study site, the GRRC, in South West Tanzania is presented in Chapter 3 followed by an outline of the research methodology in Chapter 4 which consists of a mixed-methods approach using both primary and secondary data and is heavily informed by fieldwork.

More specifically, Chapter 5 seeks to address research objective 1) "To apply two widely accepted water scarcity metrics to the Great Ruaha River Catchment, to assess change in characterisations of water scarcity over time". The chapter undertakes a historical analysis of the development of water scarcity in the GRRC, by applying the WSI and the WTA ratio metrics over three time periods. Chapter 6 addresses research objective 2) "To examine how assumptions of domestic water demand embedded in the WSI relate to field observations" through semi-structured interviews, focus group discussions and oral survey questionnaires undertaken in the GRRC in 2015 and 2016. The chapter compares contemporary field data with previously published and unpublished secondary sources studying domestic water demand in the GRRC. The chapter goes on to compare these results to other studies in arid- and semi-arid SSA and discusses the challenges of measuring domestic water consumption. It is also noted that the quantification of the human environment, engrained in holistic measures of water scarcity is problematic, as it entails subjectivity and uncertainty. Chapter 7 addresses research objective 3) "To investigate how water users characterise 'water scarcity' and how freshwater storage informs adaptive capacity" and aims to enhance the understanding of the factors that influence access to water under changing eco-hydrological circumstances. The chapter investigates how various groups of respondents perceive water scarcity in the GRRC and how they understand the role of surface and sub-surface water storage for adapting to periods of limited freshwater availability. Chapter 8 addresses the fourth research objective 'To explore a future approach for measuring water scarcity and evaluate the limits to its current development based on available field data' addressing the critique raised in Chapter 2 and informed by the findings in Chapter 5, 6, and 7. Chapter 9 provides a concluding discussion on the main findings and how they relate to the wider field of water resources management and policy.

Chapter 2 A Review of Water Scarcity Measurements

2.1 Introduction

Ensuring the availability of adequate quantities of freshwater to sustain the health and well-being of people and the ecosystems in which they live, remains one of the world's most pressing challenges (Jiménez-Cisneros *et al.*, 2014; Rockström and Falkenmark, 2015). This challenge is enshrined in the United Nations (2015) SDG 6.4 which aims "*[...to] substantially reduce the number of people suffering from water scarcity*" by 2030. Water scarcity can broadly be described as a shortage in the availability of renewable freshwater relative to demand (Taylor, 2009) yet a more precise description is required to define a robust quantitative metric. Such a metric would measure and evaluate progress towards reducing water scarcity and identify where and when water scarcity may occur in the future.

Chapter 2 critically reviews the most widely employed measures that characterise water scarcity from amongst the more than 150 indicators that have been identified (WWAP, 2003; Vörösmarty *et al.*, 2005:235). The chapter examines the evolution of these metrics as well as the data and assumptions that inform them. The central purpose of this review is to stimulate debate about how best to measure water scarcity. Furthermore, the chapter exposes substantial limitations in current metrics and critically examines the characteristics that might define a more robust metric. The analysis places particular priority on the characterisation of water scarcity in Less Economically Developed Countries (LEDCs) of the tropics where the consequences of water scarcity are projected to be most severe (Jiménez-Cisneros *et al.*, 2014) and where most of the global population are expected to live (Gerland *et al.*, 2014).

2.2 Water Stress Index (WSI)

Falkenmark and Lindh (1974) proposed one of the first quantitative links between freshwater resources and global population growth at the Third World Population Conference in Bucharest in 1974. Formal quantification of water scarcity began, however in the early 1980s with the development of the Water Stress Index (WSI) explicitly linking food security to freshwater availability (Falkenmark, 1986; 1989). Conceived in the context of famines taking place across the Sudano-Sahel of Africa, the WSI was originally intended to provide an early warning system to inform strategies for food self-sufficiency in light of anticipated future droughts and a growing population in arid- and semi-arid areas. The WSI has since become the most widely applied measure of water scarcity. Despite multiple shortcomings associated with this metric having been sporadically identified (Savenije, 1999; Chenoweth, 2008; Taylor, 2009; Brown and Matlock, 2011; Wada, 2013; Jarvis, 2013; Brauman *et al.*, 2016), the WSI continues to be applied at regional to global scales (Vörösmarty *et al.*, 2000; Alcamo *et al.*, 2003, Arnell, 2004; Wada *et al.*, 2011; Wada, 2013; Schewe *et al.*, 2013).

The WSI originally characterised water scarcity in terms of the number of people that compete to be sustained by a single flow unit of water - defined as 10^6 m^3 yr^{-1} (Figure. 2.1; Falkenmark, 1986; 1989; Falkenmark *et al.*, 1989). This 'hydraulic density of population' or "*une densité hydraulique de population"* was considered to be a powerful instrument for demonstrating differences in water availability between countries (Forkasiewicz and Margat, 1980; Falkenmark, 1986). This approach was used to examine freshwater resources availability across the globe by applying readily available records of river discharge ('river runoff') compiled by L'vovich (1979) and Forkaziewicz and Margat (1980). The basis for the threshold of water scarcity was, however, context-specific. Explicitly referring to Israel, Falkenmark (1986) argued that an industrialised country in a semi-arid zone has a gross freshwater demand[1] of approximately 500 m^3 capita yr^{-1}, equivalent to 2 000 people/flow unit. This value was set as the threshold at the time "*for operating a modern semi-arid society using extremely sophisticated water management techniques*" and "*[...] half of this value* [1 000 people/flow unit] *could be considered as relatively water-stressed*" (Falkenmark, 1986:199). Falkenmark (1989:115) later argued that "*typical water-consumption levels in a number of industrialised countries are in the interval of 100-500 persons per flow unit*". The threshold for 'water stress', here referred to as the Inverted WSI (Table 2.1) was set at 500 people/flow unit but subsequently raised to 600 people/flow unit (~ 1 667 m^3 capita yr^{-1}) "*in order to not exaggerate the situation*" (Falkenmark, 1989:116); the threshold for 'water scarcity' became 1 000 persons/flow unit or 1 000 m^3 capita yr^{-1} (Figure 2.1).

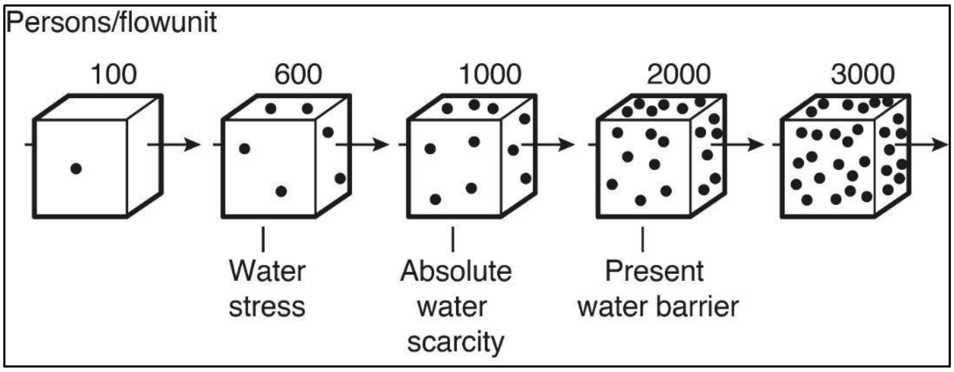

Figure 2.1: Visualisation of different levels of water competition. Each cube indicates the flow of 1 million m^3yr^{-1} available in terrestrial water systems, each dot 100 individuals depending on that water (adapted from Falkenmark, 1989:115).

[1] The definition of "freshwater demand" in this thesis refers to the mean water withdrawn in order to undertake human activities and that required to sustain Environmental Water Requirements. Freshwater demand is not to be confused with "consumption" or "consumptive uses of water", which refer to a net water use wherein water is either not returned or its quality is altered to render it unusable.

Since the conception of the WSI, different arguments have been proposed as the basis for setting the thresholds of water stress and water scarcity. Falkenmark (1986) originally proposed a gross per capita freshwater demand of 500 m^3 yr^{-1} that comprised a domestic and industrial demand of 50 m^3 capita yr^{-1} (~130 L capita day^{-1} (LCPD)) with an additional 80% to 90% of the per capita water demand allocated for irrigation. Domestic (household) freshwater demand was subsequently adjusted to assume 100 LCPD amounting to an annual domestic water requirement of 36.5 m^3 capita yr^{-1} or ~ 40 m^3 capita yr^{-1} (Savenije, 1999). Engelman and Leroy (1993) and Gardner-Outlaw and Engelman (1997) follow a similar line of reasoning but provide a different rationale for the same thresholds outlined in Table 2.1 (p.37). The authors cite Falkenmark and Widstrand (1992) to claim that agricultural, industrial and energy demands constitute 5 to 20 times the domestic requirement of 100 LCPD. Falkenmark and Widstrand (1992:14) do not, however, specify an amount required to meet agricultural, industrial and energy demands but instead argue that in order to "*[...] assure adequate health, people need a minimum of about 100 litres of water per day for drinking, cooking and washing. Of course many times this amount is necessary to carry out the activities necessary to sustain an economic base in the community*". Although what constitutes "*many times*" is not specified (Savenije, 1999), Engelman and Leroy (1993) and Gardner-Outlaw and Engelman (1997) reason that by adding agricultural, industrial and energy demands (*i.e.* 20 times domestic demand of 40 m^3 capita yr^{-1}) to domestic demand, a holistic water demand of 840 m^3 capita yr^{-1} can be computed. The authors then conclude that freshwater resources that amount to a doubling of this figure (~1 700 m^3 capita yr^{-1}) provide a boundary for differentiating between *relative water sufficiency* (> 1 700 m^3 capita yr^{-1}) and *water stress* (≤ 1 700 m^3 yr^{-1}) whereas the threshold for *water scarcity* is 1 000 m^3 capita yr^{-1}. These thresholds are identical to those derived differently from the inverted WSI (Table 2.1).

Table 2.1: Summary of *Water Stress Index* thresholds.

Category	Inverted WSI (people/flow units)*	Contemporary WSI threshold (m^3 capita yr^{-1})
No Stress	<600 people/flow unit	> 1 700
Water Scarcity	600 – 1 000 people /flow unit	1 700 – 1 000
Water Stress	1 000 - 2 000 people/flow unit	1 000 - 500
Absolute Water Stress	> 2000 people/flow unit	< 500

* a flow unit in the column for Inverted WSI is equal to 10^6 m^3. To get contemporary WSI one flow unit must be divided by the number of people competing.

Notwithstanding the separate rationales for deriving the thresholds of water stress and water scarcity in the WSI, the values of 1 700 and 1 000 m^3 capita yr^{-1} have been uncritically adopted and assimilated in the mainstream literature without an empirical basis. For example, Chapter 4 of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report on Hydrology and Water Resources (IPCC, 2001:213) states that "*[...] water stress may be a problem if a country or region has less than 1,700 m^3 yr^{-1} of water per capita (Falkenmark and Lindh, 1976)*" though no such direct claim is made by Falkenmark and Lindh (1976). Similarly, Vörösmarty *et al.* (2005) contend that *"A value of 1,700 m^3/capita/year **(20)** is widely accepted as a threshold below which varying degrees of water stress are likely to occur*"; reference '20' is the widely cited paper of Falkenmark (1989) which makes no direct reference to this threshold.

Early applications of the WSI (Falkenmark, 1986; 1989) quantified available freshwater resources in terms of river discharge or 'river runoff' equating renewable freshwater resources to mean annual river runoff (MARR). Use of MARR in the WSI has since been greatly promoted by the development of national-scale estimates of

MARR based on observational records (e.g. Shiklomanov, 2000) and proliferation of large-scale hydrological models estimating MARR (e.g. Vörösmarty *et al.*, 2005; Alcamo *et al.*, 2003; Arnell, 2004; Oki and Kanae, 2006; Schewe *et al.*, 2014; Wada *et al.*, 2014), which are reconciled to national-scale and gridded population data and projections. Rijsberman (2006) and Chenoweth (2008) investigated the links between water scarcity thresholds and indicators of national development but there remains, nevertheless, a conspicuous dearth of research assessing whether computations of water stress and scarcity based on the WSI (Table 2.1) are meaningful.

Use of MARR to define renewable freshwater resources implicitly assumes changes in soil moisture storage (ΔSMS) and groundwater storage (ΔGWS) are negligible and MARR (mean annual Q_{river}) represents the net contribution of precipitation (P) to the terrestrial water balance accounting for outflows derived from evapotranspiration (equations 2.1 and 2.2). The representation of renewable freshwater resources with the singular value of MARR masks intra- and inter-annual variabilities in freshwater resources (Taylor, 2009) yet such variabilities are particularly extreme in SSA (McMahon *et al.*, 2007). Critically, MARR does not also indicate the proportion of river discharge that occurs episodically as stormflow and that which occurs throughout the year as baseflow; the latter often results from groundwater discharge. Further, MARR also does not account for soil water (‘green water’) which can play a critical role in determining agricultural water demand (Rockström and Falkenmark, 2015), the sector that globally accounts for the majority of freshwater withdrawals and influences the amount of available blue water resources (Jaramillo and Destouni, 2015b).

$$P = ET + Q_{river} + \Delta GWS + \Delta SMS \qquad \text{(equation 2.1)}$$

$$\underline{Q_{river}} = \underline{P} - \underline{ET} \; (\Delta SMS + \Delta GWS = 0) \qquad \text{(equation 2.2)}$$

2.3 Withdrawal to Availability Ratio (WTA)

The presumption of a fixed, universal water demand, embedded in the WSI, was questioned by a second wave of water resources assessments incorporating estimates of freshwater demand both spatially and across sectors including domestic (D), industrial (I) and agriculture (A) sectors (Raskin *et al.*, 1996). The freshwater *Withdrawal To Availability* (WTA) ratio defined water scarcity in terms of the ratio or percentage of total annual withdrawals across these sectors to annual (renewable) resources estimated by MARR (equation 2.3). Conducted at national scales, a country is considered 'water stressed' if annual withdrawals are between 20% (0.2) and 40% (0.4) of annual freshwater supply and 'severely stressed' if this figure exceeds 40% (0.4) (Raskin *et al.*, 1996; Alcamo *et al.*, 2003; Rijsbermann, 2006). The WTA ratio has been applied directly in numerous contexts (Appendix 1a and b) and a sensitivity analysis of the 0.4 threshold ratio was carried out using the global hydrological model, WaterGAP 2.0 and declared "*[...] fairly robust*" (Alcamo *et al.*, 2003) although the basis for this judgment is unclear.

$$WTA = \frac{\sum DIA}{MARR} \qquad \text{(equation 2.3)}$$

The use of MARR to characterise freshwater resources means that the WTA approach, like the WSI, masks inter- and intra-annual variability in freshwater availability. The WTA approach can employ spatially and temporally variable freshwater demand functions but their estimation has their own conceptual challenges as noted by Rijsberman (2006:3): "*the limitations of the criticality ratio* [(i.e. WTA > 0.4)] *and similar indicators are that: a) the data on water resources availability do not take into account how much of it could be made available for human use; b) the water withdrawal data do not take into account how much of it is consumptively used (or evapotranspired) and how much could be available for recycling, through return flows; and c) the indicators do not take into account a society's adaptive capacity to cope with stress.*" Additionally, quantified freshwater demand, transparent in the WSI, is often opaque in applications of the WTA ratio. Nevertheless, Wada (2013) contend that the WTA threshold ratio of 0.4 corresponds to the WSI threshold of 1 700 m^3 capita yr^{-1} and a category of extreme water stress is also asserted to occur at a ratio above 0.8 and equated to the WSI threshold of 500 m^3 capita yr^{-1} though the basis for this proposed alignment of metrics is unclear

2.4 Emergence of Holistic Metrics

That measurement of water scarcity and stress may not solely be characterised by water resources but also account for both a) the capacity of societies to adapt to different levels of freshwater availability and b) environmental sustainability associated with freshwater use, and is explicitly recognised in the emergence of holistic metrics. These water scarcity metrics seek to quantify 'adaptive capacity' and to introduce the concept of environmental water requirements (EWRs) for sustaining ecosystem functions. Eight holistic approaches to the measurement of water scarcity are considered below.

2.4.1 Social Water Stress Index

Adaptive capacity is explicitly considered in the Social Water Stress Index (SWSI) (Ohlsson, 2000). The SWSI posits that distributional equity, political participation, and access to education are good indicators of the ability of a country to adapt to water shortages. To account for these social factors, the SWSI applies the Human Development Index (HDI) which incorporates the variables of life expectancy, educational attainment (*i.e.* adult literacy and combined primary, secondary and tertiary enrolment), and Gross Domestic Product (GDP) per capita, as a suitable proxy for adaptive capacity to water shortages. The SWSI allows for the comparison of country scores between the original WSI[2] and SWSI after adaptive capacity has been taken into account. The SWSI divides the number of people in a country that share one million cubic metres of annual renewable water (*i.e.* the inverted Falkenmark WSI) by the HDI (equation 2.4). The resulting value is then divided by a *scalar* which Ohlsson (2000) sets at 2. Finally, the SWSI score is compared to the HWSI score (see footnote 2), according to the rank interval classification in Table 2.2. Ohlsson (2000) shows how countries such as South Korea, Poland, Iran, the UK, Belgium and Peru, traditionally classified as water stressed according to the HWSI, would be classified as 'relatively sufficient' under the SWSI, because of their higher societal adaptive capacity (defined by HDI). In contrast, countries that are considered to have a lower level of adaptive capacity such as Niger, Burkina Faso, Eritrea and Nigeria move from relative sufficiency to water stress.

$$\mathrm{SWSI_{country}} = \frac{\mathrm{Inverted\ Falkenmark\ WSI_{country}}}{\mathrm{HDI_{Country}}} \times \frac{1}{\mathrm{scalar}} \qquad \text{(equation 2.4)}$$

[2] Note that Ohlsson (2000) labels this as the *Hydrological Water Stress Index (HWSI);* it is equivalent to the Inverted Falkenmark WSI.

Table 2.2: The SWSI Ranking system (Ohlsson, 2000)

Index Ranking Intervals	HWSI/SWSI Score	Degree of Stress
0-5	> 1 700	Relative sufficiency
6-10	< 1 700 – 1 000	Water Stress
11-20	< 1 000	Water Scarcity
20+	<500	Absolute Water Scarcity

Ohlsson (2000) considers the HDI to be *"[...] a very appropriate and widely accepted indicator [...]"*. Kovacevic (2010) argues, however, that the definition of human development in the HDI is oversimplified due to its narrow selection of variables; many of these are often of low-quality data for LEDCs (Srinivasan, 1994). Although metrics necessarily rely upon simplified characterisations of reality, the risk and consequences of misrepresentation, particularly in low-income countries where conditions of water scarcity may have the greatest impact, remain. Ogwang (1994) contends that the HDI does not reveal anything beyond traditional economic indicators due to the high correlation between individual components of the HDI and pure economic indicators such as Gross National Product (GNP) and GDP.

2.4.2 Physical and Economic Water Scarcity

The importance of adaptive capacity to the characterisation of water scarcity was highlighted by Seckler *et al.* (1998a) and later Molden *et al.* (2007) who propose future infrastructure development potential and irrigation efficiency potential (*i.e.* improved water management measures, return flows and consumptive uses) can be used as proxies of adaptive capacity. The authors then apply this measure of adaptive capacity to distinguish between 'physically' and 'economically' water-scarce countries. Physical water scarcity is said to occur in a country when more than 75% of river flows in a country are withdrawn for DIA purposes (Brown and Matlock, 2011) and the country is unable to meet future demands after accounting for its adaptive capacity. Economic water scarcity is considered to occur in countries where renewable water resources are adequate (*i.e.* water withdrawals are less than 25% of river flows) but where there is a lack of significant investments in water infrastructure in order to make these resources available (Rijsberman, 2006). The International Water Management Institute (IWMI) went on to map countries in Africa according to these criteria, to distinguish the areas which face either physical or economic water scarcity and areas expected to approach physical water scarcity by 2025 (Figure 2.2).

The distinction between 'economic' and 'physical' water scarcity appeals to reason yet both measures rely on expert judgment. Indeed, assessments of adaptive capacity through infrastructural development capacity are complicated and opaque. Seckler *et al.* (1998b:7), for example, compiled data pertaining to infrastructural development using "*secret intelligence information*" acquired by MEDEA (Measurements of Earth Data for Environmental Analysis), a United States Central Intelligence Agency group of distinguished experts who have unique access to sensitive remotely sensed information.

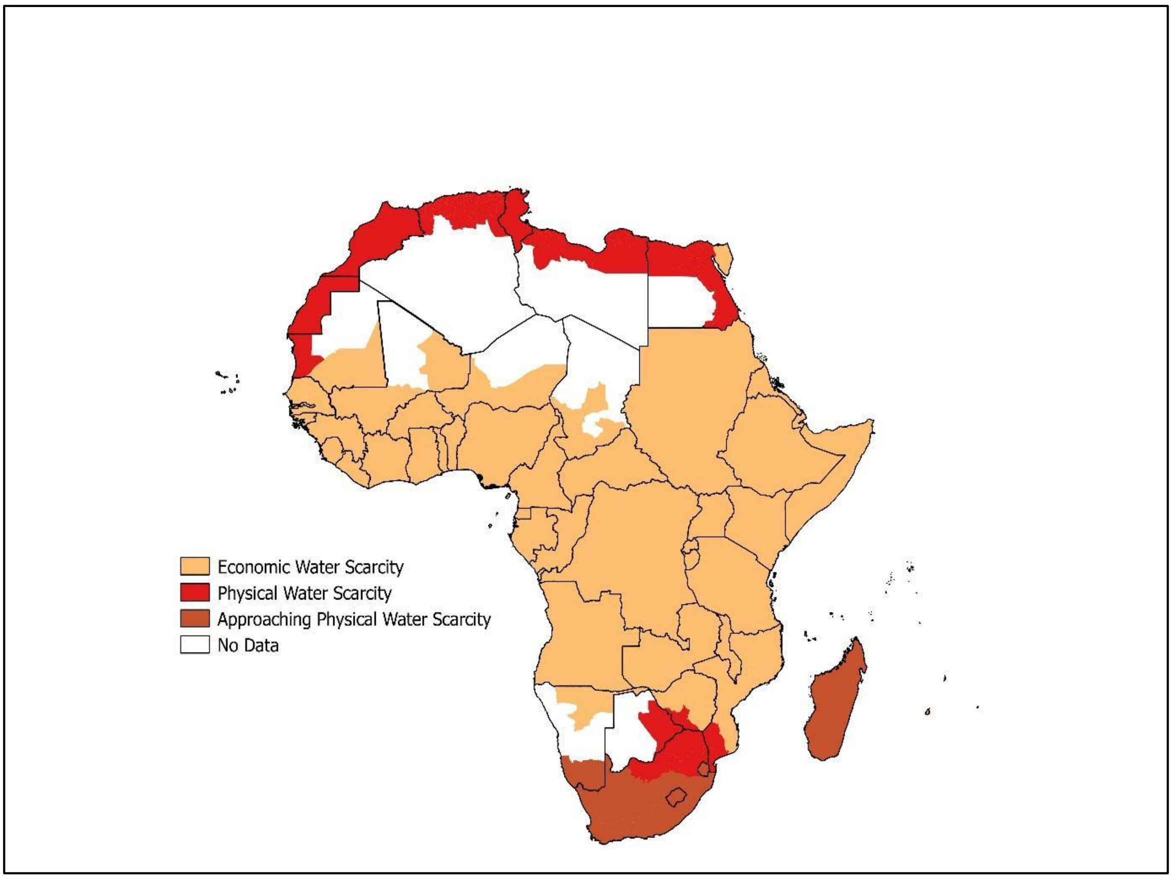

Figure 2.2: Map of physical and economic water scarcity at basin level in 2007 across the African continent. Adapted/reproduced from global map. Available at http://www.grida.no/graphicslib/detail/areas-of-physical-and-economic-water-scarcity_1570#

2.4.3 Water Poverty Index

The Water Poverty Index (WPI), originally proposed by Sullivan (2002), arose from a perceived need to advance the use of indicators that examine poverty in various dimensions (*i.e.* development, gender, food, politics, health and vulnerability) and specifically highlight the vital but overlooked links between poverty reduction and water availability. Sullivan (2002) contends that the WPI functions as a transparent and simple tool which takes a holistic approach to the representation of conditions that affect the characterisation of water stress at community and household levels. The WPI seeks to empower poor people to participate in water resources planning and assist decision-makers in determining priority interventions in the water sector.

The WPI employs a multi-dimensional approach that goes beyond the use of the HDI in the SWSI as a characterisation of social vulnerability and to include a measure to represent the maintenance of ecosystems (*i.e.* environmental sustainability). The indicator is formed by five components *i*: 1) available water resources, 2) access to water, 3) capacity for water management, 4) water uses for domestic, food and production purposes and, 5) environmental concerns. These indicators are weighted and integrated into a single measure as given in equation 2.5 where X_i refers to [indicator] *i* of the WPI structure for that location, and w_i is the weight applied to that [indicator] *i*. Each *i* is made up of a number of variables that are first combined using the same technique (Fenwick, 2010:51). The WPI has been applied at both global (Lawrence *et al.*, 2002) and community scales (Sullivan *et al.*, 2006; Fenwick, 2010).

$$WPI = \frac{\sum_{i=1}^{N} w_i X_i}{\sum_{i=1}^{N} w_i} \qquad \text{(equation 2.5)}$$

The first component *i* of the WPI, available freshwater resources, is rooted in an estimate of per capita freshwater availability defined by the WSI (Molle and Mollinga, 2003). As a result, the WPI is subject to the same limitations identified for the WSI above, including its disregard of temporal variability in freshwater resources which plays a critical role in enabling access to a reliable amount of water (Fenwick, 2010). More specifically, the WPI raises difficult questions concerning the quantification of social dimensions of freshwater availability and access. A particular challenge is the application of weights (w_i) to the various indicators (*i*) that are determined through participatory processes (Feitelson and Chenoweth, 2002; Molle and Mollinga, 2003; Garriga and Foguet, 2008). The exercise generates locally-specific results (Garriga and Foguet, 2008) that restrict comparative analyses. A standard set of indicators was originally suggested to comprise the WPI (Sullivan, 2002) in order to enable comparisons across space and time. However, this normalisation technique is thought to inhibit longitudinal studies (Fenwick, 2010). It is also difficult to translate theoretical constructs between rural and urban settings where individual variables may not equally apply to both sites. The exercise of trying to quantitatively assess and compare highly subjective and relative variables such as '*needs*' (Fenwick, 2010) becomes difficult and possibly unrealistic, given the varying perceptions and understandings of the definitions and meanings of the indicator variables. Indeed, there may be more merit to explore and discuss the individual indicators of the WPI rather than the overall water poverty score it produces (Sullivan, 2002). The WPI may thus be better suited to instigating debates around the concept of 'water poverty' as opposed to actually measuring it, as suggested by its creators: "*[...] the purpose of an index is political rather than statistical"* (Lawrence *et al.*, 2002).

2.4.4 The Environment as a Water User

The adoption of the Dublin Principles in 1992 whereby "*effective management of water resources demands a holistic approach, which links social and economic development into the protection of natural ecosystems*" explicitly recognised the water needs of the environment. This recognition promoted the inclusion of Environmental Water Requirements into metrics of water scarcity such as the 'Water Stress Index' (WSI_{EWR}) (Smakhtin *et al.*, 2004) as defined in equation 2.6. Using the WaterGAP2 model, Smakhtin *et al.* (2004) applied the WSI_{EWR} to a global water resources assessment and found that consideration of EWRs resulted in a greater number of basins having a higher magnitude of water stress. Further, they asserted that approximately 20-50% of MARR constitute an adequate proportion quantity of water to be allocated for freshwater ecosystem services in order to maintain them in a fair condition (Smakthin *et al.*, 2004).

$$\mathrm{WSI_{EWR}} = \frac{\sum DIA}{\text{MARR-EWR}} \quad \text{(equation 2.6)}$$

The assessment of an adequate amount of flow allocated for EWRs is influenced by many factors such as the size of the river, its perceived natural state, and fluctuations in seasonal environmental capacities (Acreman and Dunbar, 2004). Smakthin *et al.* (2004) showed that EWRs are the highest for rivers in the equatorial belt (e.g. parts of the Amazon and the Congo) where there is a stable rainfall input throughout the year. In areas, which are characterised by substantial monsoon-driven variability (e.g. India), EWRs are lower and generally in the range of 20 to 30% of MARR because aquatic biota are adapted to extended periods of limited or no flow. In contrast, stable river-flow regimes are much more sensitive to perturbations in river discharge.

Assessing EWRs ranges from objective-based methods to more holistic exercises that can involve cross-disciplinary teams providing expert judgment. The relationships among various functions of a river system are often difficult to establish with confidence and consequently require subjective judgements due to a lack of reliable hydrological, biological and ecological data in low-income countries (Acreman and Dunbar, 2004). Ultimately, EWR assessments involve difficult trade-offs between environmental and human uses, and it remains unclear who decides the prioritisation of competing uses of water.

2.4.5 Water Resources Sustainability

A fifth group of water scarcity metrics is based around the principle that water sustainability constitutes "*[…] systems designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental and hydrological integrity"* (Loucks and Gladwell, 1999:30). This group of holistic metrics are ambitious, seeking to incorporate considerations of infrastructure, environmental quality, economics and finance, institutions and society, human health, welfare, planning and technology (Loucks and Gladwell, 1999) as well as addressing issues such as basic water needs, minimum standard of available water resources, access to data on water resources and, democratic water-related decision-making with inter and intra-generational equity in mind (Mays, 2006).

The Watershed Sustainability Index (Chaves and Alipaz, 2007) integrates social, economic and environmental factors under the HELP Platform of UNESCO-IHP comprising hydrology (H), environment (E), life (L) and policy (P) in Table 2.3; each heading has the parameters 'pressure, state and response' scored subjectively at (0, 0.25, 0.5, 0.75 and 1). The score for H is the value of the WSI whereas E relies on the application of the Environment Pressure Index[3] and is estimated from variation in the average basin agricultural area to variation of urban basin population. L is based on variation in per capita income and HDI score; and P is determined by the HDI-Education Parameter and judgments regarding the state of Integrated Water Resources Management (IWRM) in the basin.

[3] The Environment Pressure Index is a modified version of the Anthropic Pressure Index (Sawyer, 1997)

Table 2.3: Watershed Sustainability Index parameters (Chaves and Alipaz, 2007)

Indicator	State	Pressure	Response
Hydrology	WSI variation Variation in BOD5	Long-term WSI Long-term BOD5	Water use/sewage efficiency
Environment	Environment Pressure Index	% basin with natural vegetation	Basin conservation
Life	Variation in per capita income	Basin HDI	Basin HDI Evolution
Policy	Variation in HDI Education parameter	Basin IWRM institutional capacity	Evolution of basin IWRM

The Canadian Water Sustainability Index (CWSI) is a composite index that evaluates the well-being of Canadian communities with respect to freshwater on a scale from 0 to 100. The freshwater availability component measures renewable freshwater resources using the WSI thresholds as a benchmark with a score of 100 (highest) assigned to any value over 1 700 m^3 capita yr^{-1} and 0 assigned to any value below 500 m^3 capita yr^{-1}. The CWSI was developed by the Policy Research Institute (PRI) following the global application of the WPI in 2003 in which Canada ranked second out of 147 countries. The PRI maintained that Canada still had many challenges in water resources management including securing access to safe water among its rural indigenous communities, and considered their indicator to better reflect local challenges than the WPI (PRI, 2007).

Juwana *et al.* (2012) noted that existing water sustainability indices (WPI, CWSI, Watershed Sustainability Index) had been developed in a context-specific manner to inform local challenges to water resources sustainability and proposed a specialised West Java Water Sustainability Index (WJWSI) to address issues relevant to the sustainability of water resources in West Java, Indonesia. The WJWSI applies both the WSI and WTA as components within this multi-composite index. The WSI thresholds assess whether the availability of freshwater in the study area is able to meet people's absolute minimal water requirements, whereas the WTA ratios are adopted in the context of 'water demand' to measure how much stress this demand puts on the water resources in the study area. The inclusion of WSI is specifically considered to be "[…] *extremely important for developing a water sustainability index*" (Juwana *et al.*, 2010:1693).

Ekins (1997) created a framework for measuring sustainability in terms of a gap needing to be bridged - the Sustainability GAP (SGAP). Five criteria for setting a level of sustainability for natural resources, including water, are quantified based on criteria that anthropogenic impacts on the resource do not a) go above a critical load; b) threaten biogeochemical systems; c) have a detrimental effect on human health; d) harvest the renewable resource faster than their rate of regeneration and; e) deplete non-renewable resources faster than the rate of development. Once the sustainability level has been quantified, the SGAP is calculated by considering the difference between a standard for a sustainable level and current levels of environmental impacts from a particular pressure. The methodology arrives at a Years-to-Sustainability, which is the number of years that it would take for current trends to reach sustainable levels. The development of the SGAP methodology is being done at University College London Institute for Sustainable Resources and it has been proposed that the water component of the multiple composite indicator will apply the WTA ratio metric approach (Ekins, pers. comm, 14th May 2014).

Each of the aforementioned water resources sustainability indicators seeks to quantify characteristics of the human environment in order to measure water stress and scarcity. Similar to other holistic metrics, these approaches rely upon simplistic characterisations of human environments and subjective weighting of components within each metric. Additionally, water resources sustainability indicators can be based on highly localised, community-level participatory approaches restricting their application at larger scales. Each also do not consciously make efforts to move beyond MARR in defining physical freshwater availability.

2.4.6 Planetary Boundaries

Recent discussion pertaining to the measurement of freshwater availability seeks to inform the Planetary Boundaries (PBs), proposed as the space within which humans can operate sustainably without threatening the resilience of the Earth system to persist in its Holocene-like state (Rockstrom *et al.*, 2009; Steffen *et al.*, 2015). Current debate (Steffen *et al.*, 2015; Jaramillo and Destouni, 2015b; Gerten *et al.*, 2015) revolves around the uncertainty and robustness of assessments of consumptive freshwater use at the global scale and whether or not the proposed boundary of 4 000 km^3 yr^{-1} has been reached. These deliberations represent a key departure from the scale of analyses of water scarcity reviewed above yet the PBs framework helpfully advances conceptually and computationally estimation of the distribution of freshwater availability at smaller scales. First, the PBs framework explicitly recognises that freshwater resources and their use by humans at national or basins scales are inter-connected both in terms of their hydrological dynamics and their aggregated contributions to other Planetary Boundaries such as 'Climate change', 'Biosphere integrity', and 'Land-system change' (Steffen *et al.*, 2015). Second, PBs research focused on estimating consumptive freshwater use globally has served to advance the development of computational methods to estimate EWRs around the globe (Gerten *et al.*, 2013). Third, PBs research has critically drawn attention to important feedbacks of human activity on consumptive freshwater use and downstream blue freshwater resources resulting from land-use change, irrigation, and flow regulation (Destouni *et al.*, 2013; Jaramillo and Destouni, 2014; Jaramillo and Destouni, 2015a; Gerten *et al.*, 2015).

The influence of such local controls on consumptive freshwater use exposes, however, the limitations of the current PB debate that is focused on a global aggregate measure rather than the sustainability of local-scale freshwater withdrawals that comprise this global sum.

2.4.7 Water Resources Vulnerability Indicators

Measuring the vulnerability of water resources in light of water scarcity and stress has been addressed largely in the SWSI and a separate branch of indicators has developed since. The Climate Vulnerability Index (CVI) assesses community vulnerability to a changing climate (Sullivan & Meigh, 2005). The CVI is a composite index, inspired by the WPI, and consists of the components *Resource* (R), *Access* (A), *Capacity* (C), *Use* (U), *Environment* (E) and, *Geospatial* (G), where weight *r* is determined by a detailed expert consultation relevant to the context where the assessment is undertaken (equation 2.7):

$$CVI = \frac{r_r R + r_a A + r_c C + r_u U + r_e E + r_g G}{r_r + r_a + r_c + r_u + r_e + r_g} \quad \text{(equation 2.7)}$$

The CVI was combined with a governance index to derive the Governance and Climate Vulnerability Index (GCVI) with the aim of facilitating IWRM (Jubeh and Mimi, 2012). The GCVI incorporates physical and social indicators in an attempt to encapsulate human vulnerability. Common to these indices is that the components that relate to the context of water resources availability adopt the WSI thresholds as a means of determining degrees of vulnerability of water resources to climate change. The Water Vulnerability Index (WVI) (Chang *et al.*, 2013) consists of two sub-indices that distinguish between supply-driven vulnerability and demand-driven vulnerability at the municipal scale. The WVI was applied to the Colorado River Basin and estimates renewable freshwater availability on MARR.

Babel *et al.* (2011) find that existing indicators of water vulnerability equate vulnerability to water stress, when in fact vulnerability should be considered a function of the adaptive capacity of societies and the environment. The Bagmati River Basin Vulnerability Index (BRBVI) was developed and applied to the Bagmati River Basin and is primarily concerned with the impacts of communities on the basin. The BRBVI applies the WSI as a proxy of population pressure on available freshwater resources and the WTA to examine the degree of basin exploitation.

Alessa *et al.* (2008) saw a need to determine the vulnerability of communities in the circumpolar Arctic to changes in freshwater resources availability. The Arctic Water Resources Vulnerability Index (AWRVI) adopts the WPI framework modified to the characteristics of communities in Arctic environments. The AWRVI measures resilience to changes in freshwater resources and availability from both a purely physical perspective as well as from a social point of view, which focus on the perception of and interaction with water as a resource by Arctic communities.

2.4.8 Water Accounting Frameworks

Many countries have adapted to water shortages by importing water-intensive crops that may otherwise have put an unnecessary stress on limited domestic water resources. Allan (1997) considered the concept of an embedded or virtual quantity of water attached to a country's growing food imports. Expanding this notion Hoekstra (2003) coined the concept of the 'Water Footprint' which is defined as "*the volume of freshwater used to produce a product, measured over the full supply chain*". Hoekstra and Mekonnen (2012) calculated the Water Footprint of Humanity and concluded a global co-dependency of nations on the trade of virtual water in the agricultural sector.

2.4.9 Life Cycle Assessment Frameworks

The idea of measuring water scarcity within Life Cycle Impact Assessments (LCIA) was developed by Pfister *et al.* (2009) in order to measure potential environmental damages of water use in the areas of human health, ecosystem quality and resources, by applying the WSI_{EWR} (Smakthin *et al.*, 2004) at the watershed level. Pfister *et al.* (2009) conclude that the study successfully managed to describe the impacts of freshwater consumption in the life-cycle of products and processes at the local scale within the textiles industry, but caution that "*[...] similar to the assessment of other impact categories in LCA* [Life Cycle Assessment ed.] *the uncertainties are large*" (Pfister *et al.*, 2009:4103). The LCIA, therefore, is just a screening tool and if an assessment indicates potential environmental problems, more detailed studies are recommended. Pfister and Bayer (2014) specifically addressed the need to consider the temporal aspect of water scarcity assessment within the LCIA. The authors undertook a global water scarcity LCIA using WaterGAP 2.0 at the monthly and annual temporal scale in regions with moderate consumption, moderate water stress (measured by the WSI_{EWR}) and strong seasonality, to show higher degrees of water stress at the monthly than annual scale.

The Water Impact Index (WII) (Bayart *et al.*, 2014) combines the LCA and Water Footprint framework to integrate issues relating to water volume, water scarcity and water quality into a local-scale indicator that assesses the water footprint of human uses of freshwater on the environment. The WII was successfully applied to the municipal wastewater management system of Milan, Italy, but was only deemed useful as a screening tool followed by a more detailed LCA study (Bayart *et al.*, 2014).

2.5 Discussion of review

Metrics of water scarcity have evolved from simple thresholds of per capita freshwater availability based on MARR (*e.g.* WSI) to progressively more sophisticated metrics accounting for variability in demand (*e.g.* WTA), adaptive capacity (*e.g.* SWSI, Physical | Economic Water Scarcity), environmental water requirements (*e.g.* WSI_{EWR}, Planetary Boundaries) and a range of social and environmental conditions (*e.g.* WPI, CWSI). The rationale for the WSI thresholds of water stress and scarcity was originally context-specific, based on the freshwater demand of an industrialised country in a semi-arid environment. Over the last three decades, however, the WSI and WTA ratio indicators have become globally applied standard metrics of water scarcity. Both rely upon assumptions that mask key factors affecting freshwater availability (*e.g.* inter- and intra-annual variations in river discharge) and are untested by evidence of whether computed water stress and scarcity are meaningful. This chapter shows additionally that characterisations of socio-economic dimensions of water scarcity embedded in more holistic metrics are subjective. Each of these key outcomes from this review is examined further below. However, first this chapter will review a common, but fundamental misunderstanding between measured water scarcity and access to safe water that clearly separates SDG 6.4 from SDG 6.1: *By 2030, achieve universal and equitable access to safe and affordable drinking water for all* (SDG 6.1).

2.5.1 Water scarcity is unrelated to 'Access to Safe Water'

The World Water Assessment Programme (WWAP, 2003) report 'Water for People, Water for Life' states "[...] *at present many developing countries have difficulties in supplying the minimum annual per capita water requirement of 1,700 cubic metres of drinking water necessary for active and healthy life for their people*" (WWAP, 2003:10). This statement is problematic for two reasons. Firstly, it fails to recognise that the minimum annual per capita water requirement includes water used for industry and agriculture. Second, it represents a common misconception that access to safe drinking water depends upon freshwater availability, characterised by metrics of water scarcity. As shown in Figure 2.3a, there is no statistically significant relationship ($r = 0.03$, $p = 0.86$) between access to safe water and per capita freshwater availability based on national-level statistics for African countries in 2014. Countries in North Africa such as Egypt and Morocco, which have low per capita freshwater availability and are defined by the WSI as 'water-scarce' or 'water-stressed', report near-universal (> 90%) access to safe drinking water. Excluding countries with a per capita freshwater availability exceeding 40 000 m^3 yr^{-1} (*e.g.* Congo, Gabon, Liberia), a weak *negative* association exists ($r = -0.24$, $p = 0.09$) between the proportion of the continent's population that have access to safe water and annual amount of water availability per capita (Figure 2.3b). As reported similarly by Chenoweth (2008), "*[...] there is no evidence to support the statement of the World Water Assessment Programme* [above] *that countries require at least 1,700 cubic metres per capita to sustain a healthy and active life for their citizens"*. Measured water scarcity is unrelated to measured coverage of access to safe water.

2.5.2 Uncritical adoption of water scarcity metrics

The WSI was originally conceived in order to investigate the contribution of water scarcity to famines experienced in the Sudano-Sahel of Africa during the 1980s. Available data on freshwater resources at the time were sparse and analyses employed L'vovich's hydrological maps and limited observational records to make a preliminary assessment indication of where more detailed national studies should be conducted (Falkenmark, 1989). The WSI was not specifically designed for continental and global-scale comparisons of water scarcity (Falkenmark 1989:114). Indeed, the concept of a 'water barrier' (i.e. 2 000 people/flow unit), derived from roundtable discussions in 1987, was contested from the outset (Falkenmark, 1989) as engineers saw technology as a means of increasing supply whereas economists argued that demand for water can be controlled through pricing. Proposed thresholds for water stress and water scarcity in the WSI (Table 2.1) recognised, however, limitations in both technology and pricing to influence freshwater supply and demand in Sudano-Sahelian Africa at the time (Falkenmark, 1989). Gardner-Outlaw and Engelman (1997:11), key proponents of the WSI, acknowledged that: "*It would be, inappropriate, therefore, to propose any precise levels as absolute thresholds of water scarcity, or insist that they apply equally to all countries*". Consequently, the basis for the endorsement of water stress and scarcity thresholds in the WSI and WTA for continental-scale and global-scale applications (WWAP, 2003:10 Wada, 2013; Schewe *et al.*, 2013) remains unclear.

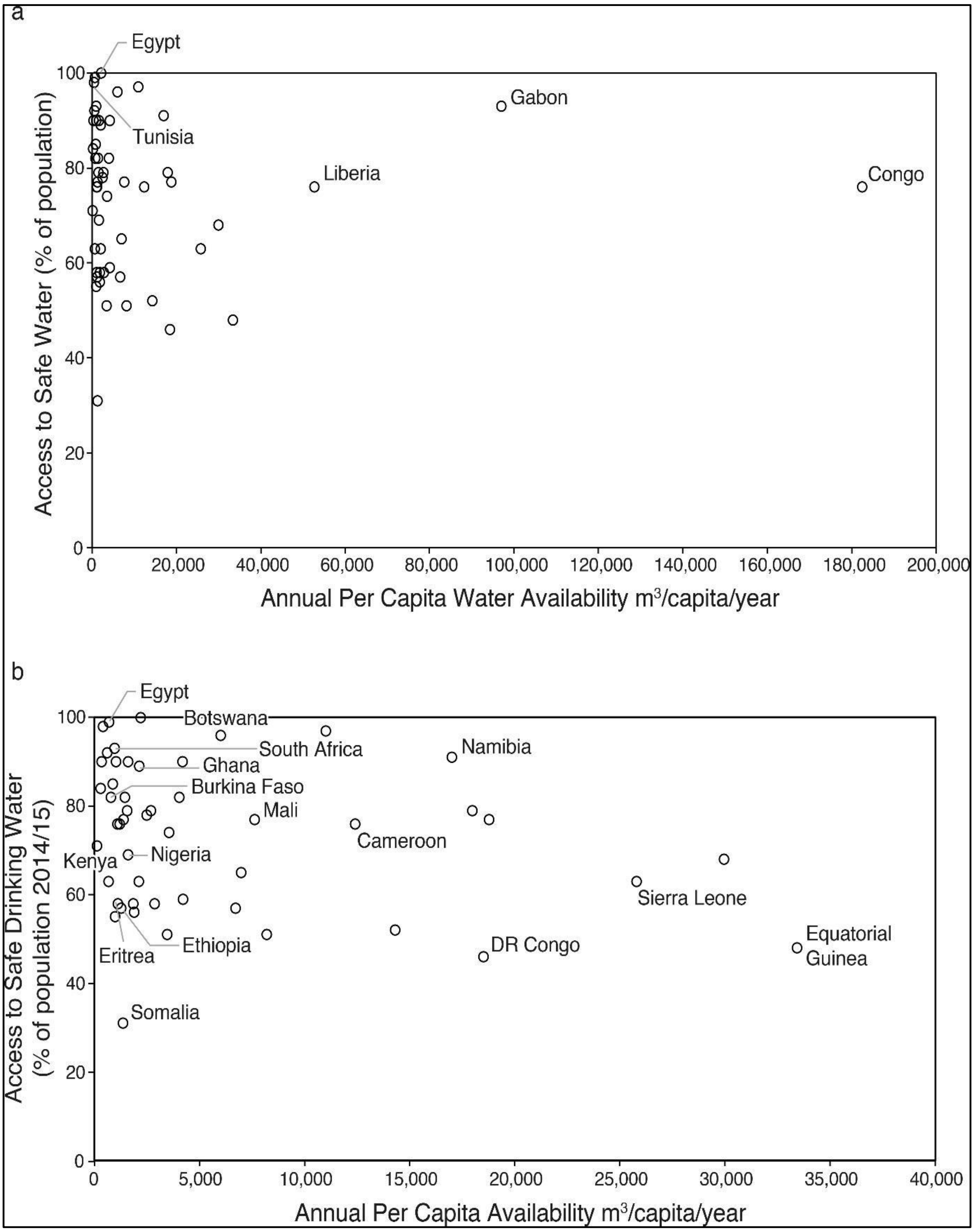

Figure 2.3a: Cross-plot relating national values of % access to safe water (World Health Organisation/Joint Monitoring Programme) to per capita freshwater availability across Africa 2014 (FAO AQUASTAT). Figure 2.3b: Cross-plot relating national values of % access to safe water (World Health Organisation/Joint Monitoring Programme) to per capita freshwater availability across Africa 2014 (FAO AQUASTAT), excluding extreme outliers in Fig. 2.3a

Application of the WSI and WTA to characterise water stress and water scarcity at national scales in Africa (Figures 2.4 to 2.6; Table 2.4) produce differing outcomes. Most countries in Africa are characterised as water sufficient by both metrics yet twice as many countries are defined as 'water scarce' or 'water stressed' using the WSI than the WTA. 11 of 53 countries are defined as 'water scarce' using the WSI (2014 data) whereas just six countries are characterised as 'water scarce' by the WTA approach. There are also some notable inconsistencies including Kenya, which is defined as 'water scarce' according to the WSI (674 m^3 capita yr^{-1}) but deemed 'water sufficient' using the WTA ratio (10%). Indeed, the uncritical adoption and application of the WSI and WTA to define freshwater availability in Africa are unreconciled to what is known of freshwater demand and supply; the latter is discussed in the next section (2.4.3) whereas the former is considered here.

First, the percentage of arable land that is irrigated in Africa remains low, <5% in Sub-Saharan Africa according to Giordano (2006) although this assessment may not account fully for small-scale irrigators across this region (Villholth *et al.*, 2013). As rain-fed crop production dominates food production, the assumption embedded in the applied WSI (Table 2.1) that agricultural and industrial freshwater demand amounts to 20 times domestic demand, is indefensible. Further, the assumption that domestic demand is 100 LCPD is exaggerated. Although domestic consumption of this magnitude may very well be desirable, particularly for hygiene purposes (Cairncross, 2003), a multi-site, longitudinal analysis of domestic water use in East Africa (Thompson *et al.*, 2001) indicates that per capita, domestic consumption is less than half the assumed volume and is declining rather than rising (Table 2.5).

The continued, widespread application of WSI and the WTA ratio to measure water scarcity across Africa and beyond derives, in part or in whole, from their ease of application and comprehension (Rijsberman, 2006). Little attention has been paid as to whether their application is meaningful. Savenije (1999) argues that "*[…there] is definitely a need to develop water scarcity indicators that give a more reliable image of the water stress that is experienced in different parts of the world. A proper indicator should take into account all the renewable resources (including green water); should consider temporal and spatial variability and the influence of climate; should distinguish between primary and secondary needs and; should use an objective key for the distribution for water resources among riparians*". At the 2014 World Water Week in Stockholm, Malin Falkenmark herself argued that the time is ripe for critically examining a move beyond the continued application of the WSI (Falkenmark, pers. comm. 2014).

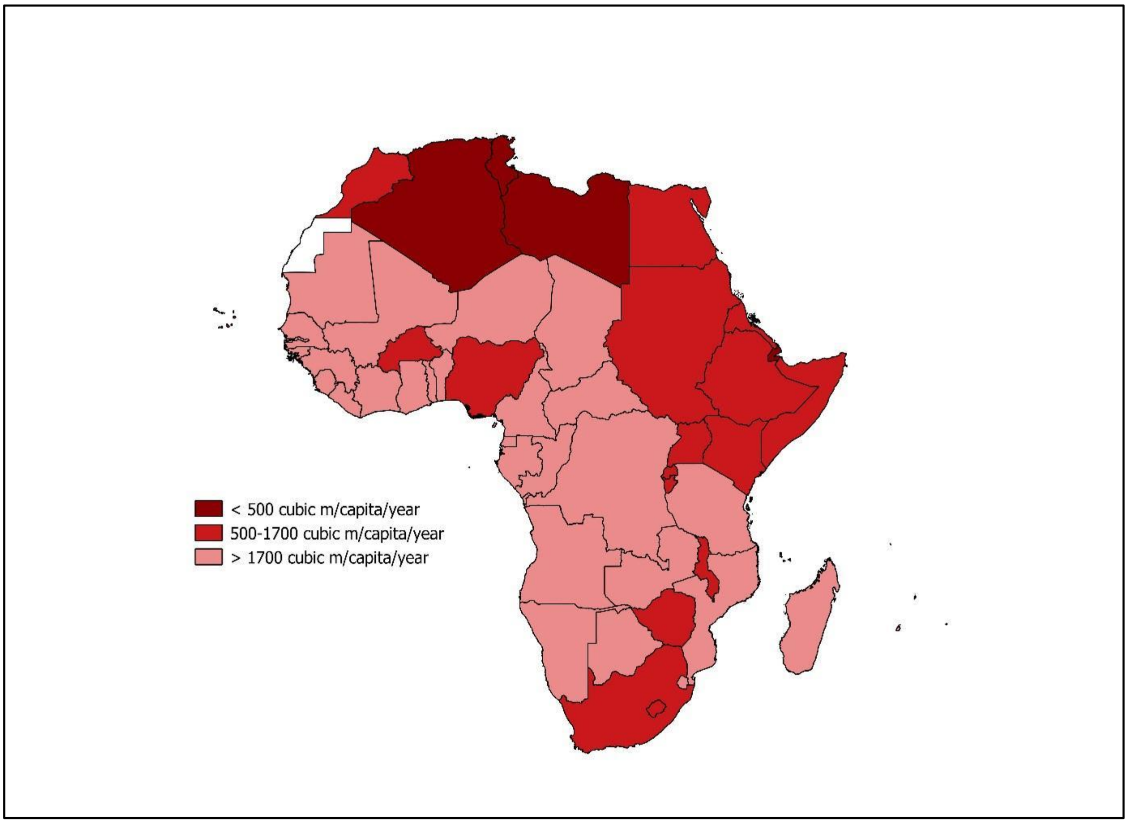

Figure 2.4: Map of national-scale water scarcity as defined by the *Water Stress Index* (WSI) across Africa using data from the year 2014 (FAO AQUASTAT)

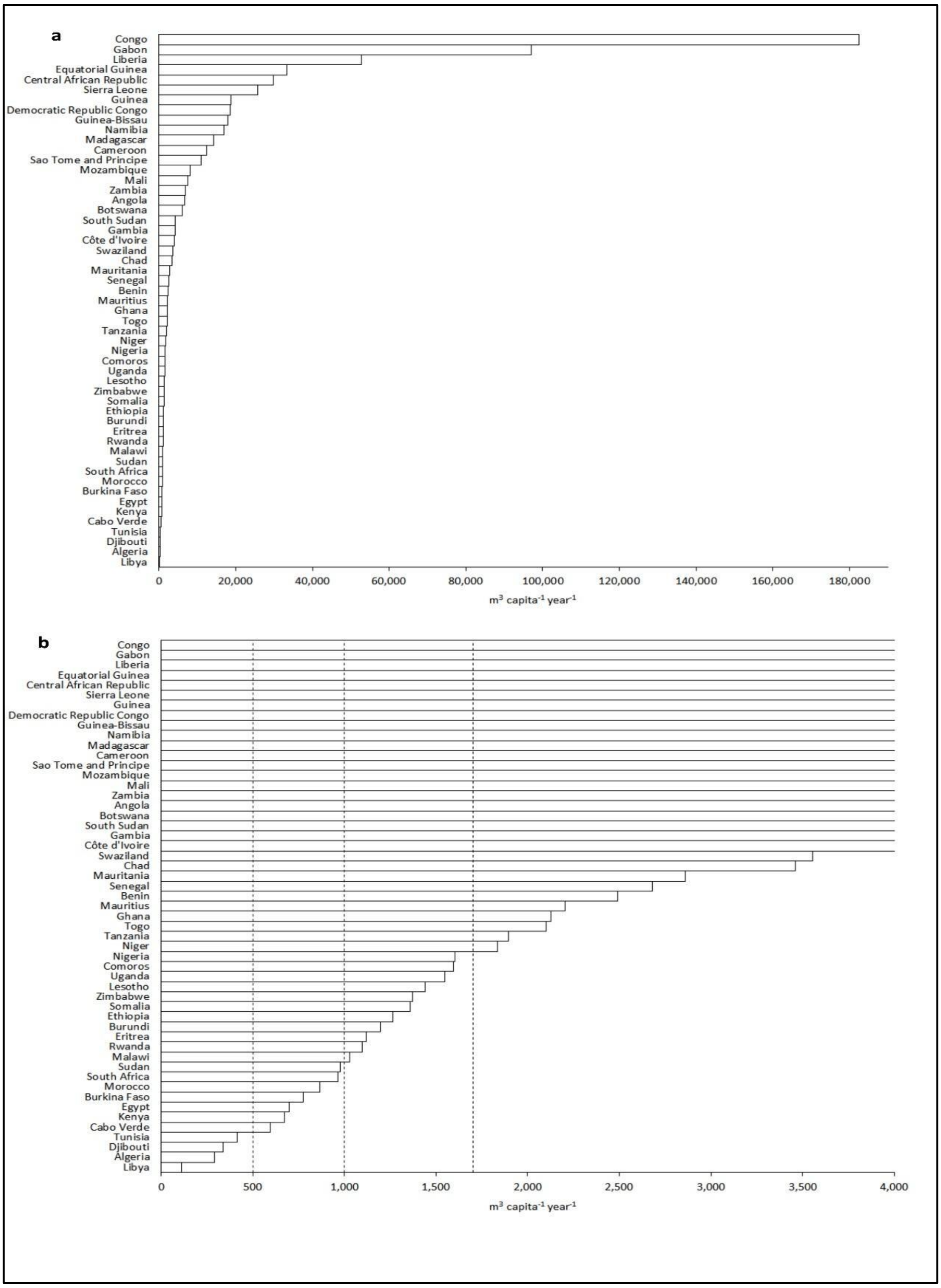

Figure 2.5a and b: National-scale per capita freshwater availability for African countries using data from the year 2014 (FAO AQUASTAT).

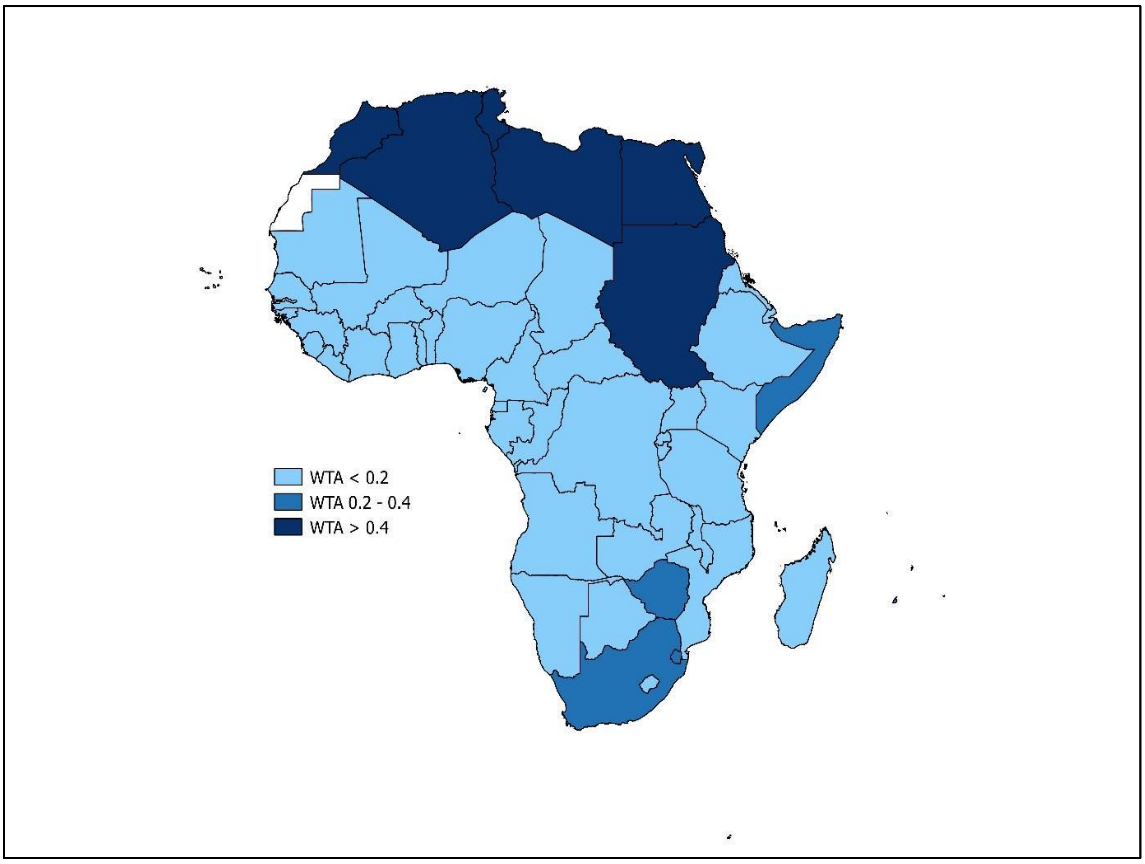

Figure 2.6: Map of national-scale water scarcity as defined by the Withdrawal-To-Availability (WTA) ratio across Africa using data from 2000-2002 (FAO AQUASTAT).

Table 2.4: Differences in WSI and WTA of African countries (FAO AQUASTAT)

Country	WSI(2014)	WSI(2002)	WTA (2002)
Algeria	Absolute Water Stress	Absolute water stress	Severely stressed
Angola	Sufficient	Sufficient	No stress
Benin	Sufficient	Sufficient	No stress
Botswana	Sufficient	Sufficient	No stress
Burkina Faso	Water Stress	Water scarcity	No stress
Burundi	Water Scarcity	Sufficient	No stress
Cabo Verde	Water Stress	Water stress	No stress
Cameroon	Sufficient	Sufficient	No stress
Central African Republic	Sufficient	Sufficient	No stress
Chad	Sufficient	Sufficient	No stress
Comoros	Water Scarcity	Sufficient	No stress
Congo	Sufficient	Sufficient	No stress
Côte d'Ivoire	Sufficient	Sufficient	No stress
The Democratic Republic of the Congo	Sufficient	Sufficient	No stress
Djibouti	Absolute Water Stress	Absolute water stress	No stress
Egypt	Water Stress	Water stress	Severely stressed
Equatorial Guinea	Sufficient	Sufficient	No stress

Eritrea	Water Scarcity	Sufficient	No stress
Ethiopia	Water Scarcity	Sufficient	No stress
Gabon	Sufficient	Sufficient	No stress
Gambia	Sufficient	Sufficient	No stress
Ghana	Sufficient	Sufficient	No stress
Guinea	Sufficient	Sufficient	No stress
Guinea-Bissau	Sufficient	Sufficient	No stress
Kenya	Water Stress	Water stress	No stress
Lesotho	Water Scarcity	Water scarcity	No stress
Liberia	Sufficient	Sufficient	No stress
Libya	Absolute Water Stress	Absolute water stress	Severely stressed
Madagascar	Sufficient	Sufficient	No stress
Malawi	Water Scarcity	Water scarcity	No stress
Mali	Sufficient	Sufficient	No stress
Mauritania	Sufficient	Sufficient	No stress
Mauritius	Sufficient	Sufficient	Water stress
Morocco	Water Stress	water stress	Severely stressed
Mozambique	Sufficient	Sufficient	No stress
Namibia	Sufficient	Sufficient	No stress
Niger	Sufficient	Sufficient	No stress
Nigeria	Water Scarcity	Sufficient	No stress
Rwanda	Water Scarcity	Water scarcity	No stress
Sao Tome and Principe	Sufficient	Sufficient	N/A
Senegal	Sufficient	Sufficient	No stress
Sierra Leone	Sufficient	Sufficient	No stress
Somalia	Water Scarcity	Sufficient	Water stress
South Africa	water stress	water scarcity	Water stress
South Sudan	Sufficient	n/a	No stress (2011)
Sudan	Water Stress	n/a	Severely stressed (2011)
Swaziland	Sufficient	Sufficient	Water stress
Togo	Sufficient	Sufficient	No stress
Tunisia	Absolute Water Stress	Absolute water stress	Severely stressed
Uganda	Water Scarcity	Sufficient	No stress
United Republic of Tanzania	Sufficient	Sufficient	No stress
Zambia	Sufficient	Sufficient	No stress
Zimbabwe	Water Scarcity	Water scarcity	Water stress

Table 2.5: Per capita domestic water use in East Africa (Thompson *et al.*, 2001).

Country	Piped Households		Unpiped Households (urban)		Unpiped Households (rural)	
	Litres/capita/day		Litres/capita/day		Litres/capita/day	
	1997	1966-1968	1997	1966-1968	1997	1966-1968
Kenya	47.4	121.6	22.9	11.3	22.3	8.2
Tanzania	80.2	141.8	25.1	17.8	16.0	10.1
Uganda	64.7	108.3	23.5	14.3	14.8	11.5

2.5.3 Misrepresentation of renewable freshwater resources by MARR

The WSI, WTA and more holistic metrics compute renewable freshwater resources based on observations or simulations of MARR. As highlighted in section 2.1, MARR represents average 'blue water' resources that derive from the difference between mean precipitation and actual evapotranspiration assuming changes in freshwater storage are negligible (equations 2.1 and 2.2). The widespread, continuous use of a singular value to characterise freshwater resources masks not only the temporal variability in freshwater resources but also the sources of this freshwater. SSA, for example, experiences substantial variations in both seasonal and inter-annual rainfall that produce the most variable river discharge in the world (McMahon *et al.*, 2007). The fundamental characteristics of water resources in this region are typically defined by this variability, which is masked through the use of MARR. Further, groundwater resources which are not explicitly represented in MARR and considered only in so far as they contribute to river discharge, are estimated to amount to more than 100 times MARR in many countries in Africa (MacDonald *et al.*, 2012). The distributed nature of groundwater in both sustaining river discharge during dry periods and enabling access to freshwater spatially in areas away from river channels is similarly obscured through the use of MARR. MARR further disregards 'green water' (*i.e.* soil water) which, as outlined above, sustains almost all food production in SSA. Consequently, water scarcity assessments employing MARR not only overestimate demand but also underestimate renewable freshwater resources (Taylor, 2009). Indeed, the importance of explicitly considering the use of 'green water' in determining (consumptive) freshwater use of blue water resources is now well recognised in the Planetary Boundaries framework (*e.g.* Jaramillo and Destouni, 2015b; Gerten *et al.*, 2015).

Recent progress has been made in characterising intra-annual variability in freshwater resources by examining the relationship between freshwater availability and demand on a monthly time step (Hanasaki *et al.*, 2008b; Wada *et al.*, 2011; 2014; de Graaf *et al.*, 2014; Mekonnen and Hoekstra, 2016); these analyses reveal previously undetected (masked) water-stressed areas. Alcamo *et al.* (2007) propose the consumption-to-Q_{90} ratio in which 'consumption' is taken as the average monthly volume of water evaporated and 'Q_{90}' is a measure of the monthly discharge that occurs under dry conditions (*i.e.* when monthly discharge exceeds the 90^{th} percentile of river flow for 90% of the time). Q_{90} was subsequently applied by Wada and Bierkens (2014) in the Blue Water Sustainability Index, which also incorporates non-renewable groundwater use, to account for environmental streamflow. Brauman *et al.* (2016) more recently developed the Water Depletion Indicator which measures the fraction of annual average renewable water (*i.e.* available surface and groundwater) which is consumptively used by human activities within a watershed, both annually, seasonally and in dry years. Critically, this study highlights the importance of seasonality, showing how watersheds that appear to be moderately depleted on an annual time-scale can in fact be heavily depleted at seasonal time-scales or in dry years.

In semi-arid areas in Africa, seasonal variability is often substantial but masked through the estimation of renewable freshwater resources in terms of MARR. Metrics of scarcity that employ MARR to define renewable freshwater resources distort actual freshwater availability in regions where there are short but intense wet seasons and long dry seasons. The computed value of MARR obscures the fact that in places the average renewable freshwater resources for half of the year can be one-tenth of the value of MARR.

2.5.4 Subjective quantifications of socio-economic factors influencing water scarcity

The emergence of holistic metrics of water scarcity recognises that socio-economic, environmental and political factors can influence the occurrence of shortages in the availability of renewable freshwater relative to demand. This chapter also questions, whether these factors can be meaningfully quantified. Scientific legitimacy is often sought through quantification. Although objectivity and neutrality may be implied through the impersonality of numbers, subjectivity is often embedded in the design of multi-component indicators including choices about which variables or parameters are included or excluded. Further, during the development of quantitative, multi-component metrics, procedures such as normalisation and weighting of variables employ subjective decisions (Freudenberg, 2003; Nardo *et al.*, 2005) for which there are rarely clear or formal declarations. The final step in multi-component metrics is aggregation, enabling direct comparisons of multiple variables transformed into a score-based outcome. A review of the normalisation, weighting and aggregation approaches taken in the formulation of the top 11 most globally applied Sustainable Development indices, revealed no consistent application of these principles yet all of these indices are generally accepted as being 'scientifically robust' (Böhringer and Jochem, 2007).

Aside from the technical challenges of objectively normalising, weighting, and aggregating a multi-component metric, quantification of the human environment in existing water scarcity metrics reduces contextual complexities to a narrow set of assumed determinants of water scarcity such as HDI and GDP. As argued by Zeitoun *et* *al.* (2016), such approaches ultimately underplay issues of equity and power. Indeed, 'reductionist' approaches oversimplify and thereby misrepresent determinants of water scarcity that could be better explored through a more integrative *Pathways Approach* (Leach *et al.*, 2007), for example, which embraces diversity in society and the environment, and is able to consider freshwater resources beyond MARR. In this context, this review argues that definitions of water scarcity might be best restricted to physical descriptions, which set a physical context within which a range of development pathways from the human environment (*e.g.* virtual water trade) can be considered to alleviate water scarcity (Hoekstra & Mekonnen, 2012)

2.6 Concluding Recommendations– redefining water scarcity in terms of storage

Current assessments of water stress and scarcity commonly employ a metric, the WSI conceived more than 30 years ago to explore potential linkages between freshwater availability and famines in the arid- and semi-arid Sudano-Sahel of Africa. The simplicity of the WSI, which has contributed to its widespread adoption, fundamentally misrepresents both freshwater resources and demand in regions such as SSA. The WSI, the WTA ratio, and more holistic metrics reviewed in this chapter define renewable freshwater resources in terms of the singular measure of MARR, which denies variability in freshwater resources and disregards both 'green water' (*i.e.* water embedded in plants and soil) and freshwater stored as groundwater or in lakes, dams and reservoirs. Indeed, the persistent focus on defining water scarcity strictly in terms of freshwater fluxes of supply and demand via metrics such as the WSI, WTA and their more recent manifestations is surprising since adaptive strategies to perennial or seasonal shortages in water supply commonly seek to utilise and amplify freshwater storage.

Freshwater storage derived from large-scale infrastructure such as dams and reservoirs has been considered explicitly in a few flux-based assessments of water scarcity. Vörösmarty *et al.* (1997) incorporated reservoir routing schemes into their global hydrological model and Hanasaki *et al.* (2008b) incorporated the 452 largest reservoirs in the world with a storage capacity of over 10^9 m^3, which account for over 60% of global reservoir storage capacity (Hanasaki *et al.*, 2008a). Similarly, Wada *et al.* (2014) updated the reservoir release simulations of Hanasaki *et al.* (2006) and van Beek *et al.* (2011) to incorporate the extensive Global Reservoir and Dams dataset (GranD) (Lehner *et al.*, 2011) containing 6 862 reservoirs with a total storage capacity of 6 197 km^3. These assessments mark an important advance on most flux-based calculations of water scarcity, but their restricted characterisation of freshwater storage to large dams and reservoirs still ignores the vital contribution of distributed freshwater storage provided by wells, small-scale dams, and rainwater harvesting (Taylor, 2009; Rockström and Falkenmark, 2015). The exclusion of groundwater storage is particularly problematic since it is the world's largest distributed store of freshwater and globally supplies ~40% of all water used to sustain irrigation and access to safe water (Jarvis, 2013; Taylor *et al.*, 2013). Döll *et al.* (2012) estimate that groundwater accounted for more than a third (~35%) of the freshwater withdrawn globally over the period from 1998 to 2002.

This thesis sets out to propose three key changes to the characterisation of water scarcity. First, redefine water scarcity in terms of the freshwater storage, both natural and constructed, that is required to address imbalances in the intra- and inter-annual fluxes of supply and demand. Research objective 1) in Chapter 5 aims to demonstrate in practice the resulting characterisation of water scarcity by the two most widely applied metrics, the WSI and the WTA-ratio, as they do not account for neither the contribution of freshwater storage to meeting demands nor differentiate between intra- and inter-annual variability in freshwater availability and demand. Ultimately, intra- and inter-annual variability of freshwater supply and demand, has great control over the magnitude and periodicity of water scarcity in the physical sense and should be more accurately portrayed if used for informing policy about when and by how much the characterisation of water scarcity amounts to. The second change necessary is to restrict the quantification of water scarcity to verifiable physical parameters describing freshwater supply and demand. Research objective 2) in Chapter 6 addresses this critique in practice by field testing the assumptions about domestic water demand that inform the WSI through quantification of water demand in the GRRC. The third change implies using physical descriptions of water scarcity as a starting point for participatory decision-making processes by which communities resolve how to address quantified storage requirements. Research objective 3) in Chapter 7 addresses this point in practice through a household questionnaire of three villages in the GRRC, to explore how water users adapt to varying conditions of freshwater availability.

The first overall effect of the proposed changes to the characterisation of water scarcity is the shift to a new way of thinking, which considers differences in fluxes of freshwater supply and demand to derive a storage requirement. After this translation, water scarcity can then be defined physically as a measure of the extent to which required freshwater storage is available and be used to inform adaptive responses reducing freshwater demand and/or increasing access to freshwater storage. Despite the availability of global databases for dams and reservoirs (Lehner *et al.*, 2011), the process of quantifying available freshwater storage to include, among others, small-scale dams and renewable groundwater storage remains challenging. Substantial improvements in groundwater mapping have occurred (MacDonald *et al.*, 2012) but robust estimates of groundwater recharge remain patchy and global-scale models of recharge remain largely uncalibrated and highly uncertain (Döll *et al.*, 2016). It is also important to recognise that interventions reducing freshwater demand (*e.g.* increased use of 'green water') or increasing freshwater storage infrastructure (*e.g.* construction of dams or pumping wells) affect river discharge, though the nature and magnitude of these effects can vary substantially. Destouni *et al.* (2013) estimate consumptive losses arising from dams and reservoirs globally to be 1 257 km^3 yr^{-1}. Although the use of distributed groundwater storage instead would theoretically reduce such losses, intensive groundwater abstraction has depleted available groundwater storage in some regions (Richey *et al.*, 2015) while inducing greater recharge in others such as the Asian Mega-Deltas (*e.g.* Shamsudduha *et al.*, 2011). Further, conversion of native vegetation to crop cover has been observed to increase evapotranspirative losses in Sweden (Destouni *et al.*, 2013) but to reduce these losses in the Sahel (Favreau *et al.*, 2009).

The proposed changes in this thesis, also recognise the problematic quantification of human environments despite the fact that socio-economic and political factors play a dominant role in defining freshwater access (Zeitoun *et al.*, 2016). This truism is well demonstrated here by the absence of a relationship between 'water scarcity' and 'access to safe water'. Finally, the changes also seek to raise the utility of water scarcity determinations so that they inform a wide range of adaptive strategies, which are not restricted to large dams and reservoirs but include use of renewable groundwater storage and rainwater harvesting as well as reducing freshwater storage requirements through the importation of food (*i.e.* virtual water trade) and increased water-use efficiencies.

Chapter 3 Site description: the Great Ruaha River Catchment, Rufiji Basin, Tanzania

Chapter 3 presents an overview of the environmental and socio-economic conditions in the Rufiji Basin, focusing on the Great Ruaha River Catchment (GRRC) and how freshwater availability has changed over time in the catchment. The chapter goes on to review national and catchment level water policy and governance structures and explores their suitability for dealing with challenges to freshwater availability in the GRRC.

3.1 The physical and socio-economic conditions of the GRRC, Rufiji Basin

The Great Ruaha River Catchment (~ 78 985 km^2) (Figure 3.1), located in the southwest of Tanzania between latitudes 7^o 41' and 9^o 25' S, and longitudes 33^o 40' - 35^{o}40' E, is the furthest upstream catchment in Tanzania's largest river basin, the Rufiji Basin (~ 177 000 km^2 - equivalent to 18% of Tanzanian mainland) (Kashaigili *et al.*, 2006). The basin also includes the Kilombero, Luwegu and Lower Rufiji catchments and drains to the Indian Ocean. The surrounding Kipengere and Poroto highlands give rise to the headwaters of the GGRC with an altitude ranging from 1 100 to 3 000 metres above mean sea level (mamsl). Many seasonal and perennial rivers flow down the steep hillside of the surrounding highlands to the lowlands. An escarpment marks the clear and visible distinction between the mountainous and rugged highlands to the south and southwest and the Usangu Plains to the north and northeast of the escarpment (Plate 3.1). The Tanzania-Zambia (TANZAM) Highway and the Tanzania Zambia Railway (TAZARA) also follow the contours of the escarpment. At the bottom of the escarpment, the rivers run through alluvial fans and the sudden shift from the steep relief of the escarpment to the flat lowland plains reduces the ability of the rivers to transport sediment.

The Usangu Plains contain the Usangu wetlands, which comprises the western and eastern wetlands. Each wetland measures 850 and 900 km^2, with 80 km^2 of the area being permanently under inundation. Two large alluvial fans, the Kimbi to the north and the Kioga to the south, separate the two wetlands and converge at Nyalahunga giving the wetlands a ‘figure eight’ shape. At Nyalahangu, the incoming rivers from the Poroto and Kipengere highlands are connected through a 200-metre long channel that funnels water from the western to the eastern wetland (Figure 3.2).

The Usangu Plains and wetlands also encompass the Usangu Game Reserve, which is home to over 400 bird species (Kashaigili *et al.*, 2006). The eastern wetland has a single outlet at the N’Giriama rock outcrop. The water level in the eastern wetland needs to be high enough to spill over this feature and discharge downstream as a single river, the Great Ruaha River (GRR). Downstream of the N’Giriama rock outcrop, the GRR runs through the Ruaha National Park (RNP) and serves as the main source of water that sustains the park. The GRR, joined by the Little Ruaha and Kisigo rivers, flows 170 km downstream to the nationally-owned and operated Mtera Dam hydroelectric power (HEP) plant (80MW). The GRR provides ~56% of the total runoff into the Mtera Dam reservoir, with the rest supplied by the Little Ruaha (18%) and the Kisigo (26%) rivers (Yawson *et al.*, 2003). Downstream of the Mtera Reservoir, the GRR is joined by the Lukosi and Yovi rivers, and flows into the Kidatu Reservoir (200 MW capacity). This HEP, combined with Mtera HEP production, make up over 50% of Tanzania's national HEP capacity potential (Kashaigili, 2008). From here onwards, the GRR is joined by the Kilombero, Luwegu and Lower Rufiji catchments, before discharging into the Indian Ocean.

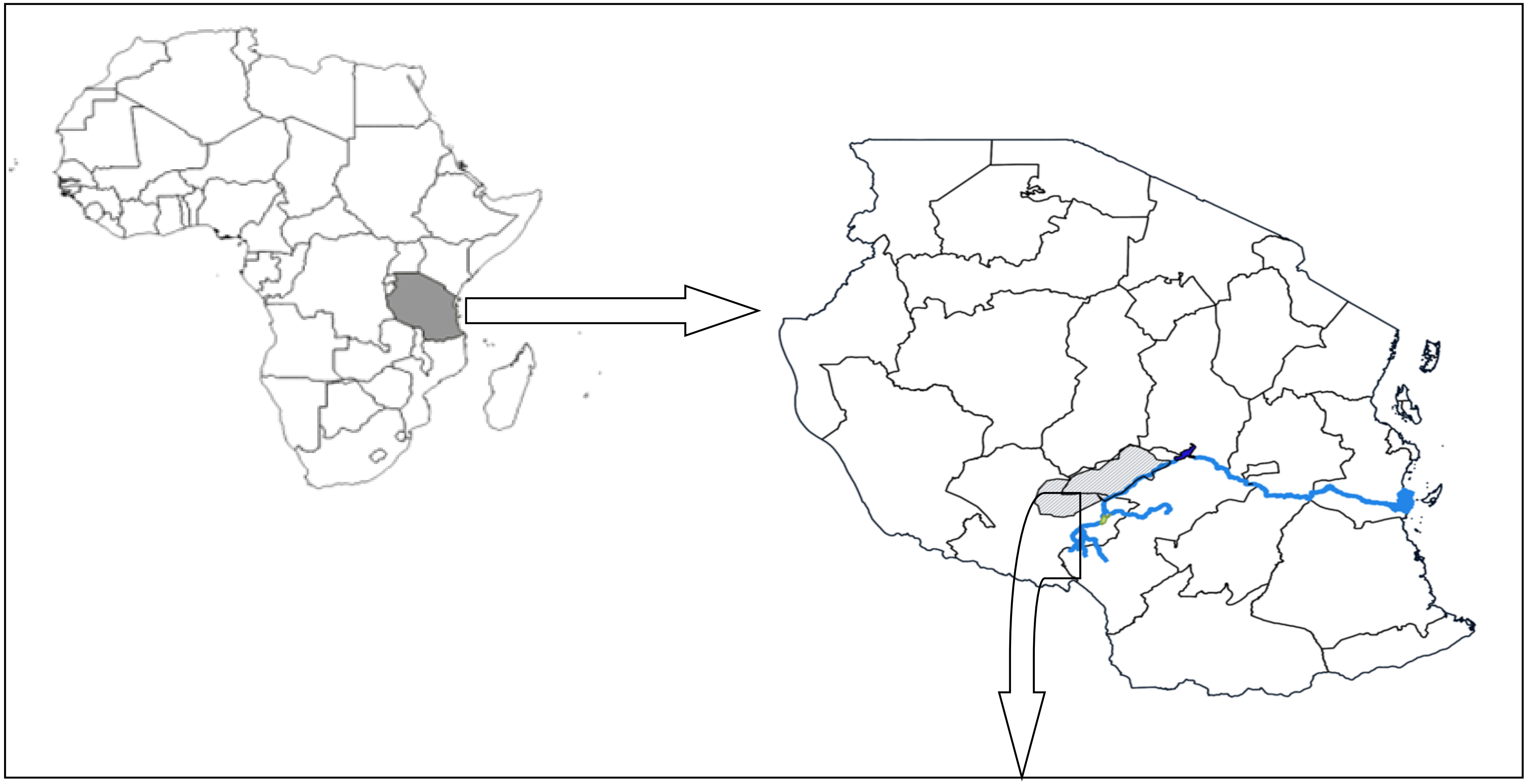

Figure 3.1: The Rufiji Basin and Mbarali District as located in Tanzania (Author version, QGIS 2019).

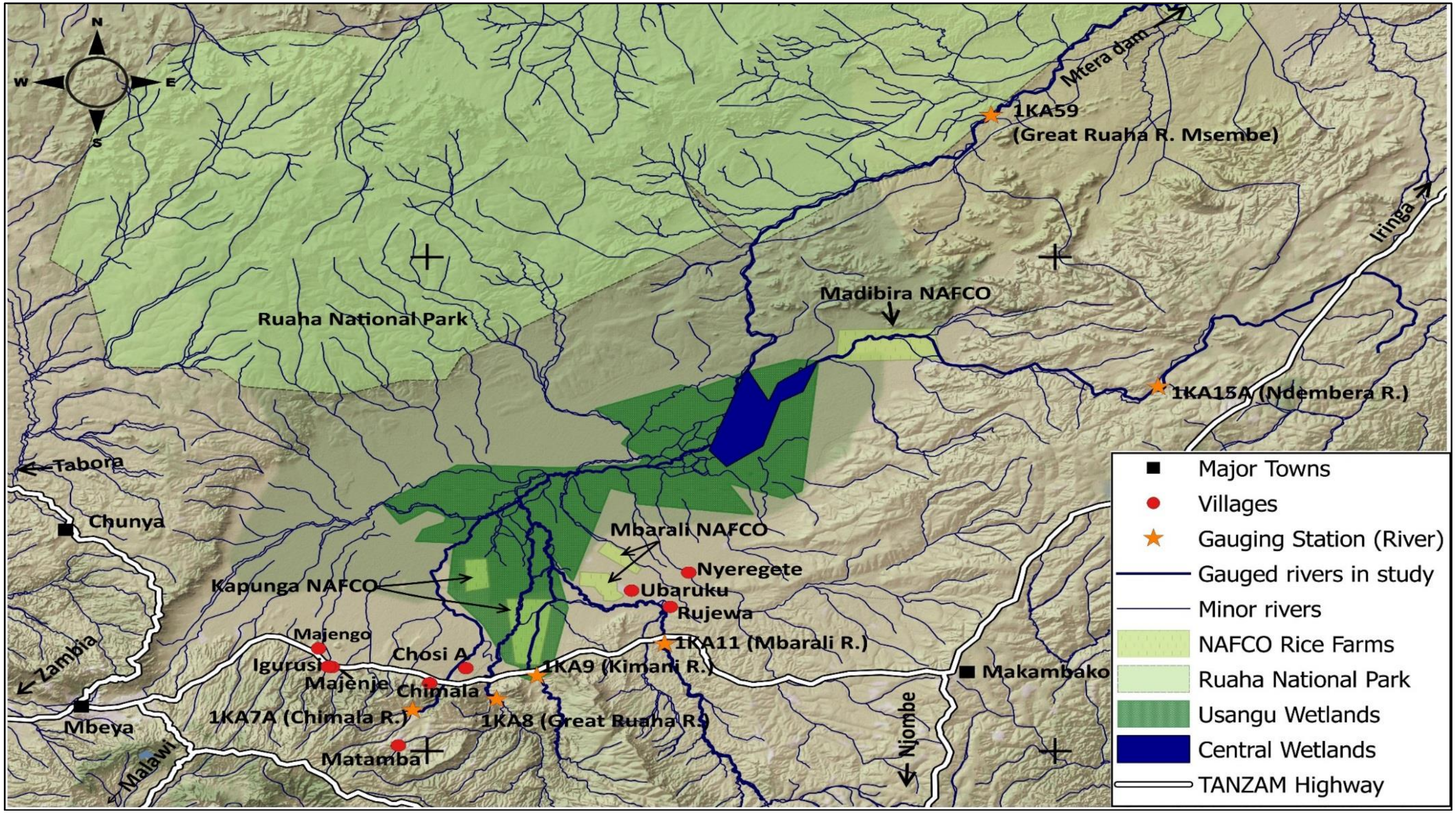

Figure 3.2: Map depicting the Great Ruaha River catchment and study villages. (Author version, QGIS 2019)

Plate 3.1: Relief differences between the Highlands (Kipengere Mountain Range) and the Usangu Plains in the GRRC (Author image, August 2015).

3.2 Population

The GRRC spans across two regions and eight districts, most of which fall within the Mbeya Region (~60%). The study area is primarily within the Mbarali District (14 548 km^2), but the rivers in the Rufiji Basin cross into parts of Iringa Region as well as the Districts of Mbeya Rural, Mbeya Urban, Chunya, Iringa Rural, Mufindi, Njombe and Makete. Establishing the proportion of people in each district within the confinement of the study area is challenging. People in the GRRC often live seasonally where they can find job opportunities, and therefore cross multiple administrative boundaries throughout the year making census data coarse. Heavy out-migration dominates the highland population structure, whereas in-migration to the Usangu Plains has historically been the dominant pattern. The vast amount of flat land available, the break-up of the National Agriculture and Food Company (NAFCO, see below) and the construction of the TANZAM Highway and the TAZARA in the 1970s have contributed to population increase in the Usangu Plains. SMUWC (2001) compiled population data in the GRRC for intervals during the period 1948 – 1999 and RIPARWIN (2006) and WREM Inc. (2012) report a 3% annual growth. The annual growth in population estimates for the study period 1972 – 2011 are presented in Figure 3.2

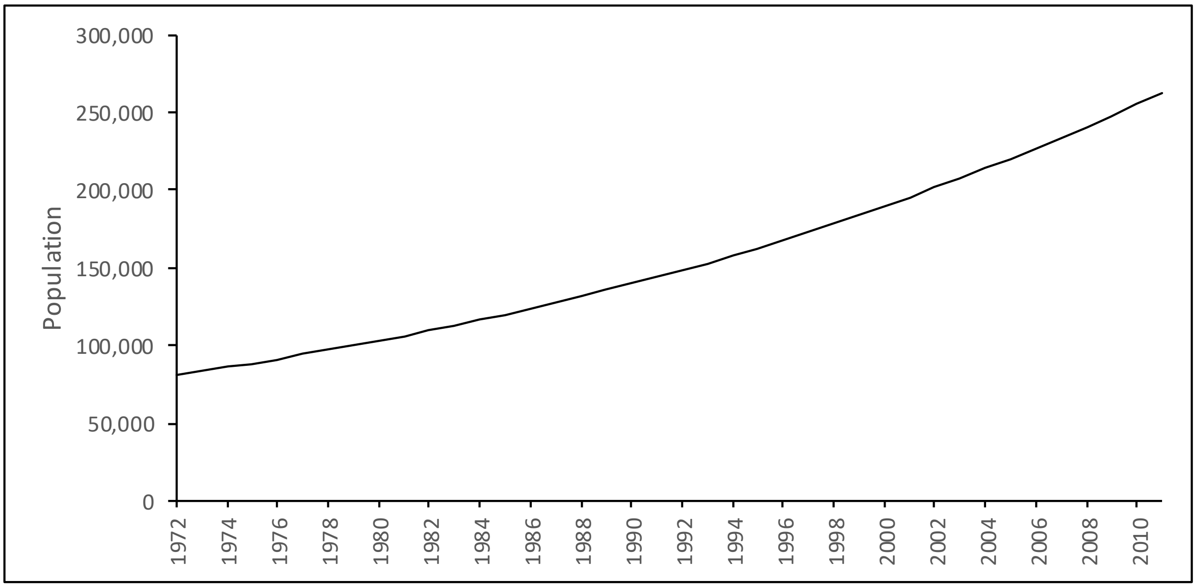

Figure 3.3: Annual population growth 1972 – 2011 based on 3% annual growth rate.

3.3 Geomorphology and Land Cover

The geomorphology of the GRRC highlands comprises plateaux and escarpments. The High Plateau (2 300 – 3 000 mamsl) forms part of the Gondwana surface (late Jurassic and early Cretaceous) and is predominantly granitic with mixed woodlands. From 1 800 – 2 300 mamsl in the west and 1 400 – 1 800 mamsl in the east lies the Intermediate Plateau of post-Gondwana surface. Here, the soils are sandy and *miombo* woodland dominates the vegetative cover. A steep escarpment demarcates the border with the Low Plateau that runs from 1 200 – 1 800 mamsl and constitutes the 'African surface' (late Cretaceous), characterised by granitic rocks, sandy soils, and *miombo* vegetation. At 1 100 – 1 200 mamsl, the late Oligocene and Miocene foothills are covered with mixed *Acacia* and *miombo* woodland. The 1 100 mamsl contour line defines the clear break between the highlands and the lowlands in the form of a distinct escarpment feature that the TANZAM highway and the TAZARA run along (Plate 3.1). From the beginning of the fans to the N'giriama rock crop outlet, the topography is level and gently rolling. The alluvial fans in the south are occupied by a mix of thorny woodland and wooded grassland, which has been subjected to large clearings and replaced by cultivation and/or secondary succession of thorn bush. In the lower fans, vegetation also consists of *Acacia* bush. To the north, the fans include a mix of bush and grassland which appears with the rains.

The swamp area, measuring no deeper than one metre, is dominated by water lilies and water chestnut, and parts are covered with grasses and wild rice that 'float' on the water surface although generally rooted. Open woodland and wooded grassland also make up part of the lowlands and plains including *Acacia* trees.

3.4 Land-use

3.4.1 Highlands

Approximately a quarter of the highland area is under cultivation and is mainly for low-intensity subsistence farming (~69%) (SMUWC, 2001). Cultivation here is primarily rainfed and irrigation is confined to bottom-valley irrigation. The geographical distribution of highland cropping reflects climatic conditions and water resources availability. As altitude and rainfall increase, the range of crops and length of growing seasons increase. Five highland systems exist (Table 3.1) that can be divided into various sub-sectors, as there is no consistent farming practice across this area. At the highest altitudes, potatoes and sorghum thrive, whereas, at lower altitudes in the highlands, maize is the dominant crop. Other crops in the range include beans, tea, vegetables, cowpeas, cassava, and groundnuts. This diversity of crops grown is reflective of the sudden and unpredictable variations in soil fertility and suitability of available land. In the upper parts of the GRRC highlands, there is very limited conversion into cultivated land. On moderate slopes and close to the main TANZAM Highway at the base of the escarpment, clearing for charcoal is extensive.

3.4.2 Lowlands

Cultivation in the lowland plains is both rainfed and irrigated. Rainfed agriculture is practised by most households in the plains and is mainly for subsistence. Maize, cassava beans, groundnuts, sweet potato and cowpeas are commonly grown here. Typically, plots are ~3-4 acres (1.4 ha) per household and the preparation of fields occurs at the end of the dry season and in the early rainy season approximately around November and December. During June and July, harvesting takes place.

3.4.3 Pastoralism and livestock keeping

Most households in the highlands keep a few cows for milk and traction. Livestock keeping is primarily done in the area from the base of the highlands and across the Usangu Plains. This practice is highly dependent on the seasonal availability of water. During the dry season, river flows into the western wetlands recede enabling movement of livestock keepers into the eastern wetlands, which is often combined with foraging activities by nomadic pastoralists including Bena, Masai, Nyakyusa, Sukuma, Sangu and Wanji tribes (SMUWC, 2001). Such movement has a history of fuelling conflict between indigenous irrigators and in-migrating livestock keepers, often nomadic in their practices. In Chapter 5, this aspect is discussed more detailed in relation to its links with water scarcity.

In 1999–2000, the SMUWC (2001) project carried out four aerial livestock surveys (two during the wet season and two during the dry season) followed by a ‘ground truth’ exercise to confirm the results of the aerial surveys and estimated that there were roughly 300 000 cattle in the Usangu Plains. King (1983) estimates that the daily consumption of one African indigenous livestock in semi-arid areas is on average ~30 LCPD and has been applied widely in previous studies of the GRRC (SMUWC, 2001).

Table 3.1: Average household land-use characteristics at various altitudes in the GRRC (Source: SMUWC, 2001)

	System 1 Potato-based	System 2 Maize-potato	System 3 Maize-bean	System 4 Maize	System 55 Rice-pastoral
Altitude (mamsl)	2 000-2 900	1 800-2 400	1 500-1 800	1 200-2000	<1 100
Rainfall (mm)	1 600	1 200-1 500	600-1 500	900-1 000	600
Growing period (days)	280	350	210	175	120
Crops					
Maize		x	x	x	x
Beans		x	x	x	x
Wheat		x	x		
Potatoes	x	x	x		
Pyrethrum	x	x			
Sweet potatoes			x	x	
Sunflower				x	
Cowpeas					
Tomatoes			x		
Fruits		x			
Green peas	x	x	x		
Groundnuts					x
Paddy					x
Farm size (acres)	6.1	7.9	4.9	4.9	13.2
Livestock					
Cattle	9	4	5	7	54
Sheep		3		2	25
Goats	10	4	5	5	24
Pigs	2	3	1	2	2
Chickens	5	6	10	12	13
Guinea pigs	8	9	9	11	4
Donkeys	3	2		2	4

3.5 Irrigated Agriculture

Water use in the GRRC is complex (Lankford *et al.*, 2004), consisting of a delicate balance between multiple uses, and approximately 80% of the population in the catchment is sustained by water-related livelihoods (Kashaigili *et al.*, 2006). Over time, demand for water in the catchment has risen. Whereas rain-fed cultivation in the highlands is considered to have a negligible impact on the overall water balance, irrigation in the plains taking place both during the dry- and wet season, is considered to have significant impact.

Small-scale irrigation in the GRRC commenced in the 1930s and, since then, a mix of indigenous smallholder irrigation schemes and the emergence of large state-owned rice farms since the 1970s have increased the total area under irrigation. During the first stage of development (1958 – 1974) the irrigated area increased from 300 ha to ~12 000 ha (Table 3.2). Over this period, irrigation characteristics changed from primarily smallholder farms to mass expansion by the state-sponsored NAFCO at Mbarali River (3 000 ha) in 1973. During the second phase of development (1974 – 1985) the area under irrigation rose by 117% to 26 000 ha and the population grew to 150 000. The third period (1985 - 1999) was characterised by increased water abstraction for irrigation because of heavy in-migration to the Usangu Plains, as well as the construction of the Kapunga and Madibira NAFCO rice farms in 1992 and 1998, respectively each at ~3 000 ha.

Large-scale NAFCO farms, constructed with heavy concrete structures, weirs and large networks of canals, allowed for significant quantities of water abstractions. Contrastingly, indigenous smallholder systems use traditional intakes and have smaller canals often dug by hand. Intakes at these traditional systems, built from rocks, sticks and other permeable materials, are typically washed away during floods thereby restricting all-year water intake. The modern irrigation system intakes, on the other hand, are not washed away during large floods and thereby retain a higher water volume and lengthen the period of water abstraction for irrigation and cropping (SMUWC, 2001). Despite the original construction of flow control gates at the intakes, there is little formal water management on the former NAFCO sites, and gates are generally missing, broken, stolen or have been vandalised. The resulting from the continued derelict state of these system have led to unregulated and continued intake of water at maximum potential installed abstraction capacity throughout the year causing low water-use efficiency (SMUWC, 2001; RIPARWIN, 2005; WREM, 2012).

Table 3.2: Growth of area under irrigation in the Usangu Plains (SMUWC, 2001)

Year	Total irrigated area at end of growing season
1967	8 500
1974	12 000 – 15 000
1985	26 000 – 36 000
1999	40 - 42 000

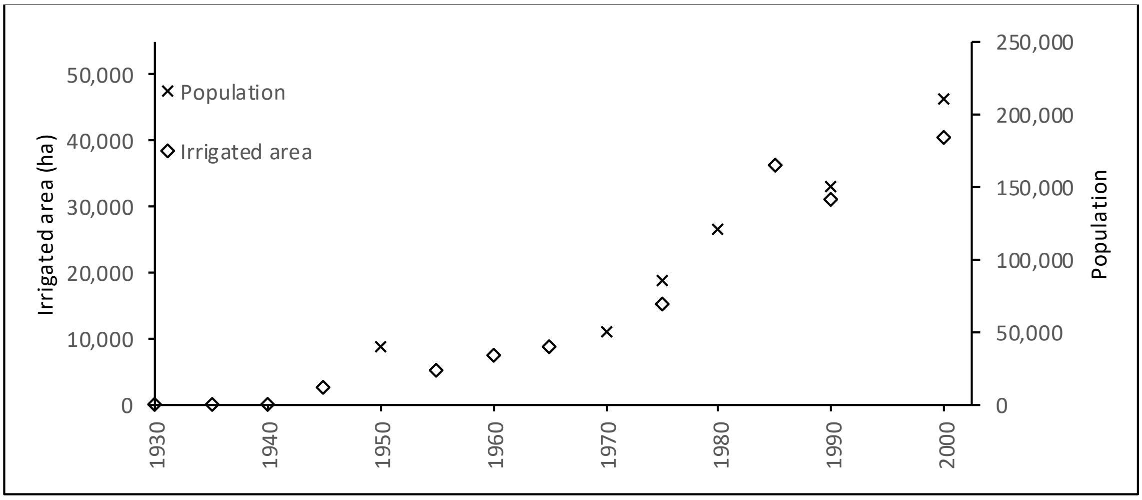

Figure 3.4: Relationship between growth in population and area under irrigation in the Usangu Plains (1930 – 1999). Graph reproduced from SMUWC (2001).

3.6 Water Resources

3.6.1 River Flow Patterns

Rivers that provide the primary flow into the Usangu Plains arise in the Kipengere and Poroto Highlands. Smaller seasonal tributaries are also found the area, but as they cease to reach the wetlands and most of them are not gauged, the focus of this study is on the Chimala River (sub-catchment ~439 km^2), the Great Ruaha River (upstream sub-catchment ~1 015 km^2), the Kimani River (sub-catchment ~598 km^2), the Mbarali River (sub-catchment ~2 461 km^2), and the Ndembera River (sub-catchment ~1

834 km^2) (Table 3.3). The first four rivers, accounting for ~75% of gauged annual flow in upstream GRRC (Shu and Villholth, 2013) flow into the western wetland and combine at Nyalahangu, where they are channelled into the eastern wetland. The Ndembera River, contributes an additional 15% of total gauged river flow and drains from the highlands in the east, directly into the eastern wetland.

Table 3.3: River Gauging Station Network References (RBWB, 2015)

River Name	Gauging Station Reference
Chimala River	1KA7A
Greater Ruaha River (upper)	1KA8A
Kimani River	1KA9
Mbarali River	1KA11A
Ndembera River	1KA15A
Great Ruaha River downstream at Msembe	1KA59

3.6.2 Rainfall

The GRRC experiences unimodal rainfall and has a dry season which runs from May – November during which the Usangu Plains receive little rainfall. During December – February, the Inter-Tropical Convergence Zone (ITCZ) brings lighter rains to the area and upon its return during March-May, large-scale convergence and instability of air masses bring with it the heaviest of rains. The spatial distribution of rainfall in the GRRC varies greatly and is strongly associated with the elevation of the terrain. The highlands receive the highest mean annual rainfall, 1 000 - 1 600 mm/a, in elevations of up to 3 000 mamsl, whereas the eastern and lower mountain ranges (1 100 – 1 600 mamsl) receive 700 – 1 100 mm/a. In contrast, the plains receive much lower mean rainfall, < 700 mm/a, and the area close to the south-eastern highlands in the rain shadow zone receive less than 500 mm/a.

3.7 Hydrological Changes in the GRRC

3.7.1 Cessation of downstream flows and irrigation abstraction increases

The GRR downstream of the Usangu Wetlands at Msembe Gauging Station, in the heart of the RNP, ceased to flow entirely during the 1993 dry season. The dry season flows subsequently stopped every year onwards and periods of zero flows commenced earlier and earlier in each successive year. Additionally, the length of no-flows conditions increased from 20 days in 1993 to over 60 days in 1997 and 1998 (Table 3.4). Even during the very wet *El Nino* event of 1997/98, flows ceased.

The unprecedented changes in the dry season flows caught the public eye when the Mtera Dam HEP faced electrical supply challenges in 1995 (SMUWC, 2001) and fears of energy shortage arose. An energy shortage was far from at risk (Yawson *et al.*, 2003; Walsh, 2012) but Kashaigili *et al.* (2005b) and Kashaigili (2008) continued to investigate the causes of the ongoing cessation of low flows at Msembe Ferry gauging station which are discussed in more detail in Chapter 5.

Table 3.4: Periods of zero flow at Msembe Ferry Gauging Station (Kashaigili *et al.*, 2005b)

Year	Date flow Stopped	Date flow started	Period of no flow (days)
1994	17/11	15/12	28
1995	19/10	23/12	65
1996	17/10	16/12	60
1997	20/09	22/11	63
1998	18/11	9/3/99	87
1999	21/09	20/12	90
2000	17/09	22/11	66
2001	12/11	23/12	41
2002	02/11	24/12	52
2003	21/09	16/1/04	104
2004	03/11	04/12	31

3.7.2 The importance of adequate water resources management in the GRRC

Prolonged and increased reduction and ultimately cessation of river flows into the RNP have been primarily blamed on upstream land-use change, including increased grazing by cattle and irrigation water withdrawals. The posited underlying reasons are further combined with evidence of derelict intake gates, unlevelled fields and a lack of improvements to formal irrigation schemes. To adequately address the long-term challenges and find solutions to the causes of the cessation of downstream river flow requires management strategies, policies and laws that are comprehensive to address the multiple uses of water in the area. The following section presents the general legal and institutional management framework for water resources management at the national and local scale in Tanzania and the GRRC.

3.8 Water Resources Management Frameworks in Tanzania

Water resources management and development frameworks in Tanzania are governed by a mix of constitutional provisions, national laws, policies and institutions. In 1998, policies and laws governing natural resources management were reviewed and replaced. The reforms enacted were framed towards enhancing Integrated Water Resources Management (IWRM), Environmental Impact Assessments (EIA), and stakeholder participation as guiding principles for natural resources management.

3.8.1 Provisions of the Constitution

The Constitution of the United Republic of Tanzania (1977) forms the most supreme law of the country and establishes an overall framework for the protection, management and utilisation of its natural resources. Article 14 provides that every person has the right to access, use and enjoy the country's natural resources, including water. The idea of responsible stewardship over natural resources by the country's citizens is laid out in Article 27(1) which holds that "*Every person is obliged to safeguard and protect the natural resources of the United Republic* [of Tanzania], *State property and all property jointly owned by the people, as well as to respect another* *person's property*." Furthermore, Article 27(2) stipulates that "*All persons shall be by law required to safeguard state and communal property, to combat all forms of misappropriation and wastage and to run the economy [...]*".

3.8.2 The 2002 National Water Policy

The reformed 2002 National Water Policy (NAWAPO) replaced the 1991 NAWAPO and establishes a framework for sustainable management, development and equitable use of water resources in Tanzania. Water resources planning is to be carried out at the basin level and include an integrated multi-sectoral approach in the preparation of basin, catchment and sub-catchment water resources management development. All surface water and groundwater use needs to conform to the provisions. The policy further suggests that the private sector should play a leading role in service provision of water, while the Government of Tanzania should provide an enabling environment through coordination of sector reforms and policy formulation.

3.8.3 The 2009 Water Resources Management Act

The 2009 Water Resources Management (WRM) Act No. 11 is the principal piece of legislation that guides water resources management in Tanzania. The WRM Act focuses on IWRM for sustainable water use and considers water as a resource interdependent with other natural resources. Furthermore, the Act stipulates that water resources management must be done at a basin scale and focus on meeting long-term multi-sector water needs. More specifically, water resources management plans must include for each basin – a water balance, options for meeting current and future water demands, classification of water resources, and reserve flow requirements for each water resource.

The 2009 WRM Act also provides an institutional framework for water resources management at all levels of governance. At the national level, a Water Board advises the Minister of Water and Irrigation. The Office of the Director of Water Resources is also established with explicit statutory roles. At the basin level, the Basin Water Boards have specific mandates to protect water sources, allocate water resources in accordance with basin plans and control water pollution. At the most local level, the WRM Act provides for the establishment of catchment and sub-catchment committees, and Water Users Associations (WUA).

3.9 Institutional Frameworks related to Water Resources Management in Tanzania

Combined, the 2002 NAWAPO and the 2009 WRM Act form the foundation for a framework that focuses on the sustainable management and development of water resources at all levels of governance (Figures 3.5 and 3.6). The two provisions separate the roles of regulation and service delivery, with the former being handled by the Government of Tanzania in the form of laws, guidelines and policies, and the latter jointly by the private sector and beneficiary communities of water development initiatives.

The institutional framework is structured so that it is consistent with the decentralisation and reform policies of the 2002 NAWAPO. Furthermore, in order to ensure consistency between water sector reforms and reform in other sectors (e.g. irrigation, environment, and energy), the National Water Sector Development Strategy (NWSDS) has a mechanism to support re-alignment of appropriate reforms across all sectors. The NWSDS further aims to strengthen the coordination of roles and responsibilities across sectors, where overlaps may occur, in order to minimise duplication of work resources.

3.9.1 National Level Institutions

The highest senior position in the Tanzanian water management institutional framework is the Minister of Water. Their role is to provide political insight into all affairs in the water sector, which includes the formulation and implementation of national water policy, laws and regulations as well as the country development strategy. The Ministry of Water is the main government institution responsible for matters that relate to water resources management. The Ministry plays a lead role in guiding water sector institutions to enhance IWRM, to improve access to water supply and sanitation services, and to secure finance.

The next level of governance is the National Water Board. Under the Water Resources' Management Act No.11 (2009), the National Water Board has the mandate of advisory body to the Minister of Water on multi-sector integration, IWRM, resolution of national (inter-sector/inter-basin) and international water disputes, sector investment priorities and financing of water. The Water Resources Management Act No. 11 (2009) also establishes the Office of the Director of Water Resources as a statutory office that has the role to coordinate basin water boards, coordinate national water resources management and implementation, and oversee water basin planning. Additionally, the Director of Water Resources liaises with all Central Government Ministries that have water-related responsibilities, including the Ministry of Finance and Economic Affairs, the Office of the Prime Minister, the Ministry of Education and Vocational Training, Ministry of Health and Social Welfare, the Ministry of Agriculture, Food Security and Cooperatives, the Ministry of Livestock Development and Fisheries, the Ministry of Industry and Trade, the Ministry of Energy and Minerals, the Ministry of Natural Resources and Tourism, Ministry of Community Development, Gender and Children, the Vice President's Office Division of Environment, and the National Environmental Management Council.

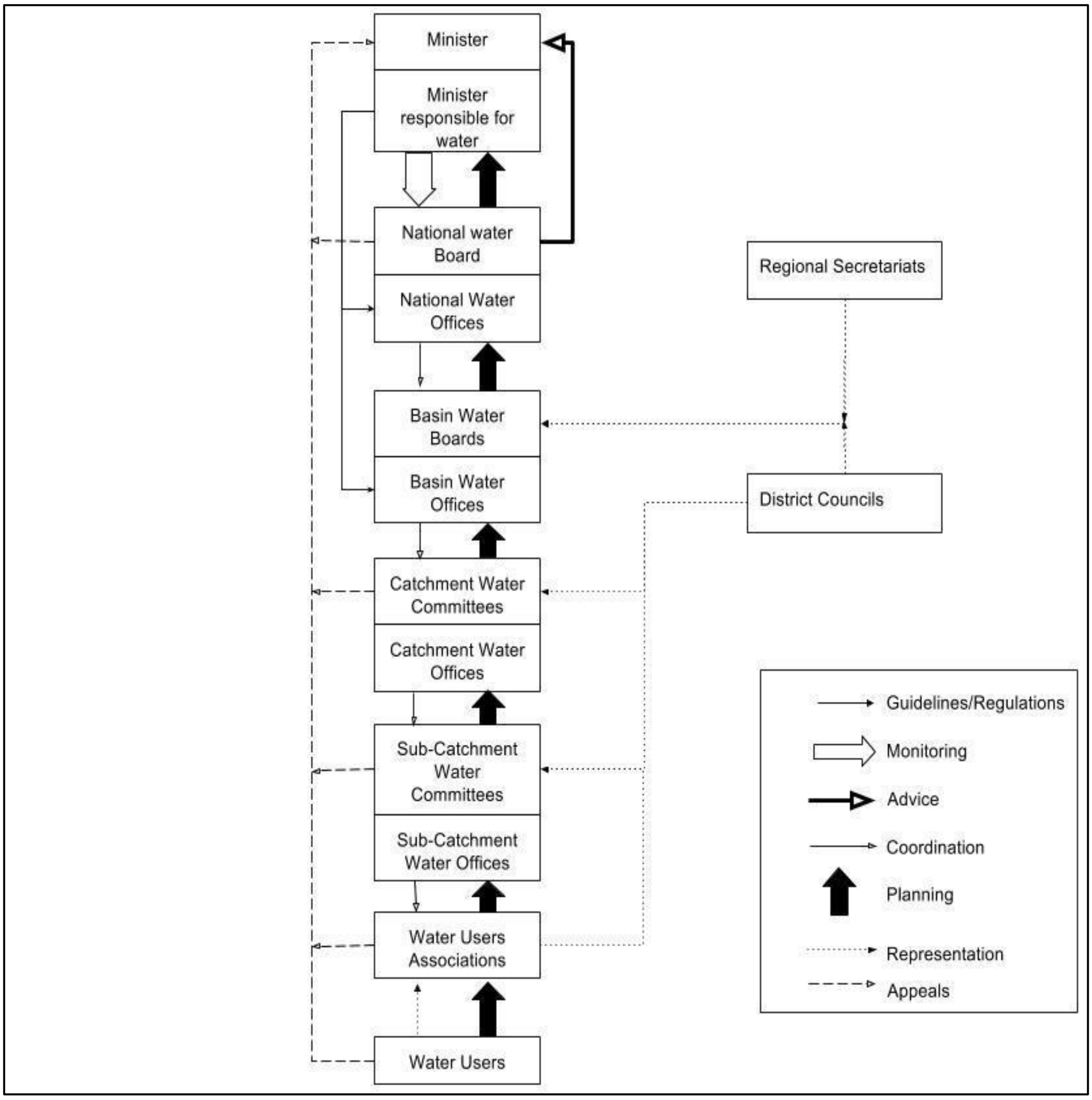

Figure 3.5: Administrative levels of National Water Governance in Tanzania (WREM, 2012)

3.9.2 Basin Level Institutions

Basin Water Boards are the lead management institutions of water affairs at the basin level. This institution coordinates and guides water resources development for multi-sectoral uses that consider environmental sustainability in the basin. The Board consists of ten members that represent different water stakeholder interests including the public and private sector as well as catchment representatives. The Basin Water Officer is the Chief Executive Officer and serves as the Secretary of the Basin Water Board. Both the Basin Water Officer and the Members of the Basin Water Board are appointed by the Minister responsible for Water Affairs. The Water Resources Management Act No. 11 (2009) grants the Basin Water Board the mandate to issue several types of permits including water use permits, discharge permits, groundwater use permits, drilling permits and easements. Other activities of the Basin Water Board include facilitating and assisting the formation of Water User Associations (WUAs) and billing and collection of water fees.

The 2002 NAWAPO and the 2009 WRM Act provide for the establishment of Catchment- and Sub-catchment Water Committees that support the Basin Water Board in water resources management at their respective scales. The 2009 WRM Act prescribes that the Catchment and Sub-catchment Boards assume delegated responsibilities of the Basin Water Board. These committees include representatives from major water stakeholder groups at the catchment and sub-catchment levels. Roles and responsibilities include the preparation and implementation of catchment and sub-catchment management plans. They also guide water resources planning activities and ensure catchment protection and sustainable use of water resources. Catchment and Sub-catchment Councils are advisory to the Catchment and Sub-catchment Committees and the Basin Water Board.

The 2009 WRM Act further designates WUAs as legal entities responsible for management and protection of water resources at the lowest level. WUAs consist of several small informal and/or formal groups along their respective sections of a particular river and can include irrigation water users, fishermen, pastoralists, and representatives from hydropower generation facilities, mining industry, and national parks. WUAs are also responsible for promoting fair and equitable water sharing among their members, draft and enforce water use rules, and support the Basin Water Board. Further responsibilities concern local-level management of allocated water resources, mediation of disputes among members, monitoring members' water use, participation in the preparation of water plans, enforcement of bye-laws, and to ensure compliance with conditions set out in granted water permits. In addition to the aforementioned core water resources management institutions, other institutions play important subsidiary roles which include regional secretariats, district, ward and local government institutions, Non-governmental Organisations (NGOs), service providers, water supply entities, education/research institutions, funding agencies and the private sector.

3.10 Water Resources Management in the Rufiji Basin

In 1991, the Government of Tanzania undertook an assessment of the country's freshwater resources stocks and identified major challenges resulting in the establishment of nine basin water boards the following year. The Rufiji Basin Water Board (RBWB) was inaugurated on 14th September 1993 and the Rufiji Basin Water office established thereafter in accordance with provisions of Act No. 42 of 1974 as amended by Act No. 10 of 1981 and No. 8 of 1997. At its inception, the RBWB operated under the old National Water Policy (1991). The old policy and its associated legislation lacked strong provisions to cater for the concepts of IWRM, was heavily focused on centralised governance, and had weak mechanisms for stakeholder, private sector, local government, and NGO participation. The old act also consisted of tedious and expensive bureaucratic processes for local communities to establish WUAs, resulting in very few associations.

In 2002, the weaknesses of the 1991 Water Policy were addressed under the 2002 NAWAPO recognising the importance of IWRM and basin-scale water resources management. To complement the new policy, the National Strategy on the Eradication of Poverty (MKUKUTA), the National Water Sector Development Strategy (NWSDS) and the Water Sector Development Programme (WSDP) were adopted, and the 2009 WRM Act implemented the 2002 NAWAPO. In parallel to the water sector reforms, the government also implemented the Local Government Reform Act which helped empower Local Government Authorities to play a more active role in decision-making over water resources and the environment.

The effectiveness of the RBWB improved with the onset of these new developments as their roles and responsibilities were streamlined. The RBWB consists of ten members and the Basin Water Officer as Secretary. The main Office of the RBWB is located ~300 km from the GRRC, in Iringa, which created the need for a Rufiji sub-basin Water Office in Rujewa, in the heart of the GRRC. The organisational structure of the Board and Office is illustrated in Figure 3.6.

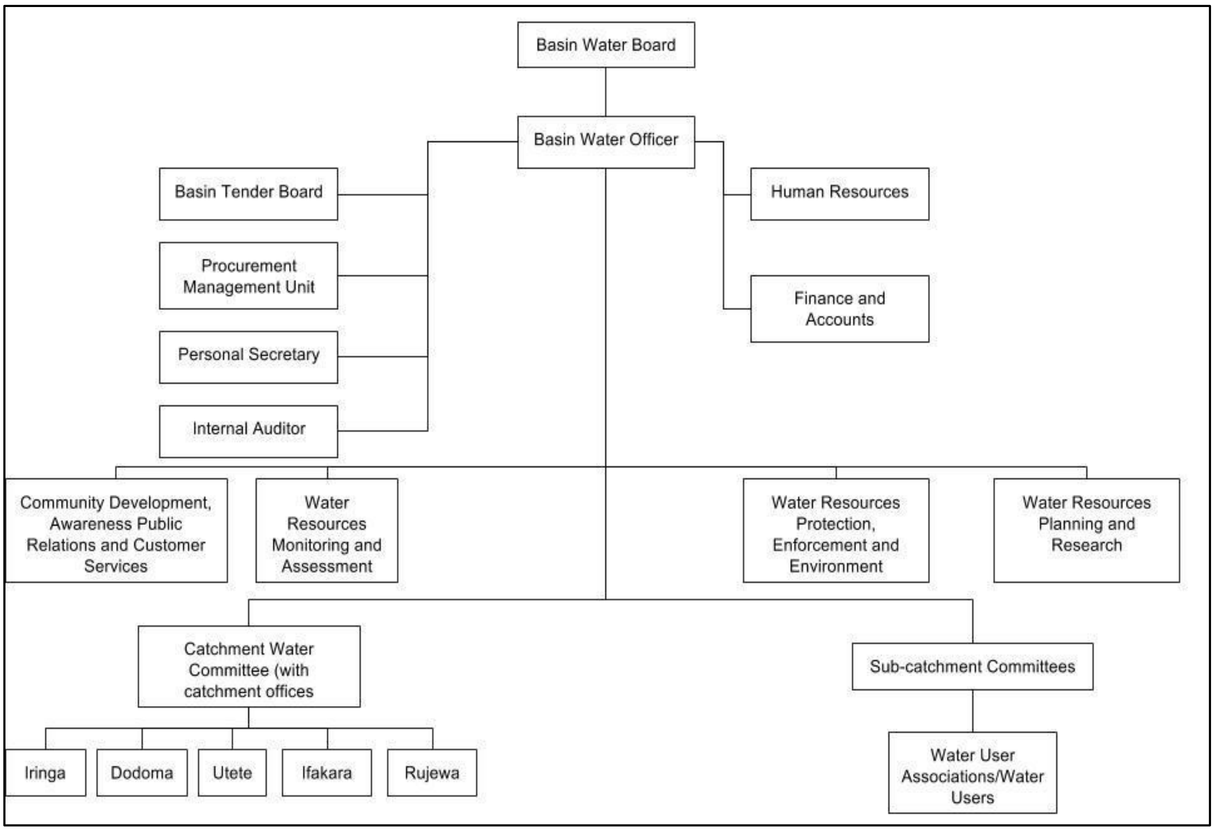

Figure 3.6: Rufiji Basin Water Actors Organisational Structure (WREM, 2012)

3.10.1 Catchment Committees and Councils in the Rufiji Basin

To date, only one out of the four catchments in the Rufiji Basin has appointed a catchment water council. The Great Ruaha Catchment Council was established by the RBWB (at the time referred to as the RBWO) in 2000 as a planning committee of 26 members for the most upper sub-catchments in the GRRC and was later expanded to address the entire catchment. Following the enactment of the 2009 WRM Act, the function ceased to exist as the Act included new provisions for the composition and operation of catchment committees and councils. One of the major challenges with the establishment of catchment committees is their composition. Under the 2009 WRM Act, catchment committees should only include three to five members appointed by the Basin Water Board. This number is small considering the large size of some catchments (e.g. the Great Ruaha River Catchment covers eight districts) and the wide range of the types stakeholders involved.

3.10.2 Sub-catchment Committees and Councils in the Rufiji Basin

In 1996, the RBWB (then RBWO) started establishing sub-catchment committees and councils. The process, however, was slow due to financial constraints, and only a small number of sub-catchment councils have been established in the Rufiji Basin. The majority of these are in the GRRC. Due to the socio-economic importance of the GRRC and its recurring shortages of freshwater availability, the catchment is perhaps the one that has benefitted the most out of all the catchments in the Rufiji Basin, in terms of institutional support. The Division of Environment in the Vice President's Office and the National Environmental Management Council have over time provided support to the RBWB for establishing WUAs in the GRRC.

3.10.3 Water User Associations in the Rufiji Basin

WUAs started to be established in 1994 by the RBWO, and there are roughly 27 WUAs across the entire Rufiji Basin. The activities of the WUAs are implemented through a management committee, a security and conflicts resolution committee, an agricultural and livestock committee, an irrigation committee, an environmental committee and a water allocation committee. Together, the irrigation- and the water allocation committees are responsible for the allocation of water and for developing timetables for water use.

3.11 Concluding Summary

This section presented the main hydrological, environmental and socio-economic conditions of the Rufiji Basin and the GRRC. The hydrological regime in the study area, the GRRC, has a high spatial and temporal variability, as well as strong intra- and inter-annual distinctions between dry- and wet season freshwater availability. Water use at both the basin- and catchment scale is complex and faced with multiple water users each serving their own interests. Water withdrawals for irrigated agriculture in the GRRC increased rapidly since the 1970s. Since the late 1990s, however, multiple studies have reported irrigation intake infrastructure at the former NAFCO schemes to have been unmaintained and broken, thereby causing unregulated flows away from the main river and into irrigation canals. This continued deterioration was also visible throughout the periods of fieldwork undertaken in this thesis and serves as the basis for the assumption made regarding irrigation water withdrawals after 1999 in this thesis. Downstream of the Usangu Plains, at the RNP, increasing periods of zero-flow conditions each year since the early 1990s have been experienced. The causes for the recurring water scarcity are discussed in Chapter 5 where competing explanations are explored.

Finally, this chapter also highlighted the nature of reformed laws and policies governing water resources management in Tanzania and the Rufiji Basin which are heavily rooted in conventional IWRM thinking and aims to decentralise decision-making related to water, environmental and natural resources management at the lowest level. However, at the sub-catchment level, WUAs have been difficult to establish across the country. The GRRC is the only catchment that has a successful track record of establishing WUAs but this was only possible due to the assistance of central government efforts.

The desired effects of IWRM and decentralised governance have not managed to implement the necessary actions to halt zero-flow conditions at Msembe. As will be discussed throughout this thesis, the naturally-occurring inter- and intra-annual variabilities in freshwater availability remain inadequately addressed in the actual implementation of the governance frameworks reviewed here. Chapter 5 provides further discussion on the competing explanations for cessation of flows at Msembe.

Chapter 4 Research Methodology

Chapter 4 presents the research methodology used to conceptualise, design, collect and analyse the data that informs this thesis. The general research process was non-linear and iterative, using a mixed-methods approach that combines elements of qualitative and quantitative research techniques, analysing both primary and secondary data from a plurality of sources.

Section 4.1 in this chapter introduces the scope and the purpose of the research, re-emphasising the key research question, sub-questions and objectives, section 4.2 presents the characteristics of the research design, and section 4.3 addresses the methods and research instruments used for collecting primary data during fieldwork. The research methodology sets up the results presented in the subsequent chapters of this thesis. Chapters 5-7 will address three main points of critique on the characterisation of water scarcity, identified in Chapter 2, through a practical case-study approach of the Great Ruaha River Catchment in Tanzania, which is followed by the exploration and evaluation of a new approach to thinking about the measurement of water scarcity in Chapter 8.

4.1 Research purpose and scope

The overarching aim of this research is to advance the characterisation and measurement of water scarcity through metrics and indicators. The thesis examines assumptions that inform current water scarcity metrics through a practical field case-study of the semi-arid Great Ruaha River Catchment in South-West Tanzania.

4.1.1. Research Question and Objectives

"To what extent are current methods for characterising water scarcity useful, especially when applied in semi-arid zones?"

This research question is guided by three sub-questions:

a) What are the deficits in current characterisations of water scarcity?

b) what are the implications for semi-arid zones and;

c) what could a more meaningful approach to measuring water scarcity look like?"

The following four research objectives were central to answering the overarching research question and sub-questions each addressed in separate empirical chapters:

1. To apply the WSI and WTA ratio indicator, two widely accepted measurements of water scarcity, to the Great Ruaha River Catchment, to assess change in characterisations of water scarcity over time.
2. To examine how assumptions of domestic water demand embedded in the WSI relate to field observations.
3. To investigate how water users characterise 'water scarcity' and how freshwater storage informs adaptive capacity.
4. To explore a future approach for measuring water scarcity and evaluate the limits to its current development based on available field data.

4.2 Research design

Theoretical framework and epistemological position

This thesis is informed by a critical realist approach which is located between the positivist and interpretivist, of the ontological spectrum (Robson, 2011) (Table 3.1). The research considers context to be highly influential in knowledge creation and that knowledge is local provisional and situation-dependent (Madill *et al.*, 2000). Chapter 2 demonstrated that there is a dearth of enquiry into the meaningfulness behind the assumptions that inform water scarcity metrics and a tradition of neglecting the role of water storage. The evolution of water scarcity indicators is primarily informed by a positivist approach where assumptions about how people experience, perceive and adapt to water scarcity are applied at the global scale without field validation. Blumer (1954) argues against the use of definitive concepts, which could include defining strict barriers for water scarcity and abundance and label that the sole reliance on numerical indicators puts "*a straitjacket on the social world*". Upon investigating the assumptions that underlie the meaning of water scarcity indicators the research questions and instruments evolved throughout the fieldwork period in order to reflect the true conditions on the ground (Sarantakos, 1993; Robson, 2011). Multiple research methods exist and each are adequate in their own respect to answer a particular research question either alone or in combination with other methods (Yin, 2009). This thesis applies an overall research protocol that is rooted in the case study design.

Table 4.1 Theoretical Perspectives in Social Science Research (Own elaboration)

Ontology	Epistemology	Methodology	Methods
What is out there to know?	*How do we know what we know?*	*How do we acquire knowledge?*	*What procedures to use?*
Objectivism: Reality is objective and governed by universal laws; independent of researchers.	**Positivism**: Knowledge material can be quantified, measured and reproduced	Deductive Reasoning	Quantitative
Constructivism: The only reality is that experienced by human who brings meaning to it through interpretation.	**Interpretivism**: Knowledge is a social construction which humans assign different meaning to.	Inductive Reasoning	Qualitative
Critical Theory/Realism/Pragmatism Reality is shaped by external conditions that shift; Beneath flux there may be certain prevailing conditions that stay the same.	Knowledge and truth claims can be **evaluated** in terms of real-world evidence; there is a possibility of a degree of shared understanding of conditions that shape circumstances.	Purpose of research: is to get below surface; to expose real relations; debunk myths and false beliefs.	A mixed methods approach is relevant

4.2.1 Rationale for a case-study approach

The case-study approach is useful because it investigates contemporary phenomena within a real-life context (Yin, 2009). The characterisation of water scarcity is a significant contemporary matter, both globally and locally, that relates directly to measuring progress towards halving water scarcity through SDG 6.4. An additional strength inherent to the case-study approach is its flexible and accommodating nature to acquiring field data, allowing for non-linear re-iterative sampling procedures and analysis of data as it emerges throughout the investigation. Finally, the approach can also be employed as a strategy for data collection that deals with a variety of primary and secondary evidence, including documents, interviews, observations, focus groups and surveys.

4.2.2 Mixed-methods

One of the multiple strengths of case-study research designs is its suitability for applying a mixed-methods approach, which allows for using both qualitative and quantitative sources in dealing with research questions and objectives within the physical- and social-sciences (Yin, 2009). Perhaps, one of the best advantages of the mixed-methods is the ability to apply a strategy of *triangulation* which makes use of two (or more) research tools (Robson, 2011). This allows the researcher to obtain various types of information on the same issue; allows the strength of one method to compensate for the deficiencies associated in other methods and; is associated with the ability to increase the validity and reliability of the research (Sarantakos, 1993). Denzin (1970:310 *in Bryman*, 2004) employs an even broader approach to the use of the concept of *triangulation* to mean an approach which uses "*multiple observervations [...], sources of data, and methodologies*", and Deacon *et al*. (1998 cited in Bryman, 2004) refer to triangulation as a process of cross-checking findings derived from both quantitative and qualitative research.

This thesis relies upon interviews, focus group discussions (FGDs), informal conversations, a household questionnaire, and observations made during transect walks in villages and irrigation schemes in the GRRC to extract primary data. Complementary to the primary data, secondary data were also acquired from Tanzania and constituted historical times-series of observed daily river discharge, information from in-country reports and unpublished studies on historical water demand and use.

The four research objectives are answered through a myriad of both primary and secondary sources making mixed-methods highly appropriate. Figure 4.1 illustrates the research process and how different research methods and strategies relate to each other in addressing the research objectives and the four main chapters in this thesis. Research objectives 1 and 4 rely primarily on secondary data, as they deal with historical observations of river discharge, rooted in the physical sciences. Research objectives 2 and 3 rely primarily on field-based derived primary data, as they address questions primarily related to contemporary phenomenon, as well as human behaviour and perceptions. The two objectives, however, also benefit from the ability to use secondary and historical data to complement contemporary insights as a method to verify or clarify statements about perceptions related to respondents' characterisations of water scarcity or applied adaptive capacity strategies. In particular, the stipulated new approach to thinking about how to measure water scarcity in Chapter 8 emphasises the importance of accounting for how behaviour unfolds within confined hydro-ecological boundaries that remain subject to extreme and unpredictable varying conditions. The next section presents the methods used to collect and analyse the data that informed the findings of this thesis.

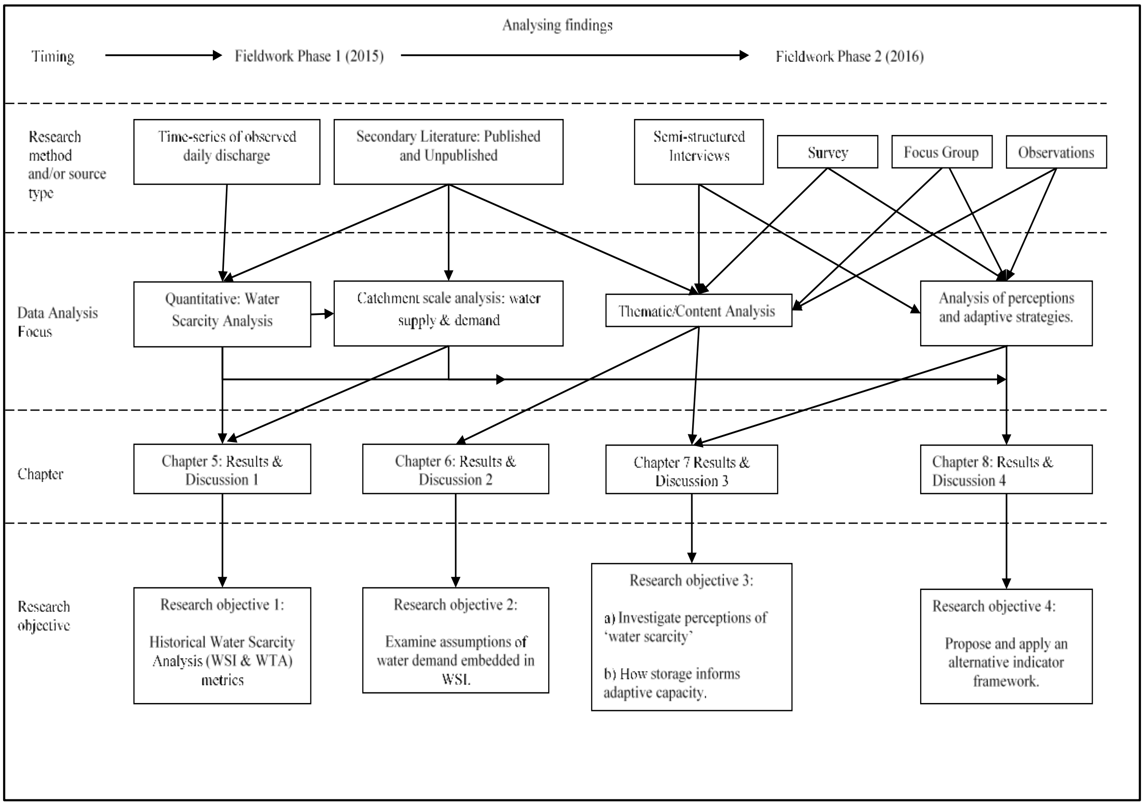

Figure 4.1: Flowchart showing how mixed methods informed the research process. (Author elaboration).

4.3. Data Collection and Research Methods

The research quantifies water scarcity at the catchment-scale and investigates domestic water demand and perceptions of water scarcity and storage to inform adaptive capacities at village- and household-levels. Section 4.3.1 introduces the rationale behind the sampling strategy and subsequently, section 4.3.2 demonstrates the practical stages of acquiring both primary and secondary data, predominantly informed by interviews (4.3.3), focus groups discussions (4.3.4), and household surveys (4.3.5).

4.3.1 Sampling Approach

Any sampling procedure is dependent on the number and type of respondents the investigation requires, whether the researcher tends to generalise to a population and the feasibility of logistical arrangements, time and funds. Two types of sampling strategies exist: probability and non-probability sampling strategies (Figure 4.2). In the former, strict rules in selection of respondents are applied whereas in the latter, a less rigid structure is applied and is less concerned with claims of universality. Probability sampling includes typologies of *simple random sampling; systematic sampling; sampling fraction method; stratified random sampling* and *cluster sampling* and non-probability sampling includes *accidental sampling*; *convenience sampling*; *purposive sampling; quota sampling*; *theoretical sampling*; and *snowball sampling*. For the critical realist the ideal number of respondents is primarily determined by the situation when in the field (Robson, 2011). The ideal sample size is in many cases related to the nature of the population and the study. Theoretical sampling has the advantage that it will direct the researcher towards the ideal number as the study progresses and a point of saturation is achieved within the time frame established. This is similar when purposive or accidental sampling procedures are used and the researcher must make the decision to judge that a sufficient number of respondents have been obtained. In such cases, really the sample size is determined in the context of the study, as the theoretical principles and basic criteria of the study are allowed to change during the field study. Representativeness in this case relates in a much higher degree to quality rather than quantity. Indeed, in critical realist terms, the main concern is not to have a sample that strives for generalisability, but findings from a particular sample may for the researcher provide evidence that they have noted that certain processes are operating in a certain context, or even more broadly, that the findings from the study of a particular sample somehow may represent similarities to what might be happening in other settings (Robson, 2011).

During the first phase of the fieldwork in 2015, where the investigation aimed to gain a better overall understanding of issues related to water scarcity and storage infrastructure development in the GRRC, a purposive sampling technique was applied. This type of non-probability sampling strategy is convenient as it allows approaching key informants that have been pre-identified relevant to the research topic. A degree of the snowball sampling technique was also relied upon, where the informant would recommend or introduce other respondents to talk to during the investigation.

During the second period of fieldwork in 2016, where the scale of the fieldwork was at village- and household-level, a quota sampling strategy was applied to administer the household questionnaire, aiming to acquire an equally weighted sample of 30 respondents in each of the three study sites. For focus groups discussions, a purposive sampling strategy was also pursued, relying on village leaders to facilitate the selection of participants.

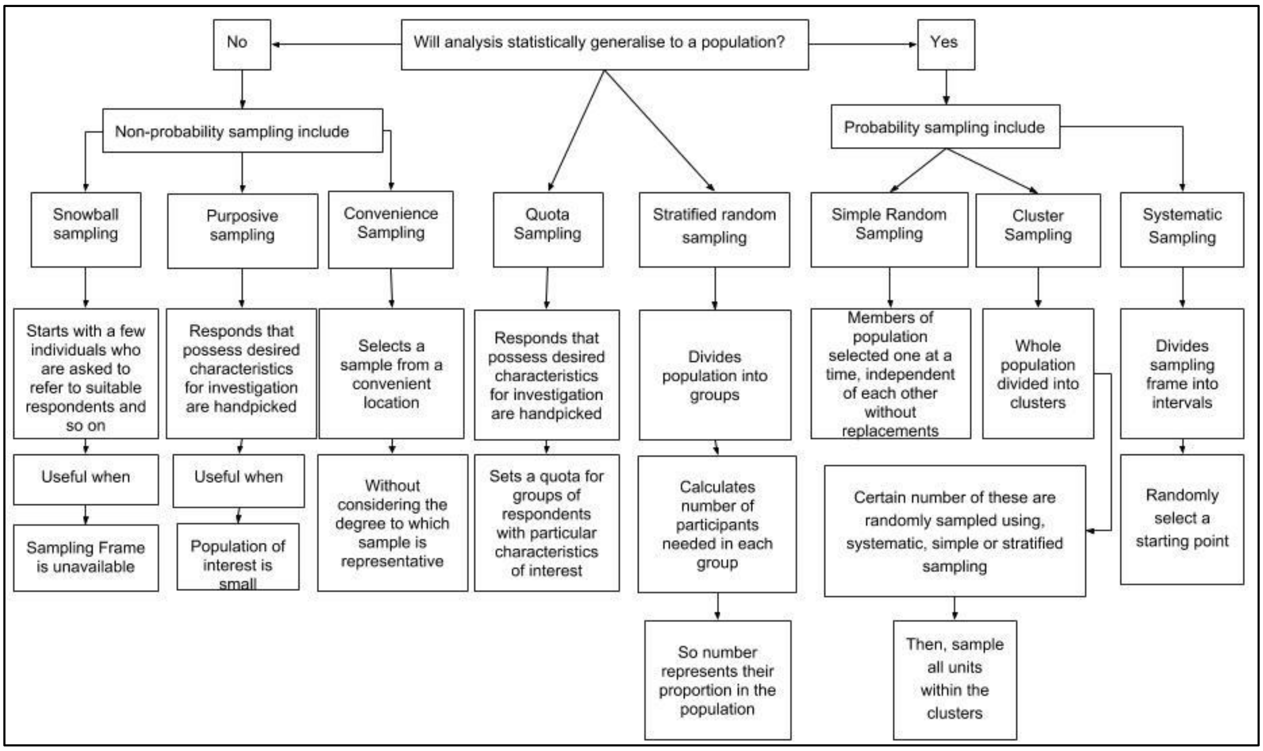

Figure 4.2 Decision-tree for sampling strategies (Author elaboration)

4.3.2 Stages of data collection

Primary data was collected through two periods of fieldwork (Table 4.1) in the capacity of Research Associate in collaboration with *GroFutures* partner, SUA. During the first period of fieldwork (May – December 2015) the majority of fieldwork was spent attending meetings and workshops with relevant stakeholders as well as interviewing staff of the Rufiji Basin Water Board. The first physical field visit to the GRRC took place in August 2015. During this trip, three irrigation schemes, considered to be representative of various approaches to freshwater storage development in the GRRC, were visited: 1) The Ruanda-Majenje irrigation scheme, 2) the Majengo Scheme and 3) the Ipatagwa Scheme (Figure 3.2, p.77).

During this stage, secondary data were also acquired in-country. Historical observations of daily river discharge from the major rivers in the GRRC were obtained from the RBWB and used to inform the methodology presented in section 4.6 for undertaking water scarcity analysis using the WSI and WTA ratio indicators (see results in Chapter 5) and the proposed new framework (see results in Chapter 8). Furthermore, information on historical water demand and use in the GRRC was derived from content analysis of local reports, and through data mining previous studies on the GRRC retrieved from the SUA National Library of Agriculture (SUANAL).

During the second fieldwork investigation, which took place in November 2016, most time was spent in the GRRC. First, a joint household questionnaire and targeted FGD guides were developed with two SUA Research Assistants (RAs) attached to the *GroFutures* project. With the RAs accompanying me into the field and working as interpreters, three villages (Ubaruku, Nyeregete and Chosi) were selected with the support of the two local co-PIs. Both field visits to the GRRC coincided with the peak of the dry season approaching. This was done intentionally so that it was possible to observe how people access water during the dry season as well as to discuss perceptions of water scarcity in real-time condition.

Table 4.2: Stages of fieldwork data collection

Step	Period	Objective	Activities
Fieldwork 1: General Description	15/5 – 15/11/2015	Gain an in-depth understanding of water issues in Tanzania. Scoping and reconnaissance of study area. Identify groups to interview. To collaborate with *GroFutures* colleagues in kicking off the project. To integrate into university life at a university in an African context, in order to expand knowledge of North-South academic collaborations.	Appointed as Research. Associate at Sokoine University of Agriculture, Morogoro, Tanzania. Meetings with relevant staff.
Secondary Data Acquisition & Analysis 1	On-going when not in the field between 15/5 – 15/11/2015	Acquire access to background reports on work done in the GRRC not publicly accessible.	On-going reading of historical reports. Obtained base figures for assuming historical demand for water in the Upper Great

			Ruaha River Catchment.
Primary Data Acquisition 1	12 - 14/6/2015	Obtain External Respondents views & understandings.	Semi-structured interview. Workshop on Environmental Flow Requirements in Rufiji Basin held in Morogoro.
Primary Data Acquisition 2	24 – 26/6/2015	Obtain Internal and External respondents view on proposed future development plans for Rufiji Basin. Observe & note interactions and opinions between all stakeholders of Rufiji Basin and respective catchments. Introductions to the Rufiji Basin Water Board.	Three-day final stakeholder analysis meeting on World Bank/WREM Int. study findings. Observations, conversation in form of semi-structured interviews.
Primary Data Acquisition 3	14-15/7/2015	Obtain views and understandings by Rufiji Basin Water Board.	Semi-structured interviews with Rufiji Basin Water Board, Iringa.
Secondary Data Acquisition & Analysis 2	Ongoing from August 2015.	Obtain and analyse historical discharge data from major rivers in GRRC, Treat hydrological data, Estimate Recharge.	Built time-series for analysis of historical flows; Undertook Water Scarcity Analysis of Upper Great Ruaha River Catchment using conventional water scarcity indicators: WSI & WTA; Estimate baseflow from time-series & plot into proposed metric based on storage (Taylor,

			2009; Damkjaer & Taylor, 2017).
Primary Data Acquisition 4	10 – 12/8/2015	Field visit to the Usangu Plains to better understand local water use, challenges and views/perceptions.	Transect walks, field notes,; observations,; semi-structured interviews, group interviews.
Secondary Data Acquisition and Analysis 3	October – November 2015	Obtain access to unpublished academic research on Great Ruaha River Catchment.	Structured Archival work in Sokoine University of Agriculture National Library physical database and online repository (PhD & M.Sc.).
Fieldwork 2: Primary Data Acquisition 5	1/11 – 1/12/2016	Field Visit with Research Assistants to *GroFutures* study sites in the Usangu Plains.	Questionnaires, Focus Group Discussions, Semi-structured interviews, transect walks,; field notes.

4.3.3.1 Observations

The study adopted a semi-structured observational method, which allowed for purposive sampling of observations and practices of interest related to domestic water use, ways of accessing water and irrigation practices. One starting point in the observational sampling protocol is the time that the observational studies take place at. As discussed above, with the aim of the field research to better understand adaptive ways of accessing limited water during the dry season (May – November), both field visits were restricted to these months.

4.3.3.2 Observations: Fieldwork 2015

The first period of the fieldwork in August 2015 included visits to three irrigation schemes in the Usangu Plains: 1) The Ruanda Majenje irrigation scheme, 2) the Majengo Scheme and 3) the Ipatagwa Scheme. These particular schemes were recommended by a *GroFutures* co-PI as suitable locations to see various storage-based strategies for using water at the height of the dry season. Access was facilitated by an Irrigation Extension Officer from Mbeya and during the transect walks, attention was paid to which crops the farmers were irrigating and the state of the water intake structures in the primary and secondary canals. Discussions with farmers also allowed for a better understanding of the different ways of using water for irrigation.

4.3.3.3 Observations: Fieldwork 2016

During the first day of working in Nyeregete, the Village Council guided us around three hamlets (Nyete, Simba and Tembo A) presenting various types of wells (hand-dug, shallow wells and hand-pumps), and their location and depth were noted. The research team also briefly discussed the historical development of groundwater in the village

4.3.4 Interviews

The interview methodology is a social science data collection tool that uses verbal questioning as its principle technique. Interview based techniques are favoured because of their openness, qualitative nature and interviewee-guided manner of being conducted (Sarantakos, 1993). A variety of types of interviews exist and whereas qualitative research often employs *unstructured/unstandardised* forms of interviewing (e.g. focused or intensive interviews), quantitative research approaches employ primarily *structured/standardised* interviewing techniques. In-between is the *semi-structured interview* technique which by nature can be both quantitative and qualitative at the same time (Bryman, 2004).

Structured interviews follow a strict procedure and can be fundamentally considered a questionnaire read out by the interviewer. This approach does not allow any room for adjustments to any of its elements, content, wording or the sequence of questions. The interviewer is expected to act in a neutral manner, and not to interpret interviewee behaviour, in order to minimise researcher bias and to achieve the highest degree of uniformity in the procedure (Sarantakos, 1993). *Unstructured interviews*, do not follow the same rigid procedure as above. The technique, has no restrictions in its wording of the questions, nor the order of questions posed. The interviewer acts freely as they deem appropriate, but still on the basis of a certain research questions, and formulates questions accordingly, as the interaction continues.

Semis-structured interviews, lie somewhere between structured and unstructured interviews and contain elements of both approaches. The degree to which they lean more towards one or the other depends on the type of information sought; the resources available and ultimately the research questions and objectives of the investigation. In the typology of *standardised* interviews, the answers are pre-determined by a set of response categories (e.g. Yes/No/Don't Know etc.) whereas in *unstandardized approaches* the questions and answers are left open. Interviews are either conducted with individuals, or in a group setting with either both a small or large number of respondents. In an individual interview, the interviewer ask questions to the respondents one at a time, and this is the most common setting. However, small group interviews can also be undertaken in the form of a conversation; and finally large-scale interviews may work in a setting where the interviewer gives the interviewees that are interviewed together a response sheets and questions are read out loud one by one.

Semi-structured interviews were held during the first phase of the fieldwork in 2015. A purposive sampling strategy allowed for flexibility to choose the most appropriate respondents and adapt the interview guide as necessary. With the pre-consideration and identification of two types of informants, the investigation categorised respondents accordingly. The first, External Respondents (ERs), are actors that engage with water resources development or decision-making that relates to the GRRC. In this case, respondents in the ER category constituted professional government staff, in particular, members of the Rufiji Basin Water Board as well as international experts with previous experience of conducting research in the GRRC. The second group of respondents, Internal Respondents (IR), are local water users and stakeholders, that engage with water use every day. In many ways, IRs are affected by the decisions and findings of the ERs but may not be particularly influential in the decision-making process themselves despite being most directly impacted.

A flexible interview guide was developed (Appendix 2) and covered various themes including water use during the dry season, water scarcity perceptions and opinions about the future of surface and sub-surface storage development in the GRRC. All respondents granted their consent to having their views incorporated into this thesis. Interviewees, however, were not recorded, as it proved more convenient to informally record data in hand, as the surroundings were often noisy and interruptions from by-passers would occur. Furthermore, statements made by respondents were not analysed *ad verbatim* and in most cases, used to identify opinions and perceptions regarding the themes discussed.

Table 4.3: List of Interviewees

Type of respondent	Interview Date	Duration	In-text reference
External			
Government	15/7/2015	30 minutes	ER1
District Official	10/8/2015	30 minutes	ER2
International Expert	14/6/2015	45 minutes	ER3
Government	14/7/2015	40 minutes	ER4
International Expert	24-26/6/2015	Three-day observational ER5-IR4 interactions in the form of a narrative	ER5
Internal			
Farmer	10/8/2015	20 minutes	IR1
WUA Chairman	11/8/2015	20 minutes	IR 2
Irrigation Extension Officer	11/8/2015	20 minutes	IR 3
All water users collectively interaction with IR5 in dialogue	24-26/6/2015	Three-day observational ER5-IR4 interactions in the form of narrative	IR4

4.3.5 Household Questionnaire

4.3.5.1 Developing the survey

The second period of fieldwork took place during the dry season in November 2016 with the primary aim of developing and administering a household questionnaire (Appendix 3). The fieldwork took place in three *GroFutures* sites: Chosi, Nyeregete and Ubaruku; all villages largely dependent on groundwater to meet domestic demands. Based on a template produced by *GroFutures* colleagues at another study site in Ethiopia, the finalisation and adaptation of the survey to the GRRC was done at SUA in collaboration with two Tanzanian M.Sc. students writing their dissertations under the *GroFutures* project on the topics of 'Groundwater Governance' and the 'Economic Viability of Groundwater Use for Agriculture'. Having developed their own instruments of enquiry, the team worked to align and harmonise the two M.Sc. surveys with the *GroFutures* standard survey template. The first step was to identify overlapping questions, in order to avoid duplication, followed by attaching additional core questions to the relevant sections of the survey. In this way, the survey ensured a coherent and systematic logic in the sequencing of the questions. The draft survey was circulated to local *GroFutures* co-PIs, with no significant changes made to it, deeming it suitable for field application.

4.3.5.2 Survey Structure

The structure of the survey applies both quantitative and qualitative methods of questioning. In the first sections A-E, the survey applied closed and fixed-alternative types of questions regarding human capital, livestock and asset holding, ownership of land, household crop production, and the household irrigation experiences. These first sections provided an overview of the socio-economic conditions of the households surveyed.

Section F on Groundwater Use applied a mixture of both fixed-alternative and open-ended types of questions with the aim for each question to apply a funnelling down sequence moving the conversation from open-ended and broad general questions to more complex specific and reflective questions. Whereas the survey applied fixed-alternative questioning regarding characteristics of well types and ownership, it also asked open-ended questions towards the end of Section F, which relate to the perceptions of the challenges to groundwater development. Section F is at the core of this thesis and was primarily used to gather information and evidence to answer research objectives 2 and 3. The former research objective being concerned with quantification of water demand as a means of field-testing assumptions regarding domestic water demand that inform the WSI, and the latter exploring perceptions of water scarcity and the role that storage plays in providing adaptive capacity. Research objective 3 is further informed by data gathered in Section G, which explores the modernisation of irrigation technology as a means to demonstrate innovative and adaptive ways of increasing water use efficiency. Section H applies straightforward fixed-alternative questions on the households' alternative income streams whereas Section I investigated perceptions of wellbeing.

4.3.5.3 Survey sample size and administration

The survey was administered orally. This approach is most appropriate during fieldwork as a means of not exposing and dealing with issues of respondent illiteracy. Through active participation in the oral sampling procedure, it was also easier to observe not only the surroundings but also the respondents' reactions and body language to particular topics, as well as factoring in the relevant commentary that passers-by would provide.

Upon deciding the target sample size, a non-probability quota sampling strategy was applied factoring in matters of logistics, such as time to administer the survey and the availability of respondents. The target sample size was set at 90 households, 30 in each village, but the final number of households surveyed was marginally lower, totalling 82. In part, the reasons for this set-back related to the short amount of time spent in each village. Indeed, the village of Nyeregete was chosen a few days before departing for the sites and therefore was new to all of the team members. This also resulted in scepticism regarding the motives of the team for requesting to work in the village, which meant participants were difficult to recruit in the beginning. A further challenge related to not having managed to pilot and time the length of interviewing one household, which was substantially longer than desired, approximating 30 – 45 minutes. However, many of the interviews turned into personal conversations with respondents informally volunteering more detailed information than requested. As such, coming up short of the target sample size of 90 households is not considered to make the quality of the research any less valuable. Indeed, Sarantakos (1993:41) holds that the well-trained field researcher is aware that a group, which at first may be perceived as a fixed sample in terms of quantity, may in fact easily change over time, as the research progresses, and enhance the quality.

4.3.6 Focus Group Discussions (FGDs)

Focus groups can be useful to acquire an overview of the study topic and its context in the location (Sarantakos, 1993). This research used FGDs at each study site before administering the household questionnaire in order to better understand the context of water use and governance in each of the locations. Selecting the participants for the FGDs in all villages was dependent on a local liaison from the Rufiji sub-basin Water Office asking village leaders to find respondents matching the criteria set out, of having groups with no more than 12 respondents (Robson, 2011) and an equal balance of men and women. Further specified criteria were that the respondents should be or have been engaged in using groundwater, and the focus groups should include members of WUAs and farmers.

A further consideration when planning FGDs relates to the location, which should provide a safe and enabling environment. The two RAs had limited experience of conducting FGDs and their first instinct was to conduct the FGD using a classroom set up (*i.e.* the investigator sits alone at the front facing the respondents who are seated in rows on chairs or benches) which resulted in respondents feeling reluctant to voice their views and the facilitator dominating the interaction through a one-way stream. After the first FGD (in Ubaruku) I suggested to change the location and layout, sitting in a circle with respondents under an *Acacia* tree. Taking this approach for the remaining FGDs provided for a more inclusive environment compared to the first classroom setting, as respondents went from looking intimidated and hesitant to passionately voicing their views and opinions in discussion with each other.

In Nyeregete Village, the hamlet and village leaders took part in the first FGD on groundwater governance. Participants expected to receive monetary compensation for their time. When it was made clear that this would not be the case, participants felt little incentive to participate in the study and left. In preparation for day two in Nyeregete, the local liaison had been instructed to organise participants for a second FDG. The liaison did as asked, but when the team showed up at the agreed-upon time and place, no participants had shown up. The previous day's announcement that monetary compensation for their time would not be provided had left the invited respondents with little incentive to show up. This set-back delayed our schedule as we lost half a day, which had been allocated to administering questionnaires, negotiating with village leaders instead. The team proposed that everyone would be served soft drinks and water during the one-hour FGD, but this was considered inadequate. Instead, the team committed a symbolic monetary token of appreciation to the village leader, which they would share equally amongst the respondents. In the two other villages, Chosi and Ubaruku, it was easy for the local liaison to gather participants for the FGDs, as a working relationship already existed.

4.4 Secondary Sources

4.4.1 Large-scale assessments of water resources

The GRRC has a long history of being subject to research on water and irrigation. This investigation accessed numerous official reports affiliated with these studies, only obtainable in-country, to build a holistic picture of historical changes to water use and development of water resources infrastructure. The next section provides an overview of the major previous studies that have been influential in shaping the knowledge of water in the GRRC. Two studies, in particular, have informed this thesis significantly – the Sustainable Management of the Usangu Wetlands and its Catchment (SMUWC) project and the successor to this study – the Raising Irrigation Productivity and Releasing Water for Inter-sectoral Needs (RIPARWIN) project.

4.4.1.1 River Basin Management and Smallholder Irrigation Improvement (RBMSIIP)

RBMSIIP was a World Bank-funded project implemented jointly by the Ministries of Agriculture and Food Security and Water and Livestock Department over the period 1996 – 2003 in the Rufiji and Pangani River Basins. One of the main objectives of this study was to strengthen RBWB's capacity to undertake water resources management as well as to establish a mechanism for issuing water rights and resolving conflicts over natural resources. RBMSIIP relied heavily on the principles of IWRM and brought attention to the necessity of recognising the needs of all water users in order to achieve equitable allocation of water. Other achievements of the project included the establishment and capacity-building of WUAs.

4.4.1.2 Sustainable Management of the Usangu Wetlands and Catchment (SMUWC)

The research project Sustainable Management of the Usangu Wetlands and its Catchment was funded by DfID and ran from September 1998 to March 2001 in response to national and local concerns about the drying up of the GRR at the RNP for several consecutive years since 1993. The aims of the project were to increase long-term local-scale responses to improved water resources management, improve rural livelihoods, increase the downstream flows, and study the nature and causes of water problems in the GRRC. The output consists of twenty-three detailed reports, obtained from colleagues at SUA and the RBWB. The reports contain information on historical changes to the environment and socio-economic conditions of the catchment, resource- and land-use change, irrigation expansion, and long-term hydrological developments.

4.4.1.3 Raising Irrigation Productivity and Releasing Water for Intersectoral Needs (RIPARWIN)

Another major study undertaken in the GRRC informing this thesis is the successor to SMUWC; RIPARWIN. RIPARWIN was funded by DfID and the International Water Management Institute (IWMI) and ran from November 2001 to March 2006, following on from the conclusions of SMUWC, which had found that there was evidence to suggest that upstream water withdrawals for irrigation had caused the recurring low-flows in the RNP. RIPARWIN, specifically addressed the research question "can river basin managers and other stakeholders raise irrigation efficiency and productivity in order to find savings that can be released for downstream and other sector needs?" The study findings conclude that the GRR downstream could be returned to its historical perennial flow state as the trade-offs between sectors may not necessarily impinge upon on core livelihood or environmental well-being, provided that water is used optimally and efficiently.

4.4.1.4 World Wildlife Fund (WWF) – Ruaha Water Programme

The World Wildlife Fund Ruaha Water Programme (WWF-RWP) was located in Iringa covering the upper south-western catchment of the GRRC. The programme ran from 2003 – 2009 and focused on IWRM and sustainable water use and management for the maintenance of ecosystems for improved livelihoods. The project, jointly funded by WWF-UK and the European Union (EU) was implemented in collaboration with the WWF Tanzania Office, the Ministry of Water and Irrigation, and various relevant Basin Water Boards including the RBWB. More specifically, the objectives of the study were to examine why the GRR at the RNP had dried up at certain times of the year, as well as define and implement appropriate Environmental Flow Requirement strategies, and plan for the restoration of downstream flows at RNP.

4.4.2 Unpublished secondary sources: Sokoine University of Agriculture National Library

This thesis also aimed to revisit previous academic research on water in the GRRC which had been undertaken by students at SUA (M.Sc. dissertations and PhD theses). The SUA National Library (SUANAL) database and the SUA Online Repository were consulted using the keywords: “Ruaha”, “Great Ruaha”, “Usangu”, “Usangu Plains” and “Rufiji”. In the SUANAL database, two PhD theses and 5 M.Sc. dissertations were physically available for consultation. In the online repository, five results were returned. After a systematic reading of all 11 sources with the attention on estimates of quantities of water for non-irrigated purposes, only one yielded additional information that had not already been used to inform this thesis (Table 4.4)

Table 4.4: List of Unpublished Secondary Data sources on the GRRC consulted at SUANAL.

Author	Title	M.Sc./PhD	Physical/Online Repository	Additional relevant material related to domestic water use in the GRRC?
Gomani, L.M. (2006)	Regulated Deficit Irrigation as a Water Management Strategy in Bean Production: A Case Study of the Usangu Plains in Tanzania	M.Sc.	Physical	No
Kadigi, R. M. J. (2006)	Evaluation of Livelihoods and Economic Benefits of Water Utilisation: The case of the Great Ruaha River Catchment in Tanzania	PhD	Physical	Already covered in published papers
Kashaigili, J.J. (2006)	Landcover Dynamics and Hydrological Functioning of Wetlands in the Usangu Plains in Tanzania	PhD	Physical	Already covered in published papers
Kayombo, W.F. (2007)	Effectiveness of River Basin Game in Facilitating Equitable Allocation of Water in Mkoji Sub-catchment of Great Ruaha River in Tanzania	M.Sc.	Physical	No
Kiagho, E.Y. (2003)	Policy Instruments in Integrated Water Resources Management and Sustainable Livelihoods in the Great Ruaha River Basin	M.Sc.	Physical	No
Kyamani, W.A. (2013)	Determinants of Rural Water Project Sustainability: A Case Study of Rufiji District, Pwani Region, Tanzania	M.Sc.	Online Repository	No
Masota, A.M. (2009)	Valuing Water Resource for Baga Watershed Management Using Water Poverty Index (WPI), Lushoto, Tanzania	M.Sc.	Online Repository	No
Mbozi, A.F. (2006)	Evaluation of Irrigation Schedules Under a Traditional Farmer Managed Irrigation System: A Case Study of Usangu Plains in Tanzania	M.Sc.	Physical	No
Mbwilo, A. J. T. (2002)	The Role of Local Institutions in Regulating Resource Use and Conflict Management: The Case of Usangu Plains, Mbarali District, Tanzania	M.Sc.	Physical	No
Ntupwa, N.W. (2010)	Livelihoods and Economic Benefits of Wetland Utilisation in the Little Ruaha Sub-	M.Sc.	Online Repository	No

	catchment, Mufindi, Iringa.			
Rajabu, K. R. M. (2007)	Water Availability and Use Dynamics and the Sustainability of Water Resources Management in The Great Ruaha River Catchment in Tanzania	PhD	Online Repository	Yes

4.5 Hydrological Data: Water Scarcity Analysis

The two most widely applied water scarcity indicators, the WSI and the WTA ratio metric, were used to undertake a historical characterisation of water scarcity in the GRRC. Common to both indicators, as discussed in Chapter 2, is that they use MARR to estimate total renewable water resources (TRWR) availability. The WSI and WTA equations however differ in the way they assess pressure on freshwater resources. The WSI considers water scarcity as a function of population pressure, whereas the WTA ratio approach derives water stress to occur as a ratio of total freshwater withdrawals for domestic, industrial and agricultural (DIA) uses.

4.5.1 Establishing Total Renewable Water Resources availability

The first component for applying the WSI and the WTA ratio metrics is the estimation of total renewable freshwater availability achieved through conversion of observations of river discharge rates (m^3 s^{-1}) into an annual volume of renewable freshwater resources measured in million m^3 a^{-1}. In the GRRC, five perennial upstream rivers (Chimala, Great Ruaha upstream, Kimani, Mbarali and, Ndembera) provide over 85% of the total inflow into the Usangu Plains (Shu and Vilholth, 2013). All rivers receive rainfall from the surrounding Kipengere and Poroto Mountains, and their discharge is gauged at the escarpment along the TANZAM Highway (Tables 4.4 & 5.1) above irrigated areas of the Usangu Plains. Below the Usangu wetlands, the Great

Ruaha River, gauged at the Msembe Ferry gauging station, represents the cumulative downstream flow of rivers into the GRRC after irrigation uses.

The duration and degree of completion of the daily observed discharge records was highly variable for all gauged rivers. The implications of this was that continuous and uninterrupted records of long-term observed discharge for all rivers did not exist, and often periods of missing data ranged from months to years. Table 4.4 illustrates the length of each discharge record and their degree of completeness. The longest records go back to 1st October 1954; the GRR and Kimani River, with ~17% and ~5% of daily observed discharge missing, respectively. The discharge records were plotted against each other in an attempt to establish common time periods where the disruption to their completeness was minimal (Appendix 6). Resulting were three time periods of approximately equal length with minimal overlaps comprising two eight-year windows (1st October 1972 – 30th September 1980 and 1st October 1998 – 30th September 2006) and a smaller five-year window (1st October 2006 – 30th September 2011). In instances where less than five days of continuous observations were missing, a simple linear interpolation technique was applied between the data observed before and after the gaps. Where the gap ranged between five and 15 days, it was filled in by calculating the long-term average mean flow of the particular date(s) during the particular time period.

Table 4.5: Summary of gauging stations records

River	Gauge reference	Record Time-series	Completeness of record (%)
Chimala River	1KA7A	01/10/1972 – 30/09/2011	~68
Great Ruaha River (GRR)	1KA8A	01/10/1954 – 30/09/2011	~83
Kimani River	1KA9	01/10/1954 – 30/09/2011	~95
Mbarali River	1KA11A	01/10/1955 – 30/09/2011	~85
Ndembera River	1KA15A	01/10/1970 – 30/09/2011	~90
GRR, Msembe	1KA59	01/10/1963 – 30/09/2011	~67

4.5.2 Establishing pressure on water in the WSI: Population

The population component of the water scarcity analysis was taken as the sum of the populations in the five sub-catchments. A stable historical growth record of 3% is reported in SMUWC (2001) and RIPARWIN (2006). This study takes the 2001 population figure from RIPARWIN (2006) and applies an annual 3% population growth between retrospectively between 1972 – 2011 (Table 4.5; Figure 3.4, p. 84).

Table 4.6: Historical population increases in the GRRC based on retrospective extrapolation of annual 3% population growth from 2001 levels (RIPARWIN, 2006)

Year	Population	Year	Population	Year	Population	Year	Population
1972	80 911	1982	109 564	1992	148 576	2005	220 172
1973	83 294	1983	112 952	1993	153 171	2006	226 777
1974	85 870	1984	116 445	1997	173 018	2007	233 580
1975	88 525	1985	120 047	1998	178 369	2008	240 588
1976	91 263	1986	123 760	1999	183 885	2009	247 805
1977	94 086	1987	127 587	2000	189 572	2010	255 239
1978	96 996	1988	131 533	**2001**	**195 435**	2011	262 896
1979	99 996	1989	135 601	2002	201 770		
1980	103 088	1990	139,795	2003	207 823		
1981	106 277	1991	144 119	2004	213 759		

4.5.3 Establishing pressure in the WTA ratio indicator: Defining water demand

The historical expansion of irrigated agriculture in the GRRC occurred over three stages (SMUWC, 2002). Prior to 1974, the area under irrigation in the Usangu Plains was small and the impacts on water resources minor (SMUWC, 2001). The first period of assessing water scarcity in the GRRC using the WTA indicator commences in hydrological year 1974, coinciding with available data on irrigated agriculture. A second window of irrigation expansion occurred in the mid-1980s, as the Government of Tanzania promoted agricultural trade liberalisation and policies that focused on increasing countrywide irrigation capacity. The third window of irrigation expansion began in the early 1990s, and by 1999 the area under irrigation using surface water had reached its maximum cover [4] (SMUWC, 2001).

No consistent reporting of historical annual water withdrawals were obtainable for the sake of this thesis. As such, annual water withdrawals were calculated as the sum of dry- and wet-season water withdrawals derived in two independent manners (i.e one for each season). First, monthly historical water withdrawals (1974 – 1999) for the 182 day dry-season (1st June – 30th November) were reported in SMUWC (Report 7, 2001:120, Figure F7.9) and could therefore be adopted directly into this study. Second, historical water withdrawals during the wet season (extending over 183 days from December 1st – May 31st) were derived from reported figures for the rates of the total installed irrigation withdrawal capacity (Table 4.6) at the beginning and end of each of the three periods of major agricultural expansion (SMUWC Overview Report, 2001:54, Table 3). This method for deriving wet season water withdrawals, however, is subject to two caveats. First, the estimate of annual water withdrawals assume that within each period of reported installed irrigation capacities, development of installed irrigation rates was linear, allowing for linear interpolation. Each annually derived installed withdrawal rate was then converted into a volumetric unit in million m^3 for six months that constitute the wet season. Secondly, the estimation of wet-season water withdrawals relies on the assumption that withdrawal intakes operate at full capacity over the six month period.

In 1999, reports indicate that the GRRC catchment had reached its maximum level of installed withdrawal capacity in the large irrigation schemes of 45 m^3 s^{-1}

[4] This figure was estimated by an irrigation impact modelled developed for the project, which estimated suggested that the amount of water available through the Usangu intakes during a historical statistically normal-to-wet year could bring in a maximum area under irrigation of ~ 41 000 ha SMUWC (2001, Supporting Report 8). Coupled with the SMUWC Community Irrigation Specialist furrow survey estimated there was ~41 000 ha of irrigated area and the SMUWC aerial photograph interpretation and survey which found ~ 43 000 of irrigated land, the figure 42 000 ha is the mean of these three studies.

coinciding with the time that the maximum irrigable area had been reached (SMUWC, 2001: Supporting Report 8, Table 2.9 & Appendix E); RIPARWIN, 2006) [5]. No readily available data on annual or wet- and dry-season water withdrawals since 1999 were obtainable. Therefore, the study assumes that for the period 2000 – 2011, withdrawal rates for both the dry- and wet season remained constant at 1999 levels with no significant variations within each year. The validity of this assumption is based on an understanding that irrigation intakes are constantly left open and unregulated throughout the entire year, equating to a constant withdrawal rate at 1999 wet- and dry-season levels, respectively. This assumption is thought to have support for two reasons. First, both SMUWC (2002) and RIPARWIN (2006) report primarily broken or missing intake gates at the major irrigation schemes and former NAFCO schemes as well as levels of water use efficiency below 10%. Second, a decade later, fieldwork undertaken in August 2015 and November 2016 noted that at all major NAFCO irrigation schemes, intake gates and sluices were either missing or broken resulting in continuous and unregulated flows into secondary and tertiary irrigation canals.

Table 4.7: Estimated yearly irrigation withdrawal rates through interpolation and assuming a linear growth rate between the start and end date of each of the three periods (in bold) of major agricultural expansion (1973 – 1999) as reported in SMUWC Overview Report (2001:57, Table 3.12)). All values are rounded.

Year	$m^3 s^{-1}$	Year	$m^3 s^{-1}$	Year	$m^3 s^{-1}$	Year	$m^3 s^{-1}$
1973	**17**	1980	23	1987	31	1994	38
1974	18	1981	24	1988	31	1995	40
1975	19	1982	26	1989	32	1996	42
1976	20	1983	27	1990	33	1997	43
1977	20	1984	28	**1991**	**34**	1998	45
1978	21	**1985**	**29**	1992	35	**1999**	**45**
1979	22	1986	30	1993	37	-	-

[5] Total abstraction capacity of water by intakes were derived from historically documented figures associated with the development and installations of water abstraction uptakes, reported as the maximum flow intake, as measured by the Mbeya Ministry of Water technicians, consultation of operational manuals for the NAFCO Farms and statements from water officers.

4.6 Positionality of the researcher

The investigator's motivations for their work; their views on scientific acquisition and their previous work experiences on the topic influences the research design and process (Bryman, 2004). Awareness and reflection of the unintentional and subconscious influence that they exert to shape the outcome of the field procedure; the relationships with respondents and collaborators. Thus, positionality serves as an internal protocol, **pre-, peri- and post** field investigation and serves as a constant exercise of reflexivity. This section briefly presents the principles that was crucial to continuously be aware of throughout the research period – the researcher's positionality protocol.

4.6.1 Researcher Credibility and Academic Diplomacy

The invitation from my Grofutures colleagues to become a Research Associate at SUA was a decisive factor in the success of this research and a much more favourable way to integrate into the local research environment. So, I quickly came to realise that my period of fieldwork was not purely for data collection but also to immerse myself into a foreign research culture.

Indeed, first impressions count when instigating field research, and not surprisingly, the fact that I was a white, foreign and male researcher from a well-established university made me stand out upon entering the study sites. The affiliation with SUA and the value that the Letter of Reference from the SUA Vice-Chancellor to the Administrative Executives carried should not be undermined because this gave us credibility amongst the respondents, we worked with and that we conducted the work in good faith. It was apparent to me very early on, that if I had not been affiliated with SUA, it would have been near-impossible to access any of the field sites and therefore I constantly reminded myself that not only did I represent UCL and the good will of visiting researchers but I also represented SUA and my conduct would reflect back on these two institutions.

The official administrative language of Tanzania is Kiswahili, and even if English is the official language of teaching across all universities, everybody spoke Kiswahili, so I was heavily reliant on interpreters during the field visits. Prior to my first fieldwork period, I took some language lessons to learn the most basics of the language as I know from previous work experiences in the region how important this is. Indeed, in a society like Tanzania which has its own customs and puts a big emphasis on greetings and that they are undertaken in the right "subject form", knowing even just a small amount of the basics can be imperative of whether a good rapport is reached. Thus, I constantly worked on the basis to remind myself about the conduct I was expected to observe both as both a representative of UCL and of SUA but also worked on the premise of showing good researcher conduct with local collaborators and follow and respect local procedure and norms.

4.6.2 Mutual respect, understanding and reciprocity

The principles of mutual respect towards both field collaborators, SUA colleagues and staff research participant was constantly applied throughout the entire research period. Indeed, I worked hard to integrate myself into the academic life at SUA, particularly by engaging with the "Ph.D. Club" – a reading group of local research students who met and discussed their research. During the second fieldwork I even felt myself as a bit of a supervisor or mentor towards the two Ph.D. students during the construction of the research survey and the following period of field visits. I assisted them by contributing with my experiences on many of the practical matters such as setting up FGDs, I drove, I paid for petrol and printing, and in return they assisted in interpretation and data acquisition.

With regards to my relationship with respondents in the field, I treated the participants with respect, no matter whether they were rural farmers or civil servants and experts. There was a general interest in the work of my thesis and overall of the GroFutures project. Most of my interaction with the respondents were time-limited, either as a "one-off" meeting or they would be encountered on the streets of the villages we worked in. but this would be in an informal capacity and we would just greet each other, out of pleasantry and respect.

One issue of contention that was apparent, but discrete regarded some government data that I had a difficult time to gain access to. As data on various hydrological components are scarce in many African countries access to- and sharing of data is a sensitive issue and in my case I had to demonstrate not only how I would use the data, but also how there would be mutual benefits in terms of acknowledgements and publication credits.

4.6.3 Prior and Informed Consent

We always ensured that the informants that took part in our FGDs, interviews and oral surveys were informed about the research and that they gave their informed consent before the data collection started. Indeed, the UCL Ethics Committee had earlier granted my research ethics approval under which I had both provided an Information Sheet (Appendix 7) and a Consent Form (Appendix 8).

In real world research, the researchers may come across many cases of illiteracy. Therefore, whereas it may be ideal to get the consent form signed in writing, we found that it was best to read out the information sheet and consent form and get their consent orally by ticking a box. The respondents were also informed that they were not required to participate and could withdraw their participation at any time.

In an ideal world, the researcher-respondent relationship should be straightforward and the participants should be able to act as they please in relation to the investigation. The presence of our local liaison, a man of political influence, from my observations had the influence that a number of respondents felt obliged to participate as if they had been ordered to do so, and were not comfortable to speak their minds freely. We managed to relinquish of his presence in the villages after the second day as the village committees had approved our presence. In part as I noted before, monetary tokens of appreciation have much more influence to incentivise research participants than soft drinks or "the benefit of our research". So, despite the controversy regarding whether to pay respondents and gatekeepers, it was necessary to take the stance that this was required. We did not pay for their information but we paid for compensation of their time. Many Western researchers view this approach as unorthodox, and granted there is the risk that we foster a culture of the impression that the foreign researcher will come and distribute money. However, as I worked with a team of Tanzanian researchers, often some of them having origins in the area, this would not foster the fear that many authors claim. The research team did not give individual payments but in front of all participants, a lump sum to each village executive, who would be held accountable for the distribution of money to those that agreed to pay. Thus, beyond informed and prior consent, the incentive to participate has to be borne in mind in research environments that are different than from the West. Every payment was signed for and considered the equivalent to an honorarium

4.6.4 Safety of participants

The research as such did not deal with any sensitive matters in the sense of the questions asked during the interviews; the oral survey and the FGDs. However, we did our outmost to ensure anonymity amongst all respondents both those interviewed and those that answered the survey, because some of the questions did relate to aspects of income, credit worthiness and asset and land ownership. However, one Co-PI mentioned that in the small hamlets and village the inhabitants know each other, and know what the other's do. During the FGDs it was clear that there was some contentious issues regarding competition for water use between farmers and livestock keepers, and as the FGDs had representatives of both, this confrontation was unavoidable. However, in this thesis we do not use any of the first names and all respondents were coded to ensure anonymity for the sake of good practice.

4.6.5 Safety of researcher

To ensure safety to myself was one of the key preparatory steps I took before I was granted permission to leave for fieldwork. A detailed risk assessment was carefully undertaken in order to demonstrate what risks I identified and what I would do to minimise them to happen and what strategy to apply in case I did get in trouble. It is vital to be "street smart" when doing real world research, especially in developing countries, where a foreigner sometimes is considered nothing more than someone to opportunitise financially from. I had previous experience of working in similar environments and on the same topic, so I felt adequately prepared to enter the field with good knowledge of what to be aware of and to ask around in order to avoid dangerous areas, circumstances, people or areas. Due to the close proximity that I would often have when I worked with my SUA collaborators, I hardly ever found myself alone in an area that I did not already know. Driving on the roads can be dangerous, but I did so myself alone and with my research assistant, and learnt by experience and observation about the unwritten rules of the road and how to deal with police check-points. I only rented vehicles from a reputable car rental agency and had the car checked by local mechanics that I knew that I could trust. When undertaking fieldwork one learns day by day, and there is no way to possibly safeguard yourself against everything but it is crucial to have considered what to do if certain situations, even extreme events, do occur.

Chapter 5 - Results and Discussion I: Field-testing water scarcity indicators in the Great Ruaha River Catchment, Tanzania.

5.1 Introduction

Chapter 5 addresses the first research objective which is to examine the characterisation of water stress- and scarcity over time by applying the WSI and the WTA ratio metrics to semi-arid GRRC. The WSI and the WTA ratio metrics are commonly applied at the national scale and used to provide a snapshot characterisation of water scarcity for an entire country.

Chapter 2 showed that there is a dearth of studies that systematically investigate the meaning behind the varying characterisations of scarcity that the WSI and the WTA produce. Studies that apply these metrics to assess water scarcity, remain largely limited to national- and global-scale investigations (Chenoweth, 2008) and are commonly used in deterministic modelling of climate change impacts on water scarcity (Vörösmarty *et al.*, 2000; Alcamo *et al.*, 2003; Arnell, 2004; Oki and Kanae, 2006; Wada *et al.*, 2011; Schewe *et al.*, 2014). Thus, field-testing these two metrics at the catchment scale over time remains largely unexplored, and provides the opportunity to gain a more thorough insight into the spatial and temporal factors that influence the manner in which they characterise water scarcity.

5.2 Results: Analysing observed discharge

5.2.1 Establishing Total Renewable Water Resources Availability

Figures 5.1a-b, 5.2a-b and, 5.3a-b illustrate long-term observed discharge records, clearly indicating long periods of month or years where data is missing. However, for each record the three dotted lines depict the three time periods used in the thesis, where there was continuous overlapping daily observations available for all six discharge record: 1973 – 1980, 1999 – 2006, and 2007 – 2011.

The first component, the supply function as numerator in the WSI metric equation and denominator in the WTA ratio indicator equation, is the estimation of annual total renewable water resources (TRWR) availability. Annual TRWR, in a volumetric measurement (million m^3 a^{-1}) is computed from estimates of MARR based on observations of river discharge (m^3 s^{-1}). Mean TRWR for the headwaters over the three time periods, calculated as the sum of TRWR of all five upstream rivers, is 1 268 million m^3 a^{-1} upstream and 121 million m^3 a^{-1} downstream at Msembe (Table 5.1). Appendix 8 shows a more detailed table of the aggregated monthly discharge figures for individual rivers.

5.2.2 Inter-annual variability in TRWR

Comparing changes in upstream TRWR (Figure 5.4, Table 5.1) for the first (1973 – 1980) and the last (2006 – 2011) time periods indicate an overall declining trend in long-term freshwater availability of ~17%. Notably, TRWR from upland catchments decreased from 1 508 million m^3 a^{-1} for the period 1973 – 1980 to 1 042 million m^3 a^{-1} for the period 1999 – 2006, resulting in an overall 31% decline in upstream discharge. However, during the 'noughties' (1999-2006 and 2007-2011) mean TRWR for the second and third periods increased by 20% upstream. The inter-annual variability in the highland discharge proves to be highly dynamic at point of measurement before it is influenced by freshwater withdrawals in the Usangu Plains.

Accounting for the inter-annual variability in the difference of TRWR (upstream minus downstream) shows a recurring long-term average of ~(-) 91% of annual upstream discharge at the headwaters consistently lost between upstream gauging stations and

Table 5.1: Total Annual Renewable Freshwater based on MARR (1973 – 1980, 1998 – 2006, 2007 – 2011) million m³

Hydrological Year	Million m³ a⁻¹						
	Chimala	**GRR**	**Kimani**	**Mbarali**	**Ndembera**	**TRWR Upstream**	**TRWR Msembe**
1973	137	616	250	589	189	1 781	181
1974	92	442	235	384	232	1 385	97
1975	94	393	170	324	185	1 166	76
1976	92	412	213	481	239	1 437	149
1977	86	407	162	364	117	1 137	96
1978	104	484	289	588	230	1 695	266
1979	150	768	286	639	230	2 072	360
1980	86	415	152	501	238	1 391	130
Sub-total long-term mean	**105**	**492**	**220**	**484**	**208**	**1 508**	**169**
1999	75	293	103	252	122	845	61
2000	37	206	78	216	78	615	52
2001	106	814	290	512	226	1948	235
2002	97	456	410	450	179	1592	147
2003	37	259	113	191	77	677	21
2004	64	389	110	282	105	951	46
2005	68	394	187	336	149	1133	68
2006	47	145	81	220	79	573	17
Sub-total long-term	**66**	**369**	**172**	**307**	**127**	**1 042**	**80**
2007	87	247	217	409	202	1162	269
2008	86	575	243	499	210	1612	113
2009	88	389	187	394	181	1238	58
2010	93	435	157	529	183	1398	82
2011	82	283	88	287	78	818	13
Sub-total	**87**	**386**	**179**	**423**	**171**	**1 246**	**107**
Total long-term average	**86**	**420**	**192**	**402**	**168**	**1 268**	**121**

Msembe. In the four instances where the difference in proportion of water lost between upstream and downstream gauging stations, is lowest (lower 70th and/or 80th percentile) the timing coincides with periods of *El Nino* events, characterised by above-average water availability upstream and is preceded by an increase in TRWR relative to the previous year in double and triple digits. Downstream long-term average TRWR for the period 1973 – 1980 and 1999 – 2006 at Msembe also declined by ~53% from 169 to 89 million $m^3\ a^{-1}$ (Figure 5.5, Table 5.1). The hydrological system therefore appears to be highly responsive to changes in upstream input. Long-term data suggests that there has to be an excess of upstream discharge of 500 million $m^3\ a^{-1}$ annually in order for the hydrological system to generate any downstream flow at Msembe (Figure 5.6).

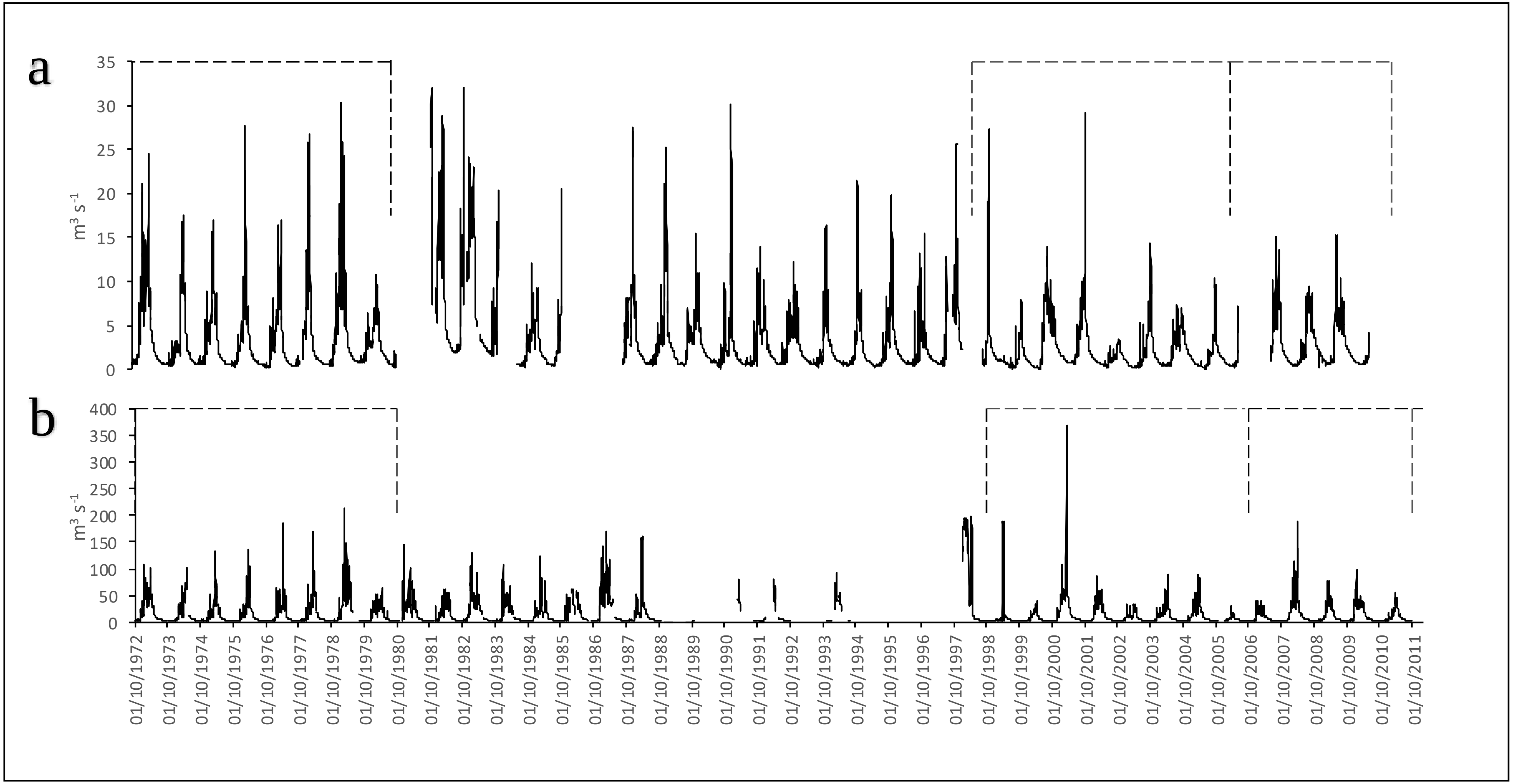

Figure 5.1a-b: Long-term daily discharge a) Chimala River and b) the Great Ruaha River upstream (1st October 1972 – 30th September 2011). The dashed lines delineate the three windows of the study.

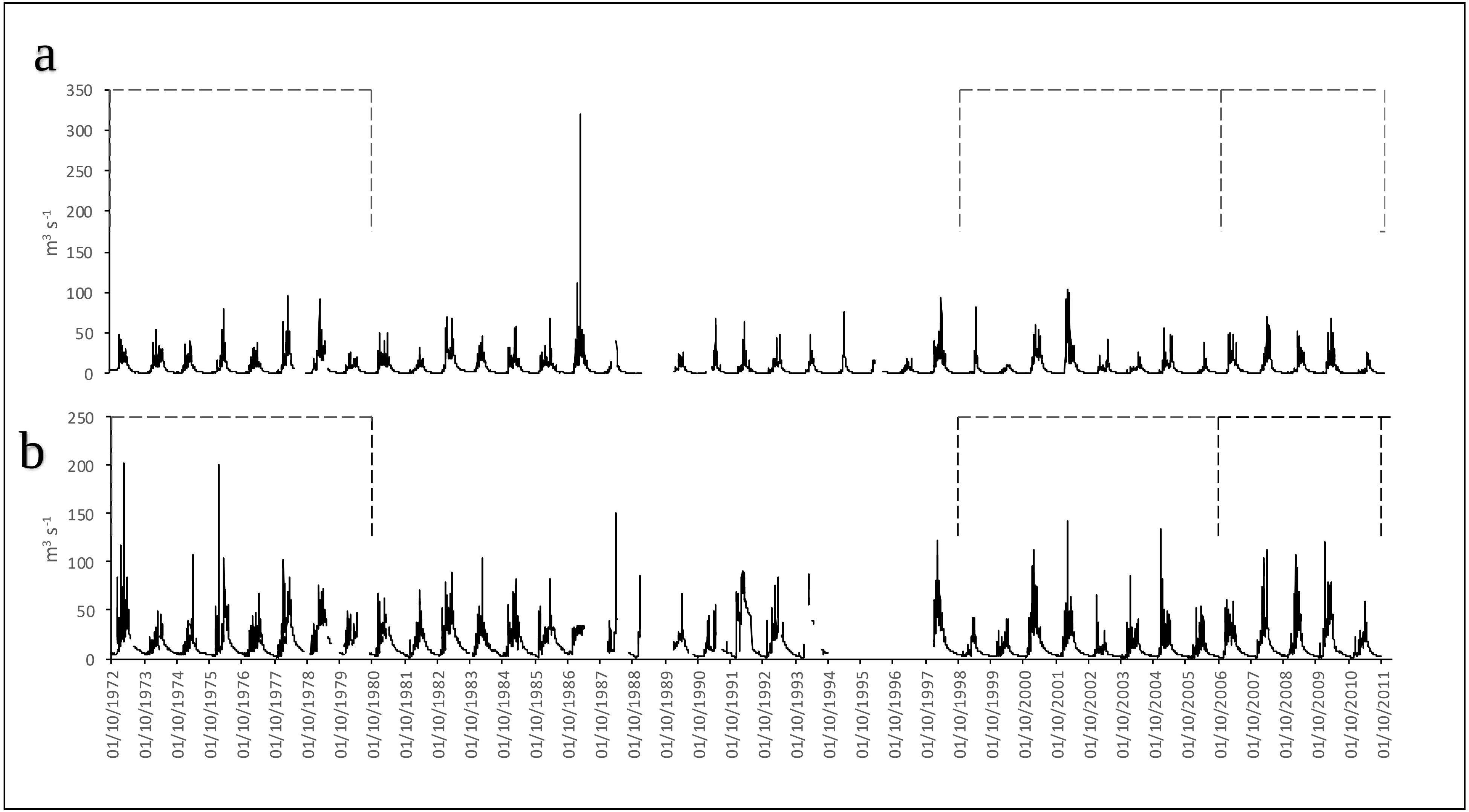

Figure 5.2a-b: Long-term daily discharge a) Kimani River and b) the Mbarali River (1st October 1972 – 30th September 2011). The dashed lines delineate the three windows of the study.

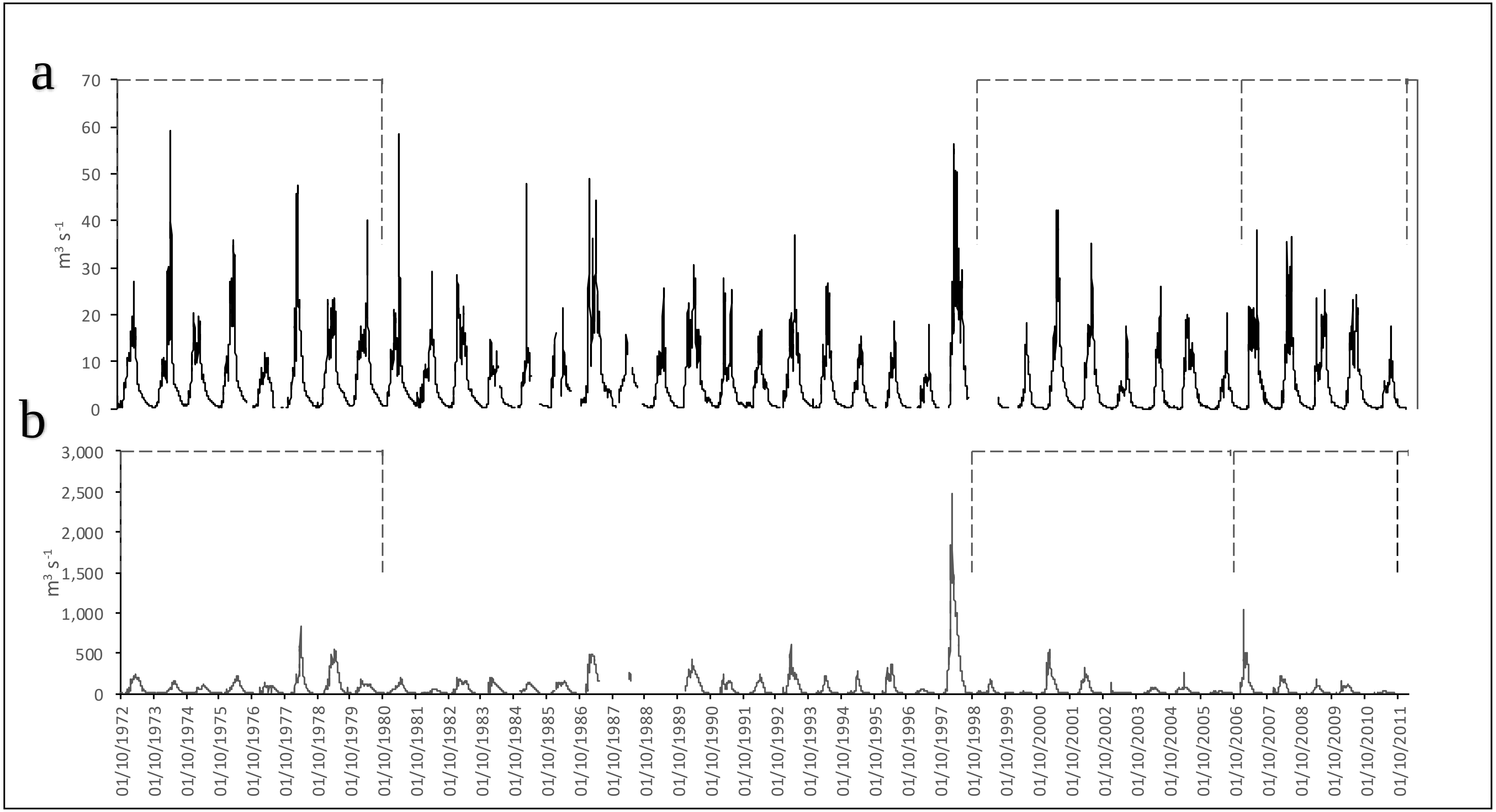

Figure 5.3a-b: Long-term daily discharge a) Ndembera River and b) the Great Ruaha at Msembe, 1st October 1972 – 30th September 2011 The dashed lines delineate the three windows of the study.

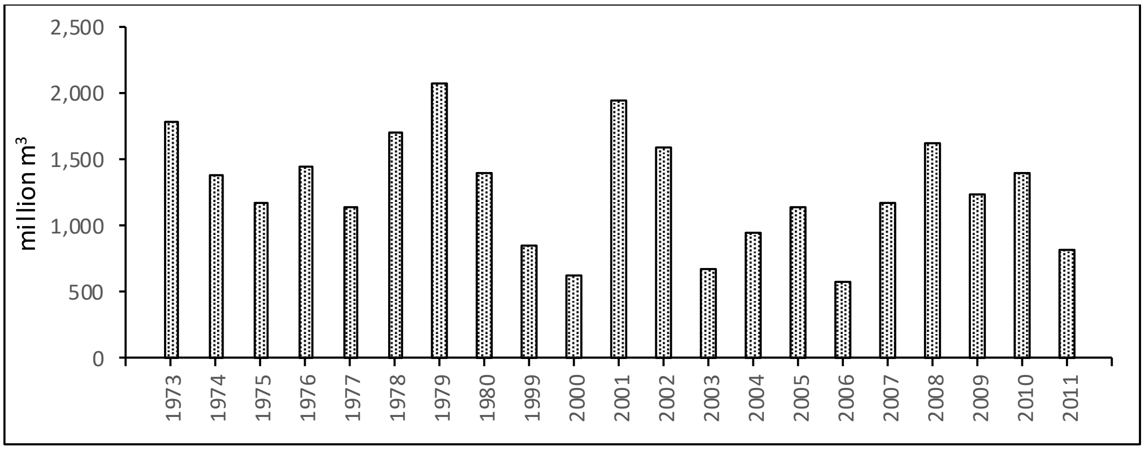

Figure 5.4: Annual renewable freshwater availability of all headwaters summed (million m^3 a^{-1})

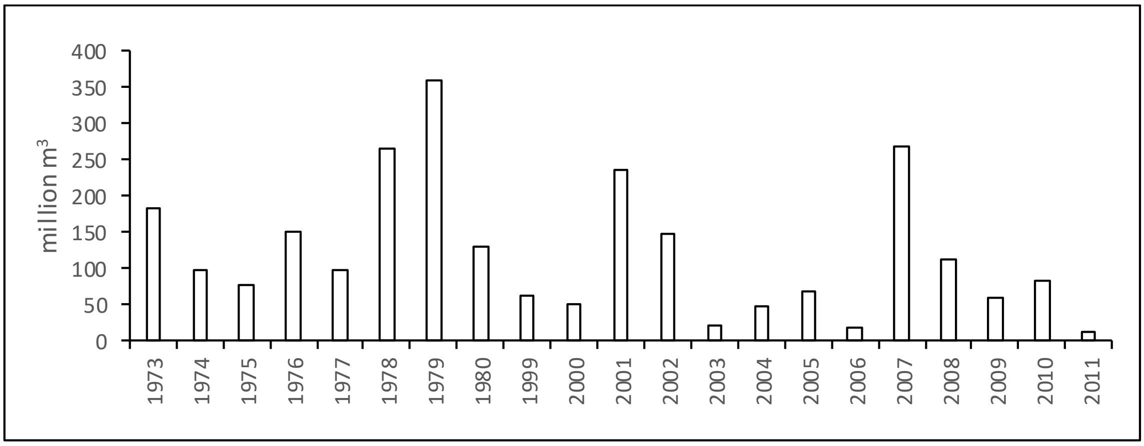

Figure 5.5: Annual renewable freshwater availability of Great Ruaha, Msembe (million m^3 a^{-1})

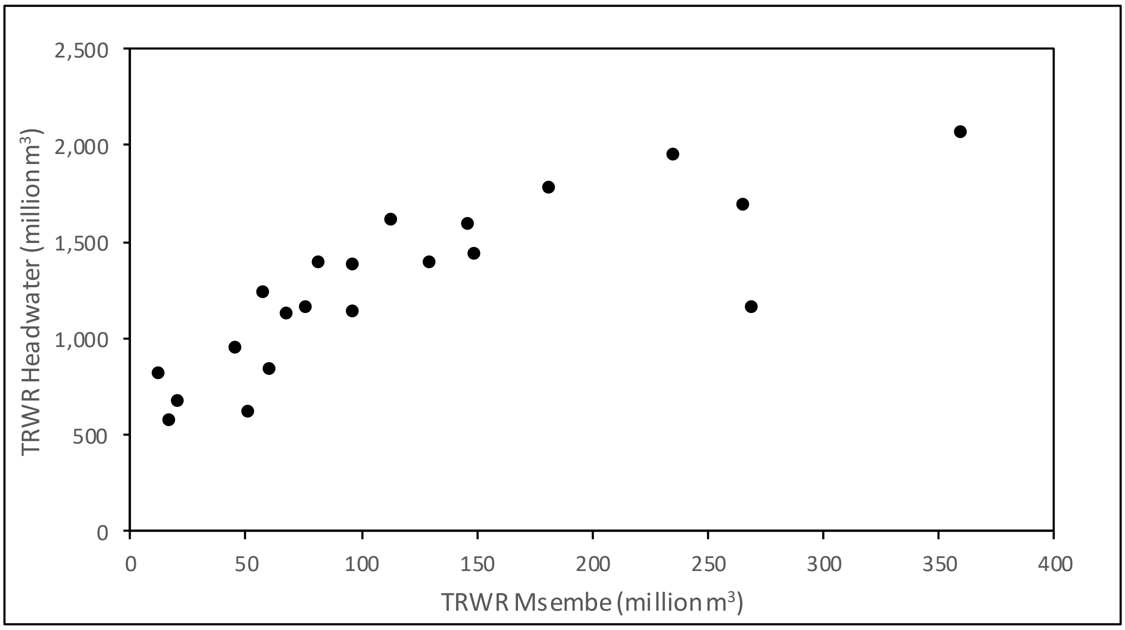

Figure 5.6: Scatter plot showing the relationship between upstream and downstream long-term TRWR (1973 – 1980, 1999 – 2011). The data suggests annual upstream flows must be in excess of 500 million m^3 in order to generate a flow downstream at Msembe.

5.2.3 Intra-annual variability

5.2.3.1 Upstream

The intra-annual variability of TRWR in the GRRC is characterised by a hydrological regime that has a unimodal distribution of discharge for all three time periods studied (Figure 5.7a-c). In August, TRWR in the upstream headwaters during all three time periods approach zero and the variability in freshwater availability at this part of the year, as indicated by the short width of the error bars, is low. Between August and November the rise in TRWR for time periods 1999 – 2006 and 2007 - 2011 has decreased compared to the first time period (1973 – 1980). From November onward the limb rises until peak discharge for all three time periods is reached in March. For the last two time periods, however the slope in the rising limb is more rapid than for the first time period. Between January and February, the hydrographs for the first two time periods show a minor stagnation in the rising limb, whereas the same part of the year during the last time period is more steady. Ultimately, as TRWR increases towards peak discharge so does the degree of variability in monthly available discharge. Appendix 9 illustrates the intra-annual variability for the five individual upstream rivers.

Thus, data on the long-term intra-annual behaviour of the hydrological regime suggests that the overall pattern of the upstream sub-catchments, characterised by unimodal distribution commencing and ending at the same period for each time window, has not changed significantly over the three time periods studied. However, long-term levels of dry-season flows have been decreasing over time, although the lowest flow levels are commonly experienced in August. The level and rate of recovery, however over the last two time periods have become lower in comparison to the first time period.

5.2.3.2 Downstream

The intra-annual hydrograph trends for the three time periods downstream (Figure 5.8a-c) show a higher degree of monthly variability in TRWR at peak discharge than upstream. Over time, peak discharge occurs earlier during the year, occurring in April during the first time period compared to February and March for the second and third time period, respectively. The onset of the rising limb occurs earlier in the year for the last two time periods (Figures 5.8b and c) compared to the first time period (Figure 5.8a). Additionally, the last two time periods also see peak discharge levels stagnate and remain flat over the wet season period. Finally, the last two time periods also experience a significantly lower magnitude of dry season discharge from May onwards compared to the first time period, yet all experiencing minimum and near zero flow conditions around August.

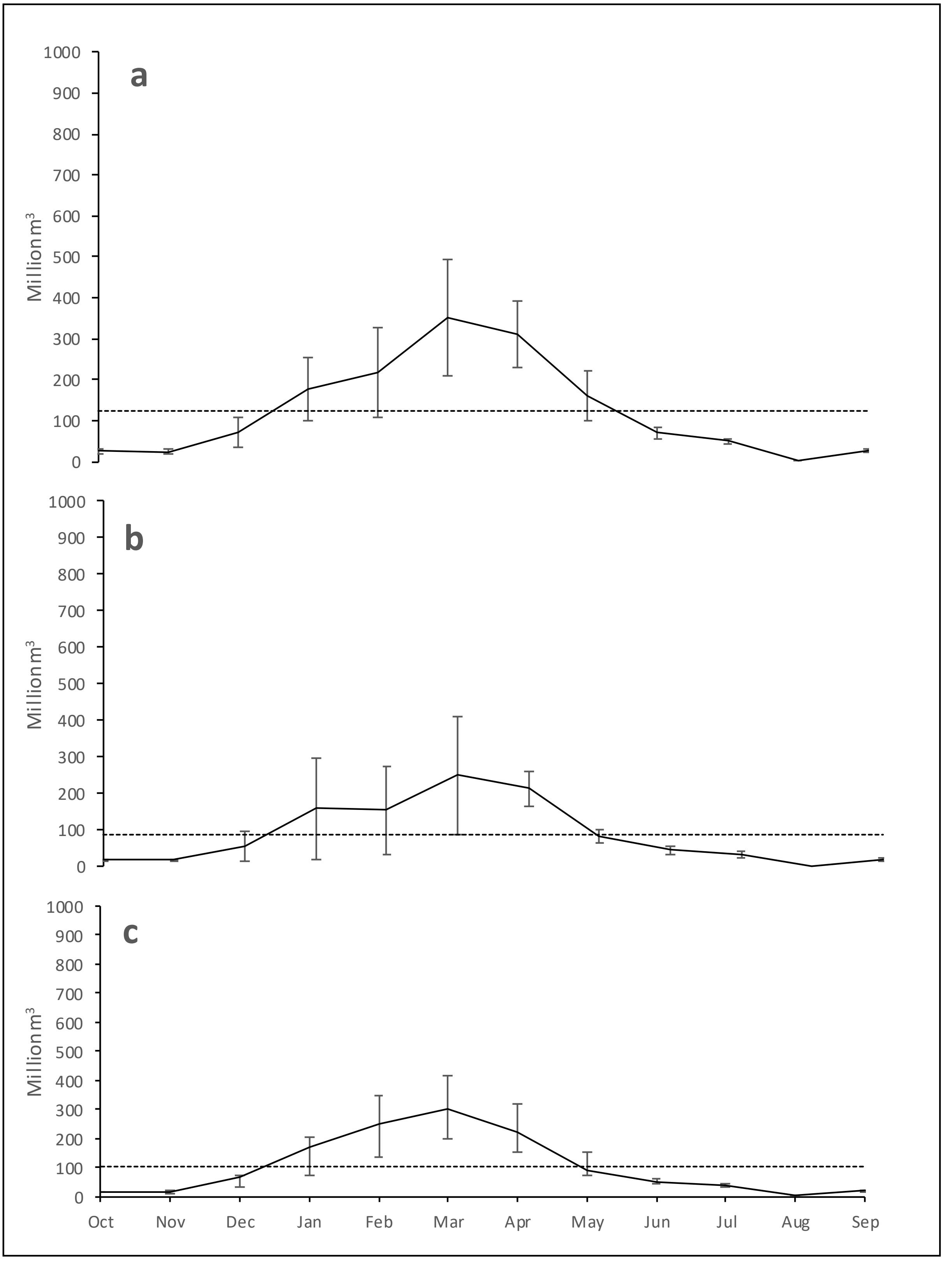

Figure 5.7a-c: Intra-annual behaviour of upstream headwaters for time period a) 1973 – 1980, b) 1999 – 2006, c) 2007 – 2011. The dotted line shows MARR for the time period and error bars depict variability characterised by standard deviation

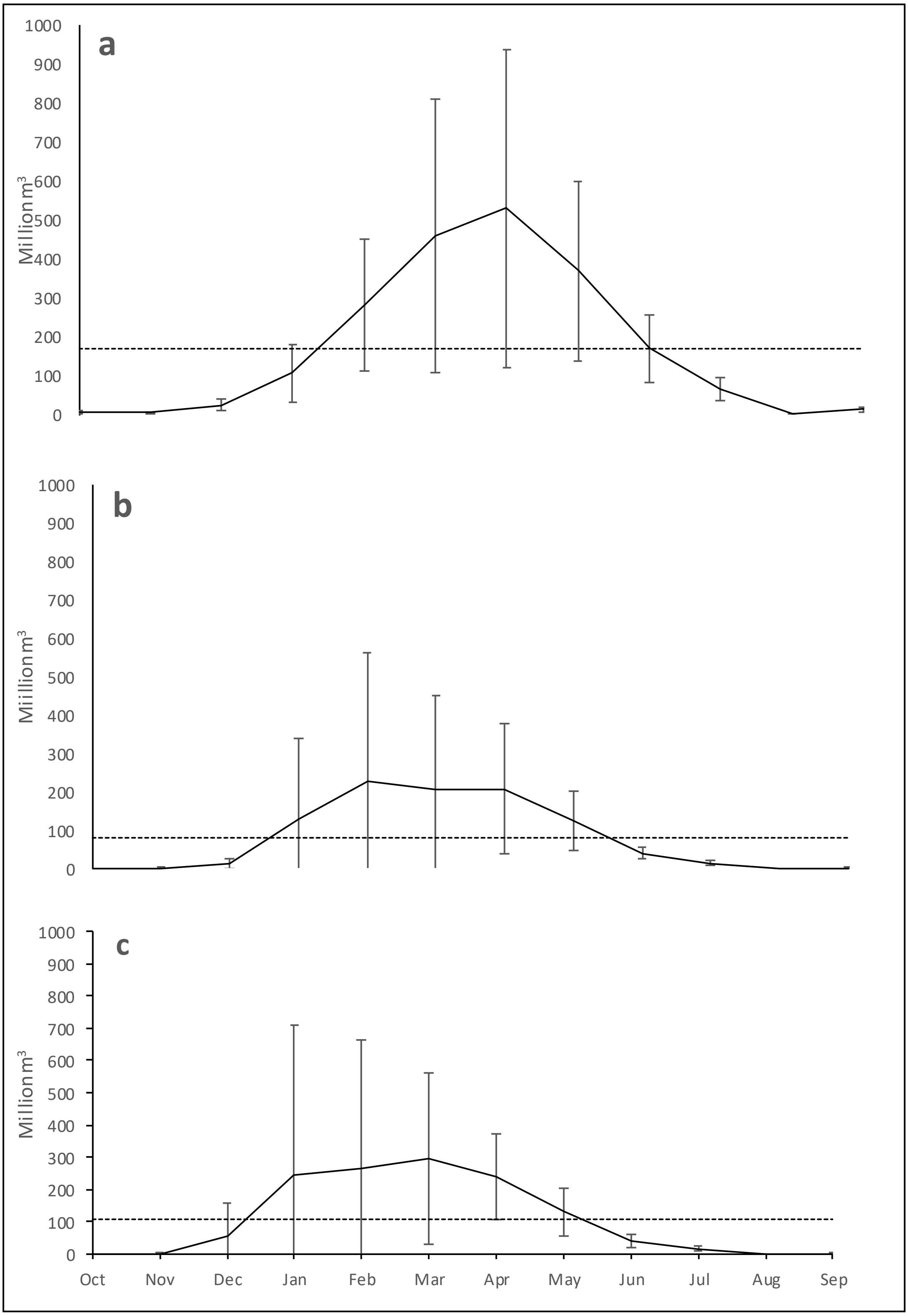

Figure 5.8a-c: Intra-annual behaviour downstream at Msembe for time period a) 1973 – 1980, b) 1999 – 2006, c) 2007 – 2011. The dotted line shows MARR for the time period and error bars depict variability characterised by standard deviation.

5.3 Results from applying the WSI in the GRRC

The results of applying the WSI upstream and downstream for the three time periods (1973 – 1980, 1999 - 2006 and, 2007 – 2011) are shown in Table 5.2. Upstream, the scores for WSI, range from as high as 21 382 m^3 capita yr^{-1} in 1973 to 2 527 m^3 capita yr^{-1} in 2006. The mean WSI score is 16 257, 5 135 and, 5 052 m^3 capita yr^{-1} for the three time periods, respectively. These scores are well-above the thresholds for both absolute water stress (< 500 m^3 capita yr^{-1}), water stress (< 1 000 m^3 capita yr^{-1}) and water scarcity (<1 700 m^3 capita yr^{-1}). WSI, measured downstream at Msembe gauging station show WSI scores that range from 3 604 m^3 capita yr^{-1} in 1979 to 49 m^3 capita yr^{-1} in 2011, with a mean score of 1 803, 404, and 445 m^3 capita yr^{-1} respectively for the three time periods. Figures 5.9 and 5.10 compare the relationship between WSI score and MARR upstream and downstream. Over time, the yearly TRWR and the WSI score have decreased. Similarly, in figures 5.11 and 5.12, which compare the population with WSI upstream and downstream, the levels of water scarcity increase with population.

Water stress according to the WSI has decreased over time upstream, but depicts the headwaters as water abundant. However, downstream at Msembe, mean long-term WSI over the first time period is approaching the threshold for water scarce conditions and drops to values well below the thresholds for absolute water scarcity during the last two time periods. Within the limitations of the data collected, these results demonstrate the vast spatial differences in levels of water stress that the WSI indicator is able to produce within a catchment. Indeed, the same population pressure is applied to both the upstream and downstream measurements of TRWR and is the reason for the highly contrasting characterisations of water scarcity. However, this finding illustrates the different characterisations of water scarcity that can be derived according to the WSI approach. While the downstream results are at fault of double counting, the assumption that it is the same population pressure that the WSI methodology prescribes is valid, considering the fact that when applied at the national scale, the assessments only regard one point of measurement which does not indicate whether freshwater supply is measured as an input occurring before withdrawal or afterwards.

Table 5.2: Historical characterisation of water scarcity using the WSI in the UGRRC (1973 – 2011)

Hydro Year	WSI upstream (m^3 capita yr^{-1})	WSI Msembe (m^3 capita yr^{-1})	Hydro Year	WSI upstream (m^3 capita yr^{-1})	WSI Msembe (m^3 capita yr^{-1})
1973	21 382	2 177	**2003**	3 258	100
1974	16 129	1 127	**2004**	4 449	215
1975	13 171	860	**2005**	5 146	311
1976	15 746	1 631	**2006**	2 527	75
1977	12 085	1 025			
1978	17 475	2 739	**2007**	4 975	1 153
1979	20 721	3 604	**2008**	6 700	470
1980	13 493	1 259	**2009**	4 996	235
			2010	5 477	320
1999	4 595	331	**2011**	3 111	49
2002	7 890	728			

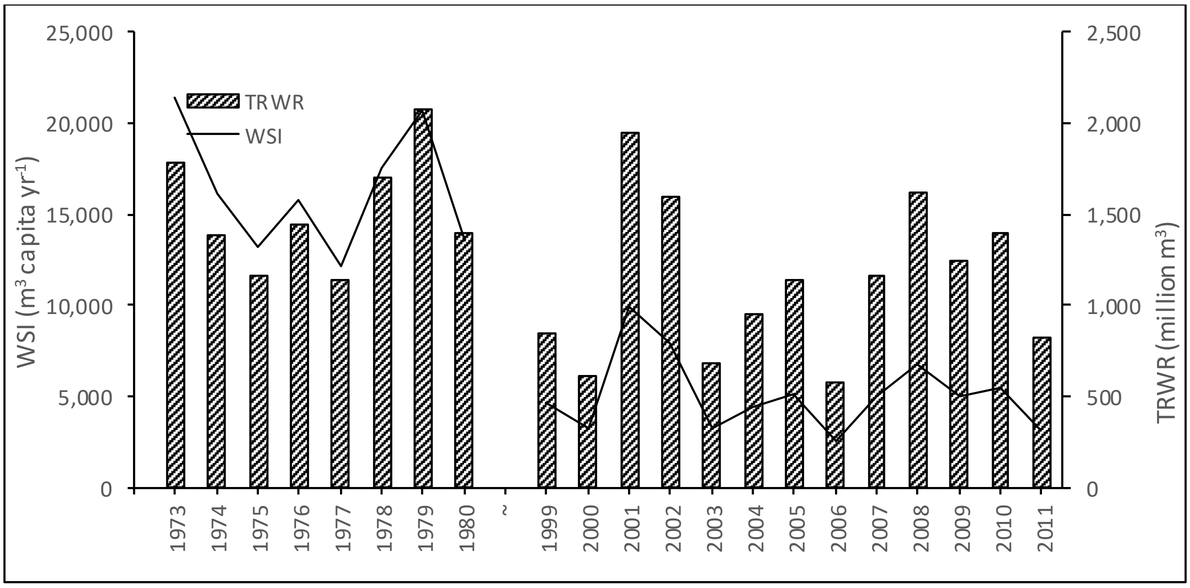

Figure 5.9: Relationship between WSI and MARR at upstream headwaters

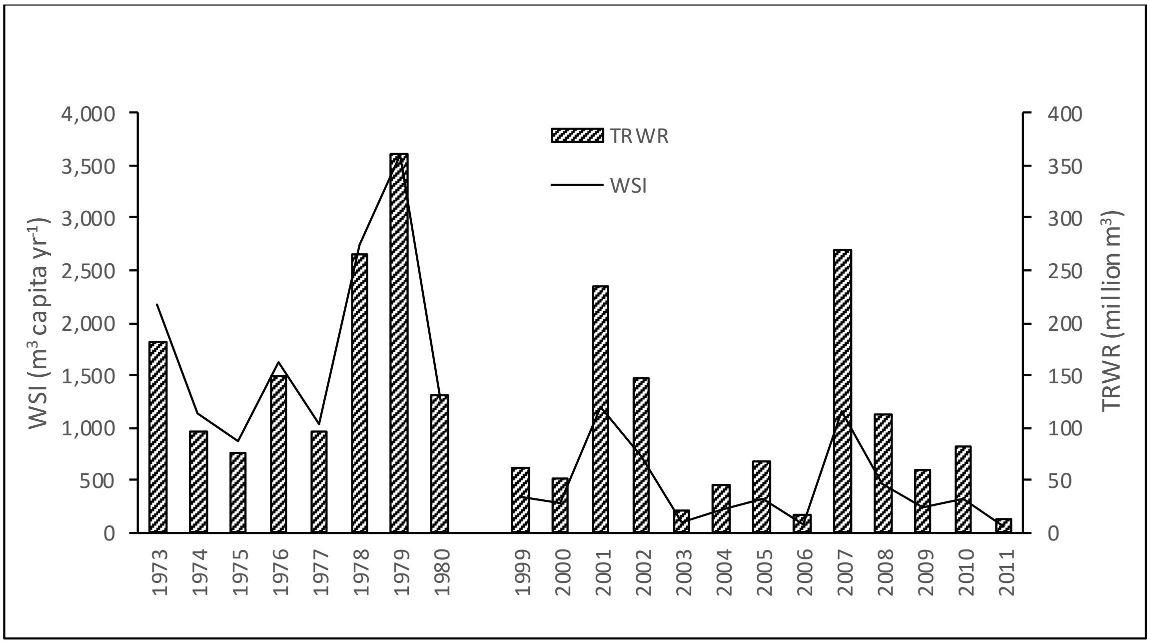

Figure 5.10: Relationship between WSI and MARR downstream at Msembe

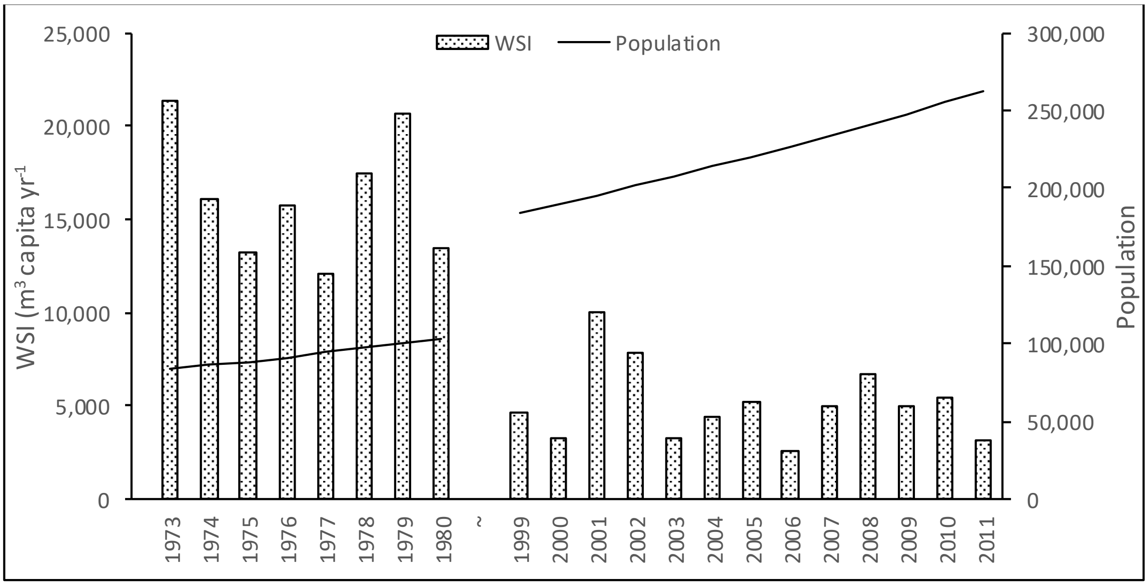

Figure 5.11: Relationship between MARR and population at upstream headwaters

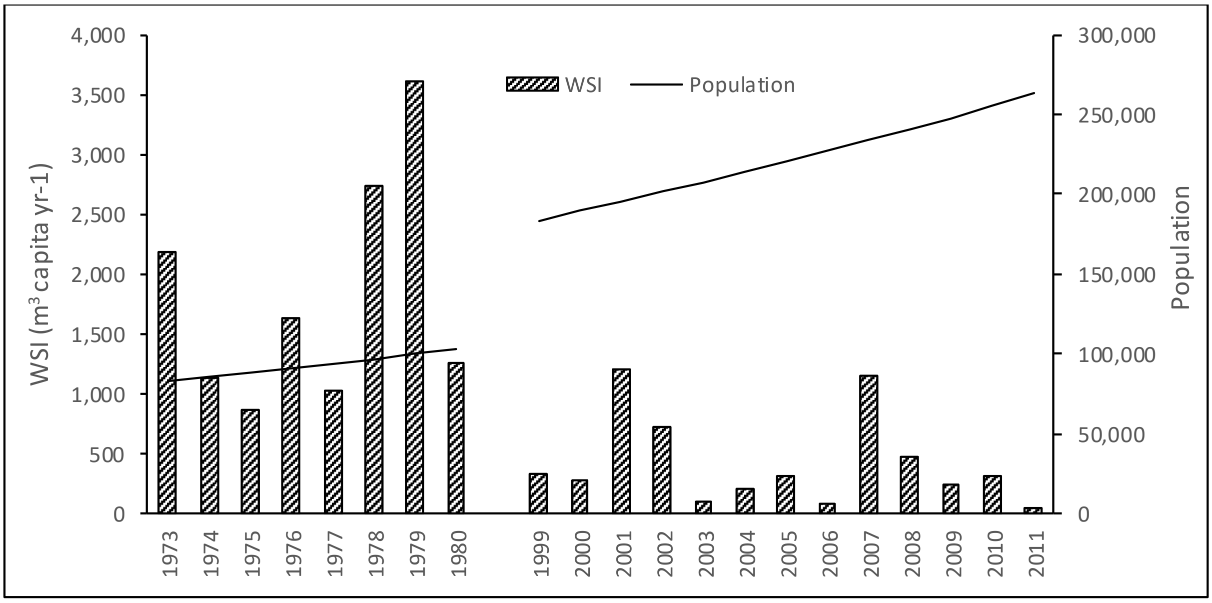

Figure 5.12: Relationship between MARR and population downstream at Msembe

5.4 Water Scarcity according to the WTA ratio indicator in the GRRC

The WTA ratio compares the total amount of annual renewable freshwater resources withdrawn to fulfil domestic, industrial and agricultural water demands to total renewable freshwater resources availability. If, the WTA ratio is above 40% (0.4), the study area is under stress. The supply side function of the WTA ratio indicator, similar to the WSI metric is derived from TRWR and the values for this second analysis therefore remain the same. Whereas demand in the WSI indicator was a function of population pressure, the next section estimates the demand function of the WTA ratio metric as a function of annual freshwater withdrawals for irrigation. The analysis is only concerned with measuring water scarcity according to the WTA ratio metric upstream, as to do so downstream at Msembe with the same level of withdrawals would be to double count, because this water has already been used. Please see Chapter 4, Section 4.5 for a detailed explanation of the assumptions and sources used to estimate historical water withdrawals in the GRRC.

5.4.1 Annual water withdrawals (1972 – 1980, 1998 – 2006, and 2007 – 2011)

Annual agricultural water withdrawals increased from ~370 million $m^3 a^{-1}$ in 1974 to ~1 000 million $m^3 a^{-1}$ in 1999, equivalent to a long-term increase of ~173% or an annual growth in water withdrawal capacity for irrigation of ~7% over 25 years (Figure 5.13). After 1999, no separate data on annual water withdrawals were available, by which the maximum level of irrigable land had been reached (SMUWC, 2001). The need to improve efficiency in irrigation water use has been stressed (RIPARWIN, 2006) but significant efforts so far have not been explicitly documented, and the state of irrigation schemes described in (SMUWC, 2001) and RIPARWIN (2001) match those observations made during this thesis in 2015 and 2016 (see section 4.5.3, p.120 for more details).

The working assumption is that during the period 2000 – 2011, the 1999 dry- and wet season water withdrawals remained constant with no change or variation within the seasons each year. To support this assumption, SMUWC (2001) reports that the 1990 - 1999 average dry season withdrawal capacity of irrigation water is 19 $m^3 s^{-1}$, the same withdrawal capacity reported for 1999 (see section 4.5.3, p.120 for more details). Indeed, these figures back up the conjecture that dry season water withdrawals peaked at the rate of ~740 million $m^3 a^{-1}$.

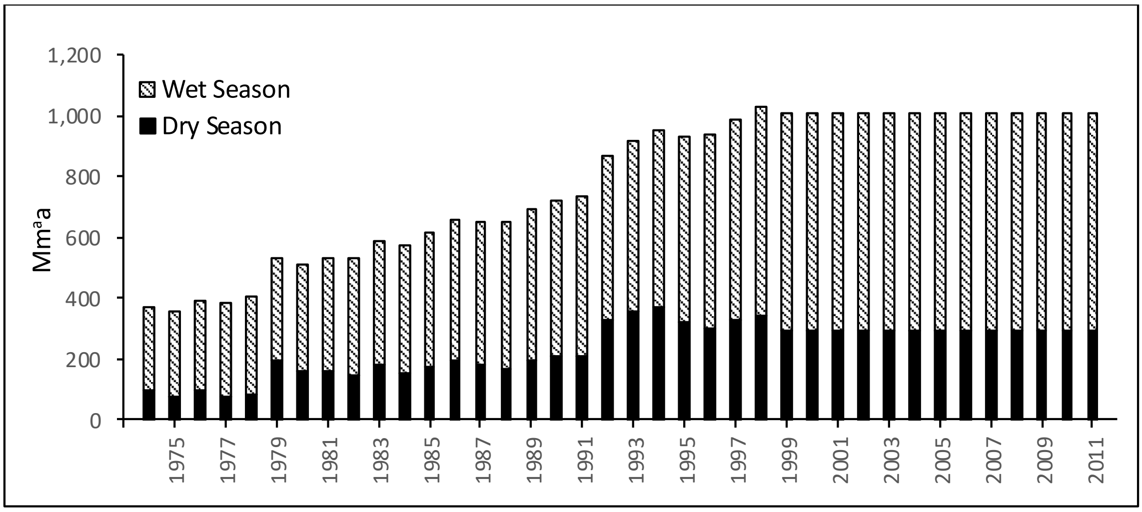

Figure 5.13: Annual Water withdrawals in the GRRC (1974 – 2011)

5.4.2 WTA Ratio upstream

The average WTA ratio for the time period 1974 – 1980 is 0.3 and during the periods 1999 – 2006, and 2007 – 2011, the ratio scores have increased to 1.1 and 0.9, respectively (Table 5.3, Figure 5.14). Over the first time period, annual WTA ratios were below the water stress threshold ratio of 0.4, with the highest WTA ratio score being 0.37 in 1980. However, over the course of the two later time periods, the WTA ratio threshold is continuously exceeded.

Table 5.3: Historical WTA scores upstream of the Usangu Wetlands

Hydro Year	WTA upstream	Hydro Year	WTA upstream
1974	0.21	2002	0.47
1975	0.31	2003	1.10
1976	0.27	2004	0.78
1977	0.34	2005	0.65
1978	0.24	2006	1.29
1979	0.24		
1980	0.37	2007	0.64
~		2008	0.46
1999	0.88	2009	0.60
2000	1.21	2010	0.53
2001	0.38	2011	0.91

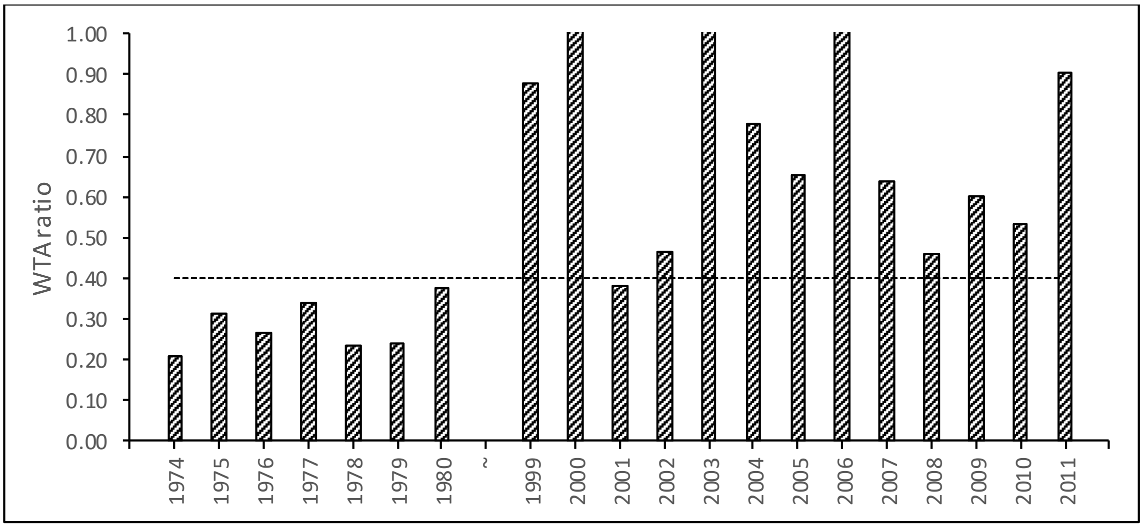

Figure 5.14: Historical WTA ratios for the GRRC headwaters for three time periods (1974 – 1980, 1999 – 2006, and 2007 – 2011) and the threshold for water stress, 0.4 (dashed line).

5.5 Discussion

5.5.1 Drivers of downstream water scarcity conditions

The application of the WSI and the WTA ratio methods over time in the GRRC reveal, within the limitations of the data collected, varying characterisations of water scarcity and stress. The WSI upstream at the headwaters before water withdrawals occur, indicates levels of abundant freshwater availability despite a rising population. In contrast, measuring water scarcity using the same indicator downstream at Msembe reveals a significant decline in conditions that fall well below the threshold for absolute water scarcity.

As discussed above, measuring levels of water scarcity based on the WSI metric downstream at Msembe assumes that the demand function (i.e. population) is similar to population upstream which explains the contrasting characterisation of water scarcity for the same pressure. However, the dynamic change in the supply-side (*i.e.* TRWR) of the indicator equation is evidently influential in defining the characterisation of water scarcity. The results presented admittedly can be scrutinised as having double counted water that has already been used downstream. However, this exploratory analysis is valid in applying the same population to the Msembe gauge as the headwaters, as the distinction between upstream and downstream users of the same water derived from the Kipengere and Poroto Mountains is difficult to estimate with confidence. Thus, the scaled down application of the WSI at catchment level also shows that conventionally applying the metric at the national scale produces coarse results and masks much crucial information, especially regarding spatial and temporal variability of freshwater availability within a defined area or boundary.

The results of the WTA ratio indicator application upstream during the first time period of the study is also indicative of abundant levels of freshwater availability. However, during the last two time periods, the WTA ratio metric indicates recurring water stressed conditions every year with scores in excess of the 0.4 threshold. The upstream hydrological regime, characterised by extreme variability in TRWR from one year to the next, has also experienced a 17% long-term decline in mean TRWR over the entire study period (*i.e.* between long-term average for the period 1973 – 1980 and long-term average for the period 2007 – 2011), marked by a significant decrease of nearly one-third (~31%) of average upstream river flow between 1973 – 1980 and 1999 – 2006. Further, comparing the long-term changes in the average proportion of water that is lost between the upstream headwater- and downstream gauging stations, indicates that this quantity consistently fluctuates around ~91% losses of upstream TRWR at Msembe.

Indeed, periods of water stressed conditions, according to the WTA ratio but not the WSI, coincide with times of expansion in the area under irrigation during the 1980s and 1990s. However, beyond 1999, there have been no reports of significant expansion in the area under irrigation, and this thesis assumes that the level of freshwater withdrawals have remained consistent and constant since that year. The dominant proposition for the causes of recurring zero-flow conditions downstream at Msembe are attributed in isolation to the expansion of upstream irrigation, the historical in-migration of nomadic pastoralists and that changes in upstream freshwater availability is negligible (Kashaigili *et al.*, 2005a; Kashaigili, 2008). The results presented in this thesis however, are not in agreement with attributing downstream losses at Msembe only to human activity. As downstream flow conditions continuously decrease despite assuming the presence of a constant in the control from 1999 - 2011 (*i.e.* the control factor for determining change in the upstream inputs for measured downstream outputs is irrigation withdrawal rates at constant levels), the influence of visible long-terms declines in upstream inputs (i.e. TRWR at headwaters) cannot be treated as negligible. During the four instances, where the estimated proportion of losses between upstream and downstream discharge were lowest in this study (Table 5.1) the timing coincides with periods of *El Nino* events, bringing a significantly heavier upstream flow, as marked by spikes in discharge records. Therefore, it is likely that the drivers of change to downstream river flow through the RNP in fact are not in isolation caused by anthropogenic factors, but also influenced by declines in upstream discharge inputs, potentially as a result of climate-driven changes to the upstream hydrological regime.

A trend analysis of flow records in the highlands undertaken by Kashaigili (2008) showed no statistically significant downward trend in changes of long-term annual and seasonal highland discharge. The author suggest there is no robust evidence to support the idea that water inputs from the highland catchment into the downstream portion of the catchment could have changed significantly over time. However, the absence of statistically significant trends, do not constitute strong grounds for the conclusion that anthropogenic factors alone have caused cessation of downstream discharge at Msembe. The presence of a 17% decrease in overall long-term mean discharge, combined with a mean inter-annual reduction in river flow of 31% between the 1972 – 1980 and 1999 – 2006 provide strong grounds for the suggestion this thesis makes that upstream climate driven changes could have impacted downstream hydrology in the GRRC and aims to contribute to the currently predominant narrative for the causes of water scarce conditions in the GRRC.

Kashaigili (2008) further examined changes in highland rainfall over the period 1955 – 1998, and claimed that there was no statistically significant evidence for changes to highland rainfall. However, to question this claim, this thesis undertook a longer-ranging inter-decadal analysis of monthly rainfall (1901 – 2010) from data based at Mbeya, similar to Kashaigili (2008), and found that since the 1960s there has been a decrease in highland rainfall over the area, marked by a modest increase during the 1990s, but declining again over the period 2000 – 2010 (Figure 5.15).

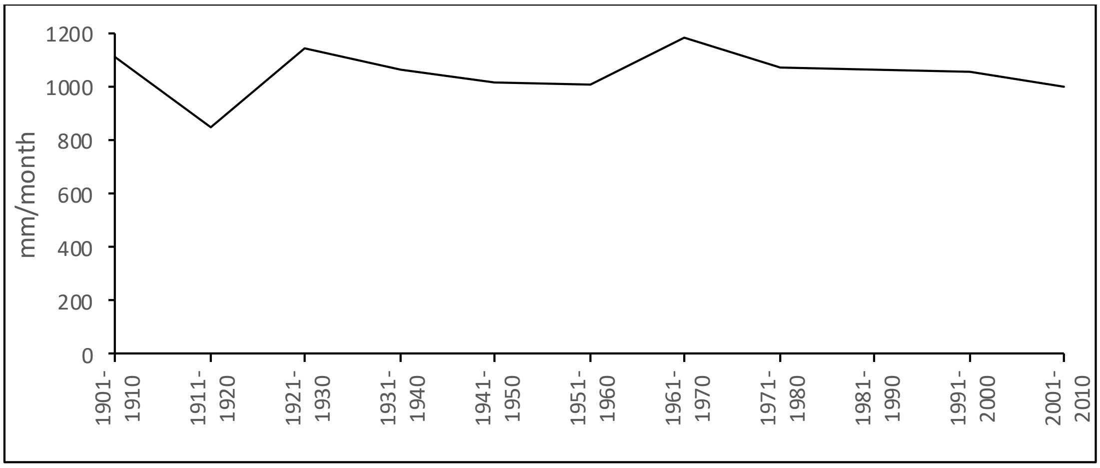

Figure 5.15: Highland inter-decadal variability in long-term aggregated monthly precipitation at Mbeya Meteorological Office (1900 – 2010).

Evidence from more recent studies also suggest visibly occurring long-term hydrological decline in upstream hydrology. Soteriou (2016) investigated mean monthly precipitation trends for the GRRC using GPCC v. 7 climate model over the period 1972 – 2010 to reveal a slightly decreasing trend (R^2 = -0.03) in annual rainfall. Furthermore, applying the recursive digital filter (RDF) method to separate and quantify base flow for the GRRC, Shu and Villholth (2012) demonstrated that there was a steady decline in baseflow from 1960 to 2009 with a rapid decrease in the period after 1989/90.

Such findings contribute to an alternative or complementary suggestion that long-term hydrological changes could have occurred upstream, which does not exclude claims of the impacts of expanding irrigation. Instead, the data suggest there is reason to posit that climate- and anthropogenic factors in conjunction could legitimately have contributed to the overall decline of the dry season flow conditions at Msembe.

5.5.2 Previously proposed explanations for the cessation of flows at Msembe

Indeed, it is clear that water resources management responses in the GRRC fail to consider environmental drivers as well as embrace variability, and instead have looked at anthropogenic factors such as irrigation expansion and in-migration to explain the continued cessation of the flows at Msembe.

From September 1992 up until October 1995, TANESCO were forced to occasionally impose power rationing and load-shedding in major cities across Tanzania. The cause stemmed from failure to produce adequate electricity through its hydropower supply in the Mtera-Kidatu HEP system 170 km downstream from Msembe. The Kidatu Dam, constructed in 1970, was primarily developed for hydropower generation, and the Mtera dam, completed in 1980, built with the purpose of storing water for HEP generation at Kidatu. In 1991, the water level at Mtera failed to refill between January and June falling to new lows in the second half of 1992 and by December 1994 it was nearly empty. Prior to 1991, the water levels at Mtera followed the dry- and wet-season pattern dropping between July and December and recovering over the subsequent six months. The failure of water levels to recover from 1991 onwards were unprecedented.

The GRR at Msembe began to stop flowing during the dry season at the same. TANESCO believed that the explanation for the falling water levels in the Mtera dam and the resulting politically unpopular action of load-shedding could be found upstream of Msembe. The immediate explanation of the situation lay with the misuse of water resources in the Usangu Plains. Following a workshop in Msembe in June 1995, which included representatives from TANAPA (Tanzania National Park Authority), TANESCO, and local NGO 'Friends of the Ruaha Society' (FoRS), TANAPA held that the issue was caused by over-grazing in the Usangu Plains, whereas FoRS and TANESCO were of the impression that retention of water by the NAFCO farms could not be dismissed. SMUWC (2001) and RIPARWIN (2006) however found that there was no significant connection between changes in the flow at Msembe and the conditions at the Mtera dam. The two projects concluded that the total volume of water flowing into the Mtera reservoir had in fact not changed over time, ruling out a direct cause and effect between the drying up of the GRR at Msembe and falling water levels in the Mtera reservoir. Instead, the problems at the Mtera dam were caused by mismanagement of the operating rules for the reservoir itself. TANESCO had been releasing far too much water into the downstream HEP-generating Kidatu dam and thereby not ponding enough water for hydropower generation the following year. No immediate and corrective action was taken, and even when the SMUWC (2001) project provided independent evidence that TANESCO had continuously followed wrong reservoir operating rules, the proof was dismissed despite recurring nationwide power cuts in the years that followed.

Another suggested cause for the continued downstream cessation flows at Msembe have been linked to increased expansion of irrigated agriculture upstream and immigration of nomadic pastoralists to the Usangu Plains. Over time more and more of the Usangu Plains became gazetted and incorporated into the Ruaha National Park, yet the problems with no-flows at Msembe continue to persist regardless of extent of irrigated area and level of pressure as the variability in TRWR upstream before the pressures of intakes of water for irrigation are accounted for.

5.6 Concluding Summary

This chapter applied two widely adopted metrics for assessing water scarcity, the WSI and the WTA, to the GRRC in order to investigate how they would characterise change in water scarcity over time. Whereas, the two metrics showed contrasting characterisations of water scarcity, the exercise opened up broader insights linked to the importance of investigating the role of inter-annual variability of freshwater supply in the GRRC. The results suggest that there are grounds to revise previous claims that the causes of water scarcity at Msembe have not been influenced by changes in upstream highland hydrology. The chapter shows visible declining trends in both upland rainfall and long-term river discharge at the headwaters.

The onset of the recurring no-flow conditions at Msembe coincided with unprecedented low water levels in the Mtera reservoir resulting in nationwide energy shortages. Such low reservoir levels however were attributed to wrong reservoir operating rules and have not direct proven links to be affected by reductions in flows at Msembe. Instead, governance responses to deal with the zero-flow conditions at Msembe were thought to be found upstream, linking irrigation expansion and migratory pastoralists to be the main cause. The significant variability in upstream water availability has not been directly considered alongside anthropogenic factors. This thesis chapter suggests that there is good reason to reconsider the narrative that the challenges faced in the GRRC only constitute a demand-side problem, when it has presented evidence to suggest that declines in upstream water supply, potentially attributed to climate change, may have had a more marked impact on downstream flows at Msembe than previously recognised.

Chapter 6 - Results & Discussion II: Investigating demand functions in water scarcity metrics: Quantifying domestic water use in the Great Ruaha River Catchment

Chapter 6 applies the critique on the characterisation of water scarcity raised in chapter 2, which was to restrict the quantification of water scarcity to verifiable physical parameters describing freshwater supply and demand and addressed research objective 2) "To examine how assumptions of domestic water demand embedded in the WSI relate to field observations" in the GRRC. Little empirical work has been done to field-test assumptions regarding domestic water demand that inform the WSI. This chapter interrogates the meaningfulness behind the threshold for water scarcity embedded in the WSI (per capita demand < 1 700 m^3 capita yr^{-1}) that is based on the assumption that people require 100 LCPD to meet their water demands (Falkenmark, 1986; Gleick, 1996). First, the results from semi-structured interviews with government officials and water users conducted during fieldwork in 2015 are presented with the aim of improving the understanding of domestic water demand in the GRRC. In 2016, a more thorough investigation was undertaken, informed by focus group discussions and household surveys across three village in the Usangu Plains. This chapter then compares field data with previously published and unpublished sources of research on domestic water demand in the GRRC.

The chapter builds upon the preceding chapter, where the application of the two most common metrics of water scarcity produced contrasting characterisations of water scarcity in the GRRC. The suggestion by the WSI that the GRRC is water sufficient conflicts with previous investigations into the long-term hydrological changes of the GRRC, which show an absence of river discharge for an increasing period of time each year since the early 1990s.

6.1 Results: Quantifying Domestic Water Demand

6.1.1 Interviews

To gauge an understanding of typical domestic water use in the GRRC, interviews with key informants were undertaken during the first phase of fieldwork in 2015. Informants were categorised into two types of respondents - External Respondents (ER) and Internal Respondents (IR) (see Table 4.3 for a list of interviewees and type). The first group constitutes actors that engage with water resources development or decision-making for the GRRC and include government officials, personnel at the RBWB and other national and international experts that have previously done research on water resources in the GRRC. ERs were approached first to scope out general trends related the quantification of water demand, before water users on the ground in the GRRC were approached. Respondents in the second group, IRs, are primarily local catchment-scale water users who are directly and indirectly affected by the decisions made by ERs in relation to water resources management. An interview guide was developed which had the flexibility to be applied to both ERs and IRs covering issues related to water use during the dry season in the GRRC.

6.1.2 Interviews with External Respondents

To develop an improved quantitative understanding of domestic water use in the Usangu Plains, the first respondent ER1, a government official was asked whether a benchmark of 100 LCPD reflected a realistic figure for water users to access in the GRRC. ER1 responded that this quantity in fact "[…] *could very well be more*". In an interview with ER2, they held that it did not make sense to talk about a fixed benchmark necessary to meet domestic water demands, because actual water use would depend on *"[…] whether people have showers and flush toilets […]. In towns like Rujewa, people might use between 20 to 50 litres per day or as high as 70*". ER2, however, explained that a 50 – 70 LCPD benchmark water use was commonly applied as a guiding rule-of-thumb range for urban water resources infrastructure planning in the Mbarali District. In contrast to ER1, ER2 found that the assertion that people in arid- and semi-arid areas, such as the Usangu Plains, need 100 LCPD to meet their basic water demands, highly inflated. In fact, ER2 mentioned that in the Usangu Plains, the further away from the TANZAM Highway people live, the less water the households use. The benchmark of 100 LCPD would be more realistic for big cities like Dar es Salaam, and attributed the high quantity to the use of flushing toilets.

6.1.3 Internal Respondents

To interrogate the contrasting views expressed by ER1 and ER2, interviews were held with local water users at the Ipatagwa Irrigation Scheme. IR1, a farmer, explained that his family used five buckets of ~20 L daily to meet their domestic requirements. The respondent did not disclose the size of their household, but expressed that the quantity, which they fetched from the main irrigation canal at the Ipatagwa Irrigation Scheme, was adequate to meet their domestic demands throughout the entire year. Subsequently, in conversation with two other farmers, IR2 and IR3 suggested that people in the nearby Ilongo Village only used ~40 LCPD and that was adequate. Furthermore, occasionally scheduled closures of the irrigation canals in the Ipatagwa Irrigation Scheme and adjacent standpipes would occur. When such restrictions tended to happen, water users found it normal to simply walk to the nearby Mkoji River located ~500 metres away. IR2 and IR3 were confident that for those who ultimately had the task of travelling to fetch water did not perceive the distance as far.

6.2 Quantifying domestic water demand through household questionnaire

In the Usangu Plains, 82 households across three villages, Ubaruku (n = 34) Nyeregete (n = 18) and Chosi (n = 30), were surveyed with regards to the quantity of water used to meet domestic demands. The average number of buckets used per day for domestic purposes for the three villages was ~7 buckets. The average size of buckets used to store water in the GRRC was estimated at ~20 L (Rajabu, 2007), and with a mean household size of the three villages surveyed calculated to consist of ~5 people, the per capita water demand across the three villages is ~28 LCPD (Figure 6.1; Table 6.1). In Ubaruku, the average amount of buckets used per day for domestic purposes across 34 households was 9, with an average household size of ~5 people, making daily domestic demand ~36 LCPD. In Nyeregete, the average number of buckets used per household was ~6, and each household consists on average of ~6 people, making the per capita water demand 20 LCPD. In Chosi Village, the average number of buckets used per household was ~5, and each household consisting of ~5 people, making average demand ~20 LCPD.

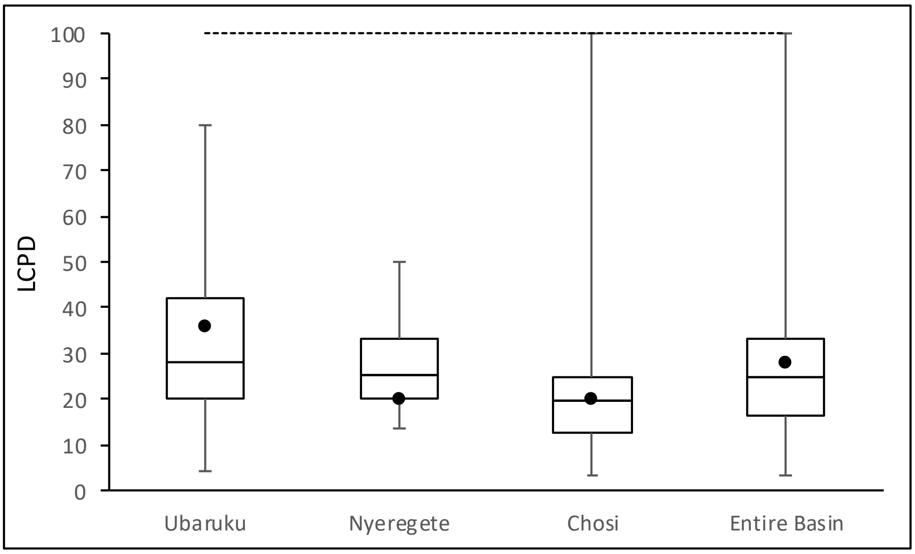

Figure 6.1: Box-plot of per capita daily water use in the study area of the household questionnaire. The dotted horizontal line represents the 100 LCPD benchmark embedded in the WSI.

Table 6.1: Per capita water use in the three villages (Own Source)

Village	Buckets (20L)	Mean Household Size (people)	Per capita daily water demand (LCPD)
All	7	~5	28
Ubaruku	9	~5	36
Nyeregete	6	~6	20
Chosi	5	~5	20

6.3. Secondary sources quantifying domestic water demand in the Usangu Plains

This section addresses a systematic review of previous work done on estimates of domestic water demand in the GRRC. First, the section reviews three major studies 1) SMUWC (2001), 2) RIPARWIN (2006) and, 3) the WREM International study commissioned by the World Bank for the development of the Rufiji Basin Decision Support System. Subsequently, the section brings to life published and unpublished academic studies on domestic water use in the GRRC retrieved at SUANAL.

6.3.1 SMUWC (2001)

The SMUWC (2001) programme provides a comprehensive and in-depth study of multiple uses of water in the GRRC, with a separate focus on water for non-irrigation purposes in three of the largest former NAFCO irrigation schemes in the Usangu Plains: the Mbarali Farm, the Kimani Farm and, the Kapunga Farm. The SMUWC study used observations and interviews with water users to estimate per capita water demand.

In the Mbarali Farm Irrigation Scheme, SMUWC (2001) surveyed nine villages (Ihanga, Ibara, Isisi, Rujewa, Mwakaganga, Ubaruku, Nyeregete, Mwanayala, and Imalilo Songwea) totalling 31 404 people that rely on access to water from the Mbarali Farm Irrigation Scheme for non-irrigation demands. The observed daily mean water demand for the nine villages was ~58 LCPD and ranged between 15 - 80 LCPD (Table 6.2). Estimates of water use for economic activities relate to livestock rearing and brickmaking, and assume an equal distribution of participation in these activities across the entire sampled population, as SMUWC did not disclose demographic information for the quantification of water demands. Inhabitants in the Mbarali Rice Farm rear ~20 363 livestock units which totals a daily per capita water demand for livestock activities of ~ 19.5 LCPD under the assumption that one livestock unit consumes 30 L day (King, 1983). Brickmaking is limited to two months during the dry season with an average daily production of ~7 200 bricks. One brick requires ~6 L of water, which totals the daily water requirement to ~43 200 L. With a population of 31 404, the average daily per capita water demand for brickmaking is thus ~1 L, making the combined per capita daily water demand for non-irrigation activities ~78 LCPD, when accounting of water for economic activities (i.e. brickmaking and livestock rearing).

Table 6.2: Non-agricultural water use in Mbarali Farm Irrigation Scheme (SMUWC, 2001)

Village	Population	Observed domestic use (LCPD)	Livestock numbers	Total livestock demand* (L unit day)	No. bricks made daily**	Brick water demands (L) No. of brick x 6 L brick
Iyanga	490	80	1 700	51 000	1 200	7 200
Ibara	1 480	80	700	21 000	800	4 800
Isisi	2 312	60	300	9 000	400	2 400
Rujewa	7 200	80	250	8 000	1 000	6 000
Mwakaganga	1 500	50	1 200	36 000	600	3 600
Ubaruku	9 600	80	600	18 000	2 200	13 200
Nyeregete	1 800	40	4 612	138 000	400	2 400
Mwanavala	3 222	40	8 000	240 000	400	2 400
Imalilo Songwea	3 800	15	3 000	90 000	200	1 200
Total	31 404	-	20 362	611 000	7 200	43 200
LCPD		**58**		**19.45**	**-**	**1.37**

* One livestock unit consumes 30 L day
** One brick requires 6 L of water

An estimated 223 households rely on water for non-irrigation uses from the Kapunga Rice Farm Irrigation scheme (Table 6.3). The average household consists of four people totalling a population of 892 and an observed total household domestic water demand of 80 L, which approximates to ~20 LCPD. Accounting for water use for economic activities, there are 300 livestock units and 200 goat units in the area.

Assuming a daily water demand of 35 L livestock unit and 4.5 L per day for one goat unit (King, 1983), the total combined water requirement is 10 500 and 900 L per unit category, respectively. On average, the per capita water requirement for goat and livestock rearing amounts to ~13 LCPD. Brickmaking activities are done for 60 days during the dry season and amounts on average to the production of bricks that can construct 40 houses. In the Kapunga Rice Farm, one house requires ~2 000 bricks with $1m^3$ (1 000 L) able to make 400 bricks, resulting in approximately 5 000 L to build one house. Therefore, total water demand for brickmaking of 40 houses over a 60 day period is ~3 300 L per day ((40/60) x 5 000 L per day). Assuming that everyone is involved in brickmaking activities amounts to an average per capita water use of ~4 LCPD. The total daily non-irrigation water demands in the Kapunga Rice Farm scheme therefore total ~37 LCPD during the two months of the dry season when brickmaking activities take place and 33 LCPD during the remaining 10 months, which gives a weighted average of ~34 LCPD. In the Kimani Irrigation Scheme only one village, Msesule, was studied in relation to water demand for domestic uses, solely. With its 200 inhabitants, the daily per capita water demand is estimated at 60 LCPD.

Table 6.3: Demand for non-irrigation water use in Kapunga Rice Farm & Kimani Irrigation Scheme (SMUWC, 2001)

Village	Pop.	Domestic water use	Livestock and goats	Brickmaking (2 months)	Total water demand incl. brickmaking (2 months)	Total wet season water demand (exl. brickmaking (10 months))	Weighted average water demand
Kapunga Rice Farm	892	20	13	4	37	33	34
Kimani Irrigation Scheme (Msesule)	200	60	-	-	-	-	60

6.3.2 Raising Irrigation Productivity and Releasing Water for Intersectoral Needs (RIPARWIN)

The RIPARWIN (2006) study was a follow-up to SMUWC (2001) and also involved an assessment of non-irrigation water demands. The study quantified water demand in the Mkoji sub-catchment for domestic uses, brickmaking and livestock activities, across three zones in the sub-catchment. Upper, Middle and Lower zones were identified and each defined to be representative of the characteristics of other sub-catchments in the GRRC and used as proxies to make assumptions about water demand in these areas. The study estimated the average per capita domestic water demand to 36 LCPD: ~34CPD during the wet season and ~38 during the dry season (Table 6.4). During the dry season brickmaking takes place. RIPARWIN (2006) estimated that 1 m^3 (~1 000 L) can make 400 bricks, which gives one brick a water requirement of 2.5 L. The average annual production rate per person is ~134 bricks, making the annual mean per capita water demand for brickmaking activities ~335 L/capita or ~1 LCPD (Table 6.5).

Table 6.4: Domestic water demand in wet and dry season 2002/2003 (RIPARWIN, 2006)

Catchment name	Households	Population	Wet Season Demand (LCPD)	Dry Season Demand (LCPD)	Average Water Demand (LCPD)
Ndembera	11 445	49 214	38	45	41
Great Ruaha Wetland	10 930	47 796	26	24	25
Mkoji	31 917	134 667	35	36	35
Kioga	23 057	95 558	26	24	25
Mbarali	23 356	97 473	37	45	41
Upper GR Sub.	4 267	17 019	37	45	41
Chimala	7 443	28380	37	45	41
Kimani sub.	2 450	9684	37	45	41
Total GRRC	114 865	479 791	34	38	36

Table 6.5: Brickmaking across the GRRC 2002/2003 (RIPARWIN, 2006)

Sub catchment Name	MSC zone Equivalency	Total Population	Brick/person/year	Total number of bricks produced per year	L/brick *	Total Amount of Water consumed per annum (L)	Total annual per capita water consumed	Daily brickmaking water demand (LCPD)
Ndembera	Middle	49 214	140	6 889 890	2.5	172 24 725.0	350	1
Great Ruaha Wetland	Lower	47 796	73	3 489 122.6	2.5	8 722 806.5	183	0.5
Mkoji	N/A	134 667	156	21 059 458.2	2.5	52 648 645.5	391	1
Kioga	Lower	95 558	73	6 975 748.6	2.5	17 439 371.5	183	0.5
Mbarali	Middle	97 473	140	13 646 178.0	2.5	34 115 445.0	350	1
Upper Great Ruaha	Middle	17 019	140	2 382 660.0	2.5	5 956 650.0	350	1
Chimala	Middle	28380	140	3 973 242.0	2.5	9 933 105.0	350	1
Kimani	Upper	9 684	206	1 994 904.0	2.5	4 987 260.0	515	1
Total	-	479 791	134	60 411 203	2.5	151 028 008.5	334	~1

*1 000 L = 400 bricks

6.3.3 WREM International Inc.

WREM International (ER5) undertook a comprehensive study of freshwater resources across the entire Rufiji Basin for the World Bank in the development of the Rufiji Basin Decision Support System (Rufiji DSS). The four-year study noted that under the Design Manual for Water Supply and Wastewater Disposal the Ministry of Water guarantees rural resident of Tanzania a basic potable water supply of 25 LCPD through water points located no more than 400 metres from the furthest household. The WREM International Inc. (2012) study computed that in 2012 water demand for the entire Mbarali District was 7 296 m^3 day equating to a per capita water demand of 25 LCPD based on a population of 291 851, corresponding well with the Ministerial provisions.

6.4. Academic Sources: Ph.D. theses and Masters Dissertations, Sokoine University of Agriculture, Tanzania

This thesis also examines previously published and unpublished academic research (dissertations and theses) related to freshwater resources in the GRRC by students and staff at SUA. The SUA National Library (SUANAL) database and the SUA Online Repository were consulted using the keywords: “Ruaha”, “Great Ruaha”, “Usangu”, “Usangu Plains” and “Rufiji”. In the SUANAL database, two PhD theses and five M.Sc. dissertations were physically available for consultation, whereas the SUA Online Repository returned one PhD and four M.Sc. theses available electronically (Table 4.4). After systematically reading all 12 sources, focusing on references to water use for non-irrigation purposes, only one source was found to add substantial new information that had not already been covered by other sources in terms of relevance to this thesis.

6.4.1 Rajabu (2007)

The PhD thesis "*Water Availability and Use Dynamics and the Sustainability of Water Resources Management in the Great Ruaha River Catchment in Tanzania*" by the late Rajabu (2007) was considered to yield the most informative content on domestic water use in the GRRC of all 12 resources consulted. This particular thesis investigates water use and demand in the Mkoji sub-catchment at three different altitudinal zones during the dry and wet seasons of 2002/03 in the villages of Ikholo and Inyala (Upper Zone of the Mkoji), Mwatenga and Mahongole (Middle Zone) and, Madundasi and Ukwaheri (Lower Zone). A follow-up survey was undertaken in 2004/05 of six different villages: Imezu and Iyawaya (Upper Zone), Igurusi and Majenje (Middle Zone) and, Mwatenga and Luhanga (Lower Zone[6]). The varying characteristics of these three zones were used as proxies of the other sub-catchments with Uturo representing the Kimani sub-catchment, and Ihahi the Great Ruaha and Chimala sub-catchments. The 2002/3 study involved a sample of 246 respondents, whereas the follow-up 2004/05 survey covered 331 respondents. The differences between the two surveys showed a negligible change in water demand for non-irrigation activities.

6.4.1.1 Domestic Water Demand: Wet and Dry Season in 2002/03 and 2004

In 2002/03, the total daily average per capita water demand during the wet season was ~34 LCPD across the whole study area, and ranged from ~26 LCPD in the Lower Zone to ~38 LCPD in the Upper Zone (Table 6.6). The 2002/03 dry-season (Table 6.7) per capita water demand across all zones remained at 34 LCPD on average but had a wider range from ~24 LCPD in the lower zones to ~45 LCPD in the higher

[6] Mwatenga and Luhanga are located between the lower part of the Middle Zone and the upper part of the Lower Zone and is the reason why Mwatenga in 2002/03 is in the Middle Zone and in 2004/05 in the Lower Zone.

zones. The 2004/05 follow-up survey results were slightly lower than for 2002/2003 with an average daily per capita demand of ~21 LCPD in the dry season and ~20.5 LCPD in the wet season.

Table 6.6: Water Demand: Wet Season 2002/2003 (Rajabu, 2007, Table 24).

Zone	Households	Household Size	Population	Water use (L household day)	Average Water Use (LCPD)	Wet Season Days
Upper	14 870	4.0	59 480	151	38	165
Middle	12 695	3.9	49 511	143	37	165
Lower	4 352	5.9	25 677	153	26	165
Total	31 917	4.6	134 667	149	34	-

Table 6.7: Water Demand: Dry Season 2003 Mkoji Sub-catchment (Rajabu, 2007, Table 29)

Zone	**Households**	**Household Size**	**Population**	**Water use L/household/day**	**Average Water Use (LCPD)**	**Dry Season Days**
Upper	14 870	4.0	59 480	131	33	200
Middle	4 352	5.9	25 677	143	24	200
Lower	12 695	3.9	49 511	175	45	200
Total	31 917	4.6	134 667	150	34	-

6.5 Synthesising domestic water demand in the GRRC

Estimates of the daily per capita water demand in the GRRC (Table 6.8) varies according to the assumptions that inform the methodology applied. Within the limitations of the primary data acquired in this thesis through the household survey in Ubaruku, Nyeregete and Chosi, estimated a mean per capita daily water demand of ~28 LCPD. This figure is slightly lower in comparison to those derived from secondary sources: ~34 LCPD (Rajabu, 2007), ~36 LCPD (RIPARWIN, 2006), and ~45 LCPD (SMUWC, 2001). The average per capita daily water demand across all of these four household survey based-studies is ~36 LCPD. The estimates in the current thesis are closer to the WREM Inc. (2012) approximations and Ministerial Design Manual minimum requirements of ~25 LCPD. Whereas the mean of all four household survey based studies is slightly higher, all surveys estimated actual domestic (non-agricultural) water use at less than the 100 LCPD embedded in the WSI.

Estimates based purely on interviews with decision-makers show a greater estimate of daily per capita water demand. These figures range from ~35 – 100 LCPD and average ~67.5 LCPD. The mean daily per capita water demand, based on rough estimates through random and purposively sampled interviews, are nearly twice as high as those achieved through household surveys. Interview-based estimates are associated with large uncertainties. In particular, the estimates made by External Respondents who tended not to be direct sub-catchment scale water users, should only be taken as indicative, yet they are helpful in gaining a general understanding of the challenges that relate to water demand at large across the GRRC.

The following discussion section compares the results for the GRRC to other parts of Tanzania and as well as arid- and semi-arid SSA. This comparison is relevant for better understanding the challenges and assumptions made when estimating domestic water demand. The results conclude that domestic water demand is neither static nor fixed, but dynamic, involving the ability to adapt to shifting availability of freshwater resources, and recognising the high variability of the hydrology in the GRRC.

Table 6.8: Synthesis of studies on domestic water demand in the GRRC

Primary Data		**LCPD**	**Mean (LCPD)**
Household Survey (2016)	Chosi A Mean	20	
	Nyeregete Mean	20	
	Ubaruku Mean	36	
	Total sampled		28
Secondary Household Surveys			
WREM Inc. (2012)	Mbarali District	25	
RIPARWIN (2006)			
	Great Ruaha Wetland	25	
	Kioga	25	
	UGRRC Domestic Wet Season	34	

	Mkoji	36	
	UGRRC Domestic All Year	36	
	UGRRC Domestic Dry Season	38	
	Mbarali	41	
	Upper GRR	41	
	Chimala	41	
	Kimani	41	
	Ndembera	41	
			36
Rajabu (2007)			
	2002/03 Dry Season Lower	24	
	2002/03 Total Lower Zone Yearly Mean	25	
	2002/03 Wet Season Lower	26	
	2002/03 Dry Season Upper	33	
	2002/03 Wet Season Total	34	
	2002/03 Total All Zones Mean Yearly	34	
	2002/03 Dry Season Total	34	
	2002/03 Total Upper Mean Yearly	35	
	2002/03 Wet Season Middle	37	
	2002/03 Wet Season Upper	38	
	2002/03 Total Middle Mean Yearly	41	
	2002/03 Dry Season Middle	45	
			34
SMUWC (2001)			
	Kapunga Farm (excl. economic use)	20	
	Mbarali Farm (excl. economic use)	58	
	Kimani Farm (excl. economic use)	60	
			46
Household Survey Based Mean			**33**
Interviews (2015)			
	ER2 - Mbarali Rural Average	35	
	IR2 - Ipatagwa Irrigation Scheme WUA	40	
	ER2 - Benchmark Planning	60	
	ER2 - Mbarali Urban Maximum	70	
	ER1 - UGRRC	100	
	IR1 - Ipatagwa Farmer	100	
Interview-based Mean			**67.5**

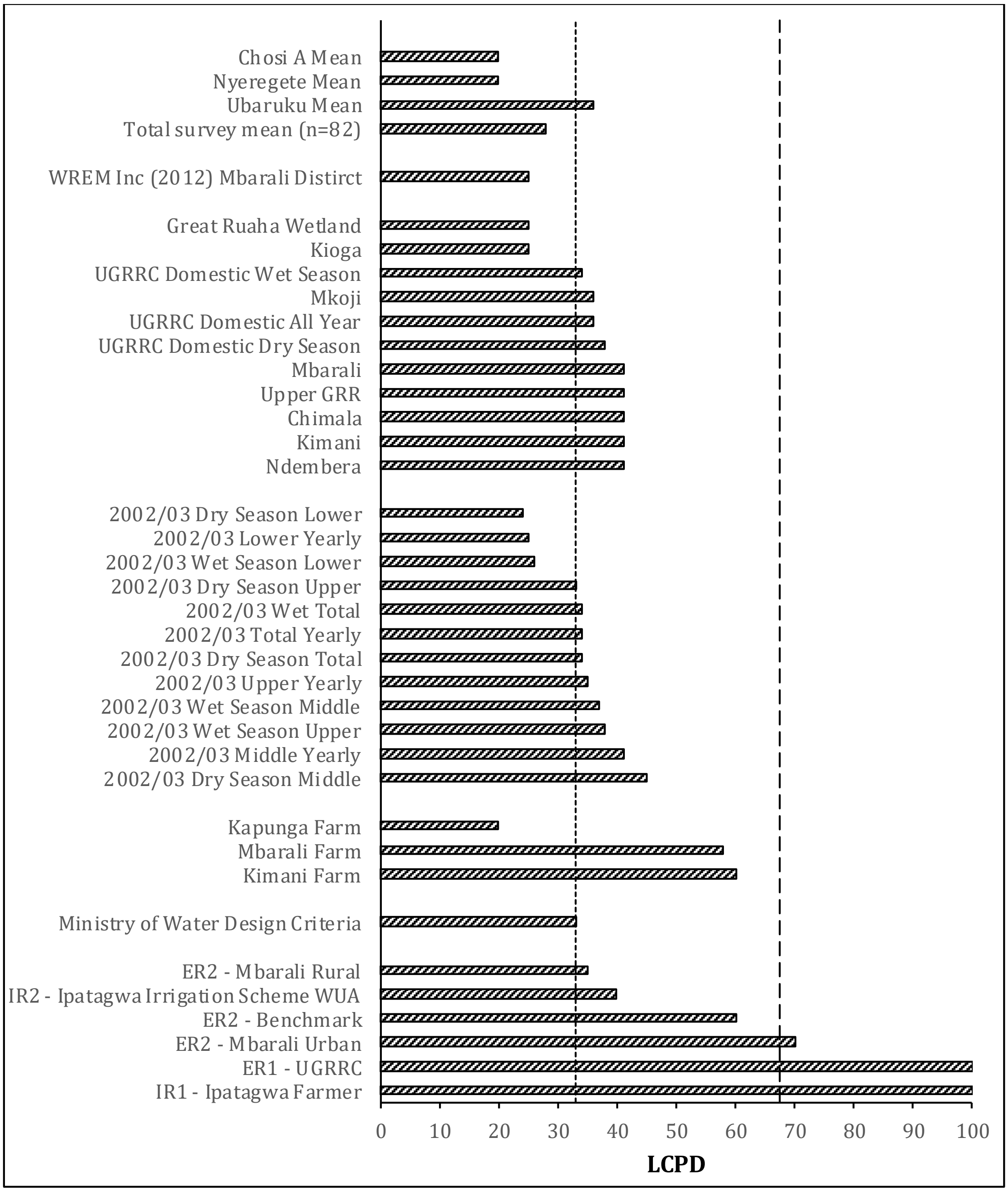

Figure 6.2: Synthesis of quantification of domestic water demand in the GRRC from primary and secondary sources

6.6 Discussion

6.6.1 Quantifying rural per capita daily water demand other parts of SSA

The findings from this study, derived from within the limitations of primary and secondary household surveys, estimate the average per capita water demand in the GRRC at ~33 LCPD (Figure 6.2, Table 6.8) not including figures from interviews. The first large-scale comprehensive assessment of domestic water use in SSA, Drawers of Water (DoW) I (White *et al.*, 1972) took place in Kenya, Tanzania and Uganda between 1966 and 1968. Thirteen fieldworkers, primarily undergraduate students at Makerere University in Uganda acquired data on domestic water demand through interviews, household questionnaires and observations of over 700 households in 34 study sites. Twelve of these sites were in rural areas whereas the other 22 were located urban- and peri-urban locations. The chief limitation of the DoW I study was the relatively short period of time allocated to examine water use in the region, making it difficult to establish long-term patterns of water user behaviour.

Three decades later, Thompson *et al.* (1997) undertook a comprehensive follow-up to the Drawers of Water I study, entitled Drawers of Water (DoW) II, to evaluate changes in domestic water demand over thirty years in East Africa. The DoW II used the same core methodology as DoW I, and carried out the research in the same or nearby households as the previous study, totalling a sample size of over 1 000 households. DoW II researchers consisted of 21 university post-graduate students using semi-structured interviews to estimate domestic water demand, crosschecked with other respondents and active observation. DoW II found, that across East Africa, the mean daily per capita of domestic water use had declined by 30% over three decades from ~61 LCPD in the mid-1960s to ~40 LCPD in the mid-1990s (Table 6.9).

In Tanzania, the national average per capita daily water use from unpiped rural sources had increased from ~10 to 16.0 LCPD over the thirty years. In comparing two unpiped rural sites in Tanzania Mkuu Village (Rombo rural) and Kipanga Village (Dodoma Rural) per capita water demand from these sources had also increased from ~8 LCPD to ~14 LCPD and ~13 LCPD to ~17 LCPD, respectively. Studies that have quantified rural water use in other parts of Tanzania, estimate the per capita water use to range between ~22 and ~36 LCPD across six villages in Sukumaland based on in-depth interviews and observations (Drangert, 1993). In Mwanza region, a study based on the number of buckets carried, estimate daily per capita water demand to range between ~10-40 LCPD (Zaba and Madulu, 1998) (Figure 6.3, Table 6.10).

Table 6.9: Change in domestic water use over three decades in East Africa (Thompson et al., 1997)

	East Africa		Tanzania total unpiped rural		Mkuu Village (rural Tanzania)		Kipanga Village (rural Tanzania)	
	DOW II	DOW I	DOW II	DOW I	DOW II	DOW I	DOW II	DOW I
Average per capita water use (L) per day	39.6	61.4	16	10.1	14.2	7.8	16.6	12.7
Principle water source	-		Spring, stream	Reservoir hydrant	Hydrant	Hydrant	Stream	Reservoir
Average time per trip (minutes)	-		44.7	17.8	31.2	28.6	49.2	4.8
Average Distance to Water source (metres)	-		769.4	569.4	342.8	1015.5	903.5	34.2

Table 6.10: Studies quantifying domestic water use in Tanzania compared to regional estimates (Author elaboration)

Study	LCPD	Reference
DOW I E. Africa Regional	61	White *et al.* (1972)
DOW II E. Africa Regional	40	Thompson *et al.* (2001)
DOW I E. Africa unpiped regional	11	White *et al.* (1972)
DOW II E. Africa unpiped regional	20	Thompson et al. (2001)
DOW I Tanzania unpiped rural	10	White et al. (1972)
DOW II Tanzania unpiped rural	16	Thompson et al. (2001)
DOW I Mkuu, Tanzania	8	White et al. (1972)
DOW II Mkuu, Tanzania	14	Thompson et al. (2001)
DOW I Kipanga Tanzania	13	White et al. (1972)
DOW II Kipanga Tanzania	17	Thompson et al. (2001)
Mwanza Tanzania min.	10	Zaba and Madulu (1998)
Sukuma Tanzania min.	22	Drangert (1993)
Sukuma Tanzania max.	36	Drangert (1993)
Mwanza Tanzania max.	40	Zaba and Madulu (1998)

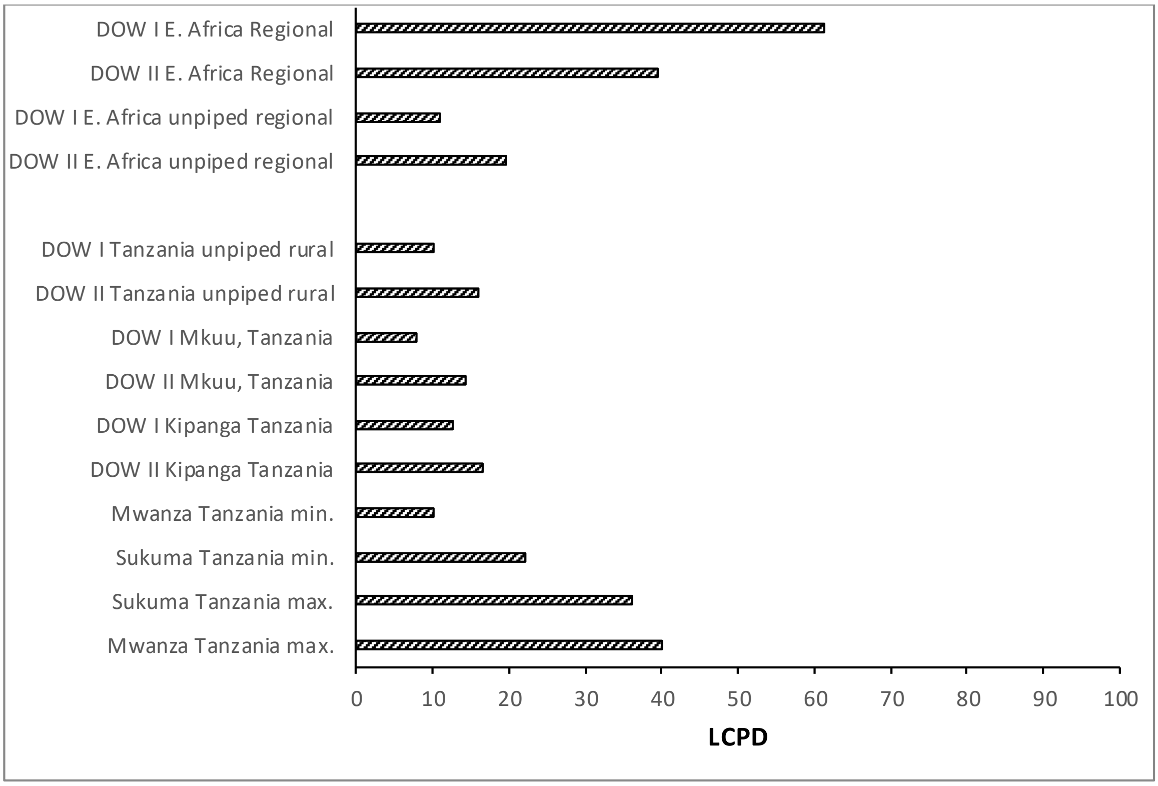

Figure 6.3: Studies quantifying domestic water use in Tanzania compared to regional estimates

Similar levels of estimated water use to that of Tanzania are also visible in other studies on domestic water use across arid- and semi-arid SSA (Table 6.11, Figure 6.4). In neighbouring Uganda, national average domestic water use for unpiped rural households, based on studies in Alemi, Iganga, Kasangati and Mwisi, were estimated to have grown from ~12 LCPD in 1967 to ~15 LCPD in 1997 (Thompson *et al.*, 1997). More recent national-level estimates consider the average water demand to be 15 LCPD (Mellor *et al.*, 2012), which concurs with studies of Jinja district, that find the average per capita water demand for unconnected households to be ~16 LCPD (WELL, 1998). In Kenya, the estimated average national per capita water demand for unpiped rural households in Kiambaa, Mukaa, Masii, Manyata, Moi's Bridge and Mutwoto increased from ~8 LCPD in 1967 to ~22 LCPD in 1997 (Thompson *et al.*, 1997). In Ethiopia, Tucker *et al.* (2014) measured domestic water use based on key informant interviews, focus group interviews, water use recall methods, and observations of jerry cans carried. The result showed that the majority of water users used between ~8 - 12 LCPD. Whereas there were no visible differences in per capita water use between the various types of livelihoods studied during the wet season, the variability was significant during the dry season. Cairncross and Cliff (1987) observed that the quantity of domestic water used is a function of collection time. In a study of water demand in the villages of Itanda and Amua, Mueda, Mozambique, average daily domestic water consumption increased from ~4 LCPD to ~11 LCPD when water collection time was reduced from 5 hours to 10 minutes.

In West Africa, quantification of per capita daily water demand produces similar results to estimates in East Africa. In Kartako village, northern Nigeria, 250 households were surveyed in relation to dry and wet season water demand in 1997 (Nyong and Kanaroglou, 1999). The average daily water demand was as high as ~37.5 LCPD in the rainy season and ~19 LCPD during the dry season (Figure 6.4, Table 6.11). In neighbouring Benin, the average daily per capita water demand in the Oueme River Basin was estimated at ~29 LCPD in the rainy season and ~25 LCPD during the dry season, according to interviews with 325 households (Arouna and Dabbert, 2009) (Figure 6.4, Table 6.11).

Per capita domestic water use in the GRRC is similar to that of other local- and national-scale studies in both Tanzania and other arid- and semi-arid countries in SSA. Such comparisons are valuable as no global database of country specific estimates of domestic water use exists. The lack of such a database can be attributed to the absence of a single standard or systematic approach to quantifying domestic water use patterns in monitoring surveys such as the JMP, GLAAS, MICS and USAID-HS. One possibly useful proxy, is the annual level of water withdrawals for municipal use reported in the FAO-Aquastat database. The shortcomings of relying on this particular proxy, however, is the assumption that water is distributed through a centralised piped network.

Table 6.11: Studies quantifying domestic water use in selected semi-arid African countries (own elaboration)

Study	LCPD	Reference
DOW I Uganda unpiped	11.5	White *et al*. (1972)
DOW II Uganda unpiped	14.8	Thompson *et al.* (2001)
Uganda national 2012	15	Mellor *et al*. (2012)
Jinja, Uganda unpiped	15.5	WELL (1998)
DOW I Kenya unpiped	8.2	White *et al*. (1972)
DOW II Kenya unpiped	22.3	Thompson *et al.* (2001)
Oromia Region, Ethiopia low	8	Tucker *et al*. (2014)
Oromia Region, Ethiopia high	12	Tucker *et al*. (2014)
Mozambique 10 minutes collection time	11.1	Cairncross and Cliff (1987)
Mozambique 5 hours collection time	4.1	Cairncross and Cliff (1987)
Kartako, Nigeria rainy season 1997	37.5	Nyong and Kanaroglou (1999)
Kartako, Nigeria dry season 1997	19.2	Nyong and Kanaroglou (1999)
Oueme River Basin Benin rainy season avg.	29	Arouna and Dabbert (2009)
Oueme River Basin Benin dry season avg.	25	Arouna and Dabbert (2009)

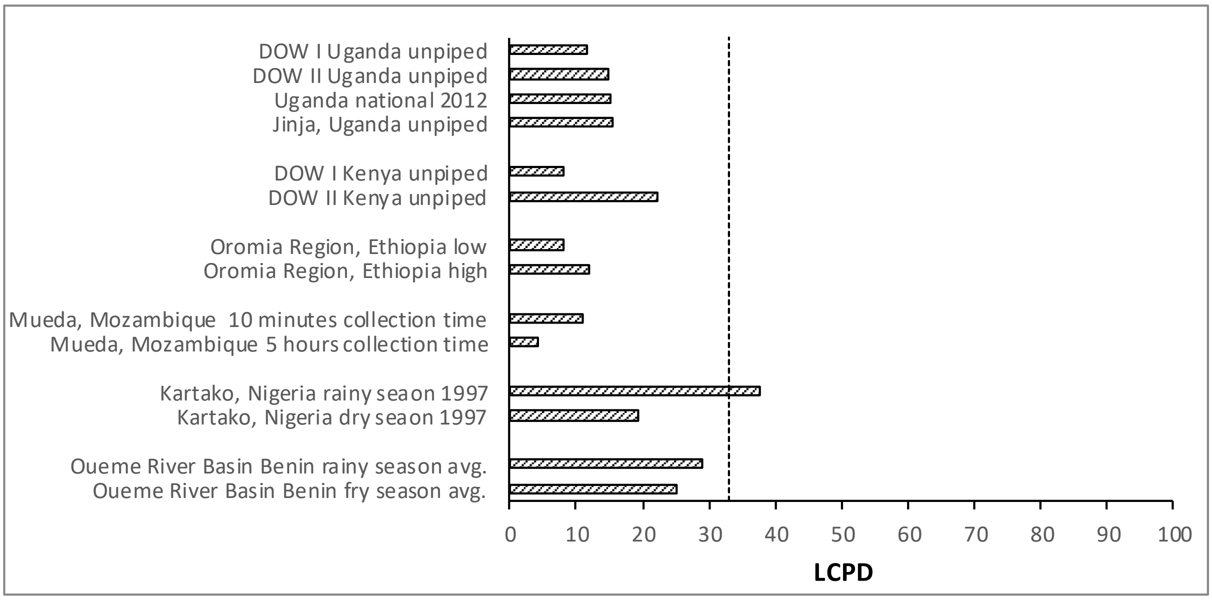

Figure 6.4: Studies quantifying domestic water use in selected semi-arid African countries

Essentially, the proxy is a better measure of national formal coverage of water supply, but is still useful in providing coarse general insights about trends in urban domestic water demand for piped households. Table 6.12 compares figures on domestic water demand from FAO-AQUASTAT with the range of domestic per capita water demand for other countries in SSA presented in Table 6.11 and Figure 6.4. For the case of Tanzania, the FAO-AQUASTAT estimate of domestic water demand at ~40 LCPD is within the range of the country-studies on Tanzania that all estimate water demand below 50 LCPD. Table 6.13 further shows per capita water demands for African countries as derived from FAO-Aquastat's database on freshwater withdrawals.

Table 6.12: Comparisons of estimated domestic water demand for countries in table 6.11, Figure 6.4 and estimates based on FAO-AQUASTAT (own elaboration)

Country	In-country study (LCPD)	FAO-Aquastat (LCPD)
Benin	25-29	~15
Ethiopia	8-12	~27
Kenya (DOW II piped)	47	~39
Mozambique	4.1-11	~31
Nigeria	19-37	~76
Tanzania	35	~40
Uganda	15	~15

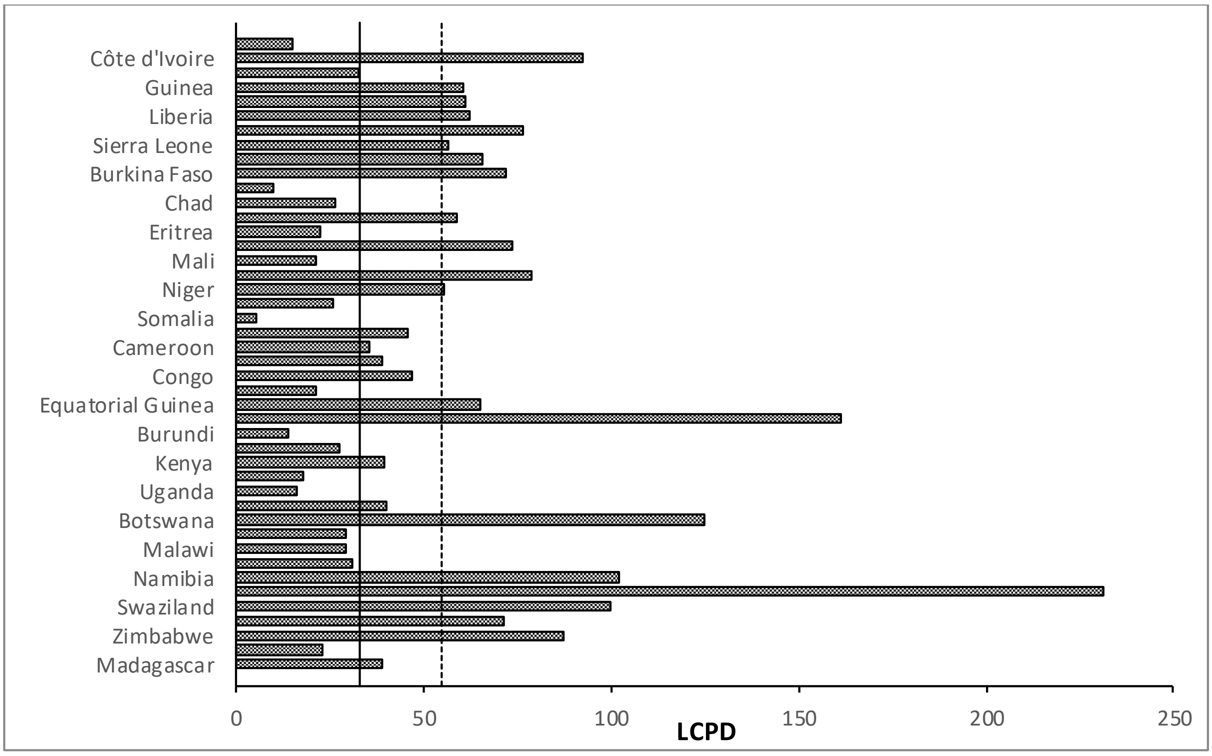

Figure 6.5: 2002 National per capita water demand, calculated from annual municipal water withdrawals across SSA (Source: FAO-AQUSTAT). The full vertical line is the average of the GRRC (~33 LCPD) and the dotted vertical line is the average per capita consumption calculated from municipal withdrawals (~54.8 LCPD)

Table 6.13: Per capita water demand in SSA based on reported municipal water withdrawals in Figure 6.5 (Source: FAO-AQUASTAT, 2002)

Country	LCPD	Country	LCPD
Benin	15.1	Central African Republic	39.2
Côte d'Ivoire	92.4	Congo	47.0
Ghana	32.5	Democratic Republic of the Congo	21.3
Guinea	60.7	Equatorial Guinea	65.0
Guinea-Bissau	61.2	Gabon	161.0
Liberia	62.4	Burundi	13.9
Nigeria	76.3	Ethiopia	27.4
Sierra Leone	56.4	Kenya	39.4
Togo	65.4	Rwanda	17.7
Burkina Faso	72.1	Uganda	16.4
Cabo Verde	9.6	United Republic of Tanzania	40.3
Chad	26.4	Botswana	124.6
Djibouti	58.8	Lesotho	29.1
Eritrea	22.4	Malawi	29.0
Gambia	73.5	Mozambique	31.1
Mali	21.3	Namibia	102.1
Mauritania	78.5	South Africa	231.2
Niger	55.5	Swaziland	99.7

Senegal	25.8	Zambia	71.3
Somalia	5.3	Zimbabwe	87.6
Angola	45.6	Comoros	22.9
Cameroon	35.4	Madagascar	39.1

The WSI has adopted an assumption that people need 100 LCPD to sustain healthy living, but the results in this research estimate that actual water use in SSA tends to be lower. Although convenient, Zaba and Madulu (1998) warn against relying on average measures of water availability, as they do not reflect the realities of local conditions. Indeed, as discussed in Chapter 2 (Figure 2.3a) there is no statistically significant relationship ($r = 0.03$, $p = 0.86$) between access to safe water and per capita freshwater availability based on national-level statistics for African countries in 2014. Countries in North Africa such as Egypt and Morocco, which have low per capita freshwater availability and are defined by the WSI 'water-scarce' or 'water-stressed', report near-universal (>90%) access to safe drinking water. Excluding countries with a per capita freshwater availability exceeding 40 000 m^3 yr^{-1} (*e.g.* Congo, Gabon, Liberia), a weak *negative* association exists ($r = -0.24$, $p = 0.09$) between the proportion of the continent's population that have access to safe water and annual amount of water availability per capita (Figure 2.3b).

Measured water scarcity is unrelated to measured coverage of access to safe water. Indeed, what constitutes a sufficient volume of water per capita is highly variable. The Sphere Project has set minimum standards for water use at ~7.5 – 15 LCPD in emergency situations and 20 – 50 LCPD in non-emergency situations (Tucker *et al.*, 2014). The WHO/UNICEF JMP that produce the Global Assessment of Water Supply and Sanitation describe reasonable access as "*the availability of at least 20 litres per person per day from a source within one kilometre of the user dwelling*" (Howard and Bartram, 2003). WELL (1998) suggest a minimum of 20 LCPD similar to Carter *et* *al.*, (1997), whereas Gleick (1996) suggested a figure of 50 LCPD. Few studies are able to capture actual water use (Tucker *et al.*, 2014) which is due to the non-existence of commonly agreed-upon standards for measuring per capita water demand as well as capturing the complexity entailed in this exercise. The next section examines the challenges related to quantification of domestic water demand, which itself may be considered the main challenge to adequately characterising water scarcity.

6.5.2 Impediments to the estimation of domestic water use

Quantification of domestic water demand in Lower Economically Developed Countries (LEDCs) is far more complex than in industrialised countries, and even more difficult in rural areas. In More Economically Developed Countries (MEDCs) most households are generally connected to a piped water network so that tap water is primarily the source of all water for domestic use and utilities have reliable records of water usage (Nauges and Whittington, 2010). In LEDCs, there are multiple factors that come in to play, which are not present in MEDCs. This section outlines three main challenges to estimate reliably per capita demand. The first, relates to the fact that water users face significant temporal and spatial variation in the dependency of water sources and the purposes they can be used for. The second challenge relates to the fact that even in instances where households are connected, meter readings often perceived as a convenient and precise way of measuring water use, are not always accurate in their recording, and thirdly, due to the existence of a wide range of methodologies on how to estimate per capita water demand, data can be highly variable.

Firstly, estimating water demand needs to consider factors, conditions (e.g. distance travelled, collection time, wait time at source, price) and attributes (e.g. income, level of education) that influence a consumer to choose one source over another (Merrett, 2002) for a particular use (Mu *et al.*, 1990). Further, the range of costs involved with collecting water from non-tap sources needs to be considered and weighed against other costs and benefits. The combination of how water users access different sources at different times can be indicative of ways in which they respond and adapt to physically changing circumstances regarding access to water and availability as well as determining cost-effectiveness of water access. Often, it becomes worthwhile to only take a proportion of water requirements from one particular source and to complement other uses with alternative sources (Coetzee *et al.*, 2016). It may be that there is limited human capital to carry cheap water and so the remaining water needs to be obtained from a more expensive source (Arouna and Dabbert, 2009. Indeed, the tendency to divide water use according to source is common but easily overlooked in research on domestic water use. Within communities, households can also be very different in the way they access water and addressing existing and differing typologies of water access can easily go unnoticed in water supply interventions.

Secondly, water use data for piped connections can surprisingly be highly dubious whether metered and unmetered (Nauges and Whittington, 2010). Where households are not metered, water users may not accurately report their actual water usage, and if temporary metres for the sake of setting a baseline are installed, this can influence user behaviour and distort long-term use estimations. However, even in households with a metered connection, readings may not always be reliable. Service provision levels are often intermittent and can cause water pressures to fluctuate. Air can then enter pipes which the meters may register as water flow. Furthermore, water tariffs are often very cheap, providing little incentive for water utilities to maintain water meters.

The third challenge to quantifying domestic water demand relates to the multitude of different approaches to estimate household water use that exist, with methods often having non-systematic protocol for data collection, inaccurate means of measurement and verification, and inadequate reporting (Wutich, 2009). Popular methods to estimate household water demand include the use of a "diary", "prompted recall" and "free recall" methods. Wutich (2009) attempted to determine whether one of these three methods would yield better comparable estimates of household water use for Villa Israel in Cochabamba, Bolivia. The results of the study were compared against known recorded parameters from the water utility and government. The study indicated, that the diary method produced the most accurate estimate of household water use. The prompted recall methodology was able to produce similar results as the diary method for hygienic and food preparation tasks but significantly different results for household cleaning tasks. The free recall methodology significantly underestimated the total water use of households (Wutich, 2009). In unmetered households, researchers often neglect to detail data collection processes and quality sufficiently whereas some completely omit their mention (Wutich, 2009).

Studies may even use a mix of prompted and free recall methods that have widely ranging recall periods from hours to months. The method used in DOW I constituted multiple approaches through which direct measurements, direct observations and survey interviews were undertaken with over 700 households, and followed up with multiple cross-checks. The replication of the study 30 years later (Thompson *et al.*, 2001) advanced the scope of the study and distinguished between dry and wet seasons in order to capture seasonal variability. Cairncross & Kinnears (1992) studied water demand in Khartoum (Sudan) where retrospective and observational studies were compared, and found that retrospective estimates of daily water use can be reasonably accurate. Retrospective behavioural data accuracy can be improved during the collection process with the use of prompts. Tools to improve accuracy of informants include direct observations in the field, but this methodological approach can be expensive (Wutich, 2009). Not all field sites are suitable for direct observations, as informants may not always be happy to allow outsiders into their private space. In fact, observational studies are more resource and time-consuming but diary methods can be used to replace them (Wutich, 2009). However, diary methods may also be prone to short-comings such as reporting errors and a failure to fill in the diary despite the provision of training and taking into consideration levels of illiteracy. Recall methods on the other hand are rapid and inexpensive but prone to memory error and inability to accurately reconstruct events the way in which they unfolded.

6.7 Concluding Summary

This chapter quantified domestic water demand in the GRRC to ~28 LCPD based on a household survey of three villages in the Usangu Plains. Combined with previous household surveys estimating domestic water demands in the GRRC, which ranged between ~34-46 LCPD, the mean domestic water demand is ~33 LCPD. Semi-structured interview methods with government officials produced higher estimates of daily per capita water use ranging from ~60 to 100 LCPD. Elsewhere in Tanzania and other parts of arid- and semi-arid SSA, estimates of per capita water use are below the 100 LCPD benchmark embedded in the WSI.

Quantification of per capita daily domestic water use in SSA often does not adequately account for the complex factors that contribute to differences in how water users in MEDCs and LEDCs access and use water, including multiple-source use, source preference, proximity, waiting time and costs. The next chapter examines the factors that influence how households in the three previously studied villages in the

GRRC use and access water for domestic purposes, with a particular focus on the role of groundwater and other storage-based sources of water.

Chapter 7 - Results and Discussion III: Water scarcity and adaptive pathways in the Great Ruaha River Catchment: water users' understandings and perceptions

Chapter 7 engages with the third critique of water scarcity metrics raised in Chapter 2 that physical descriptions of water scarcity be used as a starting point for participatory decision-making processes through which communities resolve how to address storage requirements by reducing demand or amplifying storage. The recommended shift is posed as research objective 3) "to investigate how water users characterise 'water scarcity' and how freshwater storage contributes to adaptive capacity"

The preceding chapter quantified domestic water demand in the GRRC and estimated an average per capita demand of ~33 LCPD acquired through the application of a household questionnaire. The results are in overall agreement with studies from elsewhere in Tanzania that estimate domestic water demand to range between ~8 and 40 LCPD, as well as evidence from other arid- and semi-arid countries in the SSA that estimate domestic water use is between ~4 and 38 LCPD.

To adequately characterise water scarcity, it is necessary to understand the factors that influence how people access water for domestic use under changing conditions. Within the limitations of the data collected, this chapter first presents results from semi-structured interviews and observations conducted during the first phase of fieldwork in 2015. This investigation examined how ERs and IRs perceive water scarcity in the GRRC and how they understand the role that surface and sub-surface water storage plays in adapting to periods of limited freshwater availability (i.e. water scarcity). During the second phase of the fieldwork in 2016, in-depth focus group discussions and household questionnaires in three villages in the Usangu Plains informed this research, to better understand the factors that influence how freshwater storage, in particular groundwater access, manifests itself as an adaptive capacity.

7.1 Results: Interviews on perceptions of water scarcity

To gain a general understanding of how water users and decision-makers for freshwater resources development perceive water scarcity in the GRRC, interviews with key informants (Table 4.3) were held during the first phase of the fieldwork in 2015.

7.1.1 Interview with External Respondents

Firstly, ERs were consulted on what they perceive to inform the general characterisation of water-scarce conditions in the GRRC. ER3, an international advisor with extensive work experience of freshwater management in the GRRC, was asked whether they perceived there to be water scarcity in GRRC and responded: "*No, you know there isn't. [...] there is lots of water in the Ruaha catchment. It's just that it's so seasonally biased towards the wet season*." In emphasising the heavy variability in freshwater availability, common to the GRRC, ER3 elaborated that "*[...] in a monsoonal system like this, you've got plenty of water coming down in the wet season and very little in the dry season [...]*". ER3 continued to make important links between water scarcity, variability and water storage by explaining that "[…] *for instance,* [the] *Mtera and Kidatu* [dams] *don't suffer any supply problems despite the lack of dry season flows. Because during the wet season, they* [the dams] *just fill up*". Relating these statements to their knowledge of how people in the GRRC may understand water scarcity, ER3 held that *"[...] the key thing is to get people to understand that there really is plenty of water if you can manage it properly. People's mindsets need to be* *changed to recognise that. […] people need to be more aware of the possibilities of storage. I think, there are lots of options for storing water now, as you point out, things like groundwater, which don't have nearly the sort of environmental costs that have traditionally been associated with large rather badly designed dams. Dam design has come a long way. Off-stream storage is another option. You know, there are lots of options, if one is prepared to look into them.*"

Following on, government respondent, ER2, working in the Mbarali District held that, "*In the Usangu we have plenty of water. The groundwater potential is high […]. Downstream has even more potential as the water table is higher as we approach the permanent wetlands. […] more research has to be done, but we have enough water*". Addressing water scarcity through the prism of variability, ER4 similarly expressed:

> *Well, if you asked me* ***what areas*** [emphasis added] *in the catchment of the Rufiji basin are water scarce, it would be a much better question* [than asking **if** there is water scarcity] *because there is a lot of rainfall in some areas and little in others. The GRRC is not uniform. It depends on where you are talking about. […] scarcity occurs in patches. You need to be specific when talking about water scarcity. […] scarcity in the GRRC should be compared to its uses. The GRRC has large-scale irrigation, and compared to the other catchments has the highest water irrigation use, and generally the highest water demand compared to the other catchments in the basin.*

> *Thus, the GRRC has a lot of water but also* [in places] *a high demand*."

Contrary to the views expressed by ER3 and ER4, ER1 articulated that "*Scarcity is a serious problem in the Usangu [...]. For reasons of stress, they* [the RBWB] *have stopped issuing permits*". Their definition of water scarcity occurs when "*demands exceed supply"*. They further noted that they considered water scarcity to be a seasonal problem influenced by the vast temporal and spatial differences in rainfall: "*Usangu is a dry area as opposed to Njombe* [highlands]".

7.1.2 Interview with Internal Respondents

During a joint interview with representatives from the Ipatagwa Irrigation Scheme WUA (IR2) and a local Irrigation Extension Office (IR3), these respondents explained that generally water is prioritised for irrigation purposes and access to water for domestic purposes are considered secondary and should not be taken into account during the planning phase of freshwater resources and irrigation. During the dry season, many people do not have access to water as the taps in the nearby villages are closed off, for several months. IR2 explained that inhabitants of the area have gotten so used to fetching water from the nearby Mkoji River that water users believe this river will never cease to flow. When asked what would happen if the Mkoji River dried up, IR2 was confident that people would eventually start digging until they found water.

7.2 Results: Interviews on understandings of the role of storage for adaptation

To gain an understanding of the challenges associated with developing surface- and sub-surface freshwater storage infrastructure in the GRRC, interviews with ERs and IRs, held during the first phase of the fieldwork in 2015, also addressed these topics.

7.2.1 External Respondents: Challenges with groundwater storage solutions

ER3 explained that groundwater could have the potential to complement current irrigation in the GRRC and reduce pressure on surface water resources. The respondent, however also noted that during previous work in the GRRC:

> "*[...] there were two reasons why that* [groundwater] *really wasn't a very attractive option* [to focus on]. *One was that if you are using groundwater for the irrigation, you are basically robbing Peter to pay Paul. You know that it would presumably be water that would eventually have found its way into the river, anyway downstream. And the other thing, again, is that it* [groundwater irrigated agriculture] *just opens up the option of additional rice growing. So, you wouldn't have any environmental benefits although it might have some additional rice growing benefits*."

Further concern regarding the lack of regulatory policy on storage was expressed:

> "*[...] from what I have seen, the trouble is that every time I have seen additional storage provided, it actually exacerbates the problem. It increases demand. People look at it immediately as an additional*

source of water for economical agricultural, rather than for environmental augmentation. So, unless you've got a strong implementation policy, for things like environmental flows, they do not end up getting implemented. And the problem in Tanzania is that they've really got the best of intentions, in terms of their water legislation and policy, and in terms of assessing the environmental requirements, but the amount of implementation is almost negligible."

The concerns ER3 raised with regards to the lack of a regulatory policy were further put into perspective by government officials in Mbarali, who provided their inputs into the potential and challenges of both surface- and groundwater storage-based development in the GRRC. ER2 also associated challenges to groundwater development with a lack of an enforceable regulatory regime and mentioned that during the last ten years, the number of unregistered wells had soared. RWBO staff, ER1 also emphasised the lack of enforceable law and admitted that, despite the existence of a database of registered well users, the actual number of constructed boreholes in the GRRC was/is highly uncertain. Indeed, the respondents acknowledged that the many unregistered wells constitute the predominant way for households to access water for domestic uses in the GRRC.

The second challenge according to ER4 is that the low number of motorised pumps in the GRRC limits the potential to mainstream groundwater irrigation. Furthermore, the little attention given to promoting groundwater irrigation means that the source is primarily used for domestic purposes and withdrawn by hand pumps. ER2 also emphasised that the lack of pumps for deeper wells was heavily influenced by the unaffordable and unreliable electricity supply. ER2, however, optimistically mentioned that investments into solar-powered pumps, linked to water storage tanks, had been made in Chosi Village. Although these projects only pumped water for the provision of domestic water, ER2 was positive that these pilot-schemes could also be extended to irrigation and considered the solar-powered pumps to be more economically viable in the long-run than both diesel- and petrol-powered pumps.

A third major challenge to the future of increasing groundwater use in the GRRC relates to the highly variable geology of the Usangu Plains. The key question is whether groundwater may sustain the Usangu Wetlands so that a shift from surface- to intensive groundwater-irrigated agriculture could risk depleting water flowing to the Usangu Wetlands. Despite this risk, ER4 was positive that small-scale groundwater-irrigation could produce high yields of valuable crops during the dry season. ER4 argued that groundwater systems should be based on multi-purpose design criteria so that boreholes are linked to storage tanks that are connected to sprinkler systems, providing the ability to fulfil both domestic water demands and irrigation of high-value crops during the dry season.

7.2.2 External Respondents: Challenges with surface water storage solutions

Discussion of the present status of surface-water storage infrastructure in the GRRC, commenced with an interview with ER3, who stated that there are "[…] t*wo main storages, Mtera and Kidatu which, as I understand it and I haven't seen either of them, are for hydro-electric power to supply Dar Es Salaam […]*". In relation to challenges associated with freshwater storage-based solutions for dealing with the drying up of the GRR downstream at Msembe Ferry gauging station, ER3 referred to an old proposal that involved damming the Ndembera River at Lugoda and diverting the flow directly into the GRR downstream at Msembe. They approached this solution with much caution, as they feared such developments would turn the Ndembera River into "*[...] a barrage; a storage which could then be used to augment rice growing [...]*". More generally, ER3 found that any future storage development in the GRRC is "[…] *the wrong way to go*", and declared that "*[...] the Ruaha* [catchment] *is just in such a state at the moment [...] that any sort of storages, to be honest, is likely to exacerbate that, because it won't be managed properly, such as taking into account environmental needs [...]".* However, ER3 found that the Kilombero catchment would be much better suited for increasing freshwater storage-based infrastructure:

> "*In the Kilombero you have got a lot of tributaries, so you could provide storage for some of the tributaries and leave some of the tributaries free flowing, which really minimises the kind of environmental costs. You could build dams with multiple off-takes, radial gates, which are the most expensive but give you a lot of options for releasing water down the river. And you've got a lot of water in the Kilombero."*

Therefore, any type of future freshwater storage development in the GRRC could have "*[...] real potential for an environmental catastrophe*" but also "*[...] real positive potential* [for dealing with the variability of water] *because of the seasonal differences we have talked about, but [...] it's just been badly managed so far and you can't see that it is likely to be better managed if there is additional development there*". Indeed, ER3 re-emphasised that the entire Rufiji Basin should be restored and treated as a whole system in which "*[...] storage can easily be part of* - *but it needs to be storage for river restoration and not storage for additional rice growing*".

Connecting water scarcity and freshwater storage as a solution to address seasonality in water resources, ER4 stated that, "*Upstream scarcity or scarcity-related issues may be solved by damming, but what one really does is just shifting the scarcity downstream*". Indeed, ER4 acknowledged that dams can be part of the solution, but only if their planning is done at the basin-scale and not limited to the catchment-scale because "*[...] catchment-scale effects are not negligible on downstream effects. So, any dams need to be multipurpose and balance all other uses and users*". ER4 held that the starting point would be to reach the consensus of all stakeholders in the entire basin to avoid jeopardising downstream water users. ER1 also emphasised that when it came to whether farmers would either support a campaign focused on surface- or groundwater-storage development for irrigation, dams will always win because "*People are running away from groundwater – they feel they are playing with probability [...]* [therefore, water users in the GRRC] *[...] would like to see more dams. Check dams are still the preferred option largely due to the lack of knowledge on how to access groundwater."*

Upstream-downstream conflicts over prioritising water use are problematic. ER1 reflected that upstream farmers would not consider downstream issues such as the drying up of the RNP and EWRs as a primary concern. For these stakeholders, the most important use of water is for irrigation because "*Without irrigation, life cannot move on*". ER1 also held that *"SAGCOT dams will fuel more conflic*t *[...]. SAGCOT is* ***not*** [emphasis added] *feasible in the Great Ruaha Catchment. It is already stressed, so not feasible. The Usangu will not benefit from the dams"*. Instead, ER1, similar to ER3, favoured increased water use efficiency as a way to deal with increasing water demands because "*Once efficiency has improved, then permits can start being issued again, and* *the agricultural area can potentially be increased*". On the issue of competition, ER2 stated that "*Dry season irrigation will not override domestic purposes even if groundwater is extracted and developed*" and suggests priority be given to water for domestic purposes. ER2 asserted that future groundwater development has to start understanding what local communities' domestic water requirements are and how they access water because "*the sustainability of groundwater use is dependent on domestic community requirements being fulfilled".*

7.2.3 Internal Respondents: Challenges to storage solutions

Concerning the development of groundwater, IR2 and IR3 stated there was no organised access to groundwater in Ipatagwa village nor were they confident in exactly how deep they would have to dig. They considered funding for groundwater exploration the main challenge but welcomed it, if it could achieve an expansion of irrigation.

7.3 ER-IR interactions: the future development of storage

A five-year World Bank was undertaken by WREM International Inc., to develop the Rufiji Decision Support System Model and their recommendations for future water resources development in the Rufiji Basin were presented at a Final Stakeholder Meeting on 24-26th June, 2015. ER5 (representing WREM International Inc.) commenced the presentation of their freshwater resources status assessment by expressing that, "*We cannot continue in the same way as we have done in the past".* The primary recommendation in response to the continuous drying up of the GRR at Msembe was to dam the Ndembera River at Lugoda. The consultants did not recommend any further damming of the Chimala and Kimani Rivers, because this would greatly reduce downstream water availability into the Usangu Plains. ER5 specifically did not support the recommendation of groundwater storage development because they believed that the Usangu Wetlands might be fed by upstream groundwater supplies. Plans to restore the wetlands should exclude groundwater-irrigation developments at least until increased freshwater availability had been achieved through raising irrigation efficiencies.

Local stakeholders, grouped as IR4, responded to these recommendations with some disapproval. One irrigation officer was particularly concerned with the recommendation to cease dam construction upstream of the Usangu Plains: "*Indeed, Tanzania is only using small dams for small-scale irrigation and therefore dams should be key in future development because a continued withdrawal based solely on surface river waters would not be sustainable*". One zonal irrigation officer supported this view: "*Let us not make the mistake of stopping exploring storage of water for a growing population*". A third respondent stated that the abundant seasonal water availability in the GRRC should be used to their advantage in constructing climate-resilient irrigation and dam infrastructure. Another respondent advocated that the entire Rufiji Basin should be seen from the perspective of the water-energy-food nexus and future freshwater resources development should focus on the co-existence of agriculture and energy, instead of blaming current problems on irrigated agriculture alone. A representative from the Directorate of Water concluded "*[...] dams can and should be put between the wetlands and the "water towers*". They expressed favour towards continued development of dam storage upstream of the Usangu Plains and irrigation sites, firmly insisting future discussion should not be about **whether or not** to build dams, but about **how** and **where** to agree to build them. ER5 responded to the concerns raised regarding the recommendation to cease development of upstream dams that due to the high seasonality of water in the catchment, any future development would have "*[...] to be done with due diligence".* On the matter of groundwater, ER5 clearly stated, "*I don't believe Usangu has the resources you want. I don't think that the aquifer connected to the Usangu can help you*".

Overall, there is an apparent conflict between ERs and IRs in terms of the type of storage development that are feasible and desirable. ERs appear to be more concerned with restoration of the area, in particular the RNP, and recommend minimising surface- and groundwater storage development. IRs, on the other hand, whose livelihoods are primarily dependent on the use of water for irrigated agriculture, favour the continuation of dam construction, as they are familiar with the operational nature of this type of infrastructure and much less concerned with downstream restoration requirements.

7.4 Synthesising perceptions of water scarcity and understandings of storage based development

The first part of this chapter presented the outcomes of fieldwork in 2015. Semi-structured interviews with government officials and water users were conducted in order to gain an understanding of these respondents' perceptions of the characteristics of water scarcity in the GRRC and the role that surface and sub-surface water storage can play in adapting to perceived water scarce conditions. Government respondents' and international advisors' views on whether the GRRC is water scarce were mixed, but within the limitations of the data there was consensus that the characteristics of water scarcity in the GRRC are primarily determined by extreme temporal and spatial variabilities of freshwater availability. Internal Respondent (i.e. water users, farmers) primarily perceived water scarcity to be concerned with having inadequate water for irrigation purposes.

In relation to how groundwater and other storage-based solutions might assist in adapting to water scarcity, three main challenges that hinder mainstreaming groundwater use were identified: 1) the lack of enforceable policies that regulate groundwater pumping, 2) a low number of motorised pumps due to unreliable access to electricity from the grid and/or expensive price of diesel to fuel generators, which has mainstreamed the use of manual hand-pumps limited in their capacity to serve domestic purposes and, 3) a lack of knowledge regarding both the nature of the highly localised geology present and the risks associated with increasing groundwater use on the downstream wetlands. ERs warn heavily against rapid expansion of both subsurface- and surface-water storage infrastructure. IRs, however expressed a strong preference towards expanding surface storage development, and reject the recommendations of temporarily suspending storage-based developments. A general lack of knowledge on how to access and use groundwater, coupled with a history of hand-pump use limited to domestic use and a lack of access to affordable and reliable sources of power (either from the grid or diesel to run generators for motorised pumps), influence the idea that surface water storage infrastructure is preferential to localised and decentralised small-scale groundwater networks.

The next section presents the results from fieldwork in 2016. It systematically investigates the factors that contribute to water access during the dry-season in three villages in the Usangu Plains, as well as focusing on the successes and failures of enhancing the uptake of groundwater.

7.5. Examining Water Use and adaptive capacity in three groundwater dependent villages

This section presents results from the second phase of the fieldwork during the dry season in 2016. FGDs and household questionnaires relating to household water use and access were undertaken in three villages Ubaruku, Nyeregete and Chosi (see Figure 3.2 for a map of the location of the study sites). First, FGDs were used to gain a better understanding of local conditions at the village level, before purposively sampling data at the household-level through a targeted questionnaire.

7.5.1 Focus Group Discussion Results

7.5.1.1 Ubaruku Village

In Ubaruku, two focus groups discussions (FGDs) were held. The first FGD was held with the Groundwater Users Association (GWUA) 'Ubaruku Mpakani' (UBAMPA), which consisted of 4 women and 4 men and focused on groundwater governance. The participants had good knowledge of the local water table conditions estimated to 8 metres. The group also expressed that their motivation for using groundwater had been influenced by continuously decreasing surface water availability. They considered groundwater to be the safest source in the area for drinking and domestic purposes. The UBAMPA had formally been established under a World Bank groundwater development intervention involving the installation of a borehole that pumps water into a 150 000 L storage tower. The formalisation of groundwater use and a GWUA inspired other water users to establish private boreholes and the knowledge that there was accessible groundwater in the area had been a pull factor for in-migration to the town.

Prior to the World Bank initiative, the Danish International Development Agency (DANIDA) had attempted to extend the piped network coverage in Ubaruku. Focus group participants however explained that this intervention had been a failure. As the planning process had not been done in a participatory manner, the extended coverage only benefitted the richest households that could afford the costly connection fees. Danida had failed to recognise water users' preferred ways of accessing water, which in this case constituted public boreholes. The World Bank intervention recognised that even the poorest households of Ubaruku could afford the costs associated with accessing groundwater, and so the number of public boreholes increased.

Despite the positive developments of increasing overall access to groundwater, political conflict between the UBAMPA and the Village Government followed. The UBAMBA receives direct project funding from the World Bank, bypassing the Village Government, which feels it does not benefit from this arrangement. In Ubaruku, groundwater has become an election issue and local politicians continuously promise to increase the extent of groundwater coverage, independent of the UBAMPA and the World Bank. So far, the UBAMPA have been successful in expanding groundwater use without the Village Government's involvement, but this situation could soon turn into stalemate. As all land belongs to the Village Government, widespread expansion of groundwater boreholes for irrigation would require cooperation and a positive dialogue. The UBAMPA also stated that a lack of a reliable supply of electricity from the grid by TANESCO to pump groundwater with constituted a significant challenge.

The second focus group expressed great appreciation for groundwater and held it to be more precious than surface water. In terms of the potential for groundwater expansion for irrigated agriculture, all participants agreed that there were only hindrances. Apart from the aforementioned challenges expressed by the first focus group, the second group of participants were primarily concerned with the limited knowledge they possessed in relation to groundwater-irrigable crops. Farmers feel that they may be missing out on the financial gains associated with investment in groundwater-irrigation and expressed they would highly benefit from a feasibility study into which crops can be irrigated with groundwater.

7.5.1.2 Nyeregete village

In Nyeregete village, a transect walk through three hamlets revealed a small number of derelict hand-pumps and a significant amount of functioning hand-dug shallow wells. Participants in the first focus group explained, that during the 1980s, DANIDA had started a groundwater development project by drilling boreholes and installing hand-pumps. This intervention however, took a non-participatory approach, which meant that after the construction phase, inhabitants had no knowledge regarding ownership and responsibility for the management, operation and maintenance of the pump systems. From the point of public administration, Nyeregete village consists of nine hamlets and lacks a central Village Government. As such, there was no formal institutional mechanism to decide how to govern DANIDA-financed wells. Consequently, the project failed to secure a sense of ownership of the wells and pumps by the water users. Instead, they became abandoned as water users commenced to self-supply by hand-dug and shallow-wells. Today, only two DANIDA pumps are in a working condition. However, one of these pumps has been modified, and uses a pulley system endemic to the area. The inhabitants are planning to modify the second functioning hand-pump, accordingly. The village is currently undergoing a transition in public administration and a Village Government is being set up. Hopefully, this change in governance structure can clarify the laws regarding ownership, maintenance and responsibilities for the few remaining DANIDA hand-pumps.

Generally, focus group participants felt that groundwater, regardless of whether from the DANIDA pumps or via self-supply, was always available and adequate. A small number of farmers expressed they had started to irrigate using shallow wells and successfully grown tomatoes, onions, papaya, mango and spinach. The participants further estimated that on average, one hand-dug shallow well creates about ten household beneficiaries and financing of the construction, operation and maintenance is organised on an informal basis.

7.5.1.3 Chosi Village

In Chosi Village, use of groundwater and surface waters are generally mixed, and nearby springs contribute significantly to fulfilling domestic demands. One participant stated "*We have no experience in groundwater so we may just as well continue to use surface water*". The participants all agreed that shallow groundwater sources were too salty to drink. Instead, the nearby solar-powered UNICEF borehole at Chosi A Primary School, with a storage tank of 10 000 L, serves as relied-upon source of drinking water for the nearby households.

Similar to Ubaruku, a major challenge to groundwater-fed agriculture relates to the lack of knowledge of which crops that can be irrigated using groundwater. One participant shared that they had tried to irrigate crops with groundwater, but all crops had died. The use of groundwater from shallow-wells for dry season brick-making, however, was very common. Instead of fetching water from nearby springs, water users would take advantage of the high water table (< 2m) and dig shallow wells during the dry season to access water for brick-making. In Chosi Village, DANIDA had also been involved in a project to extend the network of piped water supply. The intervention however had also failed to take a participatory approach, and with the abundance of nearby springs, complemented by the UNICEF borehole, the focus group generally felt they had sufficient water to fulfil all non-irrigation water demands.

7.6 Results: Household Questionnaire

In the Usangu Plains, 82 households were surveyed in the three villages, Ubaruku (n = 34) Nyeregete (n = 18) and Chosi (n = 30) concerning their experiences of using groundwater (Table 7.1).

Table 7.1: Summary Overview of Household Survey Responses

Indicator	Ubaruku (n = 34)	Nyeregete (n = 18)	Chosi (n = 30)	All (n = 82)
Average groundwater use history (years)	5.5	15.4	4.4	7.4
Type of well construction				
Manual	6%	56%	30%	40%
Drilled	56%	17%	37%	26%
N/A	38%	28%	33%	34%
Type of well				
Shallow/Hand-dug	21%	94%	33%	30%
Deep	38%		40%	41%
N/A	41%	6%	27%	28%
Funding Type				
NGO/International Agency	85%	22%	47%	57%
Self/community-funded	9%	56%	33%	28%
N/A	6%	22%	20%	15%
Productivity of well				
High	62%	61%	47%	56%
Medium	3%		23%	10%
Low				
N/A	35%	39%	30%	34%
Use of groundwater				
Domestic only	64%	50%	63%	61%
Domestic & livestock	18%	22%		12%

Domestic/livestock/brick making	3%			1%
Domestic/irrigation	3%	5.5%	3%	5%
Domestic/irrigation/livestock		5.5%	3%	1%
Domestic/brickmaking			7%	2%
Irrigation only			3%	1%
N/A	9%	5.5%	7%	7%
Irrigation/livestock		5.5%		1%
Livestock	3%	5.5%	3%	4%
No groundwater use			10%	4%
Motivation for groundwater use				
Proximity	62%	44%	53%	55%
Adequate quantity	6%	11%	7%	7%
Affordability		28%	3%	7%
Adequate quantity/affordability	3%			1%
Proximity/adequate quantity	12%	11%	3%	9%
Proximity/adequate Quantity/affordability	12%	6%	7%	9%
Proximity/affordability	6%			2%
Safe source			13%	5%
N/A			13%	5%
Groundwater dependency				
All year	94%	78%	67%	80%
dry season	3%	6%	13%	7%
wet season			3%	1%
N/A	3%	17%	17%	11%
All year access to groundwater				
Yes	32%	50%	80%	54%
No	50%		3%	22%
N/A	18%	50%	17%	24%
If no, why?				
Shortage of electricity	12%			11%
WUA Rules	35%			33%
Fear of typhoid	6%			6%
N/A	47%			50%

7.6.1 Length of groundwater use experience

The average number of years spent using groundwater across the three study sites was 7.4 years, with the longest experience reported being 36 years and the most frequent 4 years (Figure 7.1, Table 7.1). The average groundwater use experience was 5.5 years in Ubaruku, 15.4 years in Nyeregete and 4 years in Chosi, with the longest experiences reported being 27, 35 and, 36 years, respectively.

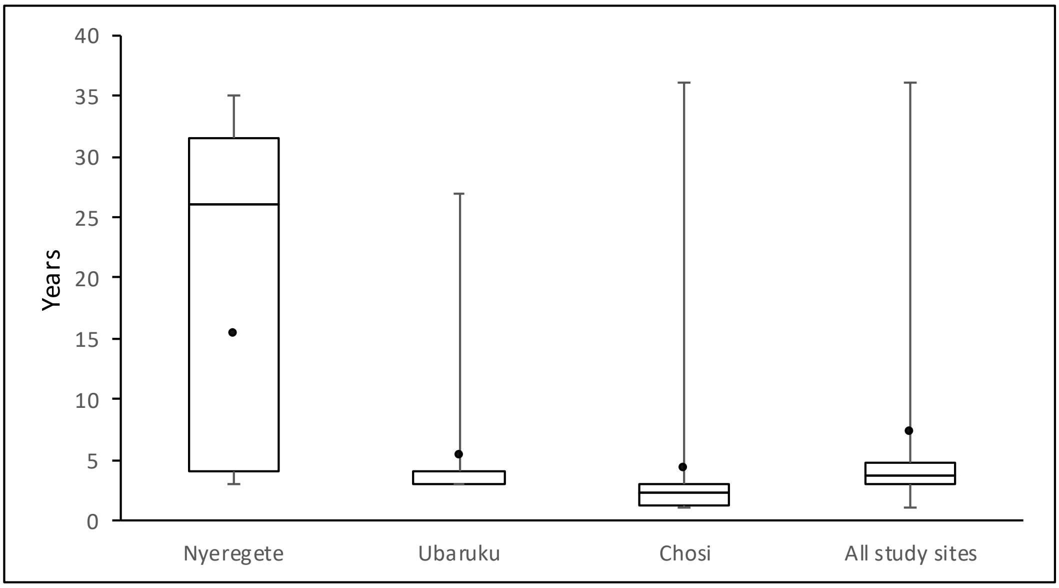

Figure 7.1: Average years of groundwater used in the three areas studied

7.6.2 Type of well construction

Concerning the type of construction used for wells across the three study sites, on average 40% had manually constructed wells and 26% accessed groundwater through drilled wells (Figure 7.2, Table 7.1). 6% of respondents in Ubaruku used manually constructed wells, 56% in Nyeregete, and 30% in Chosi. The proportion in Ubaruku that reported using drilled wells was 56% compared to 17% in Nyeregete and 37% Chosi.

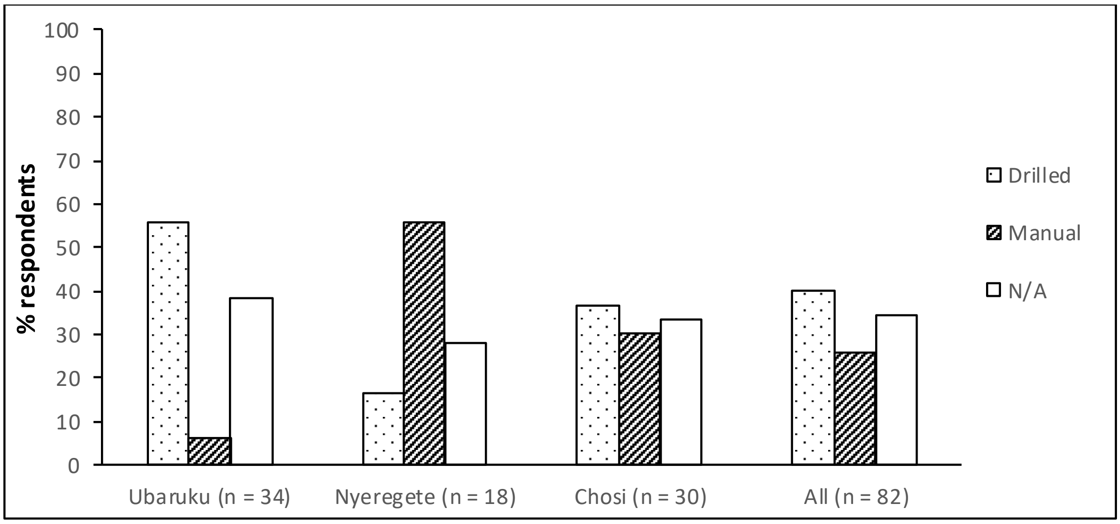

Figure 7.2: Types of well construction

7.6.3 Types of wells

In terms of the type of wells used primarily for accessing groundwater across the three sites, 41% rely on deep wells, and 30% on shallow wells (hand-dug wells and shallow wells have been pooled together) and 28% did not respond (Figure 7.3, Table 7.1). In Nyeregete, 94% of respondents reported primary reliance on shallow-wells for accessing groundwater, whereas in Ubaruku and Chosi, the tendency was for 38% and 40%, respectively to use deep wells.

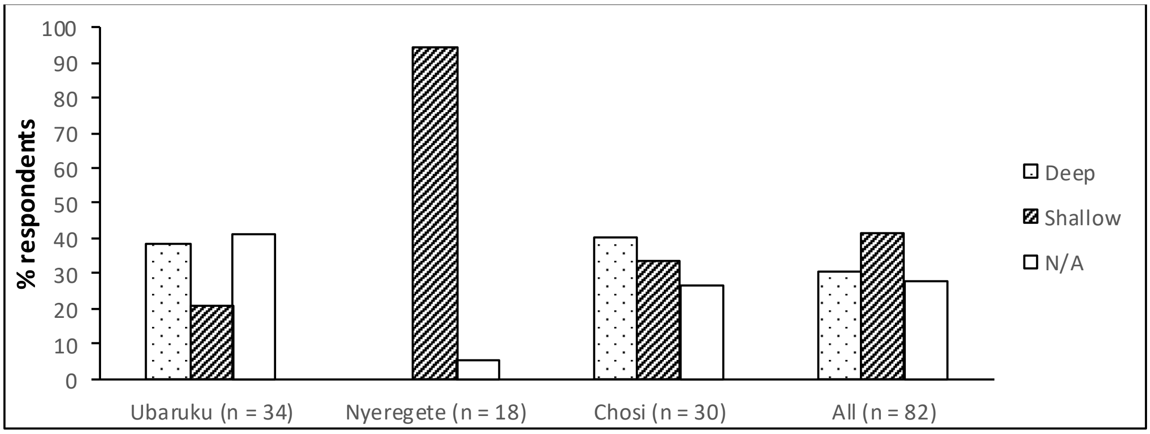

Figure 7.3: Well type

7.6.4 Sources of funding

Dominant sources of funding for well development across the three sites are Government/(I)NGO funded initiatives which constituted 57% of all households sampled. This is followed by self- or community funded initiatives (28%) (Figure 7.4, Table 7.1). Water users in Ubaruku had the highest reliance on (I)NGO/International Agency funding (85%), whereas in Nyeregete, water users were more prone to self-fund (56%).

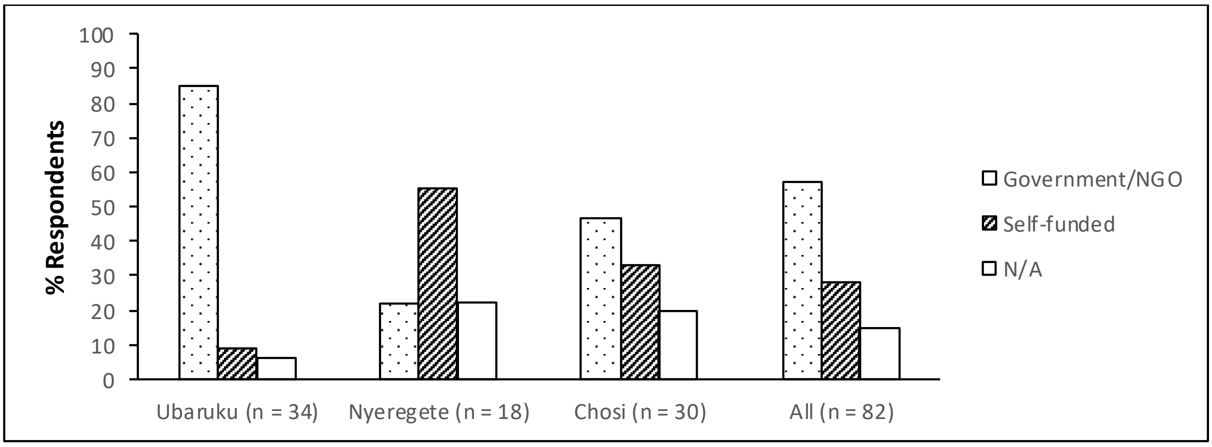

Figure 7.4: Types of funding for wells

7.6.5 Well productivity

Productivity wise, 56% of all respondents were of the opinion that the well(s) they used were highly productive (Figure 7.5, Table 7.1). The highest proportion of respondents at the village level, that found their wells had a high productivity were 62% in Ubaruku and 61% in Nyeregete.

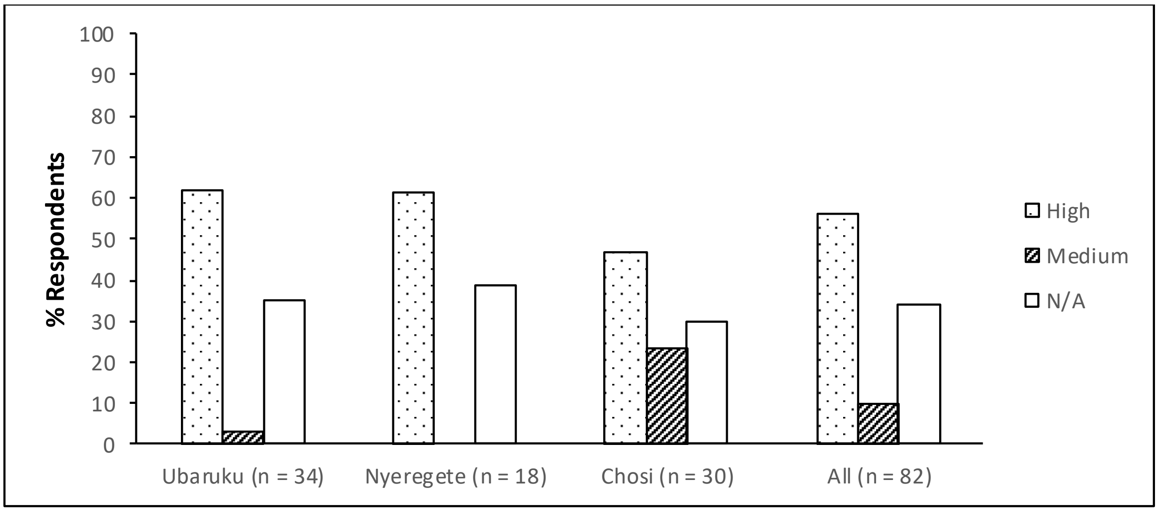

Figure 7.5: Well Productivity

7.6.6 Primary use of groundwater

The average primary use of groundwater resources across the three sites sampled was for domestic use only (61%) (Table 7.1). Groundwater for domestic purposes combined with other economic activities constituted 12% when combined with livestock keeping, 5% in combination with irrigation, and 2% in combination with brickmaking. In Nyeregete, 72% use groundwater for domestic purposes, 22% of which was used it in combination with livestock keeping, whereas Chosi had the highest proportion of respondents that use groundwater for both domestic uses and brickmaking (7%).

7.6.7 Motivations for using groundwater

The primary motivator for using groundwater to fulfil domestic demands for the three sites was associated with proximity of the source (55%) whereas 7% felt affordability was the primary motivator. 7% use groundwater due to its abundant availability and 5% based their motivations on the perception that it constitutes the only safe water source for drinking (Table 7.1).

7.6.8 Groundwater dependence

In terms of the reported period of the year that respondents stated to be primarily dependent on groundwater, on average 80% of those sampled across all three sites responded that they were dependent all the time of the year, whereas 7% claimed to rely fully on groundwater only during the dry season (Figure 7.6, Table 7.1).

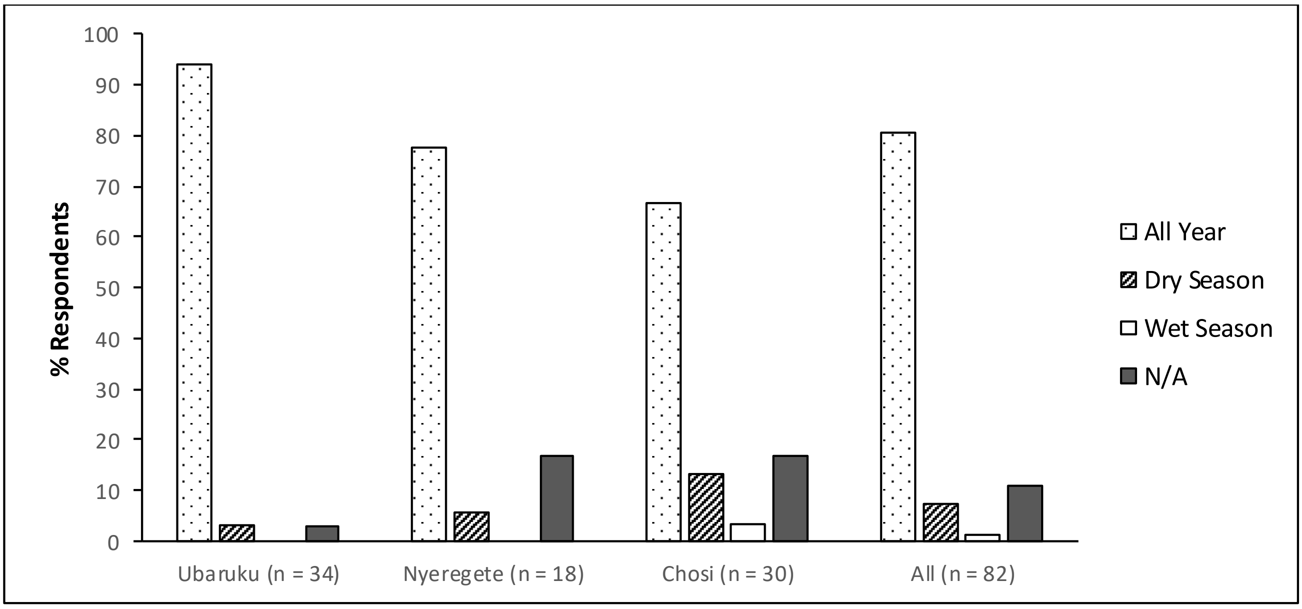

Figure 7.6: Groundwater dependence

On the issue of whether groundwater was accessible all year, 54% of the sampled population responded that they were able to access groundwater all year around and 22% said they were not (Figure 7.7, Table 7.1). Of those that responded they could not access groundwater all year, 33% related this to GWUA rules, 11% due to electricity shortages, and 6% due to a fear of typhoid contamination (Figure 7.8, Table 7.1).

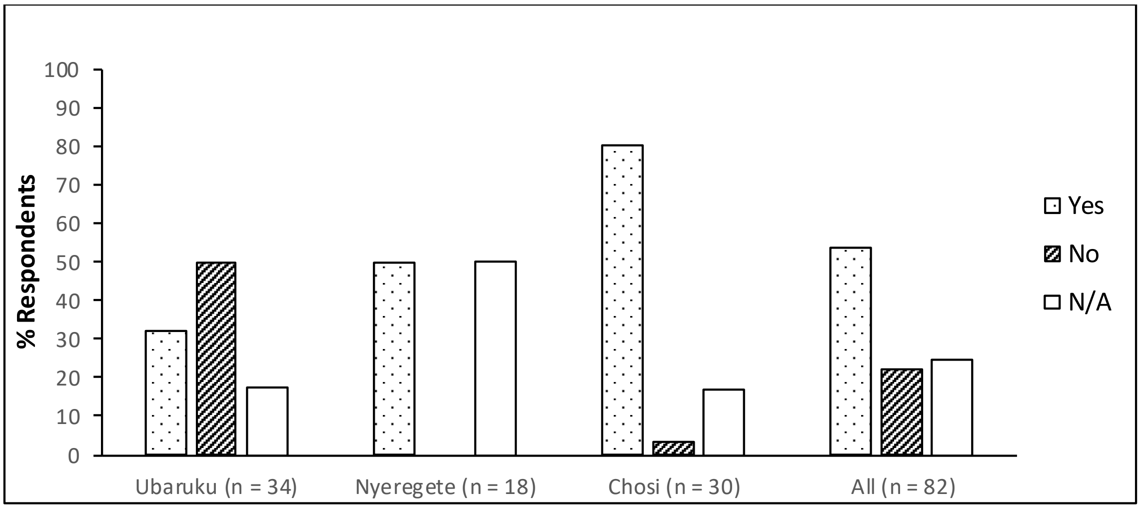

Figure 7.7: Ability to access groundwater all year

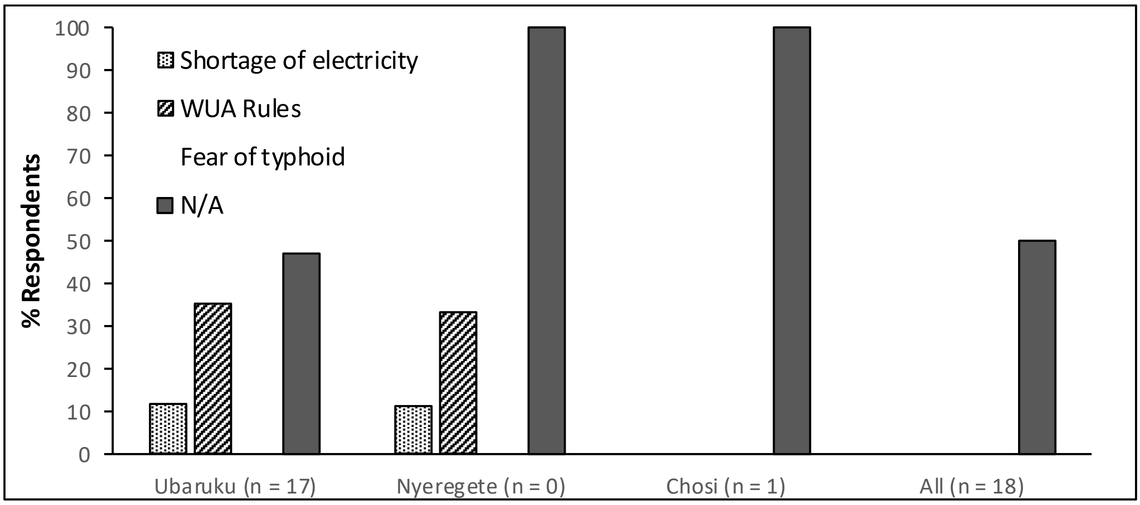

Figure 7.8: Reasons for inability to access groundwater all year

7.6.9 Challenges and drivers related to increasing groundwater irrigation

Respondents in all three villages were asked what they perceived to constitute the main hindrances and/or drivers to expanding groundwater for irrigation (Table 7.2). The main hindrances related to a combined lack of awareness, exposure and experience in using groundwater beyond domestic uses. However, 5% of those sampled claimed that they had already unlocked the potential of groundwater-fed irrigation. In Ubaruku, the primary driver for small-scale groundwater irrigation related to a visibly dwindling supply of surface water resources whereas in Nyeregete previous success with using groundwater to grow vegetables had led to an increase in the number of households who experimented with this. However, in Chosi, the most frequent response was that the presence and constant reliability of nearby springs provided very little incentive to consider shifting to alternative sources. Respondents in Nyeregete also raised concerns about competition with pastoralists for water use, which was a factor that made some water users hesitant to advance groundwater-irrigation.

Table 7.2: Drivers and Hindrances Responses to Groundwater Irrigation

Driving/Hindrance to Irrigation	**Ubaruku (n = 34)**		**Nyeregete (n = 18)**		**Chosi A (n = 30)**		**All (n = 82)**	
	Count	%	Count	%	Count	%	Count	%
Hindrance: Competition/Distance			2	11	2	7	4	5
Hindrance: Lack of awareness/exposure	1	3	1	6	10	33	12	15
Driver: Availability/Scarcity	1	3	2	11	1	3	4	5
N/A	32	94	13	72	15	50	60	73
No groundwater use					2	7	2	2

7.6.10 General constraints hindrances to the expansion of groundwater development

Concerning the perceived challenges related to the overall development of groundwater, 18% of respondents across the three study areas felt that they lacked the adequate technology to access and manage groundwater, whereas 17% felt they were missing sufficient education and awareness of how to access groundwater. A further 17% perceived issues related to finance to constitute the main barrier to accessing groundwater. In Nyeregete, one respondent noted that "*groundwater users are not willing to contribute to the maintenance and infrastructure* [of wells]". Another household had a shallow well that had collapsed and the respondents expressed that they felt this could have been avoided, if they had had the proper technical knowledge and training (Table 7.3).

Table 7.3: Response to Challenges regarding Groundwater Development

Challenge to groundwater development	Ubaruku (n = 34)		Nyeregete (n = 18)		Chosi (n = 30)		All (n = 82)	
	Count	%	Count	%	Count	%	Count	%
Finance	8	24	6	33			14	17
Experience/Education/Awareness/Capacity	4	12	2	11	8	27	14	17
Technology/maintenance/management	3	9	2	11	10	33	15	18
N/A	19	56	8	44	9	30	36	44
No challenge					3	10	3	4

7.7 Assessing formal and informal approaches to accessing groundwater

Groundwater users across the three study sites access water for domestic and economic activities in different ways. The factors that determine the pathway(s) relate amongst others to infrastructure (e.g. well type, type of well construction) and access to funding.

Ubaruku is primarily characterised as a village where groundwater access has developed in a formal manner through the establishment of mechanisms of construction and financing resulting from the World Bank intervention. In contrast, the failure of the DANIDA intervention in Nyeregete has resulted in a situation where water users access groundwater through informal pathways, due to the lack of established mechanisms regarding ownership and responsibility for the pumps. The section below tests these assumptions to see if there are statistically significant differences between the three aforementioned factors that influence how respondents in the three study sites access groundwater.

One assumption is that reliance on shallow and/or hand-dug wells represent an informal pathway where the failure of formal attempts to facilitate groundwater access have caused water users to self-supply. In contrast, deep wells indicate a successfully planned intervention and thereby an operational formal pathway. Indeed, the proportion of people that rely on shallow wells in Nyeregete is significantly higher than the number of people that rely on deep wells in Ubaruku (X^2 = 17.04, p = 0.0000, df = 1) and Chosi

(X^2 = 13.39, p = 0.0003, df = 1). Furthermore, the number of people reliant on hand-dug wells compared to deep wells in Ubaruku and Chosi has no statistically significant difference (X^2 = 0.48, p = 0.49, df = 1). Hand-dug wells are also used as a proxy for informal pathways to groundwater. There is a statistically significant difference between the types of well construction in Nyeregete and Ubaruku (two-tailed, p = 0.0001, df = 1), as Nyeregete has a much higher proportion of manually constructed wells than the predominantly drilled wells in Ubaruku. To further test for differences between formal and informal approaches, it is assumed that self- and community-funded approaches to financing well-construction constitute informal pathways to accessing groundwater. The difference between funding types in Nyeregete and Ubaruku is statistically significant, with a higher proportion of formal funding arrangements found in Ubaruku than in Nyeregete (two-tailed p = 0.0000, df = 1).

7.8 Discussion

7.8.1 Factors influencing pathways to groundwater access

The role of rural water supply interventions is to improve existing water supplies and make them more accessible (Zaba and Madulu, 1998). Common to Ubaruku, Nyeregete and Chosi is that development interventions by DANIDA were unsuccessful in improving access to water, because they did not undertake participatory consultation with water users in order to establish the most useful and preferred pathways of accessing groundwater. Furthermore, these interventions did not set up mechanisms for establishing governance over groundwater resources and ownership of the pumps. In Ubaruku and Chosi, the DANIDA-funded interventions specifically focused on extending piped water supply to dwellings, but the anticipated benefits did not materialise as few could afford to pay the associated connection fees. In Ubaruku, a subsequent World Bank funded intervention, which was conducted in a participatory manner, led to the successful establishment of the GWUA under the name UBAMPA. Consequently, there was an increase in the coverage of access to groundwater, through the drilling of new boreholes and the creation of formal mechanisms for governance, payments, use and ownership. Similarly, in Chosi, the UNICEF-funded solar-powered pump project, created reliable access to water for more than 700 people. The project was designed to generate a sense of community ownership and responsibility, primarily achieved by designating the pupils at Chosi A Primary School custodians and key-holders to the pump room. Water users in Chosi further have a variety of different accessible water sources that can be used for different purposes at different times. In Nyeregete, the DANIDA-funded hand-pumps have now deteriorated despite rehabilitation efforts by DANIDA in 1992. The remaining two functioning pumps have been altered to reflect a local and preferred technique of operation. However, hand-dug shallow wells are plentiful and considered the dominant pathway of accessing groundwater. The statistically significant differences in how respondents access groundwater are interpreted to indicate that residents in Nyeregete rely on informal pathway approaches whereas respondents in Ubaruku and Chosi villages primarily access groundwater through formal pathways.

The situation in both Nyeregete, and the failed DANIDA projects in Ubaruku and Chosi, are not uncommon to Tanzania or SSA. In Tanzania, domestic water consumption by households using un-piped sources rose from ~10 to ~16 LCPD between 1960 - 1990 (58% increase), whereas per capita water use from piped sources over the same time-period decreased by ~43%. The trend of an increasing reliance on un-piped sources and a decrease in connected piped household water use is similar in Kenya and Uganda (Table 7.4, Thompson *et al.*, 2001). Additionally, the World Health

Organisation/UNICEF Joint Monitoring Programme (WHO-JMP) (Table 7.5) estimates that over the period 1990 - 2015, the proportion of the Tanzanian urban population that use unimproved sources has increased from 5% to 20% (300% rise), whereas the coverage increase in rural areas has gone from 30% to 34% (~13% rise). Nationally, the coverage relying on unimproved water sources has gone from 25% to 30%, resulting in an increase of ~20% (~0.8% growth per annum).

Table 7.4: Change in per capita domestic water use in East Africa 1960s – 1990s (Thompson *et al*., 2001)

Piped Households	**DOW I (LCPD)**	**DOW II (LCPD)**	**% change**
Kenya	121.6	47.4	-61.0
Tanzania	141.8	80.2	-43.4
Uganda	108.3	64.7	-40.3
Total	128.1	65.8	-48.6
Unpiped Urban			
Kenya	11.3	22.9	102.7
Tanzania	17.8	25.1	41.0
Uganda	14.3	23.5	64.3
Total	15.4	23.7	53.9
Unpiped Rural			
Kenya	8.2	22.3	172.0
Tanzania	10.1	16.0	58.4
Uganda	11.5	14.8	28.7
Total	9.7	18.3	88.7

Table 7.5: Change in primary water source type reliance, Tanzania 1990 – 2015 (WHO-JMP, 2016)

Type of Source	Urban (%)		Change (%)	Rural (%)		Change (%)	Total (%)		Change (%)
	1990	2015		1990	2015		1990	2015	
Piped	31	28	-9	0	6	-	6	13	116
Other improved source	61	49	-24	45	40	-11	48	43	-10
Other unimproved source	5	20	300	30	34	13	25	30	20
Surface water	3	3	0	25	20	-20	21	14	-33

USAID-DHS (Table 7.6) estimates that in Tanzania the proportion of households served by piped connections into their dwelling in 2016 was at the same level as in 1991 - stagnant at approximately ~11% of the population. Furthermore, for the same period, 1991 – 2016, the proportion of households that use self-supply mechanisms from rainwater harvesting increased from ~0.2% to ~1.2% of the population (~500% rise), and the proportion using unprotected wells from ~15% to 17% (~14% rise).

Networks of access to rural water are complex (Merrett, 2002) and it is not uncommon for households in LEDCs to make use of multiple sources (Howard *et al.*, 2002; Coetzee *et al.*, 2016) which is a function of multiple and local-scale factors which relate to the physical proximity of sources (Nyong and Kanaroglou, 1999) as well as affordability, availability and collection time amongst others (Mu *et al.*, 1990). In Nyeregete, groundwater was the only available source within reasonable proximity whereas in Ubaruku, where respondents were within walking distance of the Mbarali Irrigation Canal system, the results show that the proximity of public borehole led to these being the preferred source for domestic use. Chosi , however is close to the nearby springs and this an influential driver with multiple water users responding that they had never considered to explore groundwater use because they did not feel the need to do so.

At the beginning of 1990, more than 25% of rural water supply extension interventions in LEDCs were considered to be non-functional and construction of new facilities were not able to keep pace with the rate of failure (Mu *et al.,* 1990). Similar to the interventions experienced Ubaruku, Nyeregete and Chosi, a big part of the failure of rural water supply interventions were identified by Mu *et al.* (1990) to occur because they were not based on a consideration of the cultural and social inclination of water users in the host country (Mu *et al.*, 1990). Rathgeber (1996), observes that water planners in LEDCs usually work under the assumption that households and social groups in rural communities will change habits in the way that they use water in order to take advantage of new and presumably improved water supply. Water managers, however, fail to recognise that in fact such resources will not be used optimally if the supply system does not conform to the norm of that social group and the local preference of technology (Therkildsen, 1988). Rural water supply extensions have been described as being "*out of touch with [...] demographics and financial realities*" (Whittington *et al.*, 1993) in which "*designs for new systems are generally made and projects constructed with little understanding of household water demand behaviour*" (Whittington *et al.*, 1991:179; Merrett., 2002). Indeed, the consequences of working with standardised assumptions about how social groups function (Rathgeber, 1996) are visible across the study sites. Habits did not change to conform to the water use behaviour that the DANIDA-funded initiatives anticipated. The importance of taking the consideration of locally preferred technologies into account is reflected in the re-appropriation of the few remaining functioning pumps that now have been altered to preferred technologies that are easier to maintain.

Indeed, across SSA more than 60% of the population live under conditions where centralised rural drinking water distribution and supply-systems do no reach them or are not affordable, and is one of the primary drivers for water users turning to "self-supply" approaches (Grönvall e*t al.*, 2010; Okotto *et al.*, 2015). Self-supply is a long-standing and common type of adaptive capacity to the extreme spatial and temporal variability of water availability in arid and semi-arid SSA, which contributes significantly to meeting domestic water demands, but are not included in formal analyses of freshwater resources assessments and development interventions (Mabugonje, 1995).

Table 7.6: Changes in the type of water sources used, Tanzania, 1991 – 2016 (USAID – DHS, 2016). All values have been rounded up.

USAID-DHS Survey	Formal Central Piped network			Formal G.W Improved Source		Alternative improved self-supply source		Unimproved or unprotected self-supply source		
	Piped dwelling	Piped Yard	Public tap/standpipe	Tubewell/ borehole	Protected well	Protected spring	Rainwater	Unimproved water source	Unprotected well	Unprotected spring
2015-16	11		16	5	13	3	1	39	17	7
2011-12	5	6	15	8	10	2	0.3	41	17	8
2010	2	5	15	2	13	4	1	46	22	4
2007-08	3	4	15	1	14	8	0.1	44	24	
2004-05	4	3	17	1	12	3	0.1	48	24	3
2001-04	4	10	20	12	5	1	0.1	47	19	7
1999	3	13	22	9	15	4	0.0	34	14	6
1996	9		29		14	6	0.1	42	14	6
1991-92	11		22		15	5	0.2	43	15	5
Change (%)	0.0	-55	-30	-50	-10	-35	500.0	-11	14	50

7.8.2 Addressing informality in measurements of progress towards development goals

The growing dependence on groundwater, which constitutes more than half of the global population's primary source for drinking, is given limited attention in metrics of international development such as the Millennium Development Goals and the Sustainable Development Goals (Grönvall et *al.*, 2010). MDG7 on halving the proportion of people without access to improved sources of drinking water was achieved in 2012 (United Nations, 2012) and its scope was replaced by SDG6 in September 2015. Measuring progress towards achieving MDG 7 relied upon data from the WHO-JMP, which tracks progress of individual countries' level of access to water and sanitation and rely upon proxy indicators to define 'improved' sources of water and sanitation. The JMP asks respondents to report on their main source of drinking water but limits this to piped sources and other "improved" sources. SDG 6.1 aims by 2030 to "*[…] achieve universal and equitable access to safe and affordable drinking water for all*". The indicator adopted for monitoring progress towards SDG 6.1, however, continues to focus on measuring progress only towards universal access to piped and "improved" sources of drinking water. Bos *et al.* (2016) have highlighted the need to redefine the ladder of drinking water sources so that it includes unimproved sources, such as shallow-wells. It is of significance that these sources of self-supply are not considered, as they constitute a measure of adaptive capacity in relation to quantities of water used to achieve improved hygiene practice (Cairncross, 2003).

7.9 Concluding Summary

Chapter 7 addressed the third research objective which was investigate how water users characterise 'water scarcity' and how freshwater storage contributes to adaptive capacity. Semi-structured interviews with ERs (i.e. government respondents responsible for water resources management and international advisors) and IRs (i.e. water users and farmers) were conducted in 2015. The purpose of this initial phase of fieldwork was to establish a broader understanding of how these stakeholders perceive the characteristics of water scarcity in the GRRC and how groundwater and surface-storage can be used to adapt to the perceived water scarce conditions. ERs expressed mixed views as to whether the GRRC is water scarce. Within the limitations of these interviews, all respondents however, agreed that the characteristics of water scarcity in the GRRC are heavily determined by the extreme temporal and spatial variability in freshwater availability. IRs on the other hand primarily perceived water scarcity to be concerned with not having adequate water for irrigation. According to their knowledge, people would always be able to find water for domestic uses, even if it meant longer travelling distance and time.

Concerning groundwater storage development, ERs identified three main challenges to mainstreaming its use. The first relates to a lack of regulatory policy on groundwater use and efficient registration of wells. Secondly, the number of motorised pumps in the GRRC remain low due to unreliable access to electricity. This keeps groundwater use from being mainstreamed, as the tendency to use hand-pumps are only sufficient for fulfilling domestic requirements and not feasible for extending to irrigation. Third, the lack of knowledge of local- and basin-scale hydrogeology and the downstream risks associated with increasing groundwater use, limits both small- and wide-scale developments. Due to this lack of knowledge, ERs warn heavily against rapid expansion of both sub-surface and surface-water storage infrastructure. Storage-based infrastructure development risks increasing the already unsustainable levels of water use and threaten much-needed catchment-scale restoration efforts. IRs, however, expressed a strong preference towards expanding surface storage development, and reject the recommendations to temporarily suspend storage-based developments. A general lack of knowledge on how to access groundwater, coupled with a history of using hand-pumps only for domestic purposes, limited access to electricity and/or expensive diesel for running generators for motorised pumping influence IRs' views that surface water storage infrastructure 'trumps' the expansion of small-scale groundwater networks for agricultural irrigation.

During a subsequent phase of fieldwork in 2016, evidence was gathered and examined in-depth, regarding the factors that influence water use in three villages in the Usangu Plains and how water users' adapt to water shortages, in particular through the use of groundwater storage. Indeed, groundwater is most commonly used for domestic purposes and is the primary source of water that is accessible all year. The main motivation for using groundwater relates to its close proximity. A lack of awareness on how to access and use groundwater, however, remain amongst the biggest challenges to expanding use of this source.

Testing for differences in how water users in the three villages access groundwater, the results indicate that where international development interventions have failed to adopt participatory approaches when expanding rural water supply networks, there is a higher statistically significant likelihood that water users will default to accessing groundwater through informal self-supply pathways. Informal pathways in this case are characterised by hand-dug and shallow wells that are community-funded and more prone to collapse. However, in those instances where international development interventions were undertaken in participatory manners, there was a good awareness of the positive benefits associated with distributed groundwater networks.

Across Tanzania, and the SSA, there is a historical trend that the proportion of people that rely on piped water supply is decreasing and un-piped increasing. Such developments have led to a widespread use of self-supply, and public borehole in rural SSA. The contribution of self-supply is significant and constitute complementary sources that facilitate adaptive capacity of water users. However, metrics that measure progress towards achieving international development goals do not adequately account for these contributions which is problematic.

Chapter 8 - Results and Discussion IV: Evaluating a new approach to characterising water scarcity

8.1 Introduction

Chapter 8 revisits the three key recommendations that were proposed in Chapter 2 for a new way to characterise water scarcity in a more meaningful manner and explores what such an approach could like in the future. The Chapter examines how each of the three proposed amendments were investigated in the case-study of the GRRC (Chapters 5, 6, and 7) and evaluates the current limitations, based on field-evidence, to adopting them into a future conceptual indicator framework and making it operational. The Chapter ends with a discussion of how the thinking behind the proposed changes to characterising water scarcity can improve former water resources management attempts at addressing issues of zero-flow conditions in the GRRC and opens up for a broader discussion on the future role of metrics in freshwater resources management and governance.

8.2 Conceptualising scarcity: towards a new measurement of water scarcity

This thesis proposed three key changes to the characterisation of water scarcity. The first proposal was to redefine water scarcity in terms of the freshwater storage, both natural and constructed, required to address imbalances in the intra- and inter-annual fluxes of supply and demand, the second to restrict quantification of water scarcity to verifiable parameters describing freshwater supply and demand, and thirdly to use physical descriptions of water scarcity as a starting point for participatory decision-making process by which communities resolve how to address quantified storage requirements.

The thesis outlines in Figure 8.1 a conceptualisation of what a future water scarcity framework incorporating these key proposals could look like, although key methodological uncertainties remain in the current implementation of such a metric. The diagram portrays how, over the duration of one year experiencing unimodal rainfall, flux-derived freshwater supply and demand relate to each other in terms of volumetric excess or deficit of freshwater availability relative to demand accounting for monthly/intra-annual hydrological variability. In the instances where deficits are identified, the magnitude and periodicity of the required volume can be computed and used as a meaningful starting point for addressing the third proposed key change which relates to using local and context-specific physical descriptions of water scarcity as a starting point for participatory decision-making processes on how communities can resolve quantified storage requirements.

Indeed, translating the conceptualisation of how to think about the characterisation of water scarcity into an operational framework and applying it to evaluate its robustness in the GRRC is beyond the scope of this thesis. However, at this stage, the aforementioned three key proposed amendments can be evaluated in terms of how well the information easily obtainable about them from fieldwork in the GRRC could conceptually be adopted into the framework, in order to identify priority areas of future research.

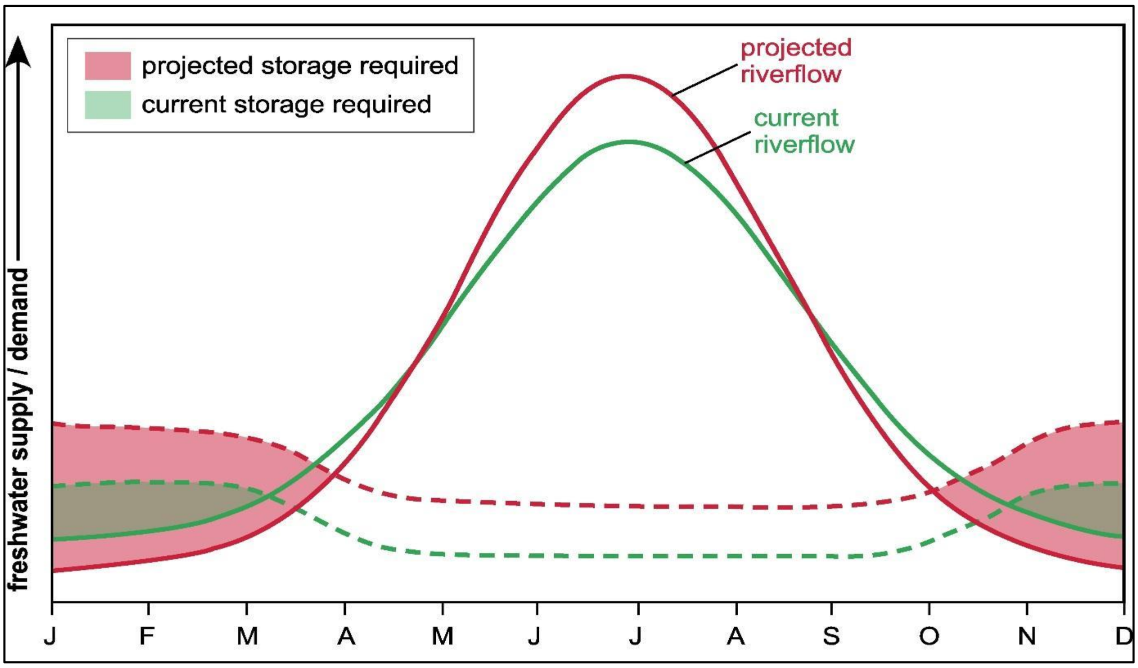

Figure 8.1: Conceptual representation of the proposed water scarcity framework: river discharge regime under a monsoonal climate exhibiting a distinct (unimodal) intra-annual variability including the projected impact of the intensification of this river regime under climate change, and (2) intra-annual variability and change in freshwater demand (dotted lines) from all sectors including EWRs. Shaded areas in mark periods when freshwater demand exceeds supply and quantify required access to freshwater storage (adapted from Taylor (2009).

8.2.1 Key proposal one: Embracing variability

The first move towards a more meaningful characterisation of freshwater resources and inherently redefining water scarcity in terms of freshwater natural and constructed storage needed to address imbalances in the intra- and inter-annual fluxes of supply and demand, requires moving beyond the reliance on MARR to estimate freshwater resources availability and to embrace hydrological variability within freshwater resources management. Ultimately, this shift entails accepting the radical proposition that "stationarity is dead" (Milly *et al.*, 2008) Indeed, inter- and intra-annual variability has greater control over the magnitude and periodicity of water scarcity in the physical sense, a fact that is vital to understand for any meaningful application of water scarcity metrics in freshwater resources planning and management.

In Chapter 5, the WSI and WTA ratio water scarcity metrics were applied to the GRRC to explore how two widely applied water stress- and scarcity metrics characterise water scarcity over time in a catchment subject to recurring zero-flow conditions downstream. The application of the two threshold-dependent metrics revealed contrasting characterisations of water scarcity. The WSI indicated upstream water abundance and downstream levels of absolute water scarcity, whereas the WTA ratio upstream showed increasing water stress upstream. The results question the meaningfulness of the sole reliance on numerical-based outputs against a threshold or benchmark and the degree of adequacy of such metrics to inform decision-making about water scarcity and for plans on how to deal with it. To properly understand the two contrasting results in practice required a broader investigation of the long-term hydrological changes in the catchment looking at both shifts at the inter- and intra-annual scale.

Previous research on the causes of downstream zero-flow conditions in the GRRC have suggested that the long-term effects of naturally occurring changes in the upstream hydrological regime on downstream flow conditions have been negligible. However, evidence presented in Chapter 5 show a noticeable declining step-wise change in upstream TRWR and long-term inter-decadal highland precipitation. These findings suggest that upstream hydrological variability may have been more influential in downstream changes to flows at the Msembe than previously anticipated.

One of the main challenges in gauging inter- and intra-annual variability in freshwater resources availability relates to the fact that the observed daily discharge data suffered long gaps, adding difficulty to the challenge of finding overlapping periods of time where the degree of missing data was less than five days for all river gauges, which in return limited the scope of the historical analysis. To deal with the challenge of missing data in future research would be to apply a rainfall-runoff model to fill in the gaps. This was not done in this thesis primarily due to a lack of access to relevant data. More importantly, the nature of this thesis was not to undertake a traditional hydrological modelling exercise of the GRRC but more specifically to investigate issues that influence the characterisation of water scarcity, one such issue relating exactly to the issue of access to readily obtainable and reliable data.

A second challenge to the quality of the river discharge data relates to the lack having access to the rating curves for the gauging rivers. Updated rating curves would have allowed for disclosure of the uncertainty in the observed river flows. More generally, observations of river discharge, on the one hand can be considered a highly detailed spatial point of measurement derived directly from the 'field'. On the other, they are not a substitute for globally-modelled data and vice versa. Indeed, the use of globally-gridded hydrological datasets would be useful for filling in missing data. This task however did not form part as one of the main objectives that the thesis addressed. Indeed, the research objectives were primarily concerned with small-scale and real-life field-based conditions. Therefore, applying the research methodology in this thesis to other basins would highly benefit from the use of modelled hydrological river flows which admittedly comes at the expensive of the quality of mimicking field-validated conditions.

8.2.2 Key proposal two: Issues of demand and freshwater withdrawals

Secondly, the multiple challenges with quantifying per capita daily domestic water use in SSA have been discussed in this thesis and include inadequately accounting for the complex factors that contribute to differences in how water users in MEDCs and

LEDCs access and use water, including multiple-source use, source preference, proximity, waiting time and costs.

More specifically, relying on simple fixed threshold assumptions of domestic water demands such as the assumed 100 LCPD in the WSI is misleading. This thesis quantified domestic water demand in the GRRC to ~28 LCPD based on a household survey of three villages in the Usangu Plains. Combined with previous household surveys estimating domestic water demand in the GRRC, which ranged between ~34-46 LCPD, the mean domestic water demand is ~33 LCPD. Indeed, elsewhere in Tanzania and other parts of arid- and semi-arid SSA, estimates of per capita water use are similarly well-below the 100 LCPD benchmark embedded in the WSI.

In order to examine the logic that underpin the assumptions embedded in the WSI and employed by Falkenmark (1986) in determining a holistic water demand (*i.e.* that agricultural water demand is 20 times per capita domestic water demand) the adjusted per capita water demand figure derived from Chapter 6 (~33 LCPD) was applied. This operation generated a holistic per capita water demand of ~693 LCPD and was converted into a volumetric quantity of monthly freshwater demand (Figure 8.2). The resulting freshwater demand however shows no improvement for advancing the meaningfulness of adopting such a future approach in the pursuit of changing the characterisation of water scarcity for three reasons. First, the multiplier of '20' remains arbitrary and a highly misleading assumption about agricultural freshwater requirements, the rationale for which remains unclear as discussed in Chapter 2. Second, the method for deriving a holistic water demand remains reliant on population to constitute the main pressure on freshwater resources, thus maintaining similar Neo-Malthusian characteristics to the WSI, a criticism which this thesis aims to move away from and towards a more holistic understanding of varying freshwater demands; use and sources and; third such an approach would fails to differentiate between differences in seasonal freshwater demands.

It is worth to point out here that the purpose of the challenge throughout this thesis regarding the meaningfulness of the assumption that people need 100 LCPD to have their demands satisfied is not to suggest that the number should be replaced with a much lower number (i.e. ~33 LCPD) for the case of the GRRC. This proposal would be an irresponsible suggestion that would put even less pressure on water resources planners and managers in fulfilling their duties of water services delivery to water users. What is important to remember is that the number that has become inherent to the development of the Falkenmark WSI can be a useful starting point for furthering the conversation on adequate domestic water demand, but only in a manner which is guiding, and that the highly ambitious benchmark at best serves to remind us about the need for adequate access to water and sanitation to achieve acceptable levels of hygiene (Cairncross, 2003).

In light of the SDGs, that aim to bring universality in efforts towards measuring progress in achieving global goals of international development, it is important to remember that benchmarks, thresholds and universal standardised assumptions, such as the 100 LCPD, should only be considered guiding and not definite, as the challenges they try to address in the end are highly localised and contextual issues.

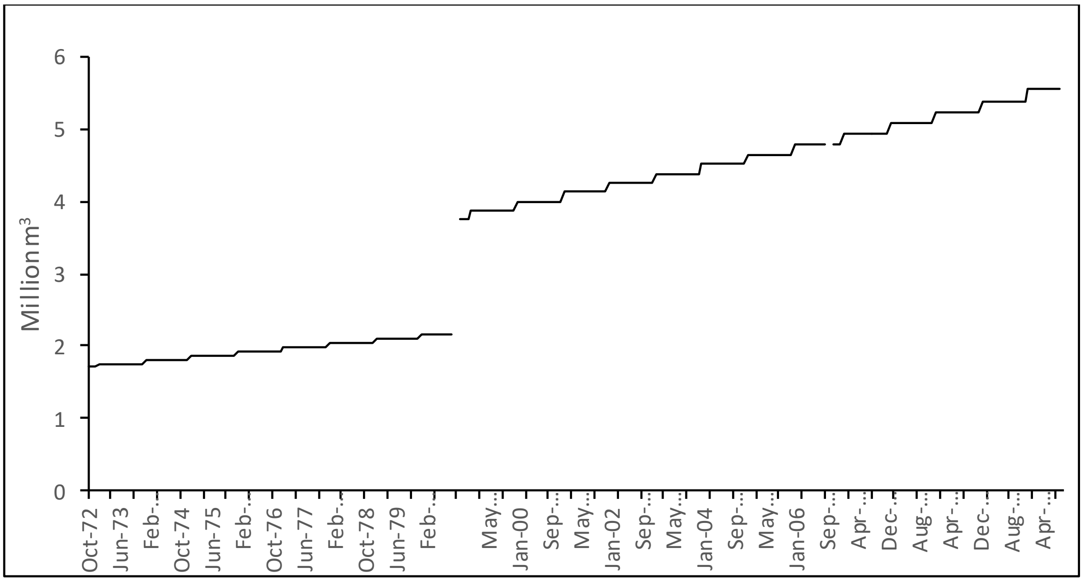

Figure 8.2: Exploratory investigation into estimating holistic freshwater demand using the derived per capita domestic water demand from Chapter 6 and the Falkenmark assumption of agricultural freshwater demands constituting 20 times more than domestic water demand. These figures were not used in the final water scarcity indicator framework.

The conceptual approach for thinking about how to characterise water scarcity presented in Figure 8.1 focuses on freshwater withdrawal and demands at the intra-annual scale differentiating between monthly available data for dry-season (1st June – 30th November) and wet-season (1st December – 31st May) freshwater withdrawals. This approach of deriving freshwater demands builds upon the methodological approach adopted in Chapter 4 for estimating annual freshwater withdrawals as the function of pressure on available freshwater resources in the application of the WTA ratio indicator in Chapter 5 To briefly recap the rationale in Chapter 4, the historical expansion of irrigated agriculture in the GRRC occurred over three stages (SMUWC, 2002). Prior to 1974, the area under irrigation in the Usangu Plains was small and the impacts on water resources minor (SMUWC, 2001). The first period of assessing water scarcity in the GRRC using the WTA indicator commences in hydrological year 1974, coinciding with available data on irrigated agriculture. A second window of irrigation expansion occurred in the mid-1980s, as the Government of Tanzania promoted agricultural trade liberalisation and policies that focused on increasing countrywide irrigation capacity. The third window of irrigation expansion began in the early 1990s, and by 1999 the area under irrigation using surface water had reached its maximum cover (SMUWC, 2001; please see footnote 4, page 126 of this thesis).

No consistent reporting of historical annual water withdrawals were obtainable for the sake of this thesis. As such, annual water withdrawals were calculated as the sum of dry- and wet-season water withdrawals derived in two independent manners (i.e. one for each season). First, monthly historical water withdrawals (1974 – 1999) for the 182 day dry-season (1st June – 30th November) were reported in SMUWC (Report 7, 2001:120, Figure F7.9) and could therefore be adopted directly into this study. Second, historical water withdrawals during the wet season (extending over 183 days from December 1st – May 31st) were derived from reported figures for the rates of the total installed irrigation withdrawal capacity (Table 4.7) at the beginning and end of each of the three periods of major agricultural expansion (SMUWC Overview Report, 2001:54, Table 3).

This method for deriving wet season water withdrawals, however, is subject to two caveats. First, the estimate of annual water withdrawals assumes that within each period of reported installed irrigation capacities, development of installed irrigation rates was linear, allowing for linear interpolation. Each annually derived installed withdrawal rate was then converted into a volumetric unit in million m^3 for six months that constitute the wet season. Secondly, the estimation of wet-season water withdrawals relies on the assumption that withdrawal intakes operate at full capacity over the six month period.

In 1999, reports indicate that the GRRC catchment had reached its maximum level of installed withdrawal capacity in the large irrigation schemes of 45 m^3 s^{-1}

coinciding with the time that the maximum irrigable area had been reached (SMUWC, 2001: Supporting Report 8, Table 2.9 & Appendix E; RIPARWIN, 2006; (please see footnote 5, p. 127 of this thesis). No readily available data on annual or wet- and dry-season water withdrawals since 1999 were obtainable. Therefore, the study assumes that for the period 2000 – 2011, withdrawal rates for both the dry- and wet season remained constant at 1999 levels with no significant variations within each year. This assumption is based on an understanding that irrigation intakes are constantly left open and unregulated throughout the entire year, equating to a constant withdrawal rate at 1999 wet- and dry-season levels, respectively. The validity of the assumption that freshwater withdrawals over the period 1999 – 2011 remained at 1999 levels is fully open to scrutiny yet was decided as the best approach based on first-handed field-observations as well as the reported conditions in official reports closer to 2011. Firstly, both SMUWC (2002) and RIPARWIN (2006) report primarily broken or missing intake gates at the major irrigation schemes and former NAFCO schemes as well as levels of water use efficiency below 10%. Second, a decade later, fieldwork undertaken in August 2015 and November 2016 noted that at all major NAFCO irrigation schemes, intake gates and sluices were either missing or broken resulting in continuous and unregulated flows into secondary and tertiary irrigation canals.

Indeed, estimating freshwater demand in this manner is vastly generalised, basing the quantified volumes entirely on installed freshwater withdrawal capacity rates in the major irrigation schemes of the area. Such a function reveals little information the proportion of water that is recycled, returned into the hydrological system or immediately lost due to the high levels of evapotranspiration. Furthermore, the assumption that domestic water demand is embedded in freshwater withdrawals for the assessments in Chapters 5 and 8 are also based on the many observations of instances where water users are dependent on surface water for domestic use, such as in the large Kapunga, Kimani, and Mbarali Irrigation Schemes, where the norm is to rely on water from the irrigation canals. This may be one of the reasons a water user may wish to break or steal the irrigation intake gates that are supposed to serve as closures for water diversion into secondary and tertiary canals. Finally, whereas Chapters 6 and 7 dedicated a lot of focus to quantifying freshwater demand met only by groundwater, the point of this exercise was only to investigate assumptions related to the assumptions that inform the WSI and final groundwater-derived domestic demands are embedded in the figures for total freshwater withdrawals based on irrigation withdrawal rates.

Figure 8.3 illustrates monthly intra-annual long-term freshwater withdrawals during the dry- and wet season. During the time period 1974 – 1980, wet-season water withdrawals are nearly three times higher than dry-season withdrawals. By 1999, average monthly wet-season freshwater withdrawals have nearly doubled since 1980 from ~55 million m^3 to over 100 million m^3 two decades later. During the time period 1999 – 2011, the proportion of wet- to dry-season water withdrawals have dropped from three-fold to double.

8.2.2.1 Comparing surface water river-discharge derived supply relative to demand in the GRRC

To explore, at the monthly time scale, instances where flux-derived freshwater supply is exceeded by freshwater demand, the two time series are plotted against each other in Figure 8.4a and the differences quantified in Figure 8.4b. During the first time period of study (1973 – 1980), the magnitude of deficits is small, with the first instance of freshwater demands exceeding supply occurring in December, 1976 with a deficit of ~16 million m^3 and once again by ~8 million m^3 in November 1980. Over the two last time periods, the period of the year where demand for freshwater exceeds supplies follow similar patterns with the highest dry-season deficit levels occurring between October and December. Wet season supply generally exceeds freshwater demands, however at the inter-annual scale over the last two time periods indicates a declining trend.

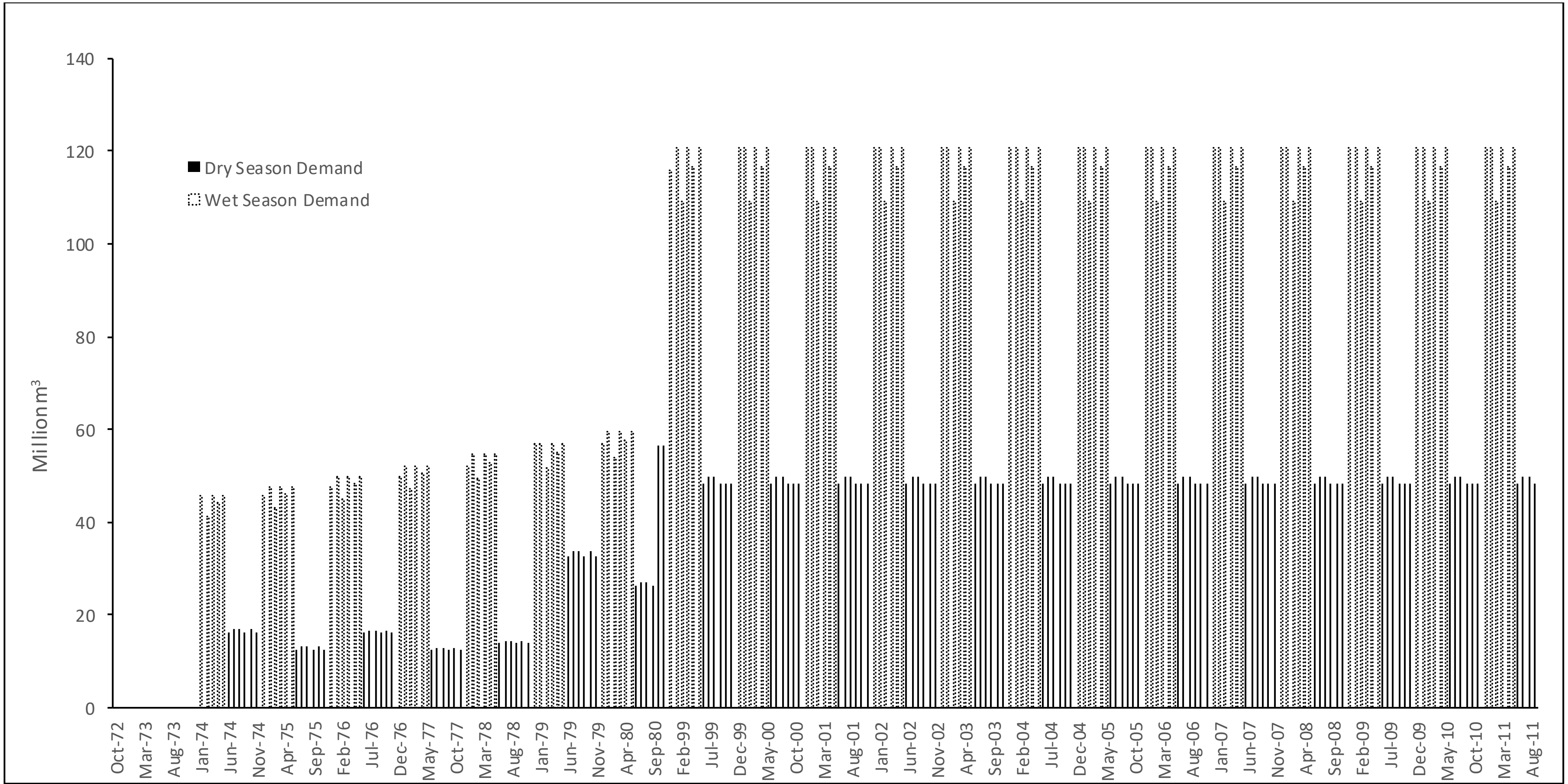

Figure 8.3: Intra-annual wet- and dry-season monthly withdrawals from major irrigation schemes in the Usangu Plains (1974 – 1980, 1999 – 2011).

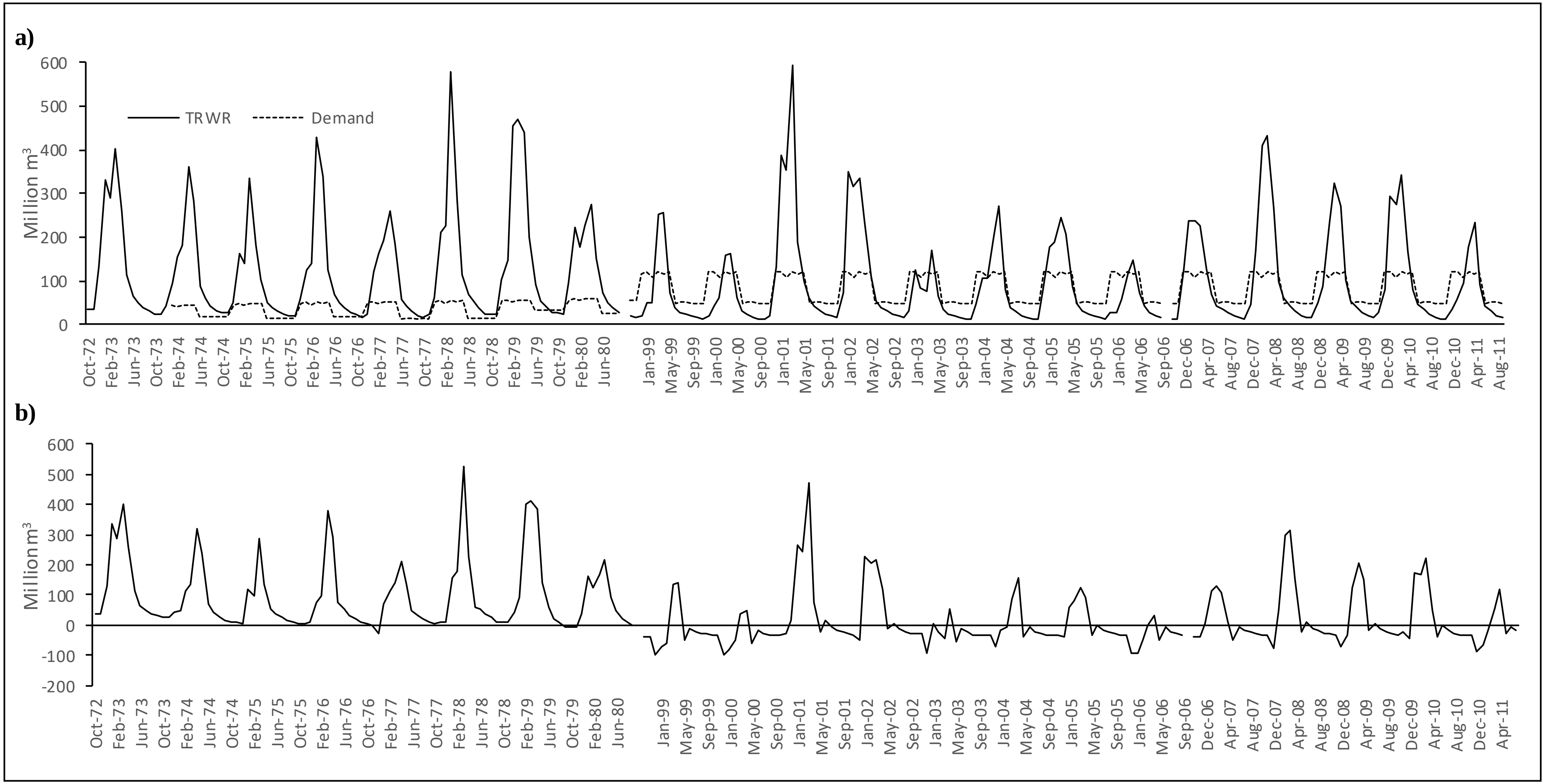

Figure 8.4a: Monthly aggregated freshwater demand and supply (upstream) indicating periods of demand- side excess. Figure 8.4b: Quantified differences from Figure 8.4a

8.2.3 Key proposal three: Physical descriptions of water scarcity as a starting point for participatory decision-making processes to resolve quantified storage requirements

The third recommendation, to use physical descriptions of water scarcity as a starting point for participatory decision-making processes by which communities resolve how to address quantified storage requirements, attempts to move away from the single numerical outputs that the WSI and the WTA ratio indicators provide in their characterisation of water scarcity which are then compared against a proscribed threshold. Instead, a new approach to characterising water scarcity is to investigate how the intra- and inter-annual variability in freshwater demand and supply creates a hydrological boundary within which adaptive responses develop.

Indeed, the first two proposed amendments provide insight into the periodicity when freshwater demands are likely to be unmet by surface water supplies alone, as well as providing information about the magnitude of excess demand to supply. The application of the WSI and WTA ratio metrics in Chapter 5, showed contrasting characterisations of freshwater in the GRRC, which were useful for demonstrating how downstream water scarcity varies both temporally and spatially. These results further confirmed the need to explore the spatial and temporal variabilities of freshwater supply and demand in the catchment, providing support for a renewed way to think about characterising freshwater scarcity. Indeed, the findings in Chapter 5 suggest that variabilities in upstream precipitation and discharge may have had a more marked impact downstream than previously considered and not adequately embracing inter- and intra-annual variability in management plans of freshwater resources leads to governance and policy solutions that do not consider the entire dynamics of water availability and use in the catchment (Walsh, 2008; Walsh 2012; Whaley and Cleaver, 2017; Cleaver and Whaley, 2018).

Chapter 7 showed that small-scale storage in the GRRC acts as an adaptive response of households to meeting domestic demands under varying freshwater availability. Such existing, but overlooked elements need to be seriously considered seriously as having the ability to reduce the periodicity each year when available surface freshwater is exceeded by water demands. As visible from the case of Nyeregete, the variability is highly influential in the characterisation of water scarcity and in turn the various manners in which the water users have responded to such characterisations through different pathways of using storage. The next logical step for advancing the characterisation of water scarcity in a place like Nyeregete would be to undertake a participatory-based study, informed by the pathways identified and challenges to governance, that aims to decide what types of storage-based development would be most preferred and optimal for the water users and their needs.

8.3 The ultimate challenge: Adequately quantifying storage

One of the major challenges to proposing a future framework for measuring water scarcity that is based on rectifying flux-derived deficits of demand with additional storage contribution to flux-derived freshwater supply lies with the inherent problem of adequately defining and quantifying freshwater in itself. Estimating freshwater storage, especially sub-surface storage can be done using a variety of methods. One widely-used method is recharge - the rate at which an aquifer is replenished – which is also one of the most complicated components of sub-surface storage, due to its complexity and variability in time and space (Healy, 2010). Consequently, a multitude of methods for estimating recharge exist, each with their own purposes depending on the type of data available, the scale of the study, time and budget (Tables 8.1 and 8.2).

Table 8.1: Timescales for application of individual methods for estimating groundwater recharge (adapted from Healy *et al*., 2011:183, Table 9.1) UZ is unsaturated zone, WB is water budget, GW is groundwater, SW is surface water.

Method	Timescales							Data collection frequency[2]
	Daily	Weekly	Seasonal	Annual	Multi-annual	Decadal	Millennial	
Water budget								
Aquifer	x	x	x	x				m
Soil Column	x	x						m
Watershed	x	x	x	x				m
Stream	x	x						1, m
Models								
UZ soil WB	x	x						0, 1, m
UZ Richards Equation	x	x						0, 1, m
Watershed	x	x						0, 1, m
GW flow	x	x	x	x				0, 1, m
Darcy methods								
UZ	x	x						m
GW	x	x	x	x				m
SW/GW	x	x						m
UZ/GW methods								
Zero-flux plane	x	x						m
Lysimeter	x	x						m
Water-table fluctuations	x	x	x					m
Surface water based								
Seepage meter	x							1
Step-response function	x	x						m
Flow duration					x	x		0
Hydrograph separation					x	x		0
Recession-curve displacement					x	x		0

[1] "Under Data Collection Frequency", 0 means that existing data are used and no new data need to be collected, 1 means that data need to be collected only one time, and m implies that data must be collected multiple times.

Table 8.2: Factors influencing applicable methods for estimating groundwater recharge Spatial scales, relative expense, and complexity of application for individual methods for estimating groundwater recharge (adapted from Healy *et al*., 2011:186, Table 9.2)

	Space scales*								
	1 m^2	10 m^2	100 m^2	1 ha	1 km^2	10^3 km^2	10^6 km^2	Relative expense*	Relative complexity*
Water budget									
Aquifer				x	x	x	x	2-4	2-4
Soil Column	x							3	3
Watershed				x	x	x	x	2-4	2-4
Stream			x	x	x			5	4
Models									
UZ soil WB	x							2	2
UZ Richards Equation	x	x	x	x				4	4
Watershed				x	x	x	x	2-5	5
GW flow				x	x	x	x	2-5	5
Darcy methods									
UZ	x	x						5	5
GW	x	x	x					2	2
SW/GW	x	x	x					3	3
UZ/GW methods									
Zero-flux plane	x	x						5	4
Lysimeter	x	x	x					1-5	1-5
Water-table fluctuations		x	x					2	2
Surface water based									
Seepage meter	x							2	2
Step-response function			x	x	x	x		3	3
Flow duration					x	x	x	1	1
Hydrograph separation					x	x		2	3
Recession-curve displacement					x	x		2	3
Tracer methods – Not applicable									

* 1 = least complex and 5 = most complex

One envisaged method for quantifying freshwater storage for the GRRC could be the use of streamflow. Streamflow data are generally much more commonly accessible in arid- and semi-arid parts of the world in comparison to groundwater specific data (Healy, 2010) which means that the currently readily accessible observations of river discharge could prove suitable for generating preliminary insights into the state of recharge and sub-surface storage behaviour in the GRRC. Indeed, baseflow, the component of river runoff which can be considered as natural groundwater recharge (Meyboom, 1961) is considered highly helpful to inform water resources management in semi-arid areas (Mwakalila *et al.*, 2002). Soteriou (2016) applied four statistical baseflow separation methods (*Sliding Interval*, *Fixed Interval*, *Local Minimum* and, *IH Low Flow*) and one Graphical Partitioning method to the Chimala River and the Msembe Ferry gauging stations. The first three baseflow statistical baseflow separation techniques were established from a study measuring water quality in Ohio, United States (Pettyjohn and Henning, 1979), whereas the fourth was established to estimate baseflow for rivers in the United Kingdom (Gustard *et al.*, 1992). For the fourth statistical baseflow separation techniques Soteriou (2016) observed that the average monthly baseflow components for the Chimala River followed a comparable trend as discharge, whereas the Graphical Partitioning method reached peaks much lower than the four other techniques as it excludes anomalous peaks in total river discharge, inherently lowering the quantified average baseflow component for all the headwaters. The real baseflow of the Chimala River the study reckoned would be somewhere in-between and defaults to relying on assumptions of averages.

Indeed, the use of daily observations of river discharge to derive recharge through baseflow separation is only one of multiple approaches that can be taken to estimating groundwater storage. It may be considered one of the least data- and resource-intense methodologies and can easily be applied using the same data used for the WSI and the WTA ratio water scarcity metrics, which allows for the convenience of comparing changes in hydrological regimes. However, the four hydrograph separation techniques were originally developed for studies in latitudes that do not experience unimodal rainfall, meaning that a separate study quantifying groundwater storage in the GRRC is required but is beyond the scope of this thesis. Further complications with relying on baseflow separation techniques to derive groundwater storage is the fact challenge of 'double-counting', since baseflow contributes to total river discharge, which was the originally defined flux of freshwater availability. Such an approach would also not be able to robustly indicate the proportion of groundwater storage that would be accessible nor its available locations across the study area. A potential starting point to redo the exercise of quantifying groundwater storage could be found in the approach taken by MacDonald *et al.* (2012) who computed groundwater storage across the entire African continent by taking published mapped data from *estimated saturated thickness* (defined as the difference among total porosity, *n*, and Specific Yield, *Sy*) and area. More broadly, achieving a robust method for quantifying groundwater storage is only meaningful if it is supported by an integrated, coherent and overarching framework for ensuring its sustainability at multiple scales which requires the field to move beyond old and long-winded discussions of traditional concepts such as 'safe yield', 'renewability', 'depletion' or 'stress'(Gleeson *et al.*, 2019).

Furthermore, quantifying surface freshwater storage infrastructure by way of big permanent dams, smaller seasonal dams, or rooftop catchment systems for rainwater harvesting which can play a significant role in meeting freshwater demands equally remains to be adequately addressed if any future changes to the measurement of water scarcity is to be considered meaningful. Indeed, in the upper part of the GRRC big permanent dams are currently non-existent (the Ruanda-Majenje dam is leaking), seasonal dams are difficult to account for as they are washed away during floods, and water harvesting infrastructure are not widespread. Incorporating surface storage from the Mtera and Kidatu HEP reservoirs would also be net zero as they are located downstream and outside of the upstream and combined downstream catchment gauged at Msembe.

This thesis has advocated throughout for their inclusion in the measurement of water scarcity, but the reality is that the quantification of the contribution of small-scale and decentralised surface water storage networks remains complex. The recommendations of this thesis serve to remind all freshwater resources managers and planners of their vital contributions to meeting seasonal freshwater demand, often widely overlooked in predominant water scarcity indicators. In the field of hydro-electricity and waste water management, quantification of the contributions of small-scale decentralised management options are also taking place and lessons learnt from these sectors may prove useful in the future.

8.4 Discussion

8.4.1 Recommendations for improving water resources management responses to water scarcity in the GRRC

Along with the eviction of large groups of pastoral nomads and gazetting off large areas of the Usangu Plains, as one proposed solution of dealing with the recurring no-flow conditions at Msembe, the Government of Tanzania also proposed another regulatory and demand-side management solution to the GRRC. Over the period 1996 - 2006, the Government of Tanzania, funded by the World Bank "River Basin Management and Smallholder Irrigation Improvement Project (RBMSIIP) attempted to introduce a regulatory framework for the issuance of water rights sold in units of "*litres per second*". The initiative, which aimed to encourage water conservation and reduce water withdrawals, however failed for two reasons. First, it fell short of recognising the existence of longstanding customary practices and rights in the area (van Koppen *et al.*, 2004) and the existence of legal pluralism in the Mbarali District (Kajembe *et al.*, 2003).

Many informal and formal laws that often contradict each other exist in the Mbarali District, which is a common characteristic of natural resources management and use in many former colonial regions. Formal law may very well have been codified on paper and applied in formal court settings (Cleaver *et al.*, 2013). However, in places like the Mbarali Rural District, customary laws and norms, which are a result of cultural, tribal, religious and spiritual rituals and thought that have developed organically for centuries, dominate in many instances when dealing with immediate questions related to ownership, appropriation of rights, conflict resolution, justice and equity (Cleaver, 2001; Kajembe *et al.*, 2003). These factors should not be overseen in water resources management as they have a possible greater influence on how small-scale and informal freshwater storage adaptive capacities develop than apparent at first and these need to be adequately reflected in water resources management plans.

A further challenge with the regulatory framework introduced by RBMSIIP was the inability to account for the extreme variability in freshwater availability in its withdrawal rate allowances. The RMBSIIP project had anticipated that a volumetric solution to water scarcity through issuing water rights would be a sustainable strategy for promoting demand-side management solutions and reducing upstream water demand in order to ultimately balance out water allocation amongst uses and users. The demand-management driven approach however failed to recognise the importance of understanding the changes in freshwater supply so as to strike a balance between demand-side management and supply-management solutions.

Previous work done on identifying possible freshwater resources management strategies for the GRRC have been associated with inadequacy of irrigation intake design parameters to deal with the concepts of equilibrium and disequilibrium environmental states – concepts from ecology which are similar to the concepts of intra- and inter-annual variability advocated throughout this thesis.

Water resources management options for the GRRC that clearly recognise the catchments' highly disequilibrium and unpredictable characteristics have been urgently required for a while, as advocated by Lankford *et al.* (2009); and the propositions of embracing variability made in this thesis still hold true a decade later. Equilibrium and disequilibrium environmental states are highly important but overlooked distinctions necessary to make when comparing environmental conditions for arid- and semi-arid catchments to those at more temperate latitudes (Lankford *et al.*, 2009). Compared with basins at temperate latitudes that are relatively stable, the coefficient of variance in river discharge is the highest in the world in southern Africa (McMahon *et al.*, 2006) which render them complex (Lankford *et al.*, 2009) and therefore water resources management planning is best informed by a shift in the characterisation of water scarcity that explicitly recognises the importance of this dynamism at play.

In catchments that demonstrate equilibrium behaviour, water supplies can be enhanced by adding surface storage, while coupled with demand side management through regulatory price-based reforms to reflect the cost of water delivery (Lankford *et al.*, 2009) which may not work in practice in the GRRC. As such, the shifts in characterisations of water scarcity this thesis advocates has direct relevance to enhancing previous recommendations for solving water resources management and challenges in the GRRC. Lankford (2010) further argued that the conditions that characterise water scarcity in the GRRC have come about as a direct product of anthropogenic irrigation intake structures that have been inappropriately designed to share water under the highly variable hydrological regime in the catchment. Similar to the line of argument presented by Kashaigili *et al.* (2005a) and Kashaigili (2008), Lankford *et al.* (2009) also primarily associated cessation of downstream flows at Msembe with expansion of the area under irrigation in the Usangu Plains. Whereas the results presented in Chapter 5 of this thesis suggest more attention needs to be given to the variability of the hydrological regime in the highlands and at the headwaters, Lankford *et al.* (2009) consider that wrongfully designed fixed irrigation intake parameters constitute the primary cause. Irrigation intakes in the GRRC have historically not been developed to have intakes that are proportional to river flow and instead designed with fixed abstraction parameters regardless of flow conditions.

There is merit to this line of thinking as it advances the need to consider the dynamic nature of the hydrological regime in the GRRC. However, as the assumption has been in this thesis, since 1999 the intake gates have not been operated in a consistent fashion on account of their state often derelict, vandalised or simply missing. Design of irrigation intakes may at first have been constructed in a fashion that would have caused uneven allocation of water for irrigation withdrawals, but assuming their significant high level of continued deterioration and disrepair rendering them inoperable, this thesis suggests that there are grounds to move beyond focusing solely on the effects of demand to explain the cessation of flows at Msembe and the recurring power cuts associated with low reservoir levels at the Mtera dam. Irrigation intake design that applies proportional allocation according to river flow is better than fixed volumetric intake designs, but does not fully move the narrative on the causes of water scarcity in the GRRC beyond the current line of thinking which is that the solutions to the zero-flow conditions at Msembe are to be found in upstream freshwater demand-side management.

So far, the findings of this thesis contribute to the acknowledgment that there is more merit to shifting the focus on water resources management in the GRRC so that it a) considers the effects of naturally occurring upstream shifts in the hydrological regime adequately, and b) pay more attention to the pathways that develop in the villages in the Usangu Plains (*i.e.* adaptation) to shifting circumstances of water availability and uses such knowledge as a meaningful starting point for any future development and planning of small-scale and decentralised water infrastructure (Franks *et al.*, 2013) with a multi-purpose use focus (van Koppen *et al.*, 2014) in the GRRC. All water users (IRs) clearly expressed their desire for solutions to increase storage in the catchment, whereas ERs suggested that restoration of the GRRC should be given priority over expanding or developing water resources infrastructure in the catchment. This thesis suggests that the two are not mutually exclusive and there is no reason why the two approaches cannot be done simultaneously. However, from the point of view of ERs' priorities, restoration of the GRRC requires that adequate attention is given to the possibility that climate-driven changes both upstream and downstream impact the overall catchment scale eco-hydrological conditions.

8.4.2 Looking ahead: The future of water scarcity metrics and international water resources management

This thesis has argued that in order for the measurement of water scarcity to be meaningful for informing future water resources management three key proposed changes must be achieved. Firstly, water scarcity needs to be redefined in terms of the intra- and inter-annual balances between supply and demand of freshwater resources, which inherently involves embracing, rather than discarding the importance of hydrological variability. Secondly, freshwater supply and demand needs to be restricted to verifiable parameters and thirdly, using physical descriptions of water scarcity as a starting point for participatory decision-making processes on how communities resolve quantified storage requirements.

In trying to transpose what these changes mean into an operational framework the limitations have been discussed above and how such recommended shifts could be manifested in freshwater resources management in the GRRC. However, more broadly, the insights that have arisen from this thesis also highlights the fact that research, whether indicator-based approaches or modelling exercises that attempt to mimic the natural environment and quantify some or several aspects of the human environment, needs to be subject to continuous scrutiny of the data, approaches and assumptions that inform the final set of recommendations presented to policymakers for decision-making.

Decisions about infrastructure development, water rights allocation, and efforts to tackle water scarcity challenges and promote climate resilience, have in themselves far-reaching implications for people and their livelihoods, which extend beyond the immediate domain of freshwater. Strengthening the basis for the understanding and implementation of Water-Energy-Food Nexus is an emerging approach that attempts to address the complexity that arises from increasing pressure and demand on these three sectoral resources. Nexus-thinking services to balance the various goals and interests of the different users of the WEF resources, while trying to maintain integrated and systematic balance and management of the three sectors (Mohtar and Lawford, 2016)

Indeed, WEF-nexus thinking has the ability to advance the widely applied traditional thought-process that underpins IWRM. Whereas IWRM takes water as the starting point for addressing WEF (Mohtar and Lawford, 2016), the WEF Nexus presents the systematic departure from putting water as the only centre of resources sustainability and instead introduces important concepts of trade-offs between costs and benefits within and between different resources for achieving an optimised balance of resources supply and demand (Kurian, 2016, Future Earth, 2018; Daher *et al.*, 2018; Bleischwitz *et al.*, 2019). Nexus thinking also addresses IWRM's lack of regard for the transboundary nature of freshwater resources and its interplay with energy- and food production at various administrative scales (Kurian, 2016).

Another approach that has merit to advancing IWRM is the so-called Polycentric Governance Approach of natural resources (Ostrom, 2010) a concept which accepts that there are multiple layers of decision-making across different levels at play in natural resources management and governance is therefore reliant on multiple distribution of responsibilities, sources of information and co-generation of knowledge that have the ability to "enhance innovation, learning, adaptation, trustworthiness, levels of cooperation of participants, and the achievement of more effective, equitable, and sustainable outcomes at multiple scales" (Ostrom 2010:552). For river basin management efforts, Polycentric Water Resources Management (PWRM) indeed also a welcomed an advancement to the IWRM paradigm which tends to use a centralised, hierarchical command and control regulatory regime (Lankford and Hepworth, 2010). In their analysis of large watersheds in SSA, composed of disparate communities and institutions founds that water resources management in such basins are actually characterised by informal localised decision-making which is based on ad-hoc local knowledge and dialogue that aims at finding flexible solutions for all parties implied. Lankford and Hepworth (2010) further show a strong degree of scarcity of readily accessible formalised data in such basins, leading to the conclusion that decentralised PWRM not only is able to provide the most effective solutions to water resources management but also provide the most relevant and reliable data to inform such decision-making about water resources management.

Relating PWRM to the future of measuring water scarcity through indicators and metrics has much merit because the ‘paradigm’ is concerned with processes that are rooted in localised sources of information, data and lived experiences and perceptions. The time therefore may be ripe to move away from the positivism that has underpinned the thinking of measuring water scarcity during the past three decades and move towards a critical realist and contextualised epistemology where water scarcity is a constantly shifting and variable phenomena, rather than a set threshold or benchmark simply demarcating abundance or absence.

Other recent developments in the international water policy arena that also relate to the need of embracing variability and freshwater storage contributions relate both to the formalisation and adoption of the Human Right to Water and Sanitation and from an international law perspective, the ratification of the 1997 U.N. Convention on the Law of Non-Navigational Uses of International Watercourses; and in 2008 the first full proposed Draft Law Articles on Transboundary Aquifers. With regards to the latter, the existence of separate legal regimes governing different parts of the hydrological cycle remain a hindrance to full integration of the cycle and is highly reflected in water resources management efforts. For example land-based sources of marine pollution see the natural overlap between inland- and seaward pollution, but is governed by two separate instruments, the Watercourses Convention and the 1982 UN Convention on Law of the Sea, which fail to overlap in terms of addressing limits to upstream diffuse and point source pollution.

It is the anticipation that the findings of this thesis are able to contribute to, more broadly, the critical need to fully integrate surface- and sub-surface freshwater storage.

As this thesis has shown, much remains to be done in relation to advancing knowledge of groundwater stores and its potential uses, let alone integrating this particular component into the full hydrological cycle. The longer-term thinking about freshwater resources management needs to be two-fold. It should be possible to promote the multiple solutions that are already in existence to dealing with increasing pressures on global freshwater resources but to do so in a manner which adopts the WEF nexus thinking in mind. Examples of this could involve making technologies such as water reuse, recycling and desalination less energy-intense, thus addressing concerns of costs to the energy sector at the expense of the water sector, as well as, addressing the food sector by increasing output through more "crop-per-drop" by using drip-irrigation. Within the water sector itself, water and wastewater tariffs that reflect the true cost of water delivery services to cover operation and maintenance cost remain to be reformed but done so in a way that does not pose the danger of unaffordability for water users.

A final note has to be made concerning the pace of change in the water sector which remains a challenge to reckon with, that hopefully Nexus-thinking and PWRM can help to facilitate. On March 22nd 2019 U.N. Water announced that the theme for the 2022 U.N. World Water Day and Water Year, will be dedicated to the importance of groundwater. Having emphasised the critical need to pay more global attention to the contribution and role of freshwater storage, throughout the thesis, this declaration by U.N. Water is welcome but comes much too late. However, perhaps not surprising, the water policy sector is a slow moving one. One good example of this slow pace relates to the long awaited ratification of the 1997 U.N. Water Courses Convention in 2014, 17 years after it was adopted the process which in itself took nearly 25 years. The main arguments of this thesis also contribute to show the slow pace of change in the water sector. Having shown that conventional measurements of water scarcity are far from adequate in relation to the assumptions made about domestic water demand, and the non-equilibrium behaviour of the hydrological climate, these assumptions have continued to go relatively unscrutinised for over three decades, and without radical change. Indeed, the points raised in this thesis in fact were highlighted by the author in a Commentary on the indicator for SDG 6.4 in 2015, when the U.N. Statistical Commission were in the final stages of adopting the indicators that measure progress towards achieving the SDGs by 2030.

8.5 Concluding Summary

Addressing the fourth research objective "to explore a future approach for measuring water scarcity and evaluate the limits to its current development based on available field data", Chapter 8 presented what a future approach for characterising water scarcity that emphasises the contribution of freshwater storage to meeting demands could look like and evaluated the limits to making it operational in light of the available data for the case study of the GRRC. Plotting monthly surface freshwater supply based on discharge against monthly freshwater demand allowed for an indication of instances where deficits of water availability could occur and allowed for the preliminary computation of the magnitude and periodicity of the required quantity. Indeed, such a calculation could be a meaningful starting point for addressing how to develop additional freshwater storage infrastructure.

Translating the conceptual model into an operational framework was concluded to be beyond the feasibility of the thesis. The evaluation of how a framework could be developed further needs to embrace the notion of variability and be at the heart of any attempts to redefine the characterisation of water scarcity. One of the main challenges in gauging inter- and intra-annual variability of freshwater resources availability in the

GRRC relates to the fact that the observed daily discharge data suffered long gaps and would require a modelling effort to fill in the missing data. Furthermore, defining a holistic water demand in the context of the data acquired from fieldwork in the GRRC remains a challenge which involves trade-offs between assumptions of fixed per capita thresholds for domestic water use and freshwater withdrawals based on irrigation intake capacities. Finally, the greatest and unresolved challenge regards a way in which to adequately quantify freshwater storage underground as well as by way of surface water storage infrastructure. The recommendations in this thesis serve to remind all freshwater resources managers and planners of the vital contributions of storage to meeting seasonal freshwater demand, which is often widely overlooked in predominant water scarcity indicators.

Indeed, further development of an indicator informed by the changes to characterising water scarcity suggested in this thesis could be used to inform revisions of conducting freshwater resources management. Previous water governance- and management frameworks that have been implemented in the GRRC as part of mainstreaming IWRM have emphasised water rights allocation based on a volumetric fixed abstraction cap for irrigation intakes. Such a recommendation, however, did not only fail to reflect the intra- and inter-annual variability in freshwater availability in the GRRC, which in part might be driven by long-term naturally-occurring fluctuations, but it also does not address longstanding customary laws and practices. Reforms in water law could benefit from adopting a reliable and robust water scarcity metric that puts special emphasis on customary norms and law, and participatory and inclusive water resources planning that include the due consideration of the need to identify informal pathways of accessing water. Further concepts discussed in the wider field of shift in water governance for adequately dealing with water scarcity include WEF-Nexus thinking and PWRM.

Chapter 9 - Conclusion

This thesis set out to investigate the question "to what extent are current methods for characterising water scarcity useful, especially when applied in semi-arid zones?" in seeking to contribute to critical research on the meaningfulness of how water scarcity is measured. Chapter 9 presents a summary of the main findings of this thesis, as guided by three research questions and four research objectives.

9.1 Summary of Research Findings

This thesis addressed a fundamental lack of critical research into the meaning and practical application of the two most widely used metrics for characterising water scarcity, the WSI and the WTA ratio. The research is significant as it contributes to advancing the methodological basis for characterising water scarcity in light of a growing attention on measuring progress towards combatting water shortages through global initiatives such as the SDGs. The literature review identified that current water scarcity indicators estimate renewable freshwater availability from equations derived from Mean Annual River Runoff (river discharge). In doing so, not only do these indicators fail to account for the contribution of freshwater storage in determining freshwater availability but also the significant intra- and inter-annual variability inherent to freshwater resources that determine the magnitude and periodicity of water scarcity.

The research set out to investigate each of these shortcomings in practice and address the criticisms by exploring what a future framework for characterising water scarcity could look like. Such an approach should ideally account explicitly for the contribution of water storage to freshwater availability as well as recognises the importance of variability in hydrological regimes. Furthermore, the investigation also specifically aimed to address common assumptions of domestic water demands that have inherently informed the threshold for water scarcity in the WSI (i.e. that people need ~100 LCPD) in semi-arid areas. The thesis also examined adaptive strategies that people employ to maintain access to freshwater under varying conditions. Central to providing an evidence base for the arguments presented in this thesis was a practical case-study and fieldwork that took place in the semi-arid Great Ruaha River Catchment in Tanzania.

Research objective one which was "to apply the WSI and WTA ratio indicator, two widely accepted measurements of water scarcity, to the Great Ruaha River Catchment, to assess change in characterisations of water scarcity over time" was addressed through the practical application of these indicators to the study site using secondary data on river discharge, population change and irrigation withdrawals over three time periods (1973/4 – 1980, 1999 – 2006, 2007 – 2011). The application of the WSI upstream portrayed the GRRC as water abundant, whereas its downstream application at Msembe revealed increasing levels of water stress below the limit for absolute water stress (< 500 m^3 capita yr^{-1}). The measurement of water scarcity using the WSI ratio indicator upstream, showed increasingly recurring periods of water stress during the 1999 – 2011 period with ratio scores in excess of 0.4 - the critical threshold for water stress. The contrasting results these indicators produce opened up the need to gain a broader understanding of the temporally and spatially dependent conditions in the catchment that influence how water scarcity is characterised.

The upstream hydrological regime, characterised by a high degree of inter-annual variability, and representative of a naturally occurring river discharge before the impacts of irrigation water withdrawals, experienced a long-term decline in mean TRWR of 17% marked by a distinct decrease of 31% in total mean annual river flow between the study periods 1973 – 1980 and 1999 – 2006. Comparing long-term annual changes in the proportion of water that is lost between the upstream headwater- and downstream gauging stations, indicates that regardless of the historical levels of irrigation intensity, an average of ~91% of upstream river flow is consistently lost between the headwaters and Msembe each year. Under assumptions that irrigation withdrawals remain constant, fluctuations in downstream river discharge still occurs. The thesis further found that downstream river flows are threshold-dependent and require annual upstream discharge to exceed 500 million m^3 yr^{-1} in order to produce flows at Msembe. These results, coupled with a noticeable inter-decadal decline in highland precipitation (1900 – 2010), suggest that naturally-occurring change in upstream inputs may have a more significant impact on downstream flow conditions at Msembe than previously anticipated. The thesis seeks suggest that there may be merit to reconsidering previous claims that have dismissed the possibility that declines in upstream precipitation and discharge could have an impact on downstream river flow at Msembe

The second research objective "to examine how assumptions of domestic water demand embedded in the WSI relate to field observations" was addressed by field-testing the common assumption embedded in the WSI, that people require 100 LCPD to satisfy their requirements. Chapter 6 quantified domestic water demand to ~28 LCPD based on a household survey of three villages in the Usangu Plains (n = 82). Combined with previous household surveys estimating domestic water demand in the GRRC, which ranged between ~34-46 LCPD, this thesis quantifies mean domestic water demand in the GRRC to be ~33 LCPD; one third of the assumptions made by Falkenmark (1986). The use of interview methods with government officials resulted in higher estimates of daily per capita water use ranging from ~60 – 100 LCPD. Household questionnaires generate responses that are based on water users' actual experiences whereas interview estimates are more likely to generalise about the broader study area. Elsewhere in Tanzania and other parts of arid- and semi-arid SSA, estimates of per capita water demand are similarly well below the assumed 100 LCPD requirement embedded in the WSI. Quantification of per capita daily domestic water demand in SSA is complex and not adequately reflected in current measurements of water scarcity. The importance of accurately quantifying water demand becomes even more important in the context of characterising water scarcity, as one rationale holds that the WSI applied domestic water use as a scalar upon which to estimate total freshwater demand and ultimately the threshold for water scarcity (i.e. water use for agricultural and industrial uses should be 20 times more than water for domestic uses). The thesis evaluated that major studies on water demand are prone to assume that water use in MEDCs and LEDCs are uniform. The inclination to mainstream this assumption overlooks the factors that contribute to the complexity of water use and demand in LEDCs such as multiple-source use and preference, proximity to the source, and waiting times at source.

Research objective three "to investigate how water users characterise 'water scarcity' and how freshwater storage informs adaptive capacity", was investigated by using semi-structured interviews to examine how stakeholders perceive the characteristics of water scarcity in the GRRC and how groundwater and surface-storage can be used to adapt to the perceived characterisations of water scarcity. ERs (*i.e.* Government respondents and international advisors) expressed mixed views as to whether the GRRC is water scarce. They all, however, agreed that the characterisation of water scarcity in the GRRC is defined by the extreme temporal and spatial variability in freshwater availability. IRs (*i.e.* farmers and water users in the GRRC) on the other hand primarily perceived water scarcity to be concerned with not having adequate water for irrigation activities.

ERs identified three main challenges to mainstreaming groundwater use in the GRRC. The first relates to a lack of regulatory policy on groundwater use and efficient registration of wells. Second, the number of motorised pumps in the GRRC remain low due to unreliable access to electricity and other energy sources. This keeps groundwater use from being mainstreamed, as the tendency to use hand-pumps are only sufficient for fulfilling domestic requirements and not feasible for extending to irrigation. Third, the lack of knowledge on local- and basin-scale hydrogeology and the downstream risks associated with increasing groundwater use, limits small-scale groundwater irrigation. Due to these challenges, ERs warn heavily against rapid expansion of both sub-surface and surface-water storage infrastructure. Storage-based infrastructure development risks threatening their calls for much-needed catchment-scale restoration efforts. IRs, however, expressed a strong preference towards expanding surface storage development, and reject the recommendations to temporarily suspend storage-based developments. A general lack of knowledge on how to access groundwater, coupled with the tendency to use outdated hand-pumps, only suitable for domestic subsistence pumping, drive IRs' views that surface water storage infrastructure trumps the localised convenience of decentralised small-scale groundwater networks.

Research objective three was further examined in relation to the factors that influence water use in three villages in the Usangu Plains and how water users' respond to water shortages. Groundwater is the most common use of water for domestic purposes and the primary source water users are dependent on all year. The main motivation that influence access to groundwater relates to the close proximity of the source. A lack of awareness of groundwater-irrigable crops proved the biggest challenge to advancing the use of groundwater beyond domestic uses. Testing for differences in the manners that water users in the three villages access groundwater, the results indicate that in the instances where international development interventions have failed to adopt a participatory approach to rural water supply planning, there was a statistically significant higher likelihood that water users access groundwater through informal self-supply pathways. The contribution of these sources is not insignificant and constitute complementary types of sources due to their adaptive nature. The importance of self-supply however is currently not adequately reflected in metrics that measure progress towards achieving international development goals such as the MDGs and the SDGs.

Addressing the fourth research objective "to explore a future approach for measuring water scarcity and evaluate the limits to its current development based on available field data" Chapter 8 presented what future characterisation of water scarcity that emphasises the contribution of freshwater storage to meeting demands could look like and evaluated the current limits to making it operational. Translating this envisaged approach to characterising water scarcity into an operational framework was beyond the scope and feasibility of this thesis. Advancing the measurement of water scarcity in a meaningful way needs to embrace the notion of variability and to be at the heart of future water scarcity indicator development. Indeed, one of the main challenges in gauging inter- and intra-annual variability in freshwater resources availability in the GRRC relates to the fact that the observed daily discharge data suffered long gaps and would require a modelling effort to fill in the missing data. Furthermore, defining a holistic water demand in the context of the data acquired from fieldwork in the GRRC remains a challenge which involves trade-offs between assumptions of fixed per capita thresholds for domestic water use and freshwater withdrawals based on irrigation intake capacities. Finally, the greatest and unresolved challenge regards a way in which to adequately and robustly quantify freshwater storage underground as well as by way of surface water storage infrastructure.

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Appendix 1a – Additional water scarcity indicators reviewed in Chapter 2

Table 1. Overview of selected indicators as they relate to water scarcity and stress

Index	Reference	Scale	Description	Specific notes on water and scarcity components
Water Requirements				
Inverted Falkenmark	Falkenmark (1986)	National	Amount of people competing for 1,000,000 m^3 of water	Available freshwater resource is based on Mean annual river runoff
Traditional Falkenmark (Water Stress Index(WSI))	Falkenmark (1986, 1989)	National	Available freshwater resources per capita. See Table 1 for more details.	Available freshwater resource is based on Mean annual river runoff
Gleick	Gleick (1996)	National	Drinking = 5 Litres/person/day (l/p/d); sanitation = 20 l/p/d, bathing = 15 l/p/d, food preparation = 10 l/p/d; Total = 50 l/p/d. However, a global complete range is estimated to be 27 – 200 l/p/d and the paper finds "Falkenmark's 100 l/p/d falls well within the middle of this bracket".	Acknowledges that available sources of water differs across the world and can be culturally and societally determined.
Domestic Water Scarcity Index	Weligamage (1998)	Community	-	-
Social Water Stress Index	Ohlsson (2000)	National	Incorporates society's adaptive capacities to water scarcity	HDI-weighted measure of WSI (0-20 point scale) (See Table 2 for more information)
Cereal Input Index	Yang *et al*. (2003)	National (Africa and Asia only)	Stipulates that the correlation between volume of available freshwater and quantity of imported food can serve as a basis for a model which investigates net cereal import as a function of renewable water resources to serve as a water deficit indicator	Available freshwater resource is based on Mean annual river runoff
Water withdrawals to availability ratio (WTA ratio)	Raskin *et al*., (1996); Alcamo *et al*., (2003); Vorosmarty *et*	Local/National	Water use is defined as the sum of water withdrawals for domestic (D); industrial (I) and agricultural sectors (A) divided by total freshwater availability. If DIA withdrawals to availability is higher than 40%/0.4	Available freshwater resource is based on Mean annual river runoff

	al. (2005); Rijsberman (2006)		there is water stress.	
Water Exploitation Index	Marcuell & Lallana (2003)	National	If mean total annual water abstractions (DIA) to total freshwater availability is over 40% there is severe water stress.	Available freshwater resource is based on Mean annual river runoff
Water Supply Stress Index	McNulty *et al*. (2010)	Local (Watershed) USGS Hydrological Unit datasets	Compares water demand to water supply (i.e. WTA ratio)	Available freshwater resource is based on Mean annual river runoff
The Emergence of Holistic and Integrated metrics				
Physical and Economical Water Index	Seckler *et al*., (1998); IWMI (2008)	National	Physical water scarcity if >75% of river flows are withdrawn for DIA. Economic scarcity if less than 25% of river flows are withdrawn for DIA but infrastructural development lacks investment.	Available freshwater resource is based on Mean annual river runoff
Water Poverty Index	Sullivan (2002); Lawrence *et al*., *(2002); Sullivan* et al., *(2003); Lawrence* et al., *(2003); Fenwick (2010)*	National; later local/community/household.	The index clusters its components in five dimensions: 1) access to water; 2) water quantity; water quality and variability; 3) water uses for domestic, food and production purposes; 4) capacity for water management and; 5) environmental aspects.	WTA ratio component applied. WSI component is on a log-scale. For both WTA and WSI available freshwater resource is based on mean annual river runoff. Water for domestic purposes is set at 50 l/p/d.
Water Scarcity Index (WSCi): population growth impact on water resources availability	Asheesh *et al*., (2007)	National	Measures magnitude of water deficit necessary to be returned into the natural system in order to sustain a balance between available water and water demand. Incorporates population growth rate, water availability, and domestic, industrial and ecological water usage	Available freshwater resource is based on Mean annual river runoff Available Freshwater resources availability based on mean annual river runoff on a log-scale.
Water Stress Index	Smakhtin *et al*.,	National	WTA ratio accounts for Environmental Water	

(incorporating Environmental Water Requirements (WSI_{EWR})	(2004)		Requirements	
Water Accounting Frameworks				
Water Footprint	Hoekstra (2003)	National, river basin, local	The water footprint (WfP) is the virtual water (embedded water) in production of a good. A global trade can be visualised as an adaptive capacity	Originally available freshwater resources is based on mean annual river runoff
Life Cycle Assessment (LCA)	Pfister *et al.*, (2009)	Local and watershed	This assessment indicator uses the WSI_{EWR} combined with traditional Life Cycle Assessment approaches to measure environmental stresses.	The WTA ratio is applied as the hydrological component. A later study, using the same methods (Pfister and Bayer, 2014) recognises the importance of considering the temporal variability of freshwater availability. Available freshwater resource is based on mean annual river runoff
Water Impact Index (WII)	Bayart *et al.*, (2014)	Local	Adopts the LCA and WfP approaches with the aim to integrate issues that relate to water scarcity and quality in a single indicator in order to assess the water footprint of human uses of freshwater on the environment.	Water scarcity component of WII applies WSI_{EWR} methodology. Available freshwater resource is based on mean annual river runoff
Water Sustainability Metrics				
Watershed Sustainability Index	Chaves & Alipaz (2007)	Watersheds below 2,500 km^2	WSIndex incorporates hydrology (H), environment (E), life (L) and policy (P), each with the parameters "pressure, state and response". The WSIndex value (ranged 0-1) is calculated as the average of HELP, all of which are also scored on a scale from 0-1. (See Table 3 for for more information)	Water quantity parameter applies Falkenmark threshold of 1,700 m^3/capita/year and state water stress occurs under this level and applies five levels of per capita water availability in relation to multiples of this minimum standards. Available freshwater resource is based on Mean annual river runoff
Canadian Water Sustainability Index	PRI (2007)	Canadian Community Scale	Fifteen indicators are holistically integrated into the components of: Freshwater Resources; Ecosystem Health; Water Infrastructure; Human Health and Well-being; and Community Capacity	Available freshwater resources is based on Mean annual river runoff: Applies Falkenmark thresholds where a score is assigned of 100 is assigned to any value over 1,700 m^3/capita/year and 0 of 500 m^3/capita/year; indicator for supply serves as a proxy for the vulnerability of the community's freshwater supply by addressing the variability of

				surface water flows and/or trends in ground water reserves. Demand indicator: demand on the resource is the amount of water annually allocated relative to the total amount of renewable fresh water.
Arab Water Sustainability Index	Ali *et al*. (2008)	National (Arab region)	Four theme-based components were proposed to reflect a meaningful representation of the situation in the region: water crowding, dependency, scarcity and environmental sustainability.	Available freshwater resource is based on Mean annual river runoff. The WSI is adopted to portray "water crowding" and the WTA ratio to measure water scarcity. This is done in the context of agricultural impact on water resources availability.
West Java Sustainability Index	Juwana (2012)	West Java, Indonesia	Composite indicator measuring components of Conservation; Water Use and Policy & Governance, incorporating water availability, demand and quality.	Available freshwater resources is based on Mean annual river runoff. The WSI is applied to portray water availability and the WTA to reflect water demand.
Water Resources Sustainability Evaluation Model	Kang & Lee (2011)		-	-
Aqueduct Water Risk Tool	Reigh *et al*. (2013); Gassert *et al*. (20130	National, Global	Publicly available global database that provides information on water-related risks worldwide for businesses, using three categories of indicators: Physical Risks: Quantity; Physical Risks: Quality; Reputational and Regulatory Risks	Available freshwater resource is based on mean annual river runoff WTA ratio approach to identify areas of water stress. The issue of seasonality in water supply between months is acknowledged as being a challenge.
Sustainability Gap Framework *In progress*	Ekins (1997; 2001)	National	Years to Sustainability is the time it will take to reach predefined sustainability goals. Years to Sustainability is the time it will take to reach a sustainability goal, which is calculated as the difference between a predefined sustainable level of impacts and the current level of environmental impacts from a specific pressure. .	*In progress*. Available freshwater resource is based on mean annual river runoff Severe stress occurs when WTA >40%.
Water Security				
Water Security Status Indicator	Norman *et al*. (2013)	Community	It's method rather than an indicator; integrates variables pertaining to water quantity and quality as	Available freshwater resource is based on mean annual river runoff.

approach			they relate to aquatic ecosystems and human health.	
Climate vulnerability index	Sullivan & Meigh (2005)		Resource (R), Access (A), Capacity (C), Use (U), Environment (E) and; Geospatial (G) divided by eight risk factors	Available freshwater resource is based on mean annual river runoff
Governance and Climate Vulnerability index	Jubeh & Mimi (2012)		Combined Climate Vulnerability and Governance Index	Available freshwater resource is based on Mean annual river runoff . Applies the WSI.
Water Vulnerability Index	Sullivan (2011)	Municipal scale	supply-driven vulnerability (from water systems) (SDWV) and demand-driven vulnerability (from water users) (DDWV) dimensions are combined	Available freshwater resource is based on mean annual river runoff .
Bagmati River Basin Vulnerability Assessment	Babel *et al.* (2011)		Combination of water stress sub-index and adaptive capacity sub-index	Available freshwater resource is based on Mean annual river runoff. Applies the Falkenmark and WTA thresholds.
Arctic Water Resources Vulnerability index	Alessa *et al.* (2008)	Communities in circumpolar Arctic	An index to assess resilience toward changes in freshwater resources: 2 sub-indices: physical (quality and quantity) and social.	Physical water supply: measured via precipitation as average annual rainfall over 30 years. For the river flow indicator, the average annual runoff in the watershed and the Coefficient of Variance for that run-off over a 30-year time series are measured; seasonal variation in water supply, the difference in monthly maximum and minimum river discharge, normalised by the monthly mean river discharge is calculated in order to determine a measure for the intra-annual water supply variation. Physical Water Supply: the ability to use infrastructure to continuously ensure that there is 20-100 l/capita/day available of water. AWRVI recognises the importance of the ability to store water to ensure resilience against times where natural supply may not be adequate to meet demands.
Groundwater Sustainability Metrics				
Groundwater Sustainability Infrastructure Index	Pandey *et al.* (2011)	National	existing knowledge, practices and institutions whose adequate strengthening helps to achieve groundwater sustainability is necessary infrastructure in evaluating progress in achieving groundwater sustainability	-

The International Hydrological Programme (IHP) Working Group on Groudwater Indicators	Lavapuro *et al*. (2008); Lamban *et al. (2011)*	National	measurable and observable data and information on groundwater quantity and quality and information on socio-economic and environmental matters	-
Social Sustainable Aquifer Yield	Molina *et al*., (2012)	Local	Introduced variable termed: Aquifer Social Yield (ASY); ASY is the social perception of the maximum acceptable aquifer exploitation, as derived at through stakeholder engagement at the local level	-

Appendix 1b - Reference from Tab1e 1 Appendix 1a not in reference list

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Appendix 2 - Interview Guide

1.How have you experienced water resources **availability** have changed over time during your work in the Great Ruaha River catchment?

2.In more particular I'd like to talk about <u>sources of water</u>, in particular hydrological stores. What can you tell me about the status and role of the following storage sources of water in the GRR?

-Groundwater
-Small dams
-Rainwater harvesting?

3.With particular regards to <u>water use,</u> can you tell me something about the sources of water for domestic uses? Specifically,

i. G.W.
ii. Small dams
iii. Rainwater harvesting

b.Have you witnessed any changes in the use of storage components over time?

i. Any particular reasons?
   1. Links to changing freshwater availability?
ii. Difference between dry season/wet season uses and sources?
iii. Any source that you think is preferred?

c.How much water do you think a person uses per day?
d.Does the RBWO/Ministry of Water have any specific standard assumptions of daily per capita water use that informs strategies and design of development?

4.What is the future of storage development in the GRR?

- o Groundwater?
- o Damming?
  - ▪ Is storage development the best way to alleviate pressures on water resources?
  - ▪ Is one type of development pathway more democratic than the other?
  - ▪ Challenges/opportunities?

5.I'd like to talk a bit about the issue of water scarcity. What can you tell me about this in the GRR?

a.How do you define scarcity?
   i. How do you define water scarcity in general?
b.Is there water scarcity? Is there enough water?

c.How do you think water users perceive the issue of water scarcity, if any?

d.Do you know anything about conventional water scarcity metrics/calculations?
   1. If yes, what do you think they say about the areas that you work in?
   2. If no [**just note**] but continue, what do you think they say about the areas that you work in?

e.Do you know what amount of water, conventional indicators assume humans need to thrive?

1.If yes, what is it?

2.If no, what do you think it is?

6.Can the development of storage in the GRR be used to deal with issues of water scarcity?

Appendix 3 - GroFutures Household Survey Questionnaire

Consent note:

We are from GroFutures project. GroFutures (Groundwater Futures in Sub-Saharan Africa) is working on the development and operation of basin observatories within the network of African groundwater observatories (NAGO) aiming at developing the scientific basis and participatory management processes by which groundwater resources can be used sustainably for poverty alleviation in Sub-Saharan Africa. We would like to know the current status of groundwater use, agricultural practices and socio-economic situation of the area that will be used to improving evidence base knowledge around groundwater availability and management in sub-Saharan Africa (SSA) so that to enable developing countries and partners in SSA to use groundwater in a sustainable way in order to benefit the poor. For this purpose we are interviewing randomly selected households. Your household is one of those randomly selected sample households and we would like to talk to you. The interview will take about _________ hours/minutes. All the information we obtain from you will remain strictly confidential and your answers will never be shared with anyone other than our project team.

May I start now?

01	Did the household consent to the interview? *(1=Yes, 2=No)*	If YES, record the date of interview and starting time and proceed with the interview. Date (DD/MM/YYYY) ____/____/____ Starting Time__________________
If the household is not willing to be interviewed, pick one from the reserve household list and continue to administer the interview.		

IDENTIFICATION

02	Country:		Country code:	
03	Region:		Region Code:	
05	District:		District Code:	
06	Village		Village Code:	
07	Name of Household Head:			
08	Household code:			
09	Type of Household	1= Male Headed, 2 =Female Headed)		
10	Number of people in household:			
11	Name (s) of HH member (s): interviewed[7]			
12	Enumerator Name:			
13	Supervisor's Name:			

7 The respondent must be the person who is capable of providing information. That could be the household head, the spouse or another adult household member.

SECTION A: Human capital

Household Characteristics[8]

Start with the household head, followed by his/her spouse, children (ranked from old to young) and lastly other household members – include only members who live with the household sharing the same household resources at least 3 months. Hhmid = Household member ID.

hhmid	Name	Relationship to head of household? **(use code 1)**	sex 1=male, 0=female	Age (age in complete years)	Marital Status 1=Single 2=Married 3=Divorced 4=Widowed/ Widower	Literacy of the household member 1=Can neither read nor write 0=Can read and write	Highest grade of school completed
01							
02							
03							
04							
05							
06							
07							
08							
09							
10							
11							
12							

[8] Household is a family unit headed under one head living in the same compound/homestead and using the same household resource

Code 1: 1=household head, 2=spouse, 3=son/daughter, 4=son-in-law/daughter-in-law, 5=grandson/granddaughter, 6=father/mother of head or spouse, 7=brother/sister of head/spouse, 8= adopted, 9= other relative of head/spouse, 10=non-relative/hired, 11=other (specify)

SECTION B: Household's Livestock, Asset and Land Holding

B-1: Livestock Holding

Asset	Did your household own the following asset? (1=yes 2=no)	Amount (number)	Average current market value/unit (TZS)	Access and control (**use code 3**)	
				Access[9]	Control[10]
Livestock					
Oxen					
Cows					
Bull					
Calves					
Small Ruminant/Shoats					
Sheep					
Goat					

Code 3: 1 = Head only 2 = Spouse only 3 =jointly, 4=other (specify)

B-1: Livestock Holding (Cont….)

Asset	Did your household own the following asset? (1=yes 2=no)	Amount (number)	Average current market value/unit (TZS)	Access and control (**use code 3**)	
				Access[3]	Control[4]
Equine					
Donkeys					
Poultry					
Cock					
Hen					
Pullet					

9 Access represents the right to use a resource/benefit,

10 Control represents the right to make decision about the use of a resource/benefit

Asset	Did your household own the following asset? (1=yes 2=no)	Amount (number)	Average current market value/unit (TZS)	Access and control (**use code 3)**	
				Access[3]	Control[4]
Swine					

Code 3: 1 = Head only 2 = Spouse only 3 =jointly, 4=other (specify)

B-2: Asset Holding

Asset	Did your household own the following asset? (1=yes 2=no)	Amount (number)	Average current market value/unit (TZS)	Access and control (**use code 3)**	
				Access[11]	Control[12]
Farm implements					
Tractor					
Power tiller					
Plough (set)					
Sickle					
Hoe					
Spade					
Fork					
Sprayer					
Axe					
Treadle pump (hand/foot)					
Motorized water pump					
Animal cart					
Water can					
Pulley					

[11] Access represents the right to use a resource/benefit
[12] Control represents the right to make decision about the use of a resource/benefit

Asset	Did your household own the following asset? (1=yes 2=no)	Amount (number)	Average current market value/unit (TZS)	Access and control (**use code 3**)	
				Access[11]	Control[12]
Other (specify)					

Code 3: 1 = Head only 2 = Spouse only 3 =jointly, 4=other (specify)

B-2: Asset Holding (cont….)

Asset	Did your household own the following asset? (1=yes 2=no)	Amount (number)	Average current market value/unit price (TZS)	Access and control (**use code 3)**	
				Access[13]	Control[14]
Other goods					
Mobile telephone					
Radio					
Television					
Bicycle					
Motorcycle					
Car					
Solar power panel					
Other (specify)					

Code 3: 1 = Head only 2 = Spouse only 3 =jointly, 4=other (specify)

[13] Access represents the right to use a resource/benefit
[14] Control represents the right to make decision about the use of a resource/benefit

SECTION C: Ownership of Land

Please note that a plot is defined based on the type of crop during each cropping season conducted in the previous production season.

Plot number	Type of land 1=irrigated 2=Rainfed 3=both (supplementary irrigation)	Plot size acres/ha	Tenure pattern (**use code 4)**	Is this plot cultivated during this production season? (1=yes, 2=no)	Does the plot have access to irrigation water (1=yes, 2 =no)	Is the plot irrigated (1=yes, 2=no)	Soil fertility 1=good fertility 2= medium fertility 3= poor fertility	Soil type 1=Clay 2=Sandy 3=Loamy 4=other, specify	If plot of land was rented-in (hired) for cash payment, how much did you pay? (TZS)	If plot of land was rented-out for cash payment, how much did you earn? (TZS)	If land was sharecropped-in/sharecropped-out, what was the division of production (e.g., 1/4, 1/3, 1/2, etc.)?
01											
02											
03											
04											
05											
06											
07											
08											
09											
10											

Code 4: 1=Own operated, 2= Hired (Rented-in), 3= Rented–out, 4= Sharecropped in hired plot 5=Share cropped in rented plot, 6=Gift from parents 7 = Inheritance,, 8=other, specify

SECTION D: Household's production and input use-previous cropping season

D-1: Non labor input use

Plot number (Refer above Table C	Type of crop grown (Code 5)	What is the cropping season per year?	What kind of agronomic practice are you using (land prep. oxen, tillage, others?)	Amount and cost of seed used			Cost of pesticide/fungicide/herbicide (TZS)	Fertilizer use						Other non-labor input expense (transport, loading, unloading, etc.) (TZS)
				quantity	Unit (Code 6)	Total cost (TSZ)		DAP			UREA			
								Qty	unit	Total cost	Qty	unit	Total cost	

Code 5: Type of crop: 1= Paddy 2=Maize 3=Wheat, 4= Barley, 5=Sorghum, 6=Pulses, 7= sunflower seeds, 8=Onion, 9=Tomato, 10=Cabbage, 11=Potato, 12=Garlic, 13=Green Pepper, 14=Mango, 15=Banana, 16=Orange, 17=Avocado, 18=Papaya, 19=Coffee, 20=Sugarcane, 21=Guava, 22=Lemon, 23=Apple, 24=Enset, 25=Khat, 26=Hopes (Gesho), 27=Fodder trees, 28=other (specify),

D-2: Labour (both family and hired labour) use by farm activity during the previous cropping season (labour days)

Plot number (Refer Table C)	Labour type	Land preparation		planting		weeding		Irrigation		Harvesting		Other	
	1 = Family, 2 = Hired, 3 = Both	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female	Male	Female

D-3: Amount and value of production

Plot number (Refer Table C	Crops grown (**use code 5)**	What is the purpose of the crop?	How much was harvested from this plot?			Amount sold	Amount consumed	Amount stored
		1= Home consumption; 2 = Commercial; 3 = Both	Quantity	Unit (**use code 6)**	Average market price/unit (TZS)	Unit: use code 6	Unit: use code 6	Unit: use code 6

Code 5: Type of crop: 1= Paddy 2=Maize 3=Wheat, 4= Barley, 5=Sorghum, 6=Pulses, 7= sunflower seeds, 8=Onion, 9=Tomato, 10=Cabbage, 11=Potato, 12=Garlic, 13=Green Pepper, 14=Mango, 15=Banana, 16=Orange, 17=Avocado, 18=Papaya, 19=Coffee, 20=Sugarcane, 21=Guava, 22=Lemon, 23=Appl e, 24=Enset, 25=Khat, 26=Hopes (Gesho), 27=Fodder trees, 28=other (specify),

Code 6: unit of measurement: 1=kg, 2= bag, 3=gram, 4= tin, 5=other, specify

1. What are the major challenges related to crop production? ____________________

SECTION E: Household's Irrigation Experience

1. Did you have experience of irrigation? 1=yes 2=no__________, If yes, when did you start irrigating? _____________

Please fill the following tables and give us the following information

History of Irrigation practice	Irrigated plot size? (ha/acre)	Type of source of water used for irrigation (**use code 7**)			Type of irrigation technology used and if possible average pumping/discharge capacity (Lit/minute/sec) (**use code 8**)						What are/were the three major crops grown? Please list by sequence of their importance/dominance (**use code 9**)			Was quantity of irrigation water for your field adequate 1=Yes, 2=No
		Source 1	Source 2	Source 3	Technology 1		Technology 2		Technology 3		#1	#2	#3	
					Type	Discharge	Type	Discharge	Type	Discharge				
Current irrigation season														
Plot 1														
Plot 2														
Plot 3														
Previous year's irrigation season														
Plot 1														
Plot 2														
Plot 3														
Since five years														
Plot 1														
Plot 2														
Plot 3														
Before five years														
Plot 1														
Plot 2														
Plot 3														

(Code 7) source of water: 1=Groundwater (hand dug well), 2=Groundwater (shallow well), 3=Groundwater (deep well), 4=Reservoir/Dam, 5=Pond (rainwater harvesting), 6=River, 7=spring, 8=Lake, 9=Perennial stream, 10=other, specify__________,

SECTION F: Groundwater use

F: If you are using or have used groundwater please fill and tell us about the following information

	Description	Type of groundwater source		
		Hand dug well	Shallow well	Deep well
1.	Year of construction			
2.	Number of wells			
3.	Average depth (meters)			
4.	Ownership [1=private, 2=shared with other farmer/s, 3=community, 4=other farmer, 5=other, specify ________]			
5.	For how many years have you been using groundwater sources?			
6.	What type of technology/material used for construction [1=labor(manual), 2=drilling machine, 3=other, specify___]			
7.	Who paid for the construction/digging of the well? [1=self, 2=government, 3=NGO, 4=community, 5=other, specify________]			
8.	What for is the well-used? [1=irrigation, 2=domestic use, 3=livestock, 4=irrigation and livestock, 5=irrigation and domestic use, 6=all, 7=other, specify]			
9	If the well is used for irrigation, what is the size of land currently irrigated (use local unit)			
10	f well is used for irrigation, what is the driving force? ____ If well not used for irrigation what is the estriction?____			
11	How productive is your well? [1=high, 2=medium, 3=low]			
12	Method of water abstraction for irrigation [1=diesel/petrol pump, 2=electric pump, 3=solar pump, 4=Rope & Washer pump, 5=treadle pump, 6=bucket, 7=other, specify]_____________________________________			
	Average pumping/discharge capacity of the abstraction technology (Lit/minute/sec)			
13.	Method of water conveyance [1=lined canal, 2=unlined canal, 3=hose, 4=PVC pipe, 5=other, specify___________]			
14.	Method of water application [1=furrow/surface system, 2=sprinkler, 3=drip, 4=on root (bucket), 5=other,			

	specify________]			
15.	Do you face problems with water quality? [1=yes, 2=no]			
16.	Can you abstract water from the well any time you want? [1=yes, 2=no]			
17.	If your answer to the above Q. is no, why? [1=govt. rules, 2=WUA rules, 3=other, specify______________________]			
18.	What is the main factor that influence your household to use a particular type of groundwater source? [1 = distance to source, 2=adequate quantity, 3=affordability of source, 4= other, specify ________________________			
19.	What period do you depend on groundwater sources? [1= dry season, 2 = rainy season, 3 = all year]			
20.	Has the duration of groundwater source use changed in the last 5 years? 1 = Yes, 2= No]			
21.	How many buckets of water does your household use per day for domestic use?______________________			
22.	What proportion of water for domestic use comes from groundwater source? [1= all, 2=more than half, 3=half, 4=less than half, 5 = None]			
23	Apart from groundwater, what other sources does your household use for domestic use? [1=Rainwater, 2= dam, 3=spring, 4= tap, 5=canal, 6 = other, specify ____			
24.	Have you experience conflicts over groundwater use? [1=yes, 2=no]			
25.	If your answer to the above question is yes, who are your competitors? 1=fellow farmers who irrigate their farmers, 2=land renters (tenants), 3=commercial farms, 4=water pumped for nearby urban/cities, 5=factories, 6=other, specify ______________			
26.	What were the causes of the related groundwater conflicts? [1 = restriction of water use, 2 = water price, 3 = destruction of water source, 4 = Other (specify)____________________________			
27	Who was involved in resolving the conflict?			
28.	Who are the most dominant ground water users in the area, 1=smallholder farmers, 2=commercial farms, 3=urban dwellers for domestic use, 4=factories, 5=others, (specify)___________________			
29.	Do you have knowledge of groundwater use law/policy? [1=yes, 2=no]			
30.	If you know about groundwater use policy/law, is it adequate? [1=yes, 2=no]			
31	What is the biggest challenge to groundwater development? ____ ____			

<u>Section G</u>: Technology Adoption and Access to Credit

G-1: If you have adopted/used an irrigation technology, please give us the following information

Type of irrigation technology (code 10)	Brand	Discharge capacity (litre/minute/second)	Supplier type (1=Gov't, 2=Private, 3=NGO)	How was it acquired? (Code 11)	Year purchased/acquired	Price/cost (TZS)[15]

Code: 10 = pump (please specify type of pump_________) 2 = water saving equipment

Code 11: 1=bought, 2=free gift; 3= communal ownership 4= other specify_______________________________

G-2: Access and use of credit

1. In general, do you have access to financial institution? 1 = yes, 2 = No____
2. If yes, which financial institutions? **[Use code 12]** ____
3. Did your household need credit during the previous production season? 1=yes 2=no
4. If yes, did your household apply for credit? 1=yes, 2=no
5. If yes, did you receive credit? 1=yes 2=no

6. If you did not apply, why? ____

7. If credit needed but not received why? ____

If you have taken credit, please fill the following information

[15] Even if the technology was a gift, please fill the current market price of the technology

Purpose credit was taken	Credit was actually used for	Amount of credit (TZS)	Source of credit (**use code**	Length of credit repayment period (years/month	Loan type (1=group 2= individual)	Annual interest rate (%)	Total repaid (TZS)	Amount of outstanding (TZS)

(code 12) purpose of credit: 1= to buy irrigation equipment, 2=to buy irrigation water application technology, 3=digging and construction of wells, 4=to buy input for vegetable production 5=to buy for fruit production 6=to buy seed, 7=to buy fertilizer, 8=to buy food, 9=to buy fodder, 10=for medication 11=for schooling, 12=for trading, 13=other (specify), ____

Code 13) Source of credit: 1=microfinance institution, 2=bank, 3= Friends/relatives/neighbors, 4=traders, 5=Cooperatives, 6=NGO (specify) 7= Government office (e.g. agriculture office), 8= VICOBA; 9= SACCOS 10= other (specify)

G-3: Irrigation equipment repair and maintenance service

Type of irrigation equipment	Did you get repair maintenance service? 1=yes, 2=no	Maintenance/repair cost	Associated transport cost
Motor (petrol/diesel) pump			
Treadle pump			
Rope and Washer pump			
Solar pump			
Electric pump			
Secondary irrigation canal			
Primary irrigation canal			
Tertiary irrigation canal (concrete)			
Tertiary irrigation canal (earth canal)			
PVC (water pipe)			
Groundwater well			
Sprinkler			
Other (specify)			

SECTION H: Household's on-farm and off-farm employment and source of income

Livelihood Activity	Did anyone in your household do this activity *(1=yes 2=No)*	Total annual income earned while doing this work? *(TSZ per annum)*
EMPLOYMENT		
Public works (food-for-work, cash-for-work)		
Employment in Government Organization		
Agricultural labourer on others farm		
Daily labourer on non-farm activities		
Employment in commercial farms		
Employment in a factory/s		
Daily labourer in urban areas		
Domestic work for others		
Other employment (specify): ____________________		
SELF- EMPLOYMENT & INCOME GENERATION		
Buying and selling crop e.g. paddy		
Selling firewood or charcoal or selling wild fruits, etc.		
Selling grass or fodder (for livestock)		
Selling construction materials (sand, wooden poles, etc.)		
Pottery		
Blacksmithing or metal-work		
Selling drink and food (Food vendor)		
Kiosk		
Other (specify)		

SECTION I: House quality and Perception of household's wellbeing

1. House quality: what kind of household do the respondent have? (Enumerator observe these parameters) [1= Mud house with thatched roof ; 2= Mud house with corrugated iron roof; 3= Brick house with corrugated iron roof, 4= Block or More advanced house type; 5 = Other)______________________

2. How do you perceive your wellbeing status as compared to an average household in your community? [1=very rich, 2=rich, 3=self-sufficient, 4=poor, very poor/destitute]________________

   a. If your answer to Q.2 is yes, why? ____

3. Does your wellbeing seasonally vary? [1=yes, 0=no)___________

4. Are there supportive social networks in your village? 1 = yes, 2 = No,

   a. If yes, what are these? ____

   b. If yes, what is their role? ____

   c. Are you a member? ____

Appendix 4 - Information Sheet

You will be given a copy of this information sheet.
Title of Project: "Investigating the Role of Hydrological Storage Components in Water Scarcity Metrics"
This study has been approved by the UCL Research Ethics Committee (Project ID Number): **6300/01**

Researcher Name	Simon Damkjaer (Ph.D. student)
Work Address	UCL-ISR; 14, Upper Woburn Place; London; WC1H 0NN; United Kingdom
Contact Details Telephone:	s.damkjaer@ucl.ac.uk +255 (0) [redacted]/+44 (0) [redacted]

We would like to invite ________________________to participate as a volunteer to be interviewed in this research project on ____/___/___ (dd/mm/yyyy).
Before you decide to participate in this interview it is important to read the following information carefully and discuss it with others or the researcher if anything is unclear. It is up to you to decide if you would like to participate or not. Choosing not to participate will not disadvantage you in any way. If you decide to participate you are still free to withdraw at any time and do not need to give a reason.

Purpose of the Study
This study is undertaken by a Ph.D. Student at University College London Institute for Sustainable Resources in collaboration with Sokoine University of Agriculture and looks at water resources and demand issues in the Great Ruaha River Catchment, Tanzania and their links with a wider research framework on water scarcity metrics.

What will happen?
If you decide to participate, we will decide on a time and place to meet to undertake an interview. Before the interview starts I will ask if you agree to be recorded during the interview and give you a consent form to sign. If you prefer not to sign such a paper but still want to participate we can record you saying that you agree on tape.

The interview will last for no more than one hour and will take the form of a semi-structured interview where I will ask you questions about your knowledge and experiences of working with water resources in the Great Ruaha River Catchment, Tanzania.

What will happen with the data and results of the study?
This study has been ethically reviewed and received clearance from the University College London Research Ethics Committee and all data will be collected and stored in accordance with the UK Data Protection Act 1998. All recorded interviews will be transcribed (written down on paper) and the mp3 file will be deleted afterwards. Written data will be kept anonymous and confidential. This means that all data will be stored safely on a password protected database and destroyed at the end of this research (December, 2017). Your real name will never be used or be associated with any statements you make. Only the investigator mentioned above will have access to the data collected, and so your participation will not put you at any risk. The researcher will use the final results to 1) write academic articles 2) to write a doctoral thesis which will be made available at the Sokoine University of Agriculture. I will also give a seminar of my preliminary findings towards the end of my stay in Tanzania (December, 2015).

What if I change my mind?
If you change your mind after the interview we can remove anything you have said from the research, by contacting Simon Damkjaer on the above e-mail address or telephone number.

What do I do now?
If you wish to participate, have any question of want more information in the study

If you have any questions or want more information please get in touch with Simon Damkjaer.

Thank you for taking the time to read this and for considering taking part in this project.

Sincerely yours,

Simon Damkjaer

Appendix 5 – Consent Form

Informed Consent Form

Please complete this form after you have read the Information Sheet and/or listened to an explanation about the research.
Title of Project: Hydrological Storage Components and Water Scarcity Metrics

This study has been approved by the UCL Research Ethics Committee (Project ID Number): **6300/01**

Thank you for your interest in taking part in this research. Before you agree to take part, the person organising the research must explain the project to you.

If you have any questions arising from the Information Sheet or explanation already given to you, please ask the researcher before you decide whether to participate. You will be given a copy of the Consent Form and Information Sheet to keep and refer to at any time.

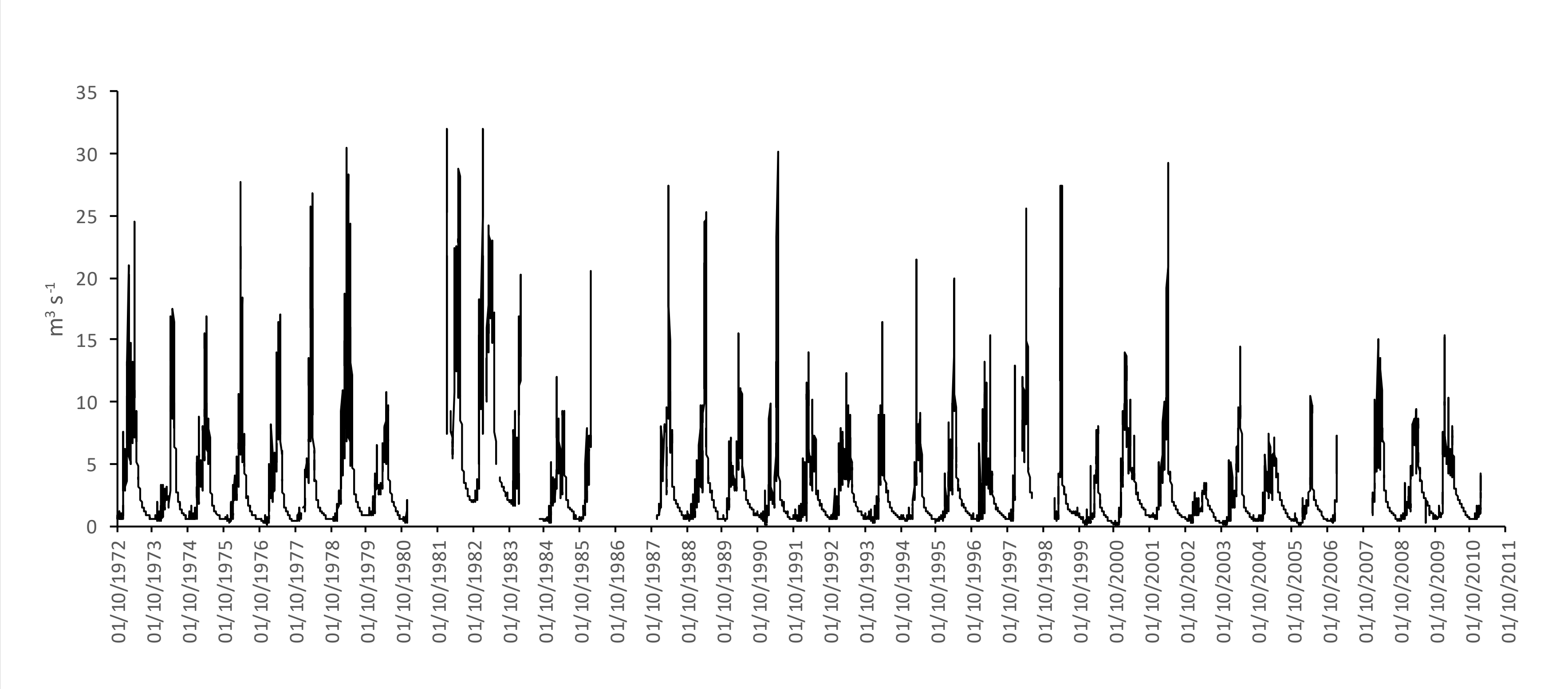
Participant's Statement

I ____ (print name)

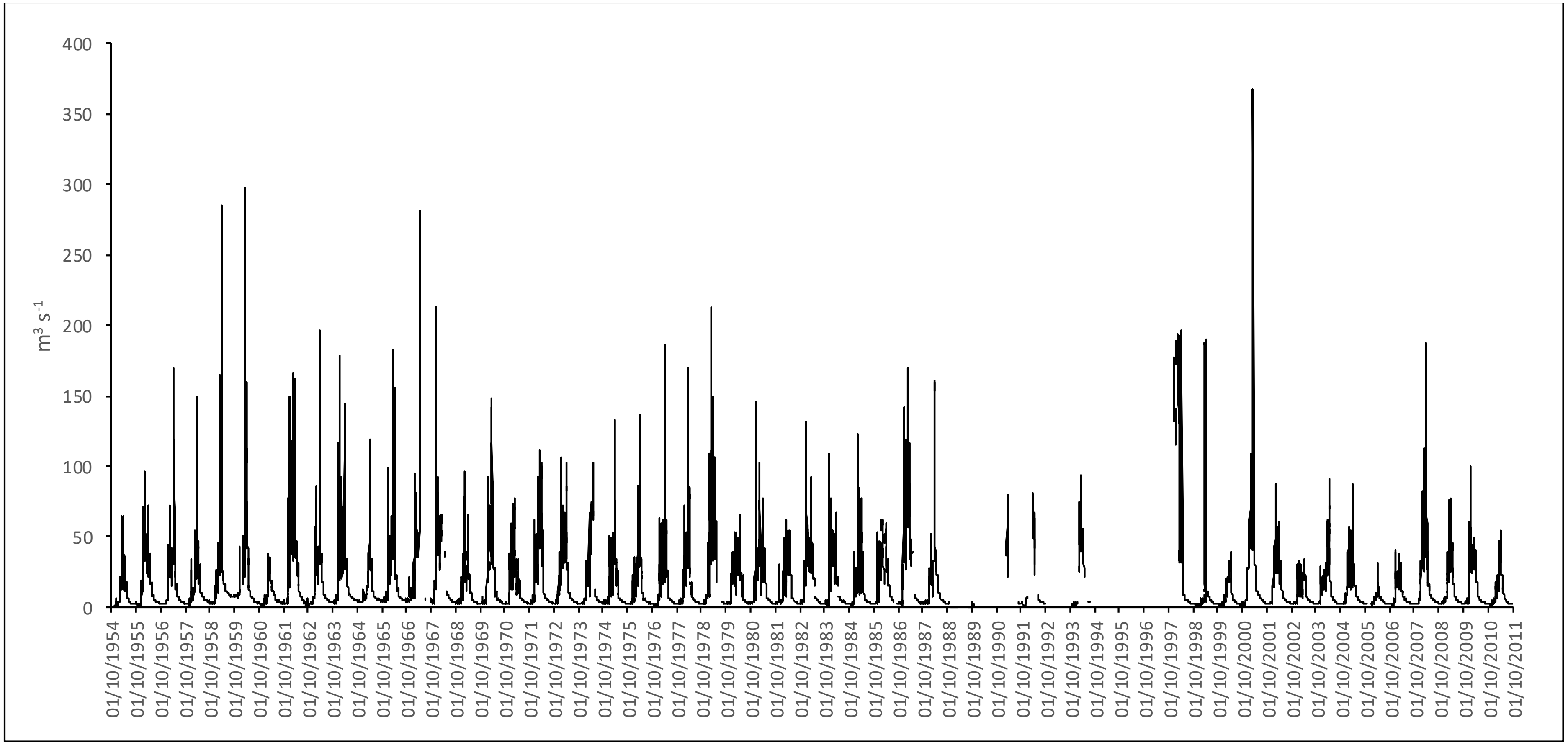
- have read the notes written above and the Information Sheet, and understand what the study involves.
- understand that if I decide at any time that I no longer wish to take part in this project, I can notify the researchers involved and withdraw immediately.
- consent to the processing of my personal information for the purposes of this research study.
- consent that my participation <u>will/will</u> not be taped (delete as appropriate) if I agree and I consent to use of this material as part of the project. The information will be destroyed at the end of the project (December, 2017).
- understand that such information will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998.
- understand that the information I have submitted will be published as a report. Confidentiality and anonymity will be maintained and it will not be possible to identify me from any publications.
- am assured that the confidentiality of my personal data will be upheld through the removal of identifiers.
- agree that the research project named above has been explained to me to my satisfaction and I agree to take part in this study.

Signed: Date:

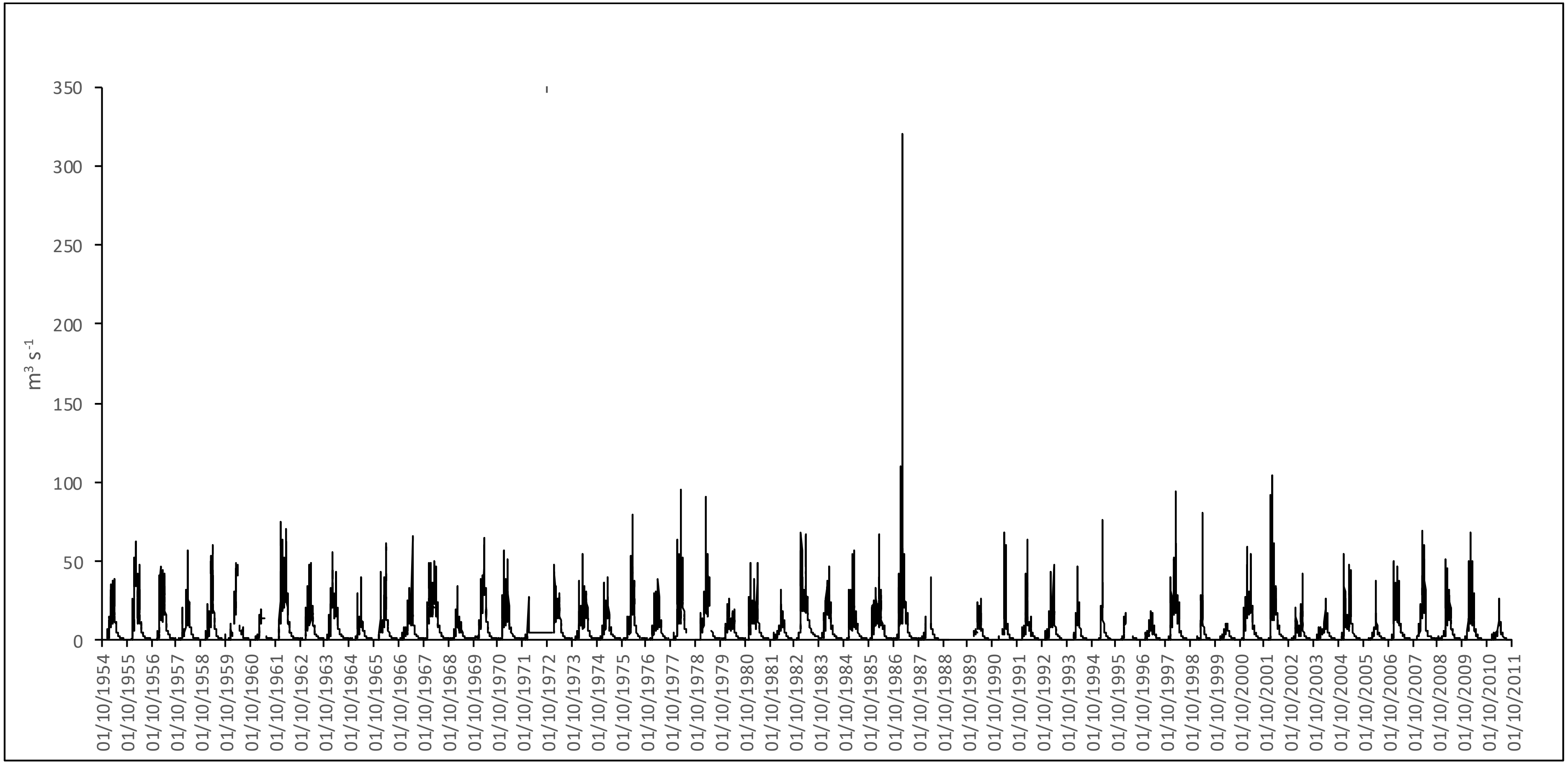
Appendix 6 – Full discharge records



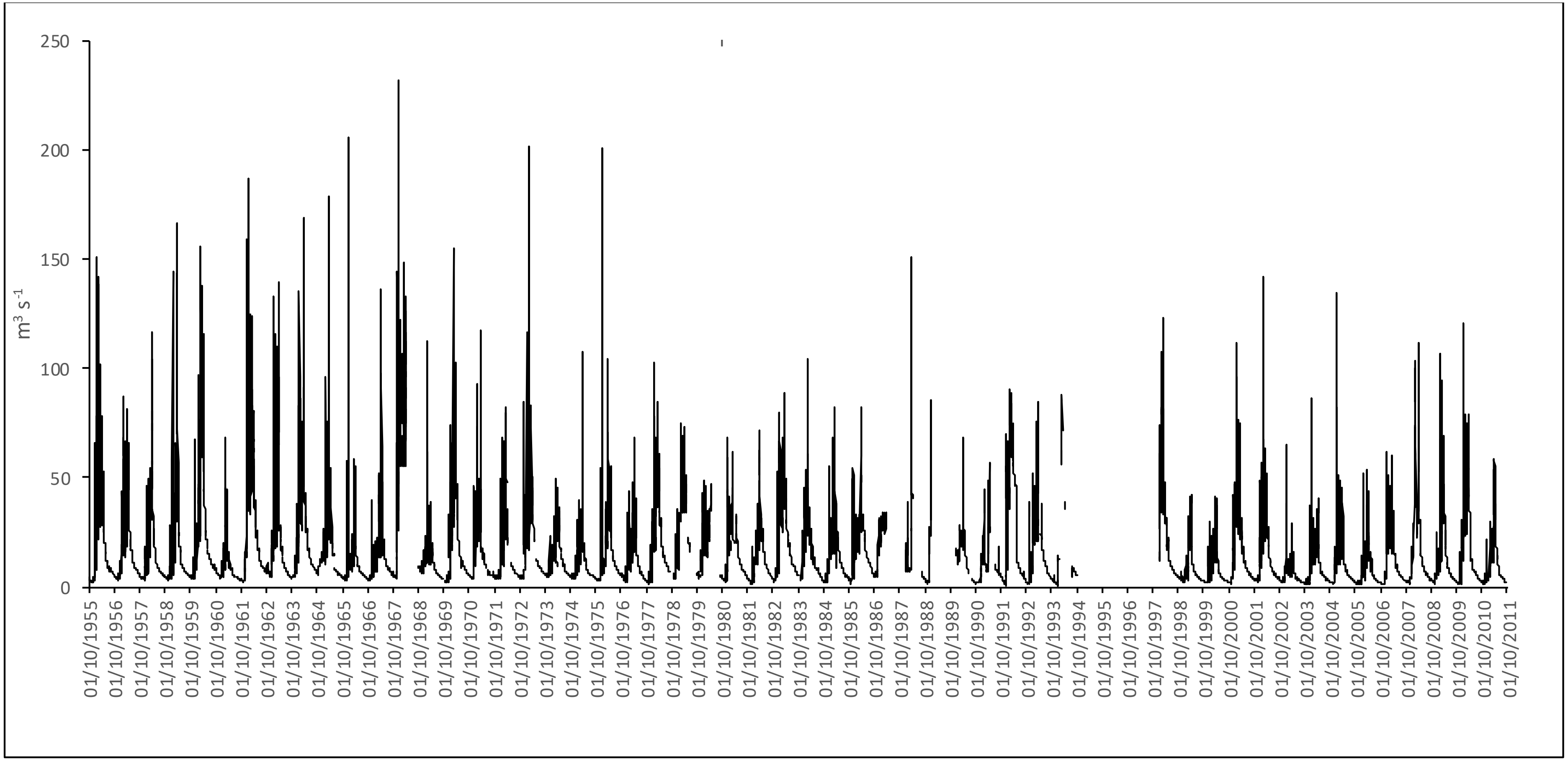
Appendix 6 Figure 1 Long-term daily discharge Chimala River, 1st October 1972 – 30th September 2011



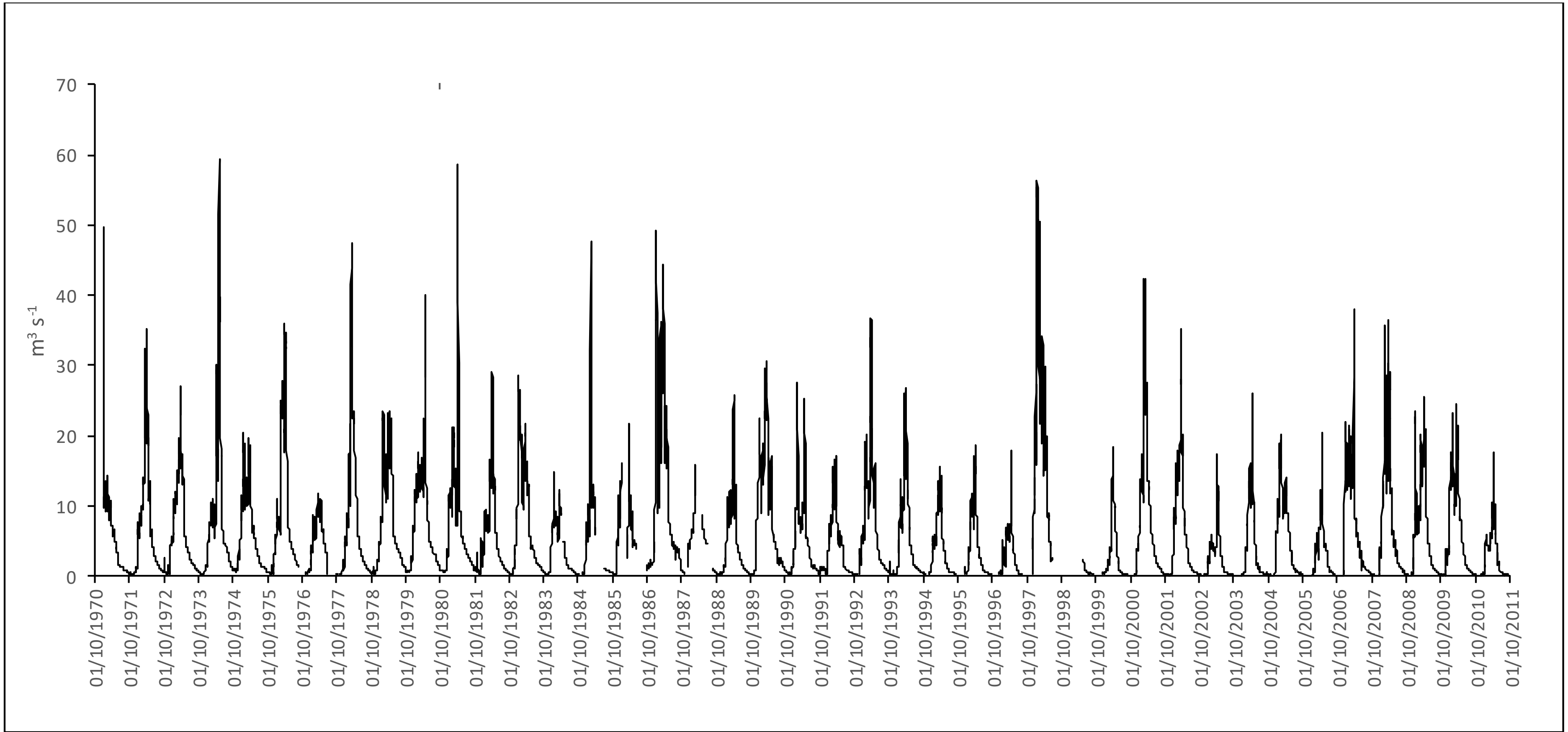
Appendix 6 Figure 2 Long-term daily discharge Great Ruaha River upstream, 1st October 1954 – 30th September 2011.



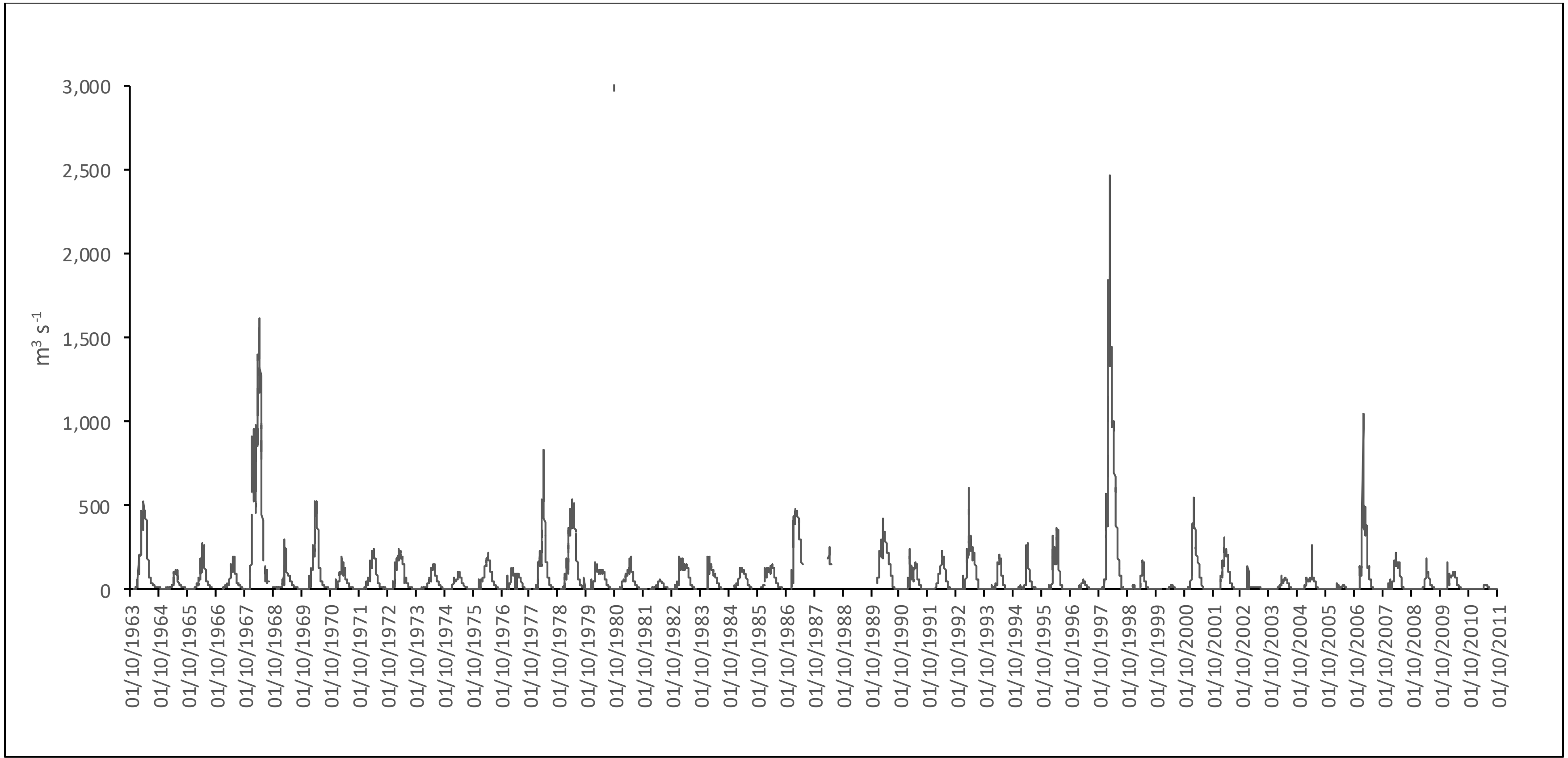
Appendix 6 Figure 3 Long-term daily discharge Kimani River, 1st October 1954 – 30th September 2011.



Appendix 6 Figure 4 Long-term daily discharge Mbarali River, 1st October 1955 – 30th September, 2011.



Appendix 6 Figure 5 Long-term daily discharge Ndembera River, 1st October 1956 – 30th September 2011



Appendix 6 Figure 6 Long-term daily discharge Great Ruaha River at Msembe, 1st October, 1963 – 30th September 2011

Appendix 7 - Baseflow Methods from the BGS Macros

1. Fixed interval method
2. Sliding interval method
3. Local Minimum method
4. Institute of Hydrology low flow method

Algorithms for methods 1 to 3
The period of surface runoff is calculated from the empirical equation

$$N=\left(\frac{A}{2.59}\right)^{0.2}$$

where
N is the number of days after which surface runoff ends, and
A is the surface drainage area in km^2.

The interval, *I*, used in the baseflow separation methods is the odd integer between 3 and 11 nearest to 2N.

Fixed interval method
In this method the minimum flow in the interval, I, is taken to be the baseflow for all of the days in the interval. The interval is repeatedly moved by I days along the period of record.

Sliding interval method
In this method the minimum flow is found over the period of one-half of the interval, I, minus one day [0.5 (I-1)] either side of the day under consideration. This miimum flow is then assigned as the baseflow to that day, i.e. the median day in the interval. The interval is then repeatedly moved by one day along the period of the record.

Local minimum method
In this method, the flow on the central day of the period one-half of the interval, I, minus one day [0.5(I-1)] either side of the day under consideration is checked to determine if it is the lowest flow in the interval. If it is then it is specified as a local minimum (and the baseflow on the median day) and connected by straight lines to the to the previous and next local minima. The baseflow on the days between the local minima is calculated by linear interpolation and constrained to equal the total flow on any day when the baseflow exceeds the total flow

Algorithm for method 4
Institute of Hydrology (IH) low flow method The following description of the method is taken from the reference cited above. The algorithm calculates the minima of five-day non-overlapping consecutive periods and subsequently searches for the turning points in this sequence of minima. The turning points are then connected to obtain the baseflow hydrograph, which is constrained to equal the observed hydrograph ordinate on any day when the separated hydrograph exceeds the observed. The procedure for calculating the baseflow is as follows:

1. Divide the mean daily flow data into non-overlapping blocks of five days and calculate the minima for each of these blocks, and let them be called Q_1, Q_2, Q_3… Q_n.
2. Consider in turn (Q_1, Q_2, Q_3), Q_2, Q_3, Q_4),… (Q_{i-1}, Q_1, Q_{1+1}) etc. In each case, if $Q_{i-1} > 0.9Q_i < Q_{i+1}$, then the central value is an ordinate for the baseflow line. Continue this procedure until all the data have been analysed to provide a derived set of baseflow ordinates QB_1, QB_2, QB_3…QB_n, which will have different time periods between them.
3. By linear interpolsation between each $QB_{i\ value}$ estimate each daily value of QB_1 … QB_n.
4. If then $QB_i > Q_i$ then set $QB_i = Q_i$

Appendix 8 - Table of aggregated monthly discharge in all rivers including periods of missing data ($m^3 s^{-1}$)

Hydro Year	Month	Chimala River	Great Ruaha River	Kimani River	Mbarali River	Ndembera River	Total Monthly Headwater
1973	Oct-72	0.74	2.59	4.57	4.45	0.7	13.06
1973	Nov-72	0.71	2.87	4.57	4.36	0.7	13.23
1973	Dec-72	3.80	16.10	4.86	20.27	4.3	49.37
1973	Jan-73	10.50	51.30	19.89	33.88	8.7	124.24
1973	Feb-73	8.75	44.77	18.37	35.54	12.0	119.43
1973	Mar-73	12.83	55.32	20.35	43.49	17.7	149.70
1973	Apr-73	7.58	35.95	12.69	29.78	14.9	100.88
1973	May-73	3.16	10.55	4.70	17.39	5.7	41.47
1973	Jun-73	1.74	5.77	2.37	11.68	3.4	25.01
1973	Jul-73	1.13	4.27	1.60	9.28	2.1	18.43
1973	Aug-73	0.80	3.46	1.21	7.81	1.4	14.68
1973	Sep-73	0.60	2.79	0.97	6.25	0.8	11.45
1974	Oct-73	0.58	2.29	0.73	5.18	0.4	9.18
1974	Nov-73	0.60	2.29	0.74	5.14	0.3	9.10
1974	Dec-73	0.70	3.11	1.88	9.39	1.0	16.12
1974	Jan-74	1.59	8.05	8.13	12.82	4.5	35.06
1974	Feb-74	2.42	21.55	12.79	18.29	8.6	63.62
1974	Mar-74	3.13	23.75	15.36	17.78	8.0	68.05
1974	Apr-74	12.18	57.68	20.94	29.85	18.5	139.14
1974	May-74	8.63	47.59	17.90	16.60	31.7	122.46
1974	Jun-74	2.45	7.86	5.55	11.09	6.9	33.84
1974	Jul-74	1.44	5.19	2.82	8.61	4.3	22.39
1974	Aug-74	0.90	3.74	1.74	6.73	2.8	15.91
1974	Sep-74	0.62	2.93	1.24	5.46	1.3	11.52
1975	Oct-74	0.66	2.79	1.02	4.84	0.8	10.11
1975	Nov-74	0.77	2.64	0.96	4.63	1.1	10.11
1975	Dec-74	1.05	4.75	2.44	5.80	5.1	19.16
1975	Jan-75	4.34	19.80	9.85	13.37	14.5	61.85
1975	Feb-75	3.59	13.12	12.39	16.96	11.6	57.63
1975	Mar-75	8.35	52.92	19.06	29.40	15.2	124.89
1975	Apr-75	8.36	27.54	9.17	15.54	9.3	69.90
1975	May-75	4.61	12.08	4.44	10.68	5.8	37.55
1975	Jun-75	1.59	5.13	2.27	7.08	3.4	19.43
1975	Jul-75	1.04	3.79	1.49	5.75	2.0	14.02
1975	Aug-75	0.71	3.07	1.12	5.17	1.2	11.27
1975	Sep-75	0.59	2.50	0.90	4.42	0.9	9.29

1976	Oct-75	0.53	2.10	0.72	3.67	0.5	7.50
1976	Nov-75	0.48	2.17	0.60	3.13	0.5	6.89
1976	Dec-75	0.74	4.98	1.42	10.85	3.5	21.45
1976	Jan-76	2.26	11.64	6.10	18.51	8.3	46.82
1976	Feb-76	3.40	17.49	9.88	12.51	14.6	57.93
1976	Mar-76	11.29	56.49	32.42	36.64	22.6	159.49
1976	Apr-76	8.63	38.29	17.87	40.70	25.1	130.56
1976	May-76	3.54	9.83	5.59	20.90	6.9	46.76
1976	Jun-76	1.64	5.08	2.67	12.98	4.0	26.42
1976	Jul-76	1.05	3.62	1.67	9.58	2.7	18.59
1976	Aug-76	0.73	2.86	1.23	7.42	1.6	13.80
1976	Sep-76	0.58	2.41	0.97	5.86		9.81
1977	Oct-76	0.50	2.01	0.82	4.95		8.27
1977	Nov-76	0.32	1.83	0.69	3.28		6.12
1977	Dec-76	0.32	2.28	1.01	4.20	0.8	8.65
1977	Jan-77	2.33	15.97	6.66	16.64	4.0	45.63
1977	Feb-77	3.44	27.21	11.59	17.81	6.8	66.87
1977	Mar-77	5.06	24.25	13.46	19.73	9.0	71.54
1977	Apr-77	9.78	40.20	14.69	27.07	9.0	100.76
1977	May-77	7.46	27.55	7.00	21.05	5.8	68.82
1977	Jun-77	1.76	6.05	2.77	9.43	2.3	22.34
1977	Jul-77	1.03	4.13	1.66	6.58	0.3	13.70
1977	Aug-77	0.60	3.18	1.14	5.06	0.3	10.33
1977	Sep-77	0.41	2.46	0.75	3.29	0.4	7.28
1978	Oct-77	0.36	1.97	0.57	2.00	0.3	5.20
1978	Nov-77	0.79	3.09	0.97	3.91	0.4	9.14
1978	Dec-77	1.00	6.37	2.30	11.17	1.9	22.75
1978	Jan-78	3.12	20.46	18.41	29.86	6.8	78.61
1978	Feb-78	5.78	25.29	19.37	29.28	13.2	92.94
1978	Mar-78	15.73	72.94	38.32	55.60	33.9	216.45
1978	Apr-78	6.59	32.08	17.23	35.94	16.4	108.20
1978	May-78	2.24	7.78		19.43	7.2	36.67
1978	Jun-78	1.31	4.97		13.94	3.5	23.68
1978	Jul-78	0.96	3.92		10.32	2.2	17.39
1978	Aug-78	0.74	3.09		7.86	1.2	12.94
1978	Sep-78	0.58	2.42			0.7	3.65
1979	Oct-78	0.53	2.10	0.70		0.5	3.87
1979	Nov-78	0.59	2.61	0.66	5.25	0.5	9.61
1979	Dec-78	1.44	9.02	7.13	17.56	2.7	37.89
1979	Jan-79	4.65	16.96	9.30	17.29	7.2	55.41
1979	Feb-79	8.88	85.29	29.50	50.72	16.4	190.78
1979	Mar-79	15.80	69.15	25.22	48.50	16.0	174.71
1979	Apr-79	12.66	70.71	24.26	42.33	19.8	169.71
1979	May-79	7.08	35.48	16.14	29.39	12.5	100.60

1979	Jun-79	2.27		4.29	18.36	5.0	29.89
1979	Jul-79	1.50		2.37		3.8	7.63
1979	Aug-79	1.01	3.34	1.61		2.6	8.56
1979	Sep-79	0.85	2.66	1.18		1.3	6.04
1980	Oct-79	0.85	2.30	0.96	5.53	0.7	10.36
1980	Nov-79	0.90	2.26	0.68	6.97	0.8	11.61
1980	Dec-79	1.83	9.40	2.97	16.73	5.0	35.97
1980	Jan-80	3.59	26.61	10.20	29.94	12.0	82.38
1980	Feb-80	2.81	24.92	10.71	20.70	14.5	73.66
1980	Mar-80	4.34	26.30	10.04	26.34	13.6	80.57
1980	Apr-80	7.01	34.60	11.51		20.9	74.06
1980	May-80	5.68	16.48	5.14		11.0	38.30
1980	Jun-80	2.48	6.09	2.35		4.8	15.68
1980	Jul-80	1.63	3.85	1.47		3.4	10.38
1980	Aug-80	1.05	2.96	1.08		2.7	7.78
1980	Sep-80	0.65	2.49	0.87		1.5	5.49
1981	Oct-80	0.52	2.12	0.64	3.79	0.8	7.90
1981	Nov-80	0.50	4.69	0.59	3.67	0.7	10.11
1981	Dec-80		29.49	11.80	23.08	3.5	67.83
1981	Jan-81		28.93	14.83	23.43	10.7	77.90
1981	Feb-81		42.41	16.83	35.07	16.6	110.90
1981	Mar-81		24.90	15.02	25.60	10.6	76.08
1981	Apr-81		29.49	16.02	28.05	27.8	101.32
1981	May-81		13.80	5.62	17.55	7.1	44.11
1981	Jun-81		5.55	2.47	11.36	4.3	23.66
1981	Jul-81		3.97	1.57	8.39	3.2	17.08
1981	Aug-81		3.19	1.13	6.68	2.2	13.22
1981	Sep-81		2.53	0.80	4.61	1.3	9.27
1982	Oct-81		2.34	0.63	3.26	1.0	7.27
1982	Nov-81		2.49	0.50	2.26	0.9	6.11
1982	Dec-81		4.58	1.02	5.70	3.4	14.74
1982	Jan-82	19.83	8.80	3.18	9.57	6.8	48.14
1982	Feb-82	11.40	23.27	6.36	19.45	7.3	67.75
1982	Mar-82	11.48	29.20	13.14	36.68	12.8	103.26
1982	Apr-82	14.64	35.31	11.99	27.52	17.2	106.64
1982	May-82	17.36	28.62	6.09	20.01	7.1	79.17
1982	Jun-82	5.33	6.14	2.49	11.22	3.1	28.32
1982	Jul-82	3.30	4.12	1.49	8.37	1.9	19.19
1982	Aug-82	2.44	2.97	1.00	5.97	1.1	13.49
1982	Sep-82	1.99	2.38	0.75	4.33	0.6	10.11
1983	Oct-82	2.10	2.40	0.54	3.14	0.4	8.56
1983	Nov-82	3.26	3.97	0.82	5.65	0.9	14.60
1983	Dec-82	11.90	19.35	5.17	17.46	6.8	60.64
1983	Jan-83	19.81	60.79	31.45	46.25	21.1	179.35

1983	Feb-83	12.93	35.02	23.00	36.30	15.2	122.47
1983	Mar-83	19.06	42.73	36.94	49.77	17.4	165.90
1983	Apr-83	18.16	29.41	21.39	32.38	12.5	113.87
1983	May-83	9.78	10.89	9.59	20.28	5.1	55.66
1983	Jun-83	4.43	5.11	5.73	14.55	3.6	33.43
1983	Jul-83	3.49	3.75	4.01	10.52	2.3	24.05
1983	Aug-83	2.87	2.82	3.12	8.26	1.4	18.50
1983	Sep-83	2.33	2.15	2.55	5.91	0.9	13.80
1984	Oct-83	2.01	2.24	1.80	5.40	0.4	11.88
1984	Nov-83	2.29	2.35	1.81	5.95	0.4	12.75
1984	Dec-83	3.44	18.63	5.41	12.85	2.8	43.11
1984	Jan-84		36.95	17.16	32.24	8.7	95.00
1984	Feb-84		36.98	20.30	37.49	7.9	102.69
1984	Mar-84		29.40	16.45	24.46	8.7	79.06
1984	Apr-84		15.40	7.01	16.97	7.0	46.34
1984	May-84		6.64	3.08	11.71	3.3	24.75
1984	Jun-84		4.73	1.73	8.44	1.3	16.23
1984	Jul-84		3.60	1.33	7.53	1.0	13.46
1984	Aug-84		2.63	0.96	5.14	0.7	9.42
1984	Sep-84	0.53	1.97	0.75	3.43	0.4	7.09
1985	Oct-84	0.38	1.68	0.62	3.50	0.3	6.46
1985	Nov-84	0.45	1.77	0.68	5.53	0.4	8.78
1985	Dec-84	2.19	14.54	10.07	18.63	2.7	48.09
1985	Jan-85	2.90	15.66	11.19	19.69	6.9	56.31
1985	Feb-85	6.80	38.50	23.64	37.47	17.7	124.07
1985	Mar-85	4.64	22.09	13.18	23.86	10.1	73.84
1985	Apr-85	8.38	38.70	10.11	26.79		83.98
1985	May-85	2.63	10.40	3.80	15.33		32.16
1985	Jun-85	1.45	4.99	2.02	9.96		18.41
1985	Jul-85	1.08	3.78	1.38	7.09	1.0	14.33
1985	Aug-85	0.73	2.85	1.04	5.40	0.7	10.76
1985	Sep-85	0.55	2.23	0.83	4.32	0.5	8.48
1986	Oct-85	0.51	1.87	0.66	3.09	0.4	6.48
1986	Nov-85	1.25	3.91	2.52	10.62	3.2	21.50
1986	Dec-85	3.88	21.76	11.37	17.39	9.2	63.60
1986	Jan-86		38.77	16.10	23.02	13.5	91.37
1986	Feb-86		45.14	14.18	22.74	8.5	90.56
1986	Mar-86		35.52	21.56	41.47	10.5	109.07
1986	Apr-86		32.81	10.85	30.81	8.5	82.98
1986	May-86		17.07	5.90	23.72	5.2	51.87
1986	Jun-86		6.73	3.27	15.19		25.18
1986	Jul-86		4.34	1.73	11.78		17.85
1986	Aug-86		3.26	1.32	9.31		13.89
1986	Sep-86		2.61	1.01	5.95		9.58

1987	Oct-86		2.42	0.82	4.86	1.4	9.52
1987	Nov-86		2.39	0.74	6.91	1.8	11.82
1987	Dec-86		38.55	8.71	24.83	8.3	80.39
1987	Jan-87		76.40	23.96	28.26	26.3	154.91
1987	Feb-87		77.65	38.49	30.73	22.8	169.68
1987	Mar-87		62.32	28.59	30.18	30.8	151.93
1987	Apr-87		36.78	12.74		20.2	69.68
1987	May-87		23.67	6.08		11.5	41.28
1987	Jun-87		6.90	2.66		5.5	15.10
1987	Jul-87		4.99	1.64		4.1	10.77
1987	Aug-87		3.18	1.14		3.6	7.90
1987	Sep-87		2.51	0.83		2.1	5.48
1988	Oct-87		2.41	0.71		0.6	3.75
1988	Nov-87		2.53	0.80		0.8	4.13
1988	Dec-87	0.98	3.13	0.98		3.7	8.83
1988	Jan-88	4.10	23.32	5.05	15.69	5.9	54.02
1988	Feb-88	4.53	21.55	13.94	9.41	10.3	59.76
1988	Mar-88	10.64	69.47	30.92	34.73	10.9	156.66
1988	Apr-88	10.35	40.59	11.81		9.5	72.27
1988	May-88	3.44	17.40	3.94		6.7	31.50
1988	Jun-88	1.86	7.70	1.93		5.0	16.44
1988	Jul-88	1.37	4.78	1.16		3.4	10.72
1988	Aug-88	0.88	3.76	0.82		1.4	6.90
1988	Sep-88	0.61	2.66	0.54	3.96	0.7	8.44
1989	Oct-88	0.67	1.98	0.41	2.94	0.4	6.36
1989	Nov-88	0.78	1.01	0.43	2.13	0.4	4.79
1989	Dec-88	1.22	0.06	0.43	35.21	0.8	37.72
1989	Jan-89	2.46	0.06			5.3	7.80
1989	Feb-89	5.06	0.06			8.7	13.82
1989	Mar-89	8.51				10.3	18.76
1989	Apr-89	14.97				14.5	29.50
1989	May-89	3.53				4.3	7.88
1989	Jun-89	2.38				2.5	4.84
1989	Jul-89	1.53				1.3	2.85
1989	Aug-89	0.89	0.06			0.7	1.69
1989	Sep-89	0.58	0.06			0.4	1.08
1990	Oct-89	0.60	1.97			0.3	2.87
1990	Nov-89	0.94				1.9	2.80
1990	Dec-89	3.18				10.9	14.12
1990	Jan-90	3.79			13.79	15.7	33.29
1990	Feb-90	3.31		5.88	15.72	17.1	42.05
1990	Mar-90	7.73		13.30	22.24	25.3	68.61
1990	Apr-90	7.44		11.57	27.53	12.3	58.86
1990	May-90	3.09		4.44	14.95	11.7	34.17

1990	Jun-90	2.08		2.06	7.50	4.5	16.18
1990	Jul-90	1.53		1.25	4.98	2.6	10.39
1990	Aug-90	1.18		0.91	3.40	2.1	7.62
1990	Sep-90	0.85		0.68	1.95	1.3	4.81
1991	Oct-90	0.78		0.52	1.95	0.6	3.86
1991	Nov-90	0.59		0.49	1.93	0.4	3.41
1991	Dec-90	0.56		0.80	5.20	1.4	7.99
1991	Jan-91	2.41		3.28	16.39	6.3	28.36
1991	Feb-91	3.83		5.68	13.91	15.4	38.83
1991	Mar-91	2.14	44.63	7.49	10.36	7.2	71.82
1991	Apr-91	13.35		23.48	23.25	13.8	73.87
1991	May-91	3.08		6.31	22.02	7.0	38.37
1991	Jun-91	1.58		2.49	14.75	3.4	22.17
1991	Jul-91	1.12		1.41	9.01	1.3	12.81
1991	Aug-91	0.70	3.12	0.93	7.41	1.1	13.31
1991	Sep-91	0.52	2.54	0.64	5.50	0.6	9.80
1992	Oct-91	0.76	2.67	0.65	4.27	0.8	9.16
1992	Nov-91	0.59	0.95	0.42	2.26	1.0	5.25
1992	Dec-91	0.77	3.42	1.80	25.92	1.2	33.11
1992	Jan-92	2.08		5.03	36.57	6.4	50.04
1992	Feb-92	5.45		12.66	65.89	10.0	93.99
1992	Mar-92	6.48		15.83	65.98	13.2	101.45
1992	Apr-92	5.15	43.94	7.08	50.48	5.9	112.60
1992	May-92	4.47	17.66	3.98	42.59	5.4	74.06
1992	Jun-92	2.22	6.36	2.07	9.63	2.0	22.23
1992	Jul-92	1.54	4.40	1.22	6.90	0.9	14.91
1992	Aug-92	1.12	3.15	0.82	5.16	0.6	10.89
1992	Sep-92	0.75	2.46	0.58	3.35	0.4	7.53
1993	Oct-92	0.60		0.42	1.98	0.3	3.28
1993	Nov-92	0.85		1.14	7.12	1.2	10.26
1993	Dec-92	1.19		2.01	6.38	4.0	13.56
1993	Jan-93	2.99		8.22	18.89	8.6	38.65
1993	Feb-93	5.18		17.61	33.45	14.8	70.98
1993	Mar-93	6.42		14.15	38.71	18.7	78.02
1993	Apr-93	4.68		11.20	36.04	16.0	67.88
1993	May-93	4.68		4.38	21.67	9.5	40.25
1993	Jun-93	2.10		2.11	13.12	3.5	20.88
1993	Jul-93	1.46		1.21	9.34	1.9	13.92
1993	Aug-93	1.10		0.86	6.37	1.3	9.60
1993	Sep-93	0.71		0.61	4.54	0.8	6.65
1994	Oct-93	0.60		0.46	2.97	0.5	4.55
1994	Nov-93	0.65	2.08	0.49	2.59	0.4	6.17
1994	Dec-93	0.45	1.59	0.37	1.09	0.3	3.85
1994	Jan-94	0.96	11.69	1.65	15.93	4.7	34.92

1994	Feb-94	1.98	34.35	5.76	54.27	9.4	105.72
1994	Mar-94	7.80	51.43	21.17	52.22	16.8	149.42
1994	Apr-94	5.50	40.76	11.47		17.1	74.86
1994	May-94	2.76		3.66		5.7	12.14
1994	Jun-94	1.71		1.73		2.4	5.82
1994	Jul-94	1.20	3.29	1.04		1.2	6.73
1994	Aug-94	0.90		0.71	7.78	0.9	10.27
1994	Sep-94	0.62		0.55	6.05	0.5	7.75
1995	Oct-94	0.60		0.46		0.4	1.43
1995	Nov-94	0.48		0.43		0.3	1.20
1995	Dec-94	0.62		0.47		0.7	1.75
1995	Jan-95	0.72		0.72		4.3	5.78
1995	Feb-95	2.20		2.81		6.0	11.04
1995	Mar-95	7.82		24.21		11.5	43.49
1995	Apr-95	6.61		7.68		9.2	23.44
1995	May-95	3.05		3.12		3.0	9.18
1995	Jun-95	1.35		1.50		1.3	4.20
1995	Jul-95	0.96		0.97		0.6	2.53
1995	Aug-95	0.69		0.63		0.4	1.74
1995	Sep-95	0.45		0.51			0.96
1996	Oct-95	0.37		0.41			0.78
1996	Nov-95	0.53		0.27			0.80
1996	Dec-95	0.71		0.51			1.23
1996	Jan-96	1.67		2.08		1.6	5.32
1996	Feb-96	4.77		11.94		7.8	24.48
1996	Mar-96	6.15				10.1	16.24
1996	Apr-96	10.56				10.4	20.94
1996	May-96	3.27				3.3	6.55
1996	Jun-96	2.03		2.00		1.4	5.44
1996	Jul-96	1.52		1.13		0.7	3.30
1996	Aug-96	1.09		0.76		0.4	2.27
1996	Sep-96	0.75		0.56			1.31
1997	Oct-96	0.64		0.39			1.03
1997	Nov-96	0.57		0.29			0.85
1997	Dec-96	1.23		1.20			2.43
1997	Jan-97	1.76		2.96		2.2	6.92
1997	Feb-97	6.97		8.54		2.6	18.11
1997	Mar-97	4.11		6.97		6.2	17.25
1997	Apr-97	4.58		6.11		8.8	19.50
1997	May-97	2.16		2.48		3.6	8.25
1997	Jun-97	1.40		1.26		1.2	3.81
1997	Jul-97	1.11		0.76		0.4	2.31
1997	Aug-97	0.82		0.49			1.31
1997	Sep-97	0.59		0.43			1.02

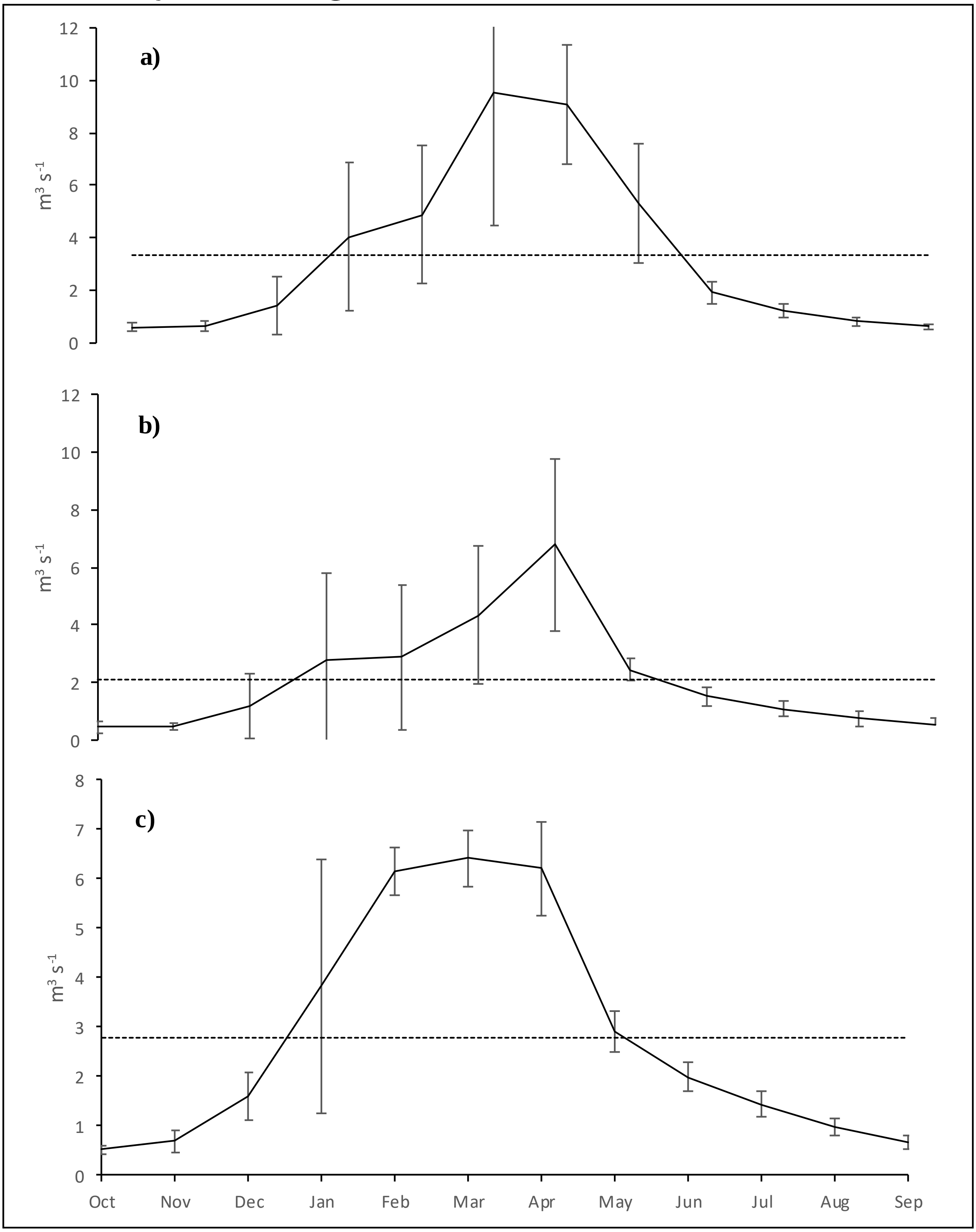
1998	Oct-97	0.59		0.38			0.97
1998	Nov-97	0.79		0.56			1.35
1998	Dec-97			13.55		9.6	23.19
1998	Jan-98		171.27	15.46	33.08	35.1	254.91
1998	Feb-98		177.95	29.73	61.29	35.7	304.68
1998	Mar-98	8.17	90.13	24.52	41.34	23.7	187.81
1998	Apr-98	14.94	105.27	13.95	30.68	20.6	185.49
1998	May-98	4.07	9.76	4.28	16.13	9.0	43.25
1998	Jun-98		5.00	2.08	10.21		17.29
1998	Jul-98		3.64	1.24	8.05		12.94
1998	Aug-98		2.87	0.86	6.62		10.35
1998	Sep-98		2.27	0.61	5.31		8.19
1999	Oct-98		1.93	0.43	3.88		6.23
1999	Nov-98		1.63	0.41	3.76		5.80
1999	Dec-98		1.56	0.32	3.02		4.89
1999	Jan-99		3.30	1.00	7.27		11.57
1999	Feb-99	0.68	3.36	1.02	6.12		11.18
1999	Mar-99	5.01	35.53	16.57	25.28		82.38
1999	Apr-99	11.29	41.16	11.60	20.02		84.06
1999	May-99	2.44	7.94	3.78	8.46		22.62
1999	Jun-99	1.52	4.59	1.84	6.09	0.9	14.93
1999	Jul-99	1.11	3.13	0.91	4.70	0.4	10.27
1999	Aug-99	1.01	2.45	0.69	3.97	0.3	8.45
1999	Sep-99	0.93	2.11	0.55	3.08		6.67
2000	Oct-99	0.72	1.90	0.50	2.44		5.56
2000	Nov-99	0.49	1.67	0.50	2.04		4.70
2000	Dec-99	0.27	2.02	0.67	3.61	0.3	6.90
2000	Jan-00	0.37	4.33	1.71	7.67	0.7	14.79
2000	Feb-00	0.91	9.66	3.35	9.29	2.3	25.48
2000	Mar-00	2.39	21.07	8.31	18.24	9.0	58.96
2000	Apr-00	4.80	21.91	7.51	17.82	11.1	63.19
2000	May-00	1.74	6.43	3.27	7.27	3.5	22.25
2000	Jun-00	1.04	3.58	1.63	4.88	0.8	11.91
2000	Jul-00	0.66	2.43	0.99	3.81	0.4	8.29
2000	Aug-00	0.38	2.07	0.73	3.04	0.2	6.47
2000	Sep-00	0.18	1.77	0.56	2.36	0.2	5.03
2001	Oct-00	0.16	2.26	0.46	1.85	0.1	4.78
2001	Nov-00	0.39	2.41	0.62	4.03	0.2	7.61
2001	Dec-00	3.62	17.68	9.19	16.30	3.1	49.89
2001	Jan-01	9.80	53.13	26.99	43.80	11.1	144.79
2001	Feb-01	7.28	51.36	25.06	41.31	21.6	146.59
2001	Mar-01	6.37	128.37	26.27	33.78	26.4	221.21
2001	Apr-01	4.49	25.64	11.93	18.76	12.2	73.06
2001	May-01	2.83	11.09	4.88	12.03	6.0	36.88

2001	Jun-01	2.03	7.30	2.59	8.33	3.3	23.60
2001	Jul-01	1.52	4.73	1.55	6.67	1.6	16.06
2001	Aug-01	1.13	3.50	1.06	5.17	1.0	11.84
2001	Sep-01	0.80	2.62	0.79	4.16	0.5	8.84
2002	Oct-01	0.74	2.14	0.58	3.27	0.3	6.99
2002	Nov-01	0.72	1.99	0.42	2.69	0.1	5.97
2002	Dec-01	1.26	3.85	13.31	6.62	1.3	26.34
2002	Jan-02	2.84	23.98	70.05	24.72	8.3	129.92
2002	Feb-02	5.80	42.56	28.70	38.25	14.9	130.20
2002	Mar-02	8.68	41.51	19.21	34.13	21.6	125.13
2002	Apr-02	10.03	28.75	13.22	25.59	12.7	90.32
2002	May-02	2.74	14.10	5.28	13.11	5.5	40.69
2002	Jun-02	1.60	6.36	2.54	8.65	2.1	21.28
2002	Jul-02	1.15	4.39	1.47	6.59	1.0	14.56
2002	Aug-02	0.86	3.34	1.01	5.25	0.6	11.03
2002	Sep-02	0.66	2.84	0.71	4.08	0.4	8.65
2003	Oct-02	0.52	2.67	0.58	2.81	0.2	6.73
2003	Nov-02	0.52	2.92	0.55	2.68	0.2	6.83
2003	Dec-02	0.59	4.29	1.27	4.23	0.5	10.87
2003	Jan-03	1.51	16.71	8.99	16.03	3.2	46.46
2003	Feb-03	1.21	14.63	6.01	8.29	4.7	34.83
2003	Mar-03	1.48	10.76	4.56	8.24	3.9	28.88
2003	Apr-03	3.00	24.16	12.81	14.57	11.1	65.69
2003	May-03	2.09	8.94	3.91	5.31	3.8	24.09
2003	Jun-03	1.37	4.73	2.13	3.74	1.1	13.09
2003	Jul-03	0.93	3.60	1.11	2.99	0.5	9.12
2003	Aug-03	0.49	3.03	0.75	2.22	0.3	6.78
2003	Sep-03	0.29	2.63	0.60	1.84	0.2	5.54
2004	Oct-03	0.18	2.53	0.45	1.63	0.1	4.89
2004	Nov-03	0.23	2.50	0.56	1.51	0.1	4.86
2004	Dec-03	0.82	8.05	2.27	6.53	0.1	17.75
2004	Jan-04	1.63	15.24	5.29	17.00	0.4	39.53
2004	Feb-04	1.97	16.61	5.39	14.70	4.6	43.31
2004	Mar-04	4.86	31.99	9.42	17.79	12.3	76.36
2004	Apr-04	8.93	46.67	10.33	23.81	15.4	105.09
2004	May-04	2.59	10.48	4.01	8.48	4.8	30.35
2004	Jun-04	1.29	5.43	1.90	5.67	1.2	15.50
2004	Jul-04	0.87	3.96	1.13	4.38	0.6	10.91
2004	Aug-04	0.54	2.81	0.73	3.32	0.4	7.77
2004	Sep-04	0.51	2.37	0.58	2.84	0.4	6.66
2005	Oct-04	0.50	1.98	0.41	2.01	0.1	5.02
2005	Nov-04	0.56	2.18	0.55	1.94	0.1	5.31
2005	Dec-04	1.59	6.63	7.07	12.91	2.2	30.43
2005	Jan-05	3.14	18.78	13.03	21.49	10.0	66.47

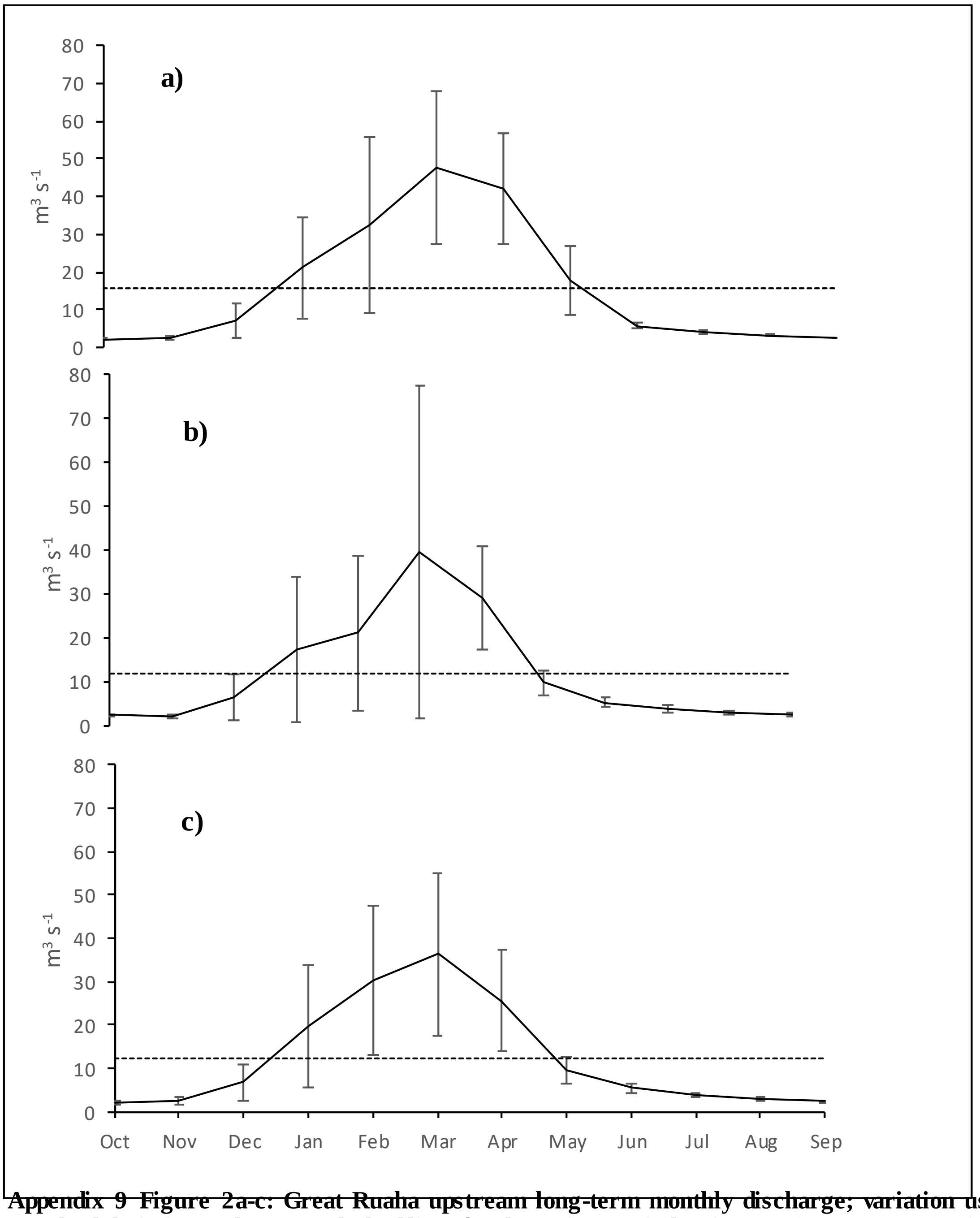
2005	Feb-05	3.93	26.01	10.41	21.99	15.9	78.22
2005	Mar-05	3.69	36.47	17.08	24.28	9.9	91.40
2005	Apr-05	5.04	30.62	13.13	19.69	10.8	79.24
2005	May-05	2.90	11.91	4.20	8.18	5.2	32.43
2005	Jun-05	1.88	5.90	2.14	5.64	1.9	17.45
2005	Jul-05	1.33	4.20	1.39	4.35	0.8	12.09
2005	Aug-05	0.85	3.35	1.03	3.44	0.5	9.19
2005	Sep-05	0.53	2.79	0.78	2.51	0.3	6.92
2006	Oct-05	0.45	2.43	0.62	1.83	0.1	5.43
2006	Nov-05	0.41		0.50	1.70	0.0	2.66
2006	Dec-05	0.16		0.49	2.51	0.1	3.24
2006	Jan-06	0.66	2.25	0.76	5.55	0.5	9.68
2006	Feb-06	1.25	4.65	2.75	10.86	3.8	23.32
2006	Mar-06	2.24	9.28	7.93	20.06	4.6	44.14
2006	Apr-06	6.68	10.24	8.84	18.68	12.1	56.55
2006	May-06	2.27	6.09	4.13	9.19	5.2	26.93
2006	Jun-06	1.50	4.05	2.15	5.20	2.8	15.67
2006	Jul-06	1.13	3.07	1.32	3.81	0.8	10.09
2006	Aug-06	0.70	2.53	0.92	2.90	0.4	7.43
2006	Sep-06	0.48	2.21	0.70	2.08	0.2	5.62
2007	Oct-06	0.41	1.90	0.51	1.48	0.0	4.34
2007	Nov-06	0.41	1.90	0.52	1.26	0.0	4.11
2007	Dec-06	1.86	9.61	8.70	17.53	9.3	46.95
2007	Jan-07		19.81	21.15	27.41	15.8	84.22
2007	Feb-07		20.98	22.80	30.78	16.6	91.20
2007	Mar-07		14.93	14.76	31.09	17.5	78.30
2007	Apr-07		8.66	6.96	18.46	8.3	42.42
2007	May-07		5.20	3.23	9.72	5.1	23.23
2007	Jun-07		3.73	1.87	6.76	2.4	14.81
2007	Jul-07		3.09	1.34	5.17	1.2	10.84
2007	Aug-07		2.70	1.04	4.02	0.8	8.51
2007	Sep-07		2.34	0.79	2.78	0.4	6.29
2008	Oct-07		2.13	0.65	2.01	0.2	4.95
2008	Nov-07		2.07	0.62	1.92	0.1	4.68
2008	Dec-07		4.44	2.73	6.93	1.2	15.31
2008	Jan-08	2.81	25.19	10.14	17.18	7.6	62.91
2008	Feb-08	6.93	57.48	25.89	57.62	21.1	169.04
2008	Mar-08	6.67	64.77	27.56	41.82	20.8	161.57
2008	Apr-08	7.24	34.84	15.36	28.37	17.3	103.07
2008	May-08	2.59	11.44	4.29	12.83	6.0	37.15
2008	Jun-08	1.59	6.79	2.37	8.57	3.7	23.00
2008	Jul-08	1.09	4.67	1.52	6.25	1.6	15.10
2008	Aug-08	0.75	3.71	1.20	4.94	0.9	11.50
2008	Sep-08	0.46	2.85	0.90	3.33	0.4	7.98

2009	Oct-08	0.47	2.51	0.77	2.63	0.2	6.57
2009	Nov-08	0.70	2.77	0.69	2.25	0.1	6.52
2009	Dec-08	1.35	3.80	2.08	8.37	3.5	19.06
2009	Jan-09	1.81	6.74	3.74	9.59	11.2	33.05
2009	Feb-09	5.90	31.21	20.95	28.06	9.1	95.26
2009	Mar-09	7.09	39.75	18.76	38.85	16.3	120.78
2009	Apr-09	6.51	34.34	14.77	30.61	17.8	104.07
2009	May-09	3.54	12.81	4.82	11.34	6.0	38.56
2009	Jun-09	2.40	6.03	2.35	7.29	2.6	20.63
2009	Jul-09	1.85	4.21	1.55	5.35	1.2	14.15
2009	Aug-09	1.25	3.20	1.20	3.92	0.6	10.20
2009	Sep-09	0.82	2.26	0.89	2.82	0.3	7.08
2010	Oct-09	0.65	1.99	0.63	1.90	0.1	5.30
2010	Nov-09	1.03	3.67	0.80	4.30	0.8	10.59
2010	Dec-09	2.25	12.95	2.29	8.24	3.5	29.24
2010	Jan-10	8.24	40.29	11.57	35.89	14.1	110.11
2010	Feb-10	5.62	31.25	14.46	47.80	14.0	113.11
2010	Mar-10	5.57	36.06	18.98	50.68	16.9	128.23
2010	Apr-10	4.66	18.05	5.60	24.32	11.2	63.88
2010	May-10	2.52	8.25	2.73	10.69	5.3	29.51
2010	Jun-10	1.92	5.13	1.33	7.25	2.1	17.73
2010	Jul-10	1.37	3.80	0.87	5.70	1.0	12.77
2010	Aug-10	0.93	2.79	0.64	3.97	0.6	8.94
2010	Sep-10	0.71	2.27	0.48	2.75	0.3	6.50
2011	Oct-10	0.56	1.86	0.33	1.96	0.1	4.83
2011	Nov-10	0.61	1.78	0.31	2.03	0.1	4.82
2011	Dec-10	0.96	3.02	1.52	6.60	0.3	12.36
2011	Jan-11		6.79	1.71	7.04	3.2	18.72
2011	Feb-11		11.41	3.18	14.04	4.0	32.61
2011	Mar-11		25.86	9.06	18.62	5.9	59.44
2011	Apr-11		32.38	10.03	31.51	10.5	84.44
2011	May-11		10.88	3.96	11.94	3.8	30.63
2011	Jun-11		5.60	1.69	6.14	1.2	14.66
2011	Jul-11		3.91	0.91	4.52	0.4	9.73
2011	Aug-11		2.66	0.58	3.27	0.2	6.75
2011	Sep-11	2.56	2.09	0.41	2.23	0.1	7.41

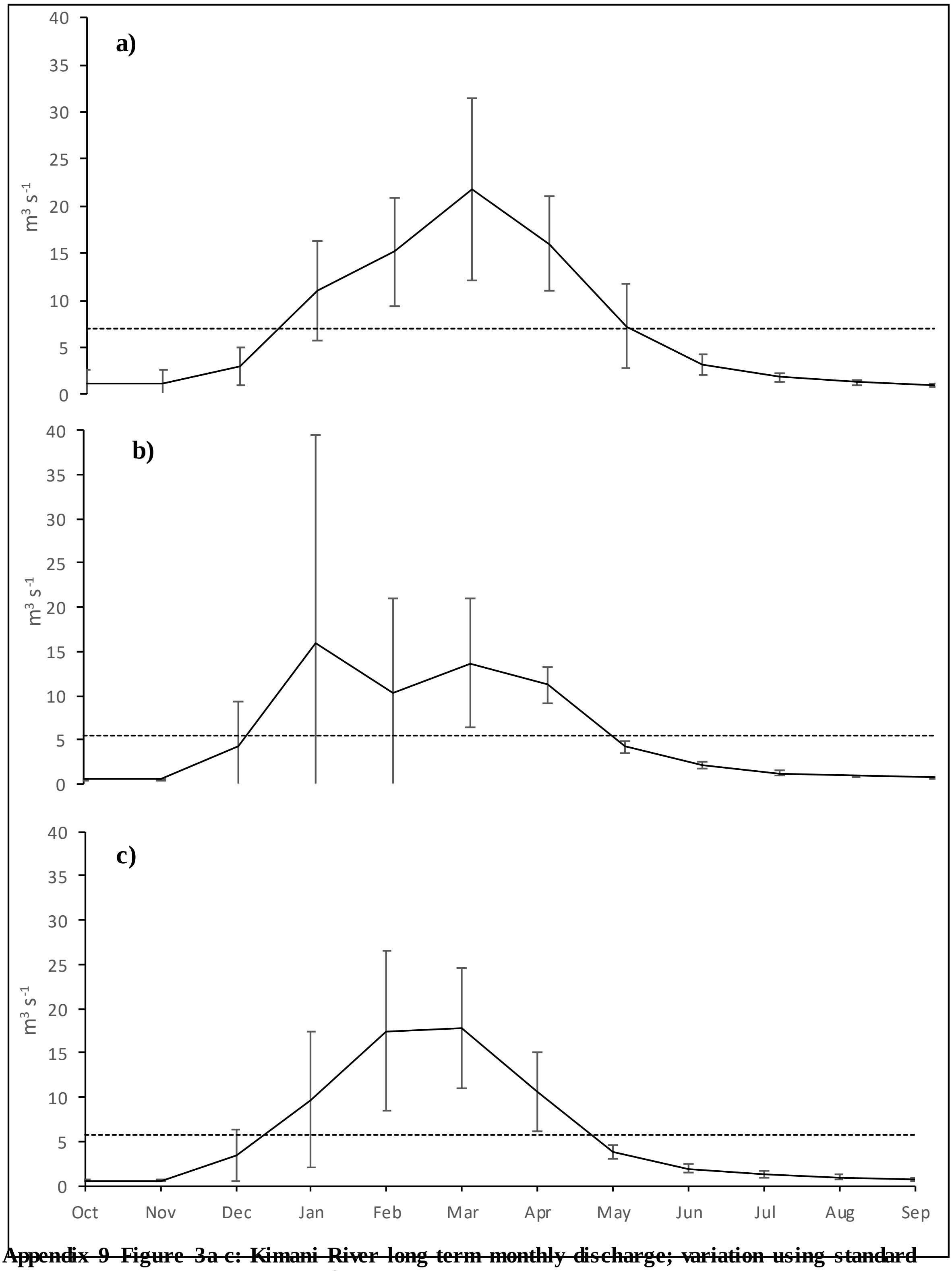
Appendix 9 – Long-term average monthly intra-annual variability in discharge for all rivers



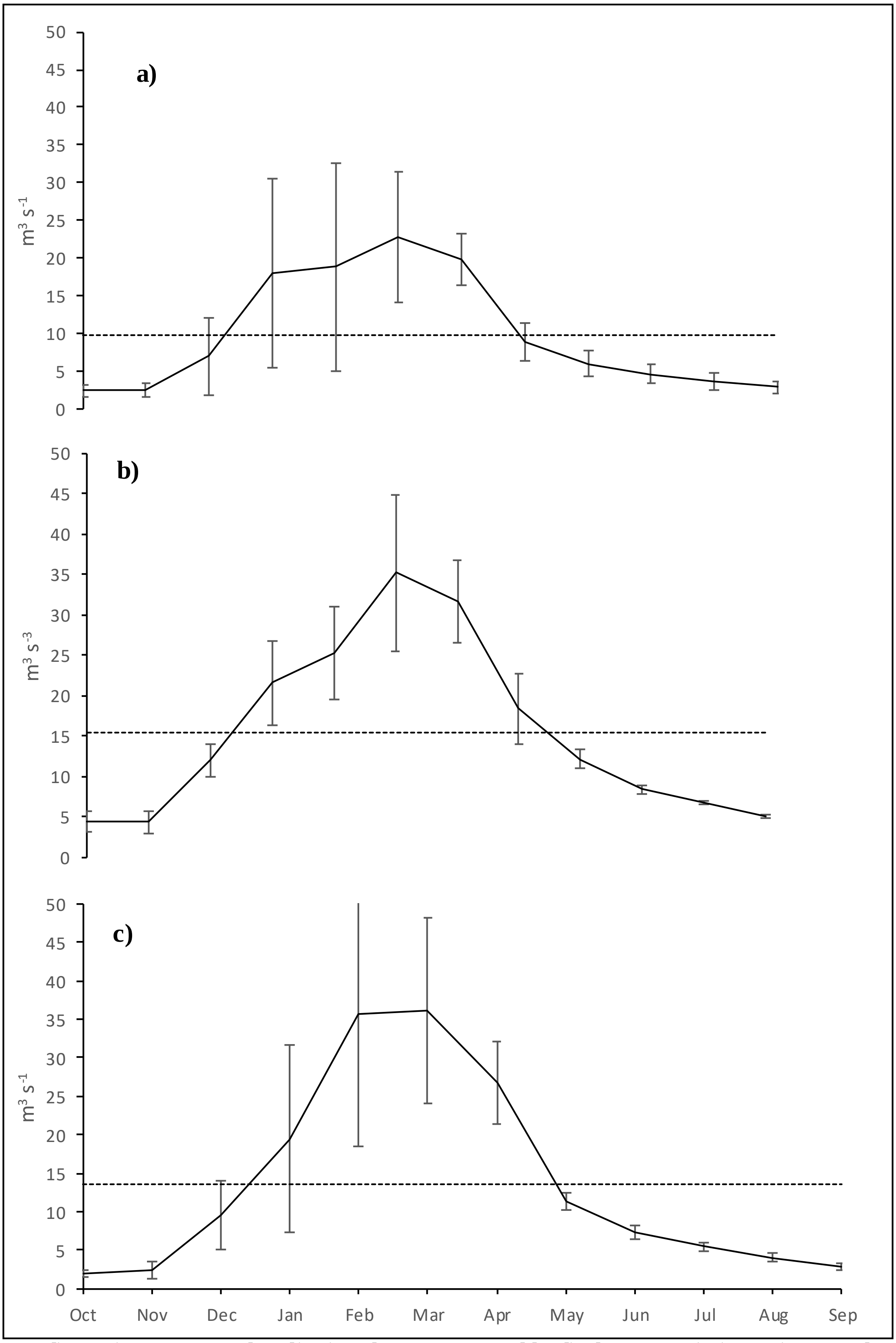
Appendix 9 Figure 1a-c: Chimala River long-term monthly discharge; variation using standard deviation and MARR (dashed line) for three time periods. Figure a (1972 – 1980); Figure b (1998 – 2006); Figure c (2007-2011)



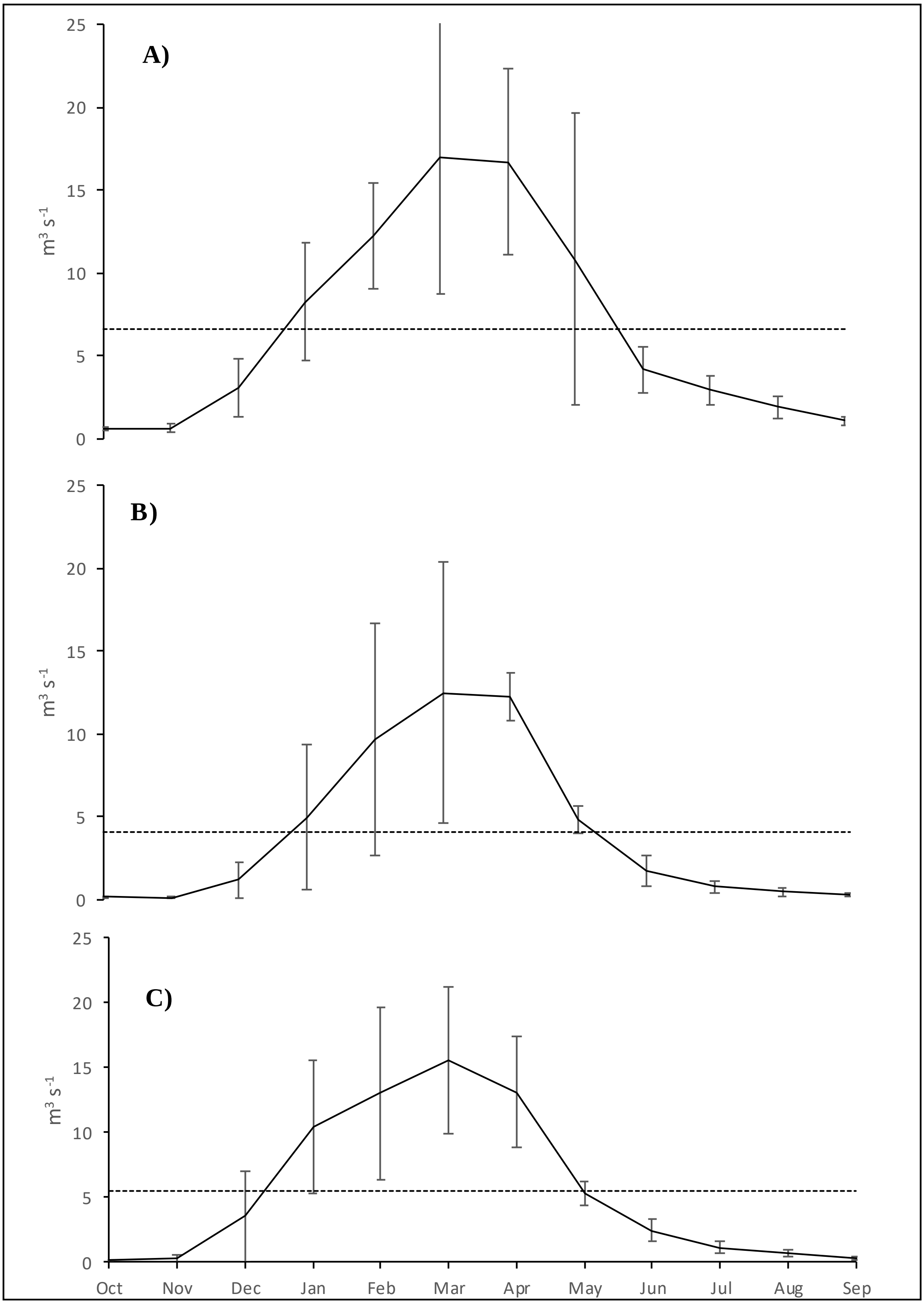
Appendix 9 Figure 2a-c: Great Ruaha upstream long-term monthly discharge; variation using standard deviation and MARR (dashed line) for three time periods. Figure a (1972 – 1980); Figure b (1998 – 2006); Figure c (2007-2011)



Appendix 9 Figure 3a-c: Kimani River long term monthly discharge; variation using standard deviation and MARR (dashed line) for three time periods. Figure a (1972 – 1980); Figure b (1998 – 2006); Figure c (2007-2011)



Appendix 9 Figure 4a-c: Mbarali River long-term monthly discharge; variation using standard deviation and MARR (dashed line) for three time periods. Figure a (1972 – 1980); Figure b (1998 – 2006); Figure c (2007-2011)



Appendix 9 Figure 5a-c: Ndembera River long-term monthly discharge; variation using standard deviation and MARR (dashed line) for three time periods. Figure a (1972 – 1980); Figure b (1998 – 2006); Figure c (2007-2011)