FLEX-Topo modelling of water use and demand in the Mara River Basin, Kenya

Master thesis

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UNESCO-IHE Institute for Water Education

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Front cover: Inhabitants and livestock collect water from a pond in the southeast of the Mara River Basin in Kenya, near the border with Tanzania.

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Preface

This thesis concludes the Master of Science programme at Delft University of Technology. The thesis work was conducted as part of the Mau Mara Serengeti (MaMaSe) Sustainable Water Initiative. This initiative aims at “improving water safety and security in the Mara River Basin in support of structural poverty reduction, sustainable economic growth and conservation of the river basin’s forest and rangeland ecosystems” (UNESCO-IHE, 2014). Although most of the thesis work was conducted in the Netherlands, the importance of reaching this goal became especially clear to me during the field work in Kenya. Hence, this thesis aims not only to contribute to science in order to satisfy our curiosity but also to improve the livelihoods of the Mara River Basin’s inhabitants.

I would like to express my gratitude to my daily supervisor, Thom Bogaard, for his practical support, patience and friendliness. Furthermore, I would like to thank Hubert Savenije for his vast knowledge and enthusiasm about hydrology. I am also grateful to Erik Mosselman for his useful feedback and to Michael McClain for his skillful leadership of the MaMaSe Initiative. Furthermore, I would like to thank anyone else who helped making my time in Kenya productive and interesting. I am also grateful to my friends for making my study time enjoyable and to my parents and siblings for their encouragements and unconditional support. Above all, I am grateful to the loving and almighty God for giving me the opportunity, ability and strength to complete this work.

Mirjam Pruijssen

Delft, November 2014

Abstract

The Mara River Basin (MRB) at the boundary of Kenya and Tanzania is one of the many river basins in the world that has to cope with increasing water scarcity. The MRB supports the world-renowned Maasai Mara National Reserve and Serengeti National Park, as well as growing numbers of farmers and pastoralists. Increasing water demand, deforestation and climate change may exacerbate water insecurity in the future. Therefore, a hydrological model of the Kenyan share of the MRB was created, to predict the impact of these changes on the balance between water demand and supply at the different water source types in this data-scarce catchment. As such, this thesis aims to contribute to water resource planning and management in the study area.

First, the main water-related problems and potential solutions in the study area were identified, using surveys and observations. Water scarcity was ranked as the main livelihood issue by all stakeholders in the Kenyan share of the MRB, although severity increased in southeastern direction. Deforestation and climate change were perceived to be the major causes. Suggested solutions usually amounted to increased amounts or volumes of water sources. To facilitate the modelling of such interventions, literature review and surveys were used to estimate the water use and demand in the study area. Distinction was made between different users, water sources, subbasins, years and months, showing significant variability for each factor.

For the creation of a hydrological model, the semi-distributed conceptual FLEX-Topo modelling concept was used, adding water use and demand to the framework. Classification of the study area into four hydrological response units (HRUs) was based on topographical characteristics, land cover and observations. Meteorological input was distributed by the selection of ground stations for each of the seven subbasins. All parameters for water use and 8 out of 19 other parameters were estimated. Parameter and process constraints were applied during calibration. The resulting model performed well during both calibration and validation. Moreover, the model performance improved with the inclusion of water demand.

Standardization of scenario evaluation included the creation of a reference model, which was assumed to be representative for the current situation. Furthermore, performance measures were established regarding the environmental flow requirements (EFRs) and the water supply to other users at each water source type. In the reference model, EFRs exceed the mean monthly flows during three months per year in maintenance years and are critical during those months in drought years. Moreover, the performance of water sources in the reference model is best for boreholes, followed in decreasing order by rivers, shallow wells, springs, ponds and rooftop rainwater harvesting reservoirs.

Scenarios included changes in water demand, land use and climate. In 20 years, the predicted changes in rainfall will probably have most impact on the performance regarding EFRs and the water availability for other users. Furthermore, complete clearance of the shrublands would significantly reduce the water availability from springs. Although deforestation of forests and shrublands would increase the peakedness, the potential impacts of increased water demand on the Mara River flows are greater. Of all considered water users, large-scale irrigation will probably have most negative impacts on the performance regarding EFRs, followed by livestock and inhabitants. Concerning water source types, the impacts would probably be most negative for increased water use from springs and rivers, followed by shallow wells. For ponds and rooftop rainwater harvesting, enhanced water use requires enlarged

storage sizes, but these interventions would hardly affect low flows and therefore performance regarding EFRs. Lastly, additional use of boreholes may even be positive for performance regarding EFRs.

For water management interventions, the southeastern Sand subbasin is the most recommended target area. Recommended interventions for reduced water scarcity throughout the MMC are enhancing the storage sizes of rooftop rainwater harvesting tanks and ponds; only in the Sand subbasin, ponds are not feasible. Prevention of deforestation is also recommended. For boreholes, further research should confirm the recharge origin and potential of the aquifer. Lastly, the uncertainty of the model results may be reduced in further research, for instance by improving the hydrometeorological input. Moreover, the model may be expanded with for instance other planned projects or water quality and erosion.

List of abbreviations and acronyms

BBM	building block methodology
BOR	bed occupancy rate
BRL	Compagnie d'aménagement du Bas-Rhône et du Languedoc
CBS	Central Bureau of Statistics
CIANEA	Community Based Impact Assessment Network For Eastern Africa
CMS	Catchment Management Strategy
DEM	digital elevation model
DIAS	District Integrated Agricultural Survey
DLPO	District Livestock Production Office
DP	deep percolation
DRSRS	Department of Resource Surveys and Remote Sensing
EFA	environmental flow assessment
EFR	environmental flow requirement
ESARPO	Eastern Southern African Regional Programme
FAO	Food and Agriculture Organization of the Unites Nations
GCM	Global Circulation Model
GLOWS-FIU	Global Water for Sustainability program – Florida International University
HAND	height above the nearest drainage
HOF	infiltration excess or Hortonian overland flow
HRU	hydrological response unit
IEA	Institute of Economic Affairs
ILRI	International Livestock Research Institute
KIHBS	Kenya Integrated Household Budget Survey
KNBS	Kenya National Bureau of Statistics
LC	Livestock Census
LVBC	Lake Victoria Basin Commission
MAFS	Ministry of Agriculture and Food Security
MaMaSe	Mau Mara Serengeti
MEST	Ministry of Education, Science and Technology
MMC	Mara Mines Catchment
MMNR	Maasai Mara National Reserve
MODIS	MODerate resolution Imaging Spectrometer
MOSCEM-UA	Multiobjective Shuffled Complex Evolution Metropolis
MPEE	Ministry of Planning, Economy and Empowerment
MRB	Mara River Basin
MRCO	Mara Regional Commissioner’s Office
MWI	Ministry of Water and Irrigation
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Statistics
NDVI	Normalized Difference Vegetation Index
NGO	non-governmental organization
NOAA	National Oceanic and Atmospheric Administration
NSCA	National Sample Census of Agriculture

NSE	Nash-Sutcliffe efficiency
OCGS	Office of Chief Government Statistician
PHC	population and housing census
SCMP	Sub-Catchment Management Plan
SID	Society for International Development
SNP	Serengeti National Park
SOF	saturation excess overland flow
SRTM	Shuttle Radar Topography Mission
SSF	storage excess or rapid sub-surface flow
TM	Thematic Mapper
TWB-MRB	Transboundary Water for Biodiversity and Human Health in the Mara River Basin
UNESCO-IHE	United Nations Educational, Scientific and Cultural Organization – International Institute for Hydraulic and Environmental Engineering
USGS	United States Geological Survey
WHO	World Health Organization
WREM	Water Resources and Energy Management
WRMA	Water Resources Management Authority
WRUA	Water Resources User Association
WWF	World Wide Fund for Nature

1 | Introduction

1.1 Introduction

In this chapter, a brief problem description is provided, indicating the relevance of the study. The problem description results in the research objectives. Lastly, the outline of the thesis is summarized.

1.2 Relevance of the study

In a global context of growing water scarcity, strategic planning of artificial or enhanced natural water storage is increasingly important, especially in Africa and Asia (Keller et al., 2000; McCartney et al., 2013; Rijsberman, 2006). Only large dams are often considered for water storage, but these are controversial (e.g. Ansar et al., 2014; Richter et al., 2010). Hydrological modelling can be a valuable tool in the selection of water storage types and their design. An example of a hydrological model is the semi-distributed conceptual FLEX-Topo model (Savenije, 2010). In this thesis, the extension of such a FLEX-Topo model with water use and demand is tested for a data-scarce African catchment.

The Mara River Basin (MRB) is one of the many river basins around the world that has to cope with increasing water insecurity. The Mara River originates in Kenya and drains into Lake Victoria in Tanzania. The MRB supports the world-renowned Maasai Mara National Reserve (MMNR) and Serengeti National Park (SNP), as well as growing numbers of farmers and pastoralists. Water demand in the MRB increases, for instance by planned hydroelectric dams and large-scale irrigation. Furthermore, the MRB has to cope with climate change and land use change, such as deforestation of its headwaters (e.g. Mango et al., 2011). As the effects of those changes on the balances between water demand and supply at the different water sources in the MRB are largely unknown, a hydrological model is created to assist in the water resource planning and management in the study area.

This study is part of the Mau Mara Serengeti (MaMaSe) Sustainable Water Initiative. The initiative aims at "improving water safety and security in the Mara River Basin in support of structural poverty reduction, sustainable economic growth and conservation of the basin's forest and rangeland ecosystems" (UNESCO-IHE, 2014). It consists of a public-private partnership coordinated by UNESCO-IHE and World Wide Fund for Nature (WWF) Kenya. Other partners include Dutch and Kenyan government agencies, private parties, non-governmental organizations and knowledge institutions. As the initiative focusses on the Kenyan share of the MRB, mainly the area upstream of Mara Mines in Tanzania – the so-called Mara Mines Catchment (MMC) – is studied in this thesis.

1.3 Objectives

The objective of this study is to predict the impact of changes in water demand, land cover and climate on the balances between water demand and supply at the different water sources in the Kenyan share of the MMC. As such, this study aims to contribute to water resource planning and management in the study area. The research has the following subgoals:

1. ***Identify water-related problems and potential solutions.*** Firstly, surveys and observations are used to identify the main water-related problems and potential solutions in the MMC. Results indicate the relevance of the study and give suggestions for water management scenarios.

2. ***Estimate water use and demand.*** Secondly, literature review and surveys are used to estimate water use and demand in the MMC. Distinguished are main users, water sources, subbasins, years and months. Results are used as input for calibration, validation and scenario design.

3. ***Create a hydrological model.*** Thirdly, a hydrological model based on the FLEX-Topo modelling concept is created for the MMC. The model should provide insight into the rainfall-runoff mechanisms in the MMC and facilitate the evaluation of water management scenarios.

4. ***Evaluate scenarios.*** Lastly, scenarios are designed for changes in water demand, land cover and climate. These are evaluated based on their impact on hydrological regime and balance between water demand and supply at different sources.

1.4 Outline

Firstly, several relevant characteristics of the study area are described in Chapter 2. Subsequently, the subgoals correspond to the next chapters, with a description of water-related issues and potential solutions in Chapter 3, estimations of water use and demand in Chapter 4, a description of the FLEX-Topo model in Chapter 5 and descriptions and evaluations of the water management scenarios in Chapter 6. Lastly, conclusions are given in Chapter 7 and recommendations in Chapter 8.

2 | Study area

2.1 Introduction

In this chapter, the study area is briefly described. Included are location, topography, rivers and sub-basins, climate and land use.

2.2 Location

The MRB is a transboundary river basin located in Eastern Africa. It is part of the Nile River Basin (see Figure 2.1). The MRB lies between 33.93^{0}E, 35.87^{0}E, 0.38^{0}S and 1.92^{0}S and covers an area of 13490 km^{2}. It comprises 1.4% of the total area of Kenya, 0.56% of Tanzania and 0.44% of the Nile River Basin; 61% of the catchment is located in the Kenyan Rift Valley Province and the remaining 39% lies in the Tanzanian Mara Region. The lower administrative boundaries frequently changed over the past decades (see Figure 2.2). At Mara Bay in Tanzania, the Mara River drains into Lake Victoria, which is the second largest fresh-water lake in the world (Lehner & Döll, 2004). The MMC covers 84% of the MRB, which is an area of about 11273 km^{2}.

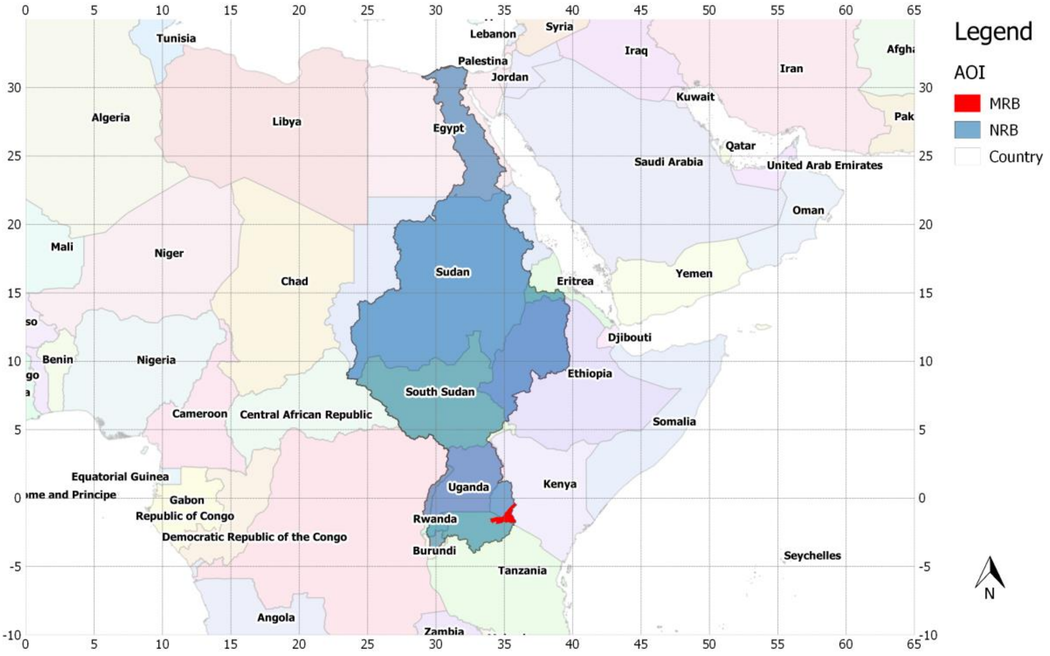


Figure 2.1 – Location of the MRB (United States Geological Survey [USGS], 2006) in the Nile River Basin (Lehner et al., 2008) and its surrounding countries (Global Administrative Areas, 2015)

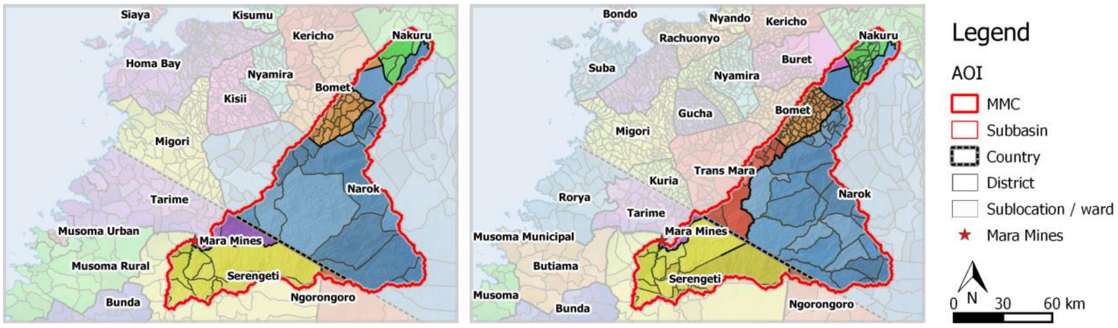


Figure 2.2 – Administrative boundaries in the MMC over the years; left: Kenyan districts and sublocations in 1989 (International Livestock Research Institute [ILRI], Famine Early Warning Systems & Tropical Soil Biological and Fertility Program, 2003) and Tanzanian districts and wards in 2002 (ILRI & National Census Bureau, 2006); right: Kenyan districts and sublocations in 1999 (Central Bureau of Statistics [CBS], 2001), and Tanzanian districts and wards in 2012 (National Bureau of Statistics [NBS], 2014)

2.3 Topography

For the delineation of the MRB and MMC, Shuttle Radar Topography Mission (SRTM) data (USGS, 2006) were used as Digital Elevation Model (DEM). This dataset consists of gridded elevation with a resolution of 3 arc-seconds, which is roughly 90 m around the equator. Altitudes in the MMC range from 3063 m in the northeast to 1185 m at Mara Mines; the surface of Lake Victoria has an elevation of 1135 m (see Figure 2.3). In the Kenyan share of the MMC, the mountainous region in the northeast is called the Mau Escarpment, the east is characterized by vast savannah plains bounded by the Loita and Sannia Hills and the west is bounded by the Soit Olooloo Escarpment (Mati et al., 2008). In Tanzania, the Mara River flows through the Serengeti plains before it reaches the Mara Swamp and subsequently Lake Victoria.

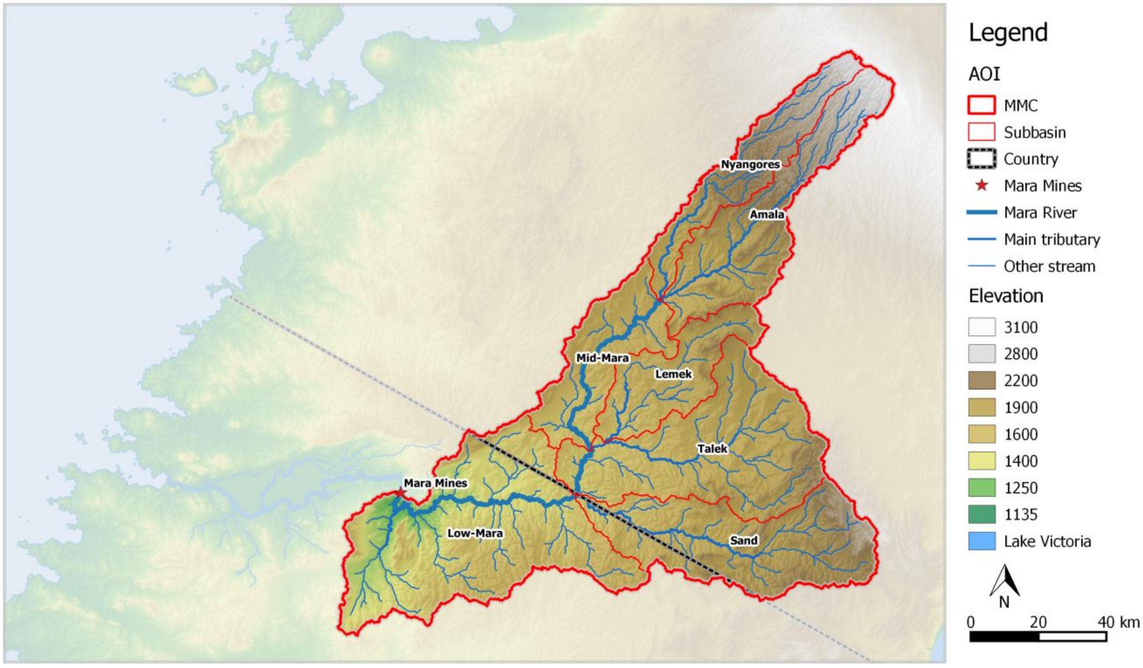


Figure 2.3 – Elevation and subbasins of the MMC (USGS, 2006)

2.4 Rivers and subbasins

Two perennial rivers, the Amala and Nyangores, originate in the Mau Escarpment. From their confluence point to Lake Victoria, the Mara River has a length of 288 km. Two other main tributaries are the intermittent Talek and Sand Rivers, which both originate in the Loita Hills. The Lemek, Olare Orok or Engare Ngobit River is a smaller tributary that originates in the Ilmotyookoit Ap Soyet ridges and joins the Talek just before it flows into the Mara River (Mati et al., 2008). Hence, seven subbasins are distinguished in the MMC (see Figure 2.3). Downstream of Mara Mines, relatively short tributaries drain the hills surrounding the Mara Swamp. The river discharge at Mara Mines is around 36 m^3/s on average but fluctuates strongly (see Figure 2.4). Most tributaries are ungauged (see Section 5.6 and Appendix H).

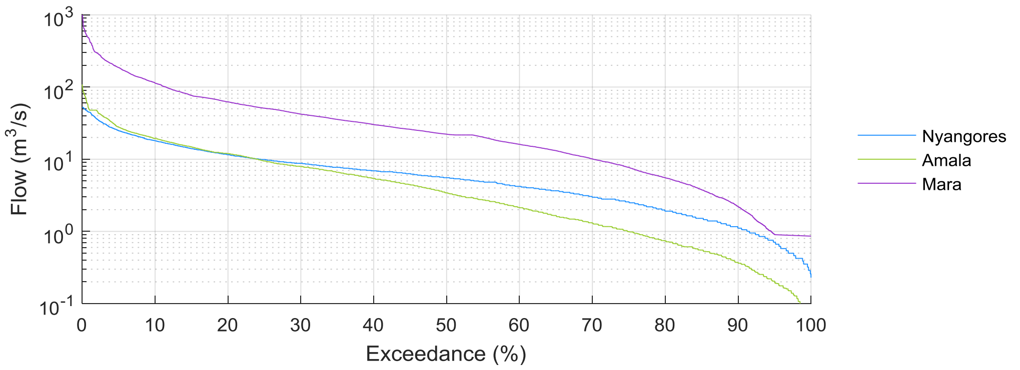


Figure 2.4 – Estimated flow duration curves of the Mara River at Mara Mines, the Nyangores River at Bomet Bridge and the Amala River at Kapkimolwa Bridge (Hulsman, 2016)

2.5 Climate

Due to the movement of the Inter-Tropical Convergence Zone, the MMC has a bimodal rainfall pattern. The "long rains" usually last from March to May and the "short rains" from November to December (see Figure 2.5). Rainfall also varies considerably from year to year and is very heterogeneous over the MMC, varying mainly with altitude. According to station data (see Section 5.6), annual rainfall ranges between 1300-1900 mm/yr in the north, 600-1000 mm/yr in the southeast and 800-1200 mm/yr in the southwest of the MMC. Temperature also varies with altitude (see Section 5.6): yearly averaged minimum, mean and maximum temperatures are 15°C, 21°C respectively 27°C in the Low-Mara subbasin and 8°C, 15°C respectively 23°C in the Nyangores and Amala subbasins. The average temperatures in June or July are 2 to 4°C lower than those in February or March. Snowfall does not occur in the MMC.

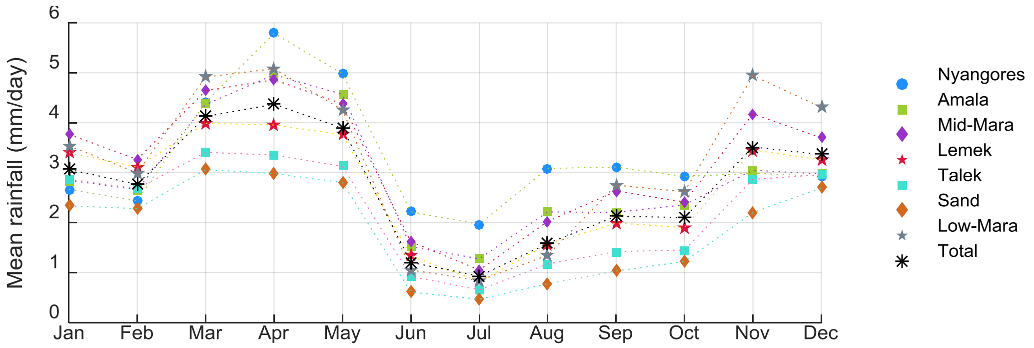


Figure 2.5 – Mean monthly rainfall in each subbasin of the MMC (Novella & Thiaw, 2013)

2.6 Land use

Small-scale agriculture is mainly found on the northern hillslopes and in the Tanzanian share of the MMC, large-scale agriculture along the Mara and Amala Rivers and pastoralism on the southeastern grasslands (see Section 5.3). Furthermore, around 43% of the MMC is designated as protected area (see Figure 2.6). The Mau Escarpment supports the Trans Mara, Southwestern Mau, Eastern Mau and Ol-Pusimoru Forest Reserves. Part of the Chepalungu Forest Reserve is also located in the MMC. Downstream, the MMNR and SNP were established on the vast grassland plains; their dispersal areas are protected in communal and private conservancies, Game Reserves and Wildlife Management Areas. The Serengeti ecosystem is world-renowned, mainly for the annual Great Migration of wildebeests, zebras and their predators. The SNP was accepted on the World Heritage List in 1981 (World Heritage Committee, 1981).

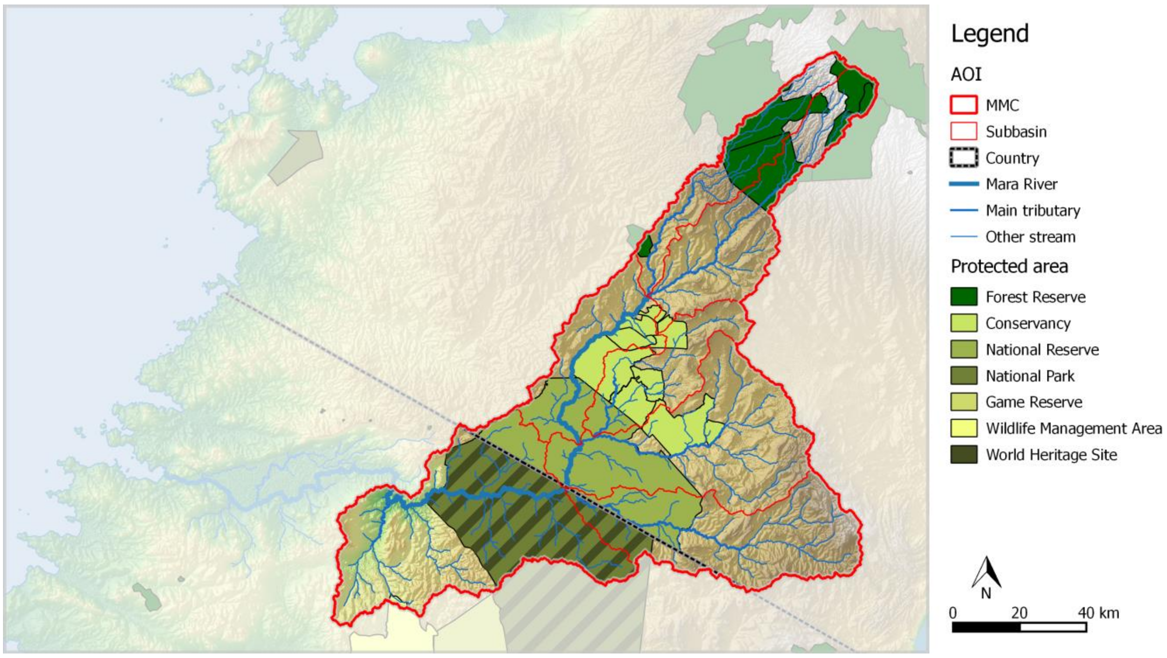


Figure 2.6 – Protected areas in the MMC (International Union for Conservation of Nature & United Nations Environment Programme's World Conservation Monitoring Centre, 2015)

3 | Problems and potential solutions

3.1 Introduction

In this chapter, a cursory analysis of water-related problems and solutions in the MMC is performed, to determine the relevance of the study and give suggestions for water management scenarios. Firstly, the main water users and their main representing institutions are identified (see also Appendix A). Subsequently, their wide ranges of livelihood issues are categorized using surveys and literature; problems related to water security are studied in more detail. Next, current water sources are classified and evaluated, resulting in lists of potential solutions. Lastly, ideal solutions proposed by stakeholders are summarized. The stakeholders' main limitations for the implementation of proposed solutions are listed in Appendix B.

3.2 Stakeholders

3.2.1 Identification

This thesis focusses on water use and demand in the Kenyan share of the MMC. The main water users and their representing institutions in this area are therefore identified. Stakeholder selection is based on literature review of previous stakeholders analyses (Community Based Impact Assessment Network For Eastern Africa [CIANEA], 2012; Krhoda, 2005; Lake Victoria Basin Commission [LVBC], 2013), water demand estimates (Dessu et al., 2014; Hoffman, 2007; Water Resources and Energy Management [WREM] International, 2008) and the institutional framework (see Appendix A). Class boundaries are refined using land use maps (see Subsection 5.3.1), field observations and survey results.

In the MMC, livelihoods are strongly related to location and ethnicity. Pastoralism is the principal livelihood of the Maasai people in the Talek, Sand and most of Lemek and Mid-Mara subbasins. Small-scale mixed farmers on the other hand are mainly found among the Kalenjin people in the Nyangores, Amala and north of Mid-Mara and Lemek subbasins, and the Wakurya people in the Low-Mara subbasin. Large-scale pastoral and crop farmers mainly live along the Amala and Mara Rivers; most are immigrants renting or leasing land on former group ranches. Hunters and gatherers, such as the Ogiek people, live in or near the Mau Forest. Most tourist accommodations are found in the protected areas.

Relevant institutions are for instance the Water Resources User Associations (WRUAs) and Water Resources Management Authority (WRMA; see Appendix A). Nature-related institutions were also contacted. The MMNR is managed by the County Councils of Narok and Trans Mara (2009); Mara conservancies manage the adjacent rangelands. Reports of other nature-related institutions, such as the Kenya Forest Service, Community Forest Associations, Kenya Wildlife Service, Tanzania National Parks and LVBC (CIANEA, 2012), were included in the literature study. Camp and lodge managers with over 10 years of experience in the MMNR were also consulted on wildlife issues.

3.2.2 Survey

Literature review was supplemented by face-to-face surveys with relevant stakeholders: 8 pastoralists, 11 small- and 4 large-scale farmers, one or more board members of 11 WRUAs, 10 tourist accommodation managers, 1 Narok County senior park warden and 2 conservancy managers were interviewed (see Figure 3.1). It was attempted to select unbiased samples and questions concerned entire communities. Questionnaires were designed per group of stakeholders, due to for instance differences in time availability, language barriers and relevance of specific questions. However, all respondents received the same introduction and all questionnaires were related to the same objectives and research goals:

- ***General characteristics.*** General stakeholder characteristics were required for classification, water use and demand calculations and scenario development. Sensitive questions and detailed questions on water use and demand were avoided during this stage of most interviews.

- ***Severity of water insecurity.*** The relevance of this thesis and recommended target areas depend inter alia on the severity and nature of water-related problems. Stakeholders were therefore asked general and open-ended questions on livelihood issues.

- ***Details of issues related to water security.*** Any issues related to water security were studied in more detail, including their effects, frequencies, durations and timings. Some stakeholders were also questioned about spatial differences, perceived causes and changes over time.

- ***Potential and ideal solutions.*** For scenario development, questions were asked about current, planned and ideal solutions for water scarcity, including perceived advantages and disadvantages of water sources. Stakeholders were also asked about their limitations (see Appendix B).

- ***Water use and demand.*** Additional details for water use and demand calculations were collected at the end of the interviews. Moreover, visits were paid to mentioned relevant features.

3.3 Problems

3.3.1 Agricultural areas

For small-scale farmers in the MMC, drought refers to unreliable and insufficient rainfall for optimal crop growth; some farmers also include low water availability for domestic and livestock use. These problems are usually experienced in January and February only. Higher yield losses occur roughly every four years. According to WRUA interviewees, the frequency of droughts has increased, rainfall patterns have become more variable, springs have dried up and fluctuations in river water levels have increased over the past three decades. Climate change is considered to be the main cause of the worsening situation, but sedimentation, increased population pressure, planting of eucalyptus trees and reduced infiltration in deforested areas are also mentioned. Deforestation is often listed as a problem as it is believed to cause local climate change.

The ranking of agricultural water scarcity varies by location. In the southeast of the Amala and north of Lemek subbasins, water scarcity is considered to be the main livelihood issue by all stakeholders. In the remaining agricultural areas, inhabitants rank maize diseases and reduced soil fertility higher than water insecurity. Similarly, WRUAs rank soil erosion first in the Nyangores and most of Amala subbasins, and human-wildlife conflict and low water quality in the Mid-Mara subbasin. However, these issues are all related to water security, for instance as human-wildlife conflict mainly occurs on the way towards water sources. Large-scale irrigation farmers are less affected by droughts; most state that they “do not have any problems” apart from relatively minor issues such as remoteness and theft.

3.3.2 Rangelands

For pastoralists in the Lemek and Talek subbasins, drought mainly refers to scarcity of pastures for livestock and water for domestic use. Water scarcity for livestock is considered to be less severe, as herds migrate anyway in search of pastures. Issues usually last the entire dry season and are especially severe at intervals of about four years. According to WRUAs, problems have worsened over the past three decades. The principal cause is assumed to be overgrazing, but low annual rainfall and restriction of access by camps are also mentioned. Drought is ranked first by all stakeholders. Livestock diseases and human-wildlife conflict are ranked second respectively third; the latter is the main reason for the small agricultural area. Other water-related issues are soil erosion, deforestation and floods.

For pastoralists in the Sand subbasin, drought refers to overall water scarcity for all users; scarcity of pastures is also included. For livestock and most inhabitants, the Sand River is the only water source during the entire dry season. During those six months, many pastoralists water their livestock on alternate days and women walk up to 20 km one way to a domestic water source. In the Sand subbasin, crop yields are low and unreliable, even during the wet season. Similar to the Talek subbasin, problems have perceivably worsened. All stakeholders in the Sand subbasin immediately rank water scarcity as their main livelihood issue. Other issues are similar to those in the Talek subbasin.

In the MMNR and conservancies, the populations of most wildlife species declined over the past three decades (see Subsection 4.6.1). Human encroachment is assumed to be the principal cause: both livestock populations and human settlements in and around the MMNR have increased substantially. Most interviewees believe that water sources for wildlife are still sufficient throughout most dry seasons, but concerns are expressed for the future. Other issues in the protected areas are poaching, inadequate wastewater treatment by camps, soil erosion due to overgrazing and off-road driving, human-wildlife conflict, scattered garbage and increased competition between tourist accommodations.

3.3.3 Overview

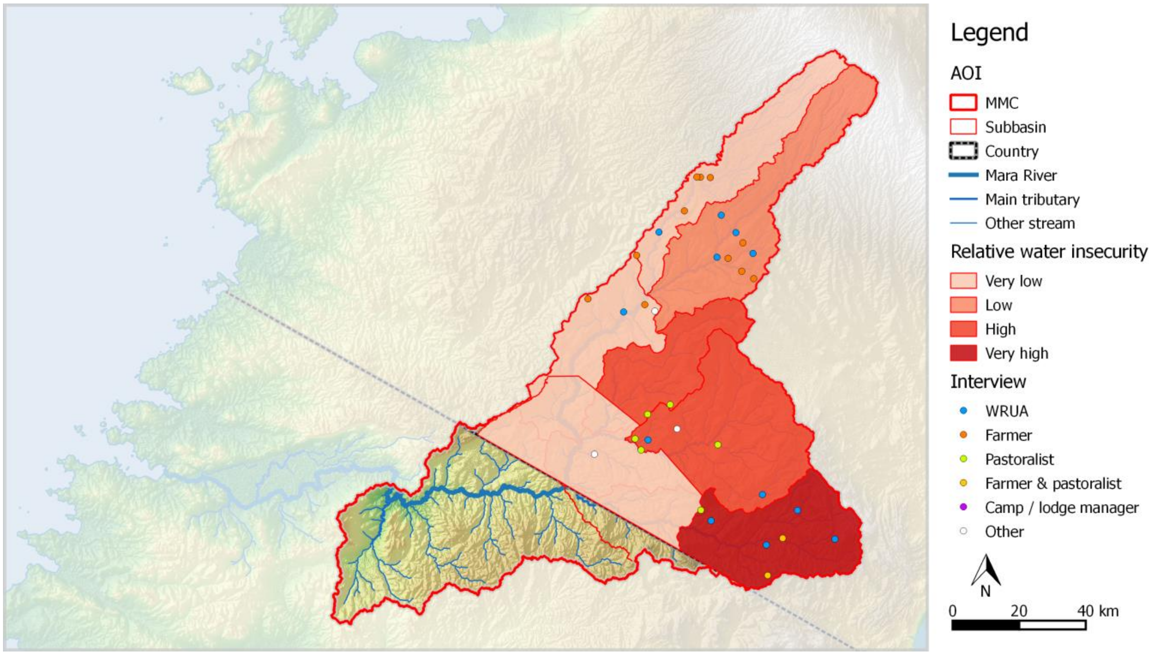


Figure 3.1 – Relative severity of water insecurity both between and within the MMNR and the subbasins of the Kenyan share of the MMC, including interview locations of the different stakeholders

“Drought” or water scarcity is ranked as the main livelihood issue throughout the Kenyan share of the MMC. For households, water scarcity results in long travelling and queuing times, diseases, human-wildlife and human-human conflict. For livestock, scarcity of water and pastures affects health and milk production. For rainfed agriculture, low and variable rainfall results in low and unreliable yields. Low water levels in rivers affect for instance fish populations. The severity of water scarcity differs considerably between subbasins (see Figure 3.1), corresponding roughly to the mean annual rainfall. Although measures related to water security could improve livelihoods throughout the entire MMC, the most recommended target area is the Sand subbasin.

3.4 Solutions

3.4.1 Water source classification

An inventory of available water source types in the MMC provides a first indication of potential solutions. For this thesis, classification is based on observations (see Appendix G), literature review (Johnston & McCartney, 2013; Keller et al., 2000; Studer & Liniger, 2013) and modelling considerations:

- ***Rooftop rainwater harvesting.*** Runoff from roofs may be collected in storage facilities such as tanks. Due to its prevalence in the MMC, rooftop rainwater harvesting is regarded separately from other water harvesting techniques.

- ***Ponds.*** All storages that collect water from overland flow only are classified as ponds, except for rooftop rainwater harvesting facilities. In the MMC, many pond types can be observed; most are located off-stream (see Subsubsection 5.5.2.2).

- ***Wetlands.*** Wetlands are defined here as sinks that collect both overland flow and groundwater flow. Hence, wetlands are off-stream sites where groundwater levels are close to the surface and saturation excess overland flow (SOF) may occur.

- ***Springs, shallow wells and boreholes.*** Groundwater, i.e. water stored in the saturated zone, may naturally emerge at the surface in springs, but may also be abstracted from aquifers with wells. Boreholes and shallow wells can be distinguished by their depth (see Table 3.1).

- ***Rivers.*** Water may be abstracted directly from rivers or other natural flowing watercourses that collect both surface and subsurface runoff. Included in this category are direct abstractions, but also inundations due to bank overtopping.

- ***Surface dams.*** Surface reservoirs are created by dams constructed across streams or rivers. A subdivision is made between large and small surface dams, with a threshold of 15 m for the dam height (International Commission on Large Dams, 2011).

- ***Sand dams.*** Sand dams are created by weirs constructed across rivers or streams, of which the reservoirs are filled by deposition of coarse sand. Subsurface dams, in which the entire barrier is located underground, are also grouped under sand dams in this thesis.

- ***Pipelines.*** Water from any of the above water source may be collected manually or supplied by pipelines. Due to the different advantages and disadvantages of piped systems and their influences on water use, piped systems are regarded separately.

- ***Root zone.*** Not only the amount of "blue" water, but also the storage in the unsaturated zone is an important water source that should be considered. Plants withdraw this "green" water from the root zone for transpiration.

Table 3.1 – Minimum, maximum and average depth of boreholes and shallow wells reported by Lilande (2016), including their standard deviation and sample size; these ranges correspond with observations and guidelines of the Ministry of Water and Irrigation (MWI, 2005)

Sources	d_{min} (m)	d_{max} (m)	$\bar{d}$ (m)	σ_s (m)	n (-)
Shallow wells	0	20	9	6	23
Boreholes	45	248	158	53	25

3.4.2 Water source comparison

The main selection criteria for water sources are derived from the surveys. Scores refer to the current situation for an entire source type. Although the main criteria differ per group of stakeholders, relative scores are similar. Domestic water use has the greatest requirements. Therefore, scores are assigned to the main selection criteria for domestic use (see Appendix D):

- ***Accessibility.*** Accessibility is expressed in estimated mean distance or collection time during the wet season.

- ***Reliability.*** Reliability is expressed in estimated average consistency of water level or discharge. Scores are therefore strongly related to sufficiency for intended uses throughout the year.

- ***Water quality.*** Water quality is expressed in average perceived suitability for different uses. Scores are for instance related to colour, smell, taste, caused diseases and education.

Especially for the construction of new water sources, costs are also considered to be very important by stakeholders. However, only qualitative and subjective indications of relative costs per unit water use are given (see Appendix D), as data are scarce and costs vary considerably between subbasins.

3.4.3 Potential solutions

The construction of additional water sources is by far the most frequently mentioned solution by all stakeholders for water insecurity. Other listed options for increased accessibility are rehabilitation, granting access to additional users, pipeline construction and transport by donkeys or motorcycles.

Furthermore, reliability may be enhanced by improved maintenance, enlarged storage sizes, reduction of losses or amelioration of the amount or timing of inflow. The most frequently mentioned options in this category are irrigation, protection of springs and their catchments, and prevention of forest degradation, reforestation or afforestation. For farms, a wide ranges of soil and water conservation practices is listed, such as agroforestry, contour bunding, conservation tillage, terracing, intercropping and planting drought resistant crops. Other mentioned options for enhanced reliability are replacing indigenous livestock by improved breeds, lining or covering sources, and constructing greenhouses.

Additionally, water quality may be improved. Water sources in the MMC are mainly polluted by sediment, fertilizers, pesticides, livestock, sewage, garbage and direct washing in sources. Most WRUAs propose erosion control as main solution, which may for instance be achieved by the construction of gabions, promotion of soil and water conservation, reforestation or river bank protection. Inhabitants on the other hand almost exclusively suggest boiling or filtration at household level. Other listed options are restring access for animals, reducing fertilizer and pesticide use, wastewater treatment and sanitation, constructing off-stream bathing places and car washes, education and abstracting water from scoop holes in streambeds instead of flows.

Moreover, mentioned solutions for other livelihood issues may impact water security. Erosion control for instance may improve the water quality and reliability of sources. Another example is land privatisation, which would probably reduce both livestock and wildlife numbers and increase the fraction of improved livestock breeds. The provision of alternative feed may have opposite effects. General solutions for poverty reduction, such as providing alternative livelihoods, may also improve water security, for instance by reducing deforestation and population growth. Lastly, adverse effects of water scarcity may be tackled, for instance by storage of harvests and improved health care.

3.4.4 Ideal solutions

Stakeholders facing water insecurity were asked to describe their ideal solution. The answer depended strongly on the water use:

- ***Inhabitants.*** For domestic use, boreholes are considered to be the ideal solution throughout the MMC, with rooftop rainwater harvesting, spring protection and pipelines as ideal alternatives. Desired are boreholes in every village and immediate repairs after breakdowns, sufficiently large rooftop rainwater harvesting tanks to last the entire dry season, and protection of both springs and their catchments. Piped systems would abstract water from rivers in the northern subbasins and springs in the pastoral areas.

- ***Livestock.*** For livestock, boreholes and large ponds are both considered to be ideal solutions throughout the MMC. If there would not be competition with domestic use, rooftop rainwater harvesting would be the ideal alternative. Private sources are desired in the northern subbasins and communal sources with a mutual distance of less than 2 km in the southeastern subbasins.

- ***Crops.*** For agriculture, most interviewees believe that irrigation is the only possible solution – if any. Motorized pumps and pipelines are desired. Direct abstractions from permanent rivers are deemed most suitable within 10 km from rivers. In other areas, preferred choices are large ponds, boreholes or dams in ephemeral streams. Sprinkler or furrow irrigation would be used in the north, whereas drip irrigation would be considered in drier areas.

- ***Wildlife.*** For wildlife, reduced competition with other water users and reforestation to reduce fluctuations in the Mara River flows are most often proposed as the ideal solution. Mentioned options for reduced competition are the regulation of livestock and human population numbers and the construction of sufficient alternative water sources for these users.

4 | Water use and demand

4.1 Introduction

This chapter aims to estimate the water use and demand in the MMC. Inhabitants, livestock, crops, tourists and wildlife are generally considered to be the main water users in the MMC (see Subsection 3.2). For this thesis, environmental flow requirements (EFRs) are also regarded as a water demand and other water users are briefly studied (see also Appendix E). Distinction is made between subbasins, water sources, modelling years and months. This requires refinements of calculations in previous studies, such as those of Dessu et al. (2014), Hoffman (2007), Lilande (2016) and WREM International (2008). Interviews (see Subsection 3.2.2), census data and guidelines are used for this purpose.

4.2 Inhabitants

4.2.1 Human population counts

In Kenya, the Kenya National Bureau of Statistics (KNBS), formerly CBS, carries out a decennial population and housing census (PHC) since 1969. For the relevant years, population counts are available at sublocation level (CBS, 1994a; KNBS, 2000a/2010a). The sublocation boundaries are available for 1989 and 1999 (see Figure 2.2). Where likely alterations could not be determined, the population data of 2009 are corrected according to reported area changes. Furthermore, Lilande (2016) created a list of water sources and their coordinates for the Kenyan share of the MMC, using questionnaires to estimate the amount of households served by each source.

In Tanzania, PHCs were carried out by the NBS in 1967, 1978, 1988, 2002 and 2012. For 2002 (ILRI & NBS, 2006) and 2012 (NBS & Office of Chief Government Statistician [OCGS], 2013a), population counts were provided at ward level. For 1988, data is only available at district level (Bureau of Statistics, 1988; NBS & Ministry of Planning, Economy and Empowerment [MPEE], 2006). The ward and district boundaries are available for 2002 and 2012 (see Figure 2.2). For 1989, it is assumed that either the relevant district boundaries did not change, or that any changes were accounted for in the analytical report of the 2002 PHC (NBS & MPEE, 2006).

As the administrative boundaries of both countries do not correspond with the subbasin boundaries, assumptions have to be made regarding the density distributions within each administrative unit. A uniform population density is assumed for each ward or sublocation, and a uniform growth rate for the Tanzanian districts between 1988 and 2002, with two exceptions:

- ***Protected areas.*** Satellite images (Google, n.d.) and observations suggest that human populations in the MMNR, SNP and forest reserves are insignificant compared to the populations in the remaining areas of each sublocation. This assumption is not deemed applicable to the conservancies and the Ikona Wildlife Management Area, as habitation is permitted and settlements are encountered in these areas (WREM International, 2008; Google, n.d.).

- ***Urban centres.*** Populations of urban centres are enumerated separately during the PHCs of both countries (CBS, 1994b; KNBS, 2000a/2010a; Brinkhof, 2014), although applied population thresholds are inconsistent both within and between PHCs. Settlements are mapped by ILRI (2000) for Kenya and by Brinkhof for Tanzania. The five settlements in the relevant sublocations and wards are regarded as points in the calculations.

Population densities are highest in the agricultural areas, especially in the northern subbasins (Table 4.1). Inter- and extrapolation are performed using mean annual population growths. Lilande's (2016) count only amounts to 24% of the expected figure for the Kenyan share of the MMC according to the PHCs. As the count is probably not inclusive for inhabitants, it is not used in further calculations.

Table 4.1 – Human population and mean household size per subbasin in 1989, 1999 and 2009 and mean annual population growth during both intervals (CBS, 1994a; ILRI & NBS, 2006; KNBS, 2000a/2010a; NBS & MPEE, 2006; NBS & OCGS, 2013a)

	Population			**Mean household size**			**Mean annual population growth (%)**	
	1989	**1999**	**2009**	**1989**	**1999**	**2009**	**1989-1999**	**1999-2009**
Nyangores	93290	139154	200753	5.7	5.1	5.0	4.1	3.7
Amala	127254	186903	251217	5.4	5.2	5.2	3.9	3.0
Mid-Mara	28774	42448	61050	5.9	5.1	5.4	4.0	3.7
Lemek	6205	9295	14303	5.3	4.6	4.7	4.1	4.4
Talek	12465	17552	27830	4.6	4.5	4.9	3.5	4.7
Sand	11934	19396	30755	4.5	4.6	5.9	5.0	4.7
Low-Mara	63574	87623	121774	5.7	5.7	6.0	3.3	3.3
Total	**343496**	**502371**	**707682**	**5.5**	**5.2**	**5.3**	**3.9**	**3.5**

4.2.2 Water use and demand per capita

Mean daily water use per capita strongly depends on the accessibility of the source (Howard & Bartram, 2003; Katui-Katua, 2004; MWI, 2005). The World Health Organization (WHO) estimated likely domestic use at different service levels (see Table 4.2). The MWI (2005) and WRMA (2009) established guidelines specifically for Kenya (see Table 4.3). Classification of the MMC is based on observations, interviews and census data on water sources (see Subsection 4.2.3). All sublocations and wards but one are rural (NBS & OCGS, 2013a; NBS & Mara Regional Commissioner's Office [MRCO], 2003; KNBS, 2010a), but there are urban centres with piped supply. Based on the guidelines, the mean domestic water use in these towns would be 50 L/(capita · d). For rural areas, a distinction is made between agricultural and pastoral households, with 20 L/(capita · d) respectively 5-15 L/(capita · d).

The guidelines are compared with samples. For piped connections, aggregated supply records and served populations in secondary data sources do not seem accurate, as results range up to three orders of magnitude for the same systems (Bomet District Water Office, 2009; Bomet Water Company, 2014b; WREM International, 2008). Actual records for eight months are however obtained from Bomet Water Company (2014a), which operated ten metered supply systems in Bomet district in 2014. Mean daily use was 44 L/(capita · d), with σ_s = 13 L/(capita · d); the high standard deviation is partly due to frequent breakdowns. For unpiped dwellings, a small sample was drawn using interviews in the Kenyan share of the MMC. Results for farmers ($\bar{x}$ = 21 L/(capita · d), σ_s = 5 L/(capita · d), n = 7) and pastoralists ($\bar{x}$ = 6 L/(capita · d), σ_s = L/(capita · d), n = 13) differ with a confidence level of 99.99% in a *t*-test. The sample results correspond with the guidelines and are used for the calculations.

Table 4.2 – Mean water collection in L/(capita · d) for domestic purposes at different service levels according to the WHO; reliability and costs are also considered of influence but to a lesser extent (Howard & Bartram, 2003)

Service level	Access measure		Average quantity collected (L/(capita · d))	Level of health concern
	Distance (m)	Total collection time (min)		
No access	> 1000	> 30	< 5	Very high
Basic access	100 – 1000	5 – 30	< 20	High
Intermediate access	< 100	< 5	50	Low
Optimal access	Multiple taps in house continuously		> 100	Very low

Table 4.3 – Mean water collection in L/(capita · d) for domestic purposes at different service levels in Kenya according to the MWI and WRMA; the "potential" in rural areas depends on the mean annual rainfall and the "housing class" depends on the amenities available (MWI, 2005; WRMA, 2009)

With/without individual connections	Rural areas: potential			Urban areas: housing class		
	High	Medium	Low	High	Medium	Low
With	60	50	40	250	150	75
Without	20	15	10	-	-	20

Throughout the MMC, domestic demand is higher than use (see Section 3.3). According to the WHO, a minimum use of 20 L/(capita · d) is needed for basic health protection; the WRMA (2009) prescribes 25 L/(capita · d) (Dessu et al., 2014; LVBC & WWF-Eastern Southern African Regional Programme [ESARPO], 2010). An increase from no access to basic access would result in substantial health gains (see Table 4.2) and an increase in overall welfare. By rural inhabitants, a further increase to intermediate access is desired, but optimal access is neither deemed necessary nor realistic. Optimal access may however be reached in the urban areas during the coming decades.

4.2.3 Water sources

The KNBS and Society for International Development (KNBS & SID, 2013) surveyed the main water sources of households in Kenyan sublocations (see Table 4.4). For the model, the amount of classes is reduced, roofwater harvesting is regarded separately and distinction is made between agricultural and pastoral households. For the Low-Mara subbasin, averages of the MMC are used. Additional assumptions are made based on field observations and interviews:

- ***Rooftop rainwater harvesting.*** It is assumed that each household with a corrugated iron sheet or similar roof collects rainwater (see Table 4.4). Other roofs in the MMC are made of grass or a combination of mud and dung, which makes water hard to collect and deemed of insufficient quality for any use. Sharing with neighbours is not taken into account.

- ***Piped supply.*** For the agricultural areas, it is assumed that all piped supply is obtained from rivers (Bomet District Water Office, 2009). In the pastoral areas on the other hand, the contributions of boreholes and springs are roughly equally important (WREM International, 2008).

- ***Seasonality.*** The main water sources of households vary by seasons (WREM International, 2008), as for instance spring discharges may decrease and shallow wells and ponds may dry up during the driest months. The seasonality is accounted for in the modelling, assuming that the proportions in Table 4.4 are representative for the wet season only.

- ***Alternatives.*** Harvested rainwater is assumed to be the first choice for household use. Furthermore, it is assumed that springs are preferred over the river and that boreholes or other piped systems are not available as alternative.

Table 4.4 – Percentage of the population according to their main source of domestic water (KNBS & SID, 2013), and estimated percentage of the households applying rooftop rainwater harvesting as supplementary water source, based on their main roofing material (KNBS & SID, 2013)

Subbasin	Population according to main domestic water source (%)						Households with rooftop rainwater harvesting (%)
	River	Spring	Pond	Shallow well	Borehole	Piped	
Nyangores	47	16	14	10	7	6	67
Amala	51	24	9	8	6	2	62
Mid-Mara	31	6	53	6	3	1	26
Lemek	44	32	9	3	5	7	49
Talek	47	10	15	5	11	12	34
Sand	39	27	9	12	7	6	22
Total	**47**	**19**	**16**	**8**	**6**	**4**	**56**

4.2.4 Uncertainty

In the estimated water use by inhabitants, most uncertainty is found in the per capita water use. This is mainly due to the variation between and within each subbasin and the small sample size. Furthermore, uncertainty in population counts and water sources is mainly caused by the misalignment of administrative and subbasin boundaries. Miscounts are also expected in areas predominantly populated by Maasai people, due to superstitions, mistrust and seasonal migration. The water source partitioning on the other hand is most uncertain in the Tanzanian share of the MMC. For future projections, most uncertainty is found in the availability of sources, which influences both the water use per capita and the partitioning between sources. Although mean population growth rates in most subbasins remained fairly constant over the considered intervals, these might change in the future.

4.3 Livestock

4.3.1 Livestock population counts

Many data sources are used to estimate the livestock populations in the MMC (see Table 4.5). Most Kenyan data are available at district level. Due to frequent constitutional changes, district boundaries of 1991 to 1993 and 2007 are uncertain; only for cattle in 1992 and 1993, data from the District Livestock Production Offices (DLPOs) could be reconstructed. Most Tanzanian data on the other hand are only available at regional level. A uniform livestock population density is assumed for each administrative area, with three additional assumptions:

- ***Protected areas.*** Aerial survey data (Ogutu et al., 2011) and observations suggest that livestock populations in the MMNR, SNP and forest reserves are insignificant compared to the populations in the remaining portions of each distinguished area, although pastoralists allegedly enter the MMNR at night. The assumption is not deemed applicable to the conservancies and the Ikona Wildlife Management Area, as livestock grazing is permitted and large herds are encountered in these areas (Ogutu et al., 2011; WREM International, 2008).

- ***Aerial surveys.*** The aerial surveys of the Department of Resource Surveys and Remote Sensing (DRSRS) have insufficient spatial coverage in the Nyangores, Amala, Mid-Mara and Low-Mara subbasins (see Subsection 4.6.1). 8% of the Lemek, 6% of the Talek, and 16% of the Sand subbasin areas are also uncovered, but livestock population densities in these areas are assumed equal to those in the outer ranches.

- ***Ngorongoro district.*** Listed data sources for Tanzanian livestock populations cover Mara Region only. Less than 1% of the MMC is located in Ngorongoro district in Arusha Region; this share is assumed to be insignificant.

Table 4.5 – Summary of data sources for the livestock population in the MMC, including their – sometimes national – data collection occasions, applied spatial boundaries and corresponding maps, livestock data collection years and methods, and amounts of distinguished livestock categories

Data source	Occasion	Spatial boundaries	Years	Data collection method	Species/ breeds
KNBS (2010c)	PHC	Kenya: districts (KNBS, 2010c)	2009	Questionnaires	9
KNBS (2006)	Kenya Integrated Household Budget Survey (KIHBS)	Kenya: districts (CBS, 2001)	2005/2006	Questionnaires	7
WREM International (2008); Hoffman (2007)	Studies by the DLPOs	Kenya: districts (CBS, 2001)	1991-1995, 2002-2007	Unspecified, possibly vaccination programs	≤ 21
Lilande (2016)	Water source inventory	Kenya, MMC: points (Lilande, 2016)	2015	Questionnaires	3
Ogutu et al. (2011)	Studies by the DRSRS	Kenya, MMC: protected areas, survey grid (Ogutu et al., 2011)	1970s-2000s	Aerial survey	3
NBS & MRCO (2003), NBS & OCGS (2007/2012)	National Sample Censuses of Agriculture (NSCAs)	Tanzania: districts (ILRI & NBS, 2006; NBS & OCGS, 2012)	1994, 2003, 2008	Questionnaires	5, 10, 13
Ministry of Agriculture and Food Security (MAFS, n.d.), NBS & MRCO (2003), NBS & OCGS (2007)	District Integrated Agricultural Survey (DIAS)	Tanzania: regions (ILRI & NBS, 2006)	1998/1999	Unspecified	5
NBS & MRCO (2003)	Livestock Census (LC)	Tanzania: regions (ILRI & NBS, 2006)	1984	Unspecified	3
MAFS (n.d.)	Unspecified	Tanzania: regions (ILRI & NBS, 2006)	1993-2005	Unspecified	3

Based on daily water use per subbasin of different livestock types, only cattle and shoats are included in the calculations. Water use by donkeys may be significant in the southeastern subbasins according to DLPOs (Hoffman, 2007), but the results of all other data sources are an order of magnitude smaller. Other excluded livestock categories are beehives, chickens, various other poultry species and breeds, camels, pigs, horses, fish farms, rabbits, guinea pigs, dogs and "other" livestock. Distinction is made between indigenous and "improved" cattle. As common in pastoral Africa (King, 1983), most cattle in the MMC are of indigenous breeds of the zebu (*Bos indicus*) subspecies, but improved cattle are also found (Nyariki et al., 2009; Onjala, 2004), especially on large-scale farms. As these are excluded from the NSCAs (NBS & OCGS, 2007/2012), the average improved fraction of the Kenyan share is used for the Low-Mara subbasin.

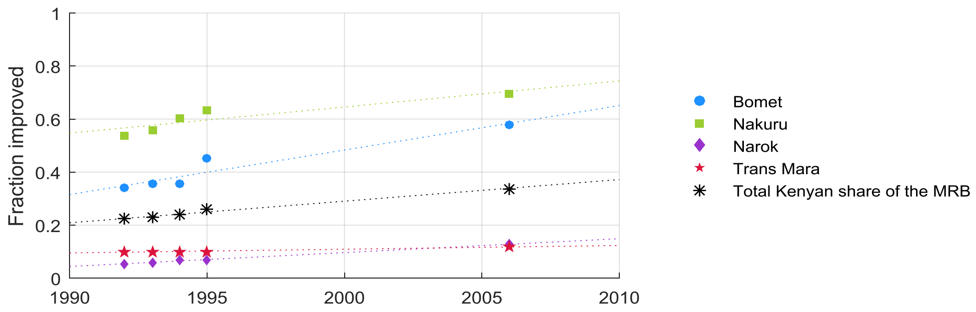


Figure 4.1 – Fraction of improved cattle breeds in the total Kenyan share of the MMC and in the districts comprising this share, including their linear regression lines (Hoffman, 2007; WREM International, 2008)

For regression analysis (see Figure 4.2), omitted data sources are the water source inventory, as it includes only few water sources for livestock (Lilande, 2016); the PHC for cattle in Narok South district, because of cultural and political stances of the Maasai population (KNBS, 2010c); and the LC, as its data was collected during a major drought (NBS & MRCO, 2003). Cattle populations are constant in most subbasins but decline in the Nyangores and Amala. For shoat populations in the Kenyan share of the MMC, there are no significant trends in the southeast until 1993, after which populations in all subbasins started increasing rapidly. Shoats populations in the Tanzanian share of the MMC seem to increase more gradually. In the model calculations, means are used for intervals without significant trends and linear or exponential regression for remaining years. Regression coefficients are determined by the method of least squares.

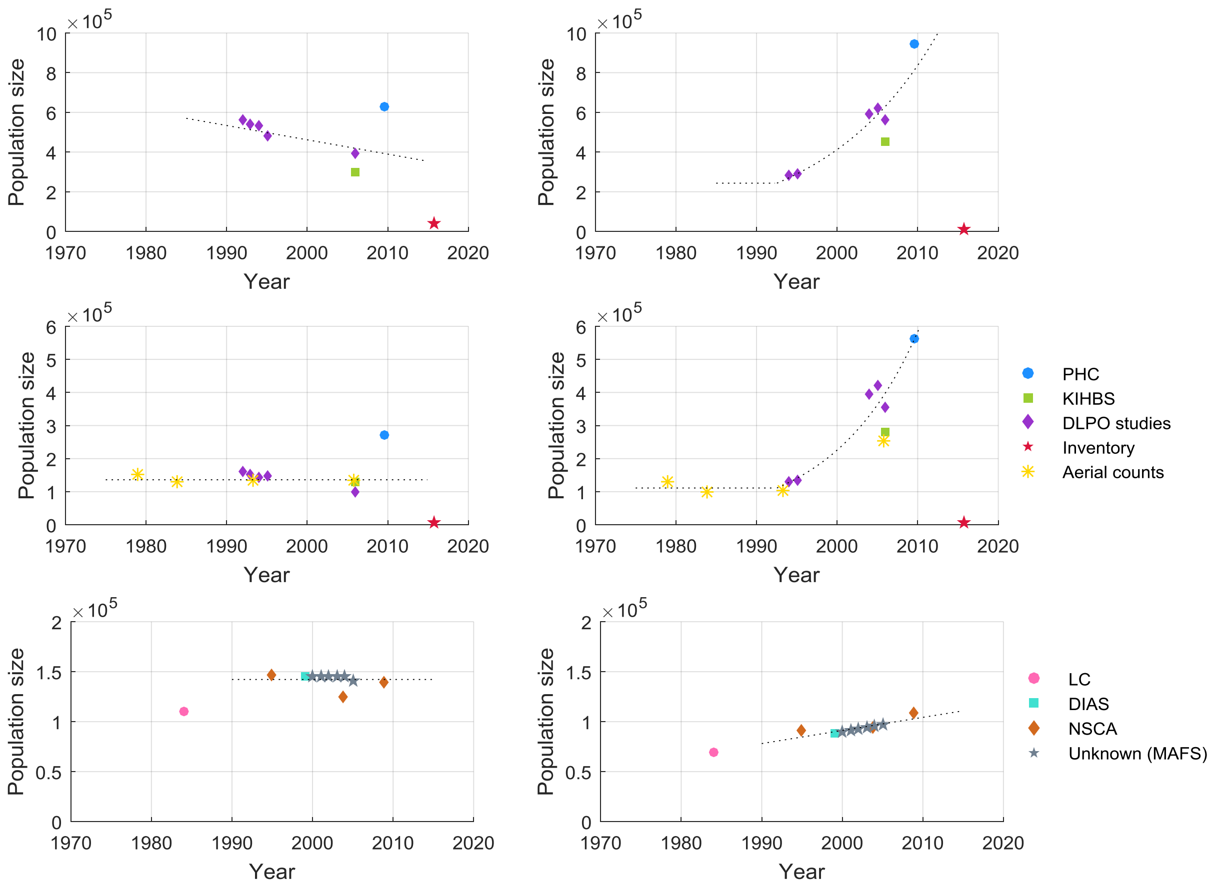


Figure 4.2 – Cattle (left) and shoat (right) populations in the MMC by all available data sources (see Table 4.5), including regression lines; data are aggregated the total Kenyan share of the MMC (top), subbasins in the Kenyan share for which sufficient aerial survey data is available (middle), and the total Tanzanian share of the MMC (down)

4.3.2 Water use and demand per animal

In general, livestock drinking water use is low compared to water use for their feed (Mekonnen & Hoekstra, 2012). However, only drinking water is considered in this subsection as pastures are already included in the hydrological model (see Subsubsection 5.4.1.2). Mean daily drinking water use per animal depends on species and breed, size and environmental circumstances (King, 1983). Guidelines should therefore apply to the conditions in the MMC. King provides mean water uses and "practical guidelines for development" for livestock on African pastoral lands. The Food and Agriculture Organization of the Unites Nations (FAO) also provides guidelines for livestock water use in its design manual on small earth dams on dry African pastures (Stephens, 2010). Lastly, the MWI (2005) and the WRMA (2009) list the water use of prevalent livestock categories for Kenya (see Table 4.6).

Table 4.6 – Water use for mature livestock of different types according to literature and interviews in L/(animal · d) (Stephens, 2010; King, 1983; WRMA, 2009; MWI, 2005)

Water use (L/(animal · d))		King (1983)		Stephens (2010)	MWI (2005), WRMA (2009)
		Mean	Design		
Cattle	**Improved**	-	-	40-80	50
	Indigenous	16.4	25	-	17
Shoat	**Goat**	2.0	5.0	3-8	3.3
	Sheep	1.9	5.0	2-6	

The guideline values are compared with samples. Most interviewees expressed the daily water use per animal in the amount or portion of 20 L containers. As one shoat uses only a small fraction, the results for shoats ($\overline{x}$ = 4.5 L/d, σ_s = 1.4 L/d, n = 13) probably have a positive systematic error. The figure from the MWI (2005) is therefore applied for shoats. The estimates for cattle (improved: $\bar{x}$ = 55 L/d, σ_s = 15 L/d, n = 6; indigenous: $\bar{x}$ = 17 L/d, σ_s = 4 L/d, n = 14) correspond with the guidelines and are used for the calculations. According to the interviewees, the actual water use does not always equals demand. For optimal supply, the practical guidelines for development provided by King (1983) are used for indigenous cattle and shoats, and the upper limit by Stephens (2010) for improved cattle.

4.3.3 Water sources

According to interviewees, only the weakest animals drink from rooftop rainwater harvesting tanks or shallow wells; their water use is assumed to be insignificant. Boreholes are only used for livestock in the agricultural areas of the MMC during the driest months; the fraction of households with access to boreholes (see Subsection 4.2.3) is used as upper limit. Springs and ponds are also used by livestock, but some are protected to prevent trampling or pollution of the source and domestic water use usually has priority. Access to rivers is usually not limited. Assuming uniform density distributions and use of the nearest available source, Voronoi diagrams of potential sources can be used to estimate the partitioning between sources. As some sources are seasonal, the results vary over the year.

4.3.4 Uncertainty

In the estimated water use by livestock, most uncertainty is found in the population counts. Areas used for data aggregation do not correspond with the subbasin boundaries, differ per source and year and are large compared to the subbasin areas. Furthermore, methods for data collection are unspecified or unreliable: aerial counts are for instance affected by limited visibility of livestock (Ogutu et al., 2011), inventories may be incomplete and questionnaire responses are affected by superstitions and mistrust.

The timings of the counts may also affect the results due to seasonal migration and fluctuations over the years, which are for instance caused by recurrent droughts or disease epidemics (Mati et al., 2008; Nyariki et al., 2009; Onjala, 2004).

However, as clear trends in the population numbers are visible when the most unreliable data sources are omitted, the uncertainty in water use per animal and partitioning between sources may be equally important. The water use per animal may differ considerably between individuals, locations and seasons (King, 1983), but the sample sizes are small and samples are biased. Moreover, data on water sources for livestock in the MMC is scarce. For future projections, most uncertainty remains however found in the population numbers, as different types of curves may be fitted through the data and population growth may be limited by the carrying capacity of the land. Water use per animal may also increase due to the increased use of improved species or increased water availability, which is closely related to the partitioning between sources.

4.4 Crops

4.4.1 Areas under irrigation

Large-scale irrigation in the MMC (see Figure 4.3) was included in at least five inventories. According to Hoffman (2007), 660 ha were under pivot and 30 ha under floppy irrigation in 2007, spread over four farms in the Mid-Mara and Amala subbasins. Dessu et al. (2014) reported an expansion to around 1000 ha due to the establishment of Malasa Farm. Lilande (2016) and the Japan International Cooperation Agency (1992/2013) also listed irrigated areas in the MMC, but their results are internally inconsistent respectively incomplete. Individual mentions of the farms are scarce. Irrigation started at least in 1984 in the MMC (Sigei, 2014) and in 2000 at Olerai Mara Farm (Wachira, 2012). Of the latter, 156 ha has been currently converted to tourism (Jimmy Naritoi, personal communication, 4 October 2014). Planned irrigation projects include 2350 ha in the Nyangores subbasin, 2500 ha in the Amala subbasin and 28340 ha just downstream of Mara Mines.

For the 1980s and 1990s, data on large-scale irrigation is derived from satellite images obtained by the Landsat Thematic Mapper (TM; National Aeronautics and Space Administration [NASA] Landsat Program, 2016). Maps of the Normalized Difference Vegetation Index (NDVI) are derived and analysed together with "natural colour" and thermal infrared images. The results in 2007 and 2012 correspond with the data of Hoffman (2007) respectively Dessu et al. (2014). No evidence is found of large-scale irrigation in the MMC outside the listed farms. Irrigation did not yet take place at Shimo Farm during the 1980s and early 1990s. For Ndakaini and Lemontoi Farms, definitive conclusions cannot be drawn due to limited data quality and coverage.

For small-scale irrigation, data in Tanzania were collected at district level during the NSCAs (NBS & OCGS, 2007/2012). About 1.8% of the households in the Tanzanian share of the MMC applied small-scale irrigation, which had increased to 2.1% by 2007. The mean irrigated area per household was around 0.65 ha. In Kenya, data on irrigation by households were collected during the KIHBS in 2005/2006 (KNBS, 2006). However, no distinction was made between small- and large-scale irrigation, which probably leads to overestimations for the MMC. Combining the Tanzanian figures with Tanzanian and Kenyan population data (see Subsection 4.2.1), the small-scale irrigated area in 2005/2006 would be $1.5 \cdot 10^3$ ha.

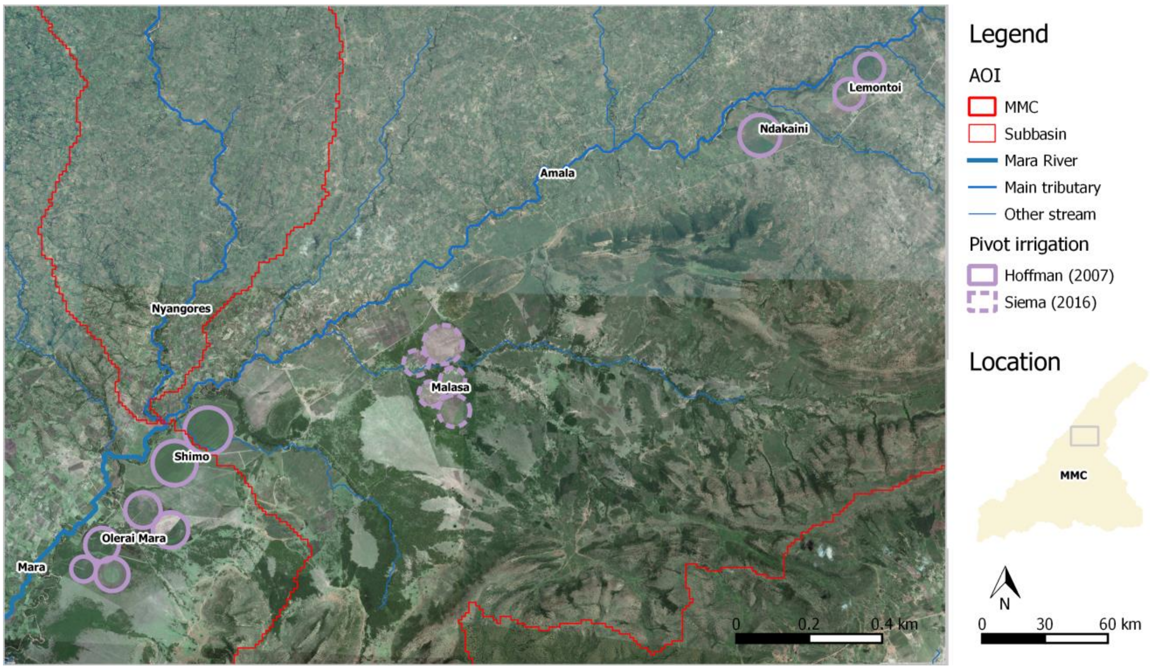


Figure 4.3 – Pivot locations of large-scale irrigation farms in the Kenyan share of the MMC (Google, n.d.) according to Hoffman (2007; solid line); the additional pivot locations at Malasa Farm are listed by Lilande (2016; dashed line)

4.4.2 Water use and demand per area

Irrigation water demand depends on climate, soil type, crop, growing calendar, watering strategy and irrigation technology. Measurements or estimations of irrigation water use in the MMC are however scarce. It is assumed that the meteorological input, model structure and parameter values of the agricultural hydrological response unit (HRU) of the model are representative for all irrigated areas in the MMC (see Subsubsection 5.4.2.5). Water use is then calculated by the model. Information on other required factors is mainly obtained by interviews with WRUA members and farmers:

- ***Crops.*** The large-scale farms mainly grow cereals, such as maize, wheat and barley, although French beans are also cultivated; small-scale irrigation is mainly limited to vegetable fields, with tomatoes and cabbage as representative crops (Dessu et al., 2014; Onjala, 2004; Lilande, 2016; Wachira, 2012; WREM International, 2008).

- ***Growing calendar.*** As the northwestern subbasins are relatively wet, cultivation here is usually year-round, even at rainfed farms. In the drier and predominantly pastoral subbasins, irrigation outside the growing season is negligible; planting usually occurs in January or February and harvesting in July or August.

- ***Irrigation method.*** At the large-scale irrigated farms, water is abstracted by motorized pumps (Hoffman, 2007) and conveyed through pipes – which are in good condition (Lilande, 2016) – to large storage pans; overhead irrigation is applied (Hoffman, 2007; Dessu et al., 2014). The irrigators mainly use hand buckets or watering cans (NBS & OCGS, 2007/2012).

- ***Irrigation strategy.*** At the large-scale irrigated farms, any moisture-stress is avoided during all seasons; it is assumed that their water use equals demand, Small-scale subsistence farming in the MMC is essentially rainfed (Hoffman, 2007; WREM International, 2008): irrigation is only applied to stabilize or improve yields when rains fail and the applied amounts are limited due to the labour-intensive irrigation method and water availability.

4.4.3 Water sources

According to Hoffman (2007) and Lilande (2016), all large-scale farms in the MMC abstract their irrigation water from the rivers, with storage in on-farm ponds. In the Tanzanian share, 42% of the small-scale irrigating households obtained their irrigation water from rivers, 40% applied boreholes or wells and 19% used ponds (NBS & OCGS, 2007/2012). The division between shallow wells and boreholes is assumed to be the same as for household water. For Kenya, WRUAs and small-scale farmers report that irrigation water sources are the same as those for domestic use, except for rooftop rainwater harvesting. However, domestic and livestock use receive priority over small-scale irrigation and the fraction of water use from rivers is assumed to be higher.

4.4.4 Uncertainty

In the estimated water use by large-scale irrigation, most uncertainty is found in the water use per area. As data on the actual use are unavailable or unreliable, calculations are based on assumptions derived from few interviews and observations. For large-scale irrigation, consistent data are however available on current areas, locations and water sources. For small-scale irrigation, these data only cover the Tanzanian share of the river basin, where the areas used for data aggregation are large compared to the subbasin areas. For future projections and reconstructions of past water use, most uncertainty for both types of irrigation is found in the irrigated areas, as data on past or planned irrigation projects are scarce but suggest large increases in irrigated areas.

4.5 Tourists

4.5.1 Tourist population counts

Two inventories of tourist accommodations in the MMC were recently taken (see Table 4.7). The coordinates of the camps and lodges listed by Hoffman (2007) are derived from various maps (Google, n.d.; Hoffman, 2007; “Hotels in the Mara,” 2015; “Major abstractors in the Mara River Basin,” 2015; Watson & Watson, 2013). Lilande (2016) included locations in her inventory of water sources; as some accommodations abstract water from multiple sources, duplicates were removed. According to Hoffman, there were no camps or lodges in the Tanzanian share of the MMC. Indeed, neither focal areas of interest nor official accommodations in the SNP were located in the MMC (WREM International, 2008) and high season visitor densities in the SNP are 17 times lower than in the MMNR (County Councils of Narok & Trans Mara, 2010).

Table 4.7 – Amounts of accommodations and beds in the subbasins of the MMC (Hoffman, 2007; Lilande, 2016)

	Hoffman (2007)		Lilande (2016)	
	Accommodations	**Beds**	**Accommodations**	**Beds**
Amala	0	0	1	21
Mid-Mara	21	992	40	1396
Lemek	8	118	14	237
Talek	25	991	45	1666
Sand	11	657	19	950
Total	**65**	**2758**	**119**	**4372**

Walpole (2003) collected data on bed occupancy rates (BORs) from tourist accommodations in and around the MMNR between 1997 and 2000. The bimodal rainfall pattern, annual Great Migration and main holiday periods of visitors result in varying mean monthly BORs throughout the year. However, seasonal variations in MMNR visitor numbers are even greater (see Figure 4.4) due to the closing of many small-scale facilities in the low season. Therefore, the mean monthly BORs from January to June are corrected with the normalized visitor numbers of 2005 and 2007 (WREM International, 2008).

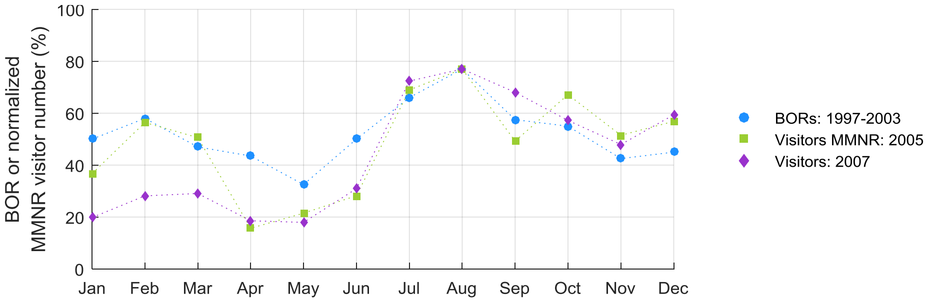


Figure 4.4 – Mean monthly BORs in accommodations in and around the MMNR from 1997 to 2000 (Walpole, 2003) and normalized monthly MMNR visitor numbers in 2005 and 2007 (WREM International, 2008)

Visitor numbers are subject to many factors, such as political instability, terrorism and competition with other destinations (Fletcher & Morakabati, 2008; Laing, 2013; Walpole, 2003). Trends for the MMC are derived from Economic Surveys and Statistical Abstracts (see Figure 4.5). All inventoried accommodations are located in the zone "Maasailand". It is assumed that the mean BOR of Maasailand in 2007 is representative for the MMC; monthly BORs are scaled accordingly. For all other modelling years, normalized occupied bed nights in Maasailand are used for additional scaling, with 2007 as base year and many corrections for outliers and inconsistencies in the data.

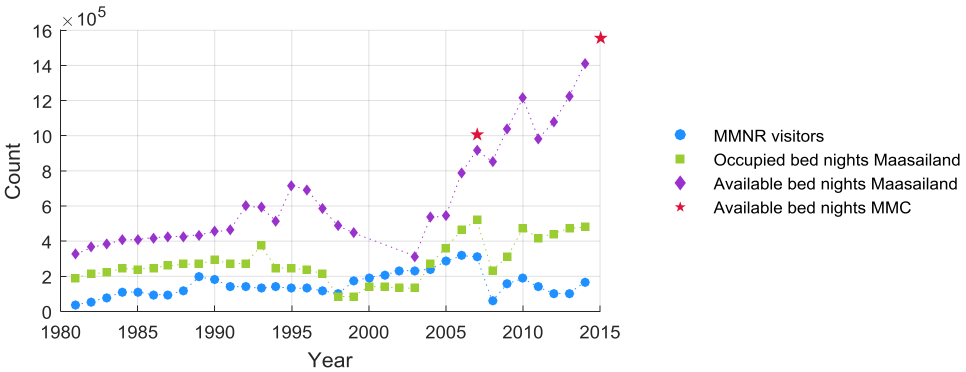


Figure 4.5 – Annual visitors to the MMNR and occupied bed nights in Maasailand (CBS, 1985/1989/1992/1996/2000a/2004; KNBS, 2008/2011/2015a), available bed nights in Maasailand (CBS, 1990/2000b; KNBS, 2013/2015b) and available bed nights in the MMC (Hoffman, 2007; Lilande, 2016)

4.5.2 Water use and demand per tourist

Facilities and amenities offered vary greatly between accommodations and therefore also the mean daily water use per tourist. Only the most basic camps offer short-drop toilets and safari showers. Most have flush toilets, running water in sinks, hot showers and baths. Examples of other water-consuming facilities and amenities are swimming pools, laundry and cleaning services, food preparation and greenery. To take the variation into account, Hoffman (2007) classified the camps and lodges into 36 mid-range and 29 high-end accommodations (e.g. Williams, 2012).

All samples are obtained from luxury camps and lodges. Hoffman (2007) collected yearly water use estimates from eight of the largest and most luxury accommodations in the MMC. Based on corrected BORs, their mean water use was 0.1 to 1.8 $m^3/(tourist \cdot d)$, with an overall mean of 0.9 $m^3/(tourist \cdot d)$. Of the camps interviewed during the field work, only five could estimate their water use and visitor numbers. Results were 0.3 to 1.8 $m^3/(tourist \cdot d)$, with an overall mean of 0.7 $m^3/(tourist \cdot d)$; low season values were slightly higher than high season uses as the water use of some facilities and amenities and staffing rates are not proportional to the number of guests. No distinction was made between use and demand, as none of the interviewed accommodations took substantial measures to reduce water consumption.

Because of the small sample sizes and high standard deviations, the mean daily water uses per tourist are mainly estimated with guidelines. The Washington State Department of Health (2009) suggests an mean of 0.4 to 0.6 $m^3/(tourist \cdot d)$ for luxury camps, but does not specify characteristics or environmental circumstances. According to Dodds (2005), these values would be classified as excellent performance for mid-range respectively luxury hotels for the climatic circumstances in the MMC, whereas more realistic figures would be 0.6 $m^3/(tourist \cdot d)$ for mid-range and 0.8 $m^3/(tourist \cdot d)$ for luxury hotels. These values correspond with the samples and are used for the calculations.

4.5.3 Water sources

Lilande (2016) lists the water sources used by each tourist accommodation in the MMC (see Table 4.8). Not included in her inventory is rooftop rainwater harvesting, which is practised by some accommodations (Ecotourism Kenya, n.d.). For this thesis, it is assumed that this practice contributes insignificantly to the total water abstractions for tourism and the total amounts of rainwater harvested.

Table 4.8 – Water sources of tourist accommodations in the MMC (Lilande, 2016)

	Accommodations		Water sources of the beds (%)				
	Camps	**Beds**	**Borehole**	**Spring**	**River**	**Shallow well**	**Pond**
Amala	1	21	0	100	0	0	0
Mid-Mara	40	1396	31	12	40	9	8
Lemek	14	237	72	2	17	9	0
Talek	45	1666	39	33	16	12	0
Sand	19	950	21	60	6	13	0
Total	**119**	**4372**	**34**	**31**	**22**	**11**	**2**

4.5.4 Uncertainty

In the estimated water use by tourists, most uncertainty is found in the per capita water use, which is mainly due to the high variation in facilities and amenities offered by accommodations, small sample size, biased sample and low data quality. Regarding tourist counts, the inventories may for instance be incomplete, the data for Maasailand may not be representative for the MMC and monthly BORs may have changed over the years or differ over the MMC. The uncertainty in water sources on the other hand is low, although rooftop rainwater harvesting might not be insignificant. For future projections, most uncertainty is found in visitor numbers, as these are strongly affected by for instance political instability, terrorism and competition with other destinations (Fletcher & Morakabati, 2008; Laing, 2013; Walpole, 2003). Regarding regulation, even if the development of accommodations would be limited, there would be much room for increased BORs.

4.6 Wildlife

4.6.1 Wildlife population counts

The most comprehensive wildlife counts in the MMNR and adjoining rangelands, in terms of spatial coverage and series length, were produced by aerial surveys (Ogutu et al., 2011; Ottichilo et al., 2000; Serneels & Lambin, 2001). From 1977 to 2009, 49 monthly aerial surveys were conducted in the study area, with most gaps in recent years (Ogutu et al., 2011). As the original DRSRS data are not available, spatially (see Figure 4.6) and temporally aggregated data are used (Ogutu et al., 2011). Fourteen wildlife species were included in the aerial counts (see Table 4.10). The systematic ground counts by Reid et al. (2003) on the other hand included 34 taxa. This count covered 86% of the MMNR and 98% of the Koyiaki group ranch, but only 182 km^2 of the other ranches; it was conducted in November 2002. Most other ground counts are sporadic, in small and unmarked areas, or for private use only (Lamprey & Reid, 2004; Ogutu et al., 2009; Reid et al., 2003).

Within the MMNR, Reid et al. (2003) compared the wildlife densities in the Mara Triangle, Musiara and Sekenani, but found no significant differences. Uniform population densities are therefore assumed for each area distinguished by Ogutu et al. (2011). For the ground count, it is assumed that the Koyiaki group ranch is representative for the inner ranches and the Ol Chorro Oirowua private ranch for the outer ranches. Counts for the entire SNP are not deemed representative for the MMC due to the seasonal movements of wildlife, but counts for its northern part only are not available. It is therefore assumed that the densities in the SNP are the same as in the MMNO. Wildlife water use outside these areas distinguished by Ogutu et al. and the SNP is assumed to be insignificant.

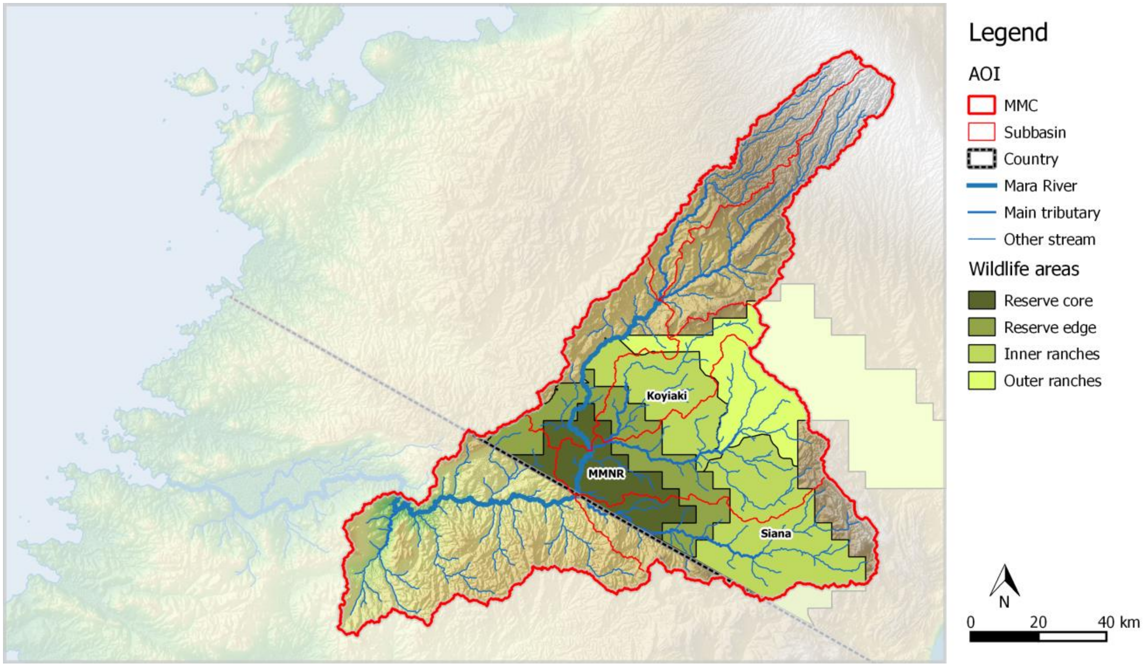


Figure 4.6 – Partitioning of the DRSRS population counts applied by Ogutu et al. (2011)

Because of the annual Great Migration, a distinction is made between the wet and dry season for wildebeest and zebra (see Figure 4.7 and Table 4.9). The migrating herds reside in the MMC roughly from June to November (Maddock, 1979; Ogutu et al., 2011; Ottichilo et al., 2001). Total biomass densities are considerably higher in the dry season than the wet season, but this is the other way around on the outer ranches due to seasonal movements of resident wildlife (Maddock, 1979; Ottichilo et al., 2001). In the dry season, wildebeests outnumber all other species combined in the MMNR, but their predominance decreases with distance from the reserve core (Ogutu et al., 2011; Reid et al., 2003). Of the "other" species, hippopotamuses accounted for 84% of the biomass (Reid et al., 2003). Analysis of the aerial survey data shows a progressive decline to about a third or less of the former abundance for both migratory and most resident species between 1977 and 2009, with little difference between the MMNR and the ranches (Ogutu et al., 2011; Ottichilo et al., 2000; Serneels & Lambin, 2001).

The aerial counts are consistent with the ground counts of Reid et al. (2003), with some exceptions: Thomson's gazelles may have to be regarded as migratory species instead (Serneels & Lambin, 2001; WHC, 2014) and the population density in the ranches may not be uniform (Lamprey & Reid, 2004; Serneels & Lambin, 2001). The ground counts of the Masai Mara Ecological Monitoring Programme (Ogutu et al., 2009) are also consistent with the aerial survey data (Ogutu et al., 2011). Although some species may not even be included in the ground counts, their combined biomass densities are probably insignificant (Reid et al., 2003; WREM International, 2008).

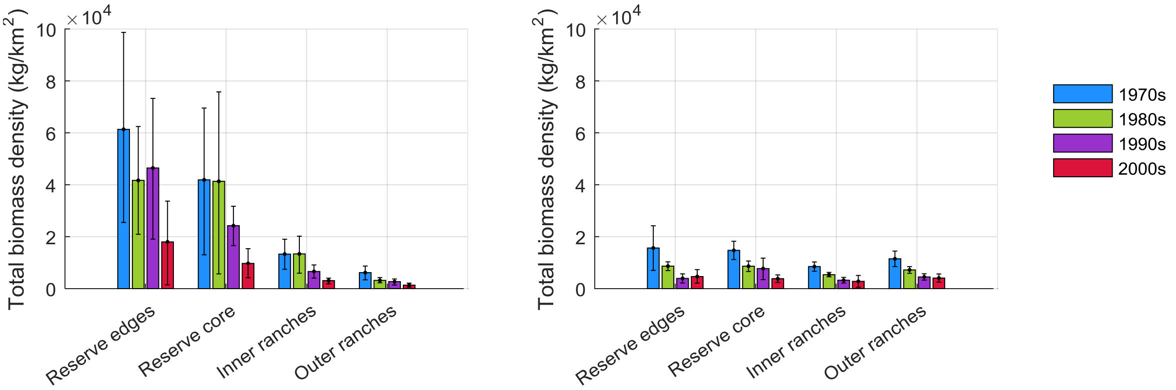


Figure 4.7 – Combined biomass densities of all wildlife included in the aerial surveys during the dry season from June to November (left) and the wet season from December to May (right) and over the past four decades (Ogutu et al., 2011); the 95% confidence intervals concern the wildlife counts only and not their mean individual weights

Table 4.9 – Biomass density of all wildlife species excluded from the aerial surveys in three protected areas and their percentage of the total biomass during the dry and wet season (Reid et al., 2003); wildebeest and zebra densities during the wet season are estimated with proportions resulting from Ogutu et al. (2011)

	Biomass density (kg/km^2)	Dry season (%)	Wet season (%)
MMNR	$4.4 \cdot 10^4$	1.8	8.5
Koyiaki	$2.7 \cdot 10^4$	2.2	2.4
Ol Chorro Oirowua	$0.7 \cdot 10^4$	1.6	0.9

4.6.2 Water use and demand per animal

Wildlife drinking water use is probably low compared to water use for their feed. However, only drinking water is considered in this subsections, as pastures are already included in the hydrological model (see Subsubsection 5.4.1.2). The daily water use per animal depends inter alia on species, size and environmental circumstances (King, 1983; Robbins, 1983). Data on actual water use by wildlife in the MMC is not available. However, mean daily water requirements per individual can be estimated for each species using the mean body weight of its individuals (Robbins, 1983; du Toit, 2002). Robbins (1983) for instance aggregated thirty studies to obtain the following empirical formula with $R^2 = 0.96$ for the water use of free-ranging mammals:

$$U = 0.12 \cdot w^{0.84} \qquad \text{(Eq. 4.1)}$$

in which U is the water use (in L/(animal · d)) and w is the individual body weight (in kg). However, most wildlife included in these studies lived under very different environmental conditions than those in the MMC and had a mean body weight of under 100 kg (Robbins, 1983). Du Toit (2002) on the other hand specifically investigated water requirements of common species under African game ranching conditions, resulting in a conversion factor of 0.04 L/(kg · d). As animals of all ages and genders were included in the population counts, mean individual weights are obtained from sources that take population structures into account (see Table 4.10). Lastly, even though actual water use may not always equal demand, no different figures are used due to the lack of data.

Table 4.10 – Unit body weight (Coe et al., 1976; *Reid et al., 2003) of the wildlife species included in the aerial counts

Common name	Scientific name	Unit body weight (kg)		
		Min	Max	Adopted
African buffalo	*Syncerus caffer*	310	664	450
African elephant	*Loxodonta Africana*	210	544	1725
Coke's hartebeest	*Alcelpahus buselaphus cokei*	1700	4990	125
Eland	*Taurotragus oryx*	680	800	340
Giraffe	*Giraffa Camelopardalis*	32	50	750
Grant's gazelle	*Gazella granti*	90	141	40
Impala	*Aepyceros melampus*	32	60	40
Ostrich	*Struthio camelus massaicus*	-	-	114*
Thomson's gazelle	*Gazella thomsoni*	12	15	15
Topi	*Damaliscus lunatus korrigum*	82	130	100
Warthog	*Phacochoerus africanus*	30	70	45
Waterbuck	*Kobus ellipsiprymnus*	130	205	160
Wildebeest	*Connochetes taurinus*	108	226	123
Zebra	*Equus burchelli*	160	290	200

4.6.3 Water sources

According to interviewees and observations, wildlife in the MMC rarely drinks from artificial or protected water sources: none have reportedly been constructed specifically for wildlife; most artificial and some natural ponds are protected against wildlife to prevent trampling and pollution of the source; springs are often located in villages or camps and protected by concrete structures; and none of the observed piped systems, boreholes or shallow wells had drinking facilities for wildlife. Instead, ponds are the main water sources for wildlife in the MMC, followed by rivers. Assuming uniform density distributions and the use of the nearest available water source, Voronoi diagrams of potential water sources can be used to estimate the division between different source types. As some sources are seasonal, this division varies over the year.

4.6.4 Uncertainty

For water use by wildlife, most uncertainty is due to the lack of data for the northern part of the SNP, variation in unit weights, lack of data on water sources for wildlife and difficulties in counting wet season population densities of migratory species. The latter is mainly due to the clustering of wildebeest and the varying timing of the annual Great Migration (Ogutu et al., 2011; Ottichilo et al., 2001). Moreover, some species are deemed hard to count, for instance due to their size, preferred habitat or hunting behaviour or nocturnality (Reid et al., 2003). Wildlife numbers may also fluctuate over the years, for example due to disease epidemics or recurrent droughts (Mduma et al., 1999; Musiega & Kazadi, 2004; Ogutu et al., 2008). Lastly, parts of the water requirements may be met by preformed and oxidative water (King, 1983; Robbins, 1983). For future projections, most uncertainty is found in the management activities in the protected areas, which may lead to trend reversal or further declines in wildlife populations.

4.7 Other users

4.7.1 Institutions

4.7.1.1 Schools

Data on school attendance status for school-going age groups are available at district level for Kenya (KNBS, 2000b/2010c) and at regional level for Tanzania (NBS & MPEE, 2006; NBS & OCGS, 2015). Data on age distribution is provided by the KNBS (2000a/2010b) and NBS and OCGS (2013b). Administrative boundaries are given in Figure 2.2. Resulting school attending populations are 29% in 1999 and 37% in 2009. Differences between the subbasins are up to 64%, with the lowest percentages in the southern subbasins. As the water use at schools is probably of the same order of magnitude as domestic water use, schools are included in the model.

Water use samples from schools in the MMC are not available. The MWI (2005) suggests 50 L/(student · d) for boarding schools and 25 or 5 L/(student · d) for day schools with respectively without toilets. To prevent double counts, domestic water use is abstracted for boarding schools. The proportion of day schools with toilets is unknown; 15 L/(student · d) is therefore used, except for schools without available water. The Ministry of Education, Science and Technology (MEST, 2015) lists the amount of schools per accommodation category for each Kenyan district, distinguishing between primary and secondary education. The amount of students at each educational level is given by the KNBS (2010c).

The MEST (2015) also provides data on water sources of Kenyan schools. No distinction is made between administrative areas or accommodation types, but only between educational levels and public or private schools. The amounts of enrolments in all categories are provided at district level (MEST, 2015). For the entire MMC, this results in a water supply of 53% by boreholes, 24% by harvested rainwater and 19% by rivers. An estimated 4% of the students has “no access to water”. For these students, the same rules are applied as to domestic use: it is assumed that springs are a preferred alternative over rivers and that other sources are not available.

4.7.1.2 Other institutions

WREM International (2008) made an inventory of health facilities in the Kenyan districts comprising the MMC, including their locations. The MWI (2005) suggests a water use of 5000 L/(facility · d) for dispensaries and health centres, L/(bed · d)for districts hospitals and 100 L/(bed · d) for local hospitals, both with a minimum of 5000 L/(facility · d). Service levels of Kenyan health facilities are given by Afya360 (n.d.). For the MMC, this results in a total water use of 0.4 to 0.8 L/(capita · d), depending on subbasin. Mean populations served by most health facilities in the MMC are below the target values of the MWI. The difference with domestic water use is about an order of magnitude and will probably increase in the future. Therefore, health facilities are not included in the model.

Data on other institutional water users in the MMC, such as churches and legal institutes, are scarce. Dessu et al. (2014), Hoffman (2007) and WREM International (2008) for instance do include any institutional water use. The MWI (2005) and WRMA (2009) do not provide guidelines for other institutional water users than schools and health facilities. Only Lilande (2016) lists institutional water abstractions in the Kenyan share of the MMC. The maximum water use for these institutions 0.1 L/(capita · d). Therefore, it seems safe to assume that the water use of other institutions than schools is insignificant; only schools are therefore included in the model as institutional water use.

4.7.2 Industry

4.7.2.1 Hydropower production

Currently, the only hydropower plant in the MMC observed and mentioned in reports is exploited by the Tenwek Hospital at a 14 m waterfall in the Nyangores River (LVBC, 2013; Compagnie d'aménagement du Bas-Rhône et du Languedoc [BRL] Ingénierie, 2013; Lilande, 2016; McKay et al., 1989; WREM International, 2008). The plant has a production capacity of $P_{max} = 3.2 \cdot 10^5$ W (McKay et al., 1989). The associated discharge Q_p (in m^3/s) is unknown, but may be estimated with:

$$P = \eta \cdot \rho \cdot g \cdot H \cdot Q_p \qquad \text{(Eq. 4.2)}$$

in which P is the actual hydropower production (in W), η is the coefficient of efficiency (-), ρ is the density of water (in kg/m^3), g is the acceleration of gravity (in m/s^2) and H is the head difference (in m). With an assumed value of $\eta = 0.8$ (Mendoza et al., 2011), and assuming that the waterfall height equals the head difference, this results in $Q_p = 3$ m^3/s. Future hydropower generation may require much larger reservoirs and flows. For instance, a preliminary feasibility study and detailed identification have been conducted for a large hydropower dam in the Nyangores River (BRL Ingénierie, 2013). This Mugango dam would have a height of 50 m and a storage capacity of $1.1 \cdot 10^5$ m^3. Furthermore, for the shelved Ewaso-Ngiro Hydropower Project, a mean flow of 2.6 m^3/s with a maximum of 6 m^3/s would be transferred from the Amala River to a tributary of the Ewaso-Ngiro River, located to the east of the MMC (WREM International, 2008).

4.7.2.2 Other industries

Mining is the main industrial water use factor in the MRB (Dessu et al., 2014; Hoffman, 2007; LVBC, 2013; Yanda & Majule, 2004). Two large-scale mining sites are located in the MRB (Tanzania Minerals Audit Agency, 2015), but both withdraw their water from sources downstream of the Mara Mines gauging station. Even though artisanal mining also takes place in the MRB, this is usually only at a small scale near the large-scale mining sites (Yanda & Majule, 2004). In the future, mining operations may expand, since the area is rich in minerals such as gold (Yanda & Majule, 2004), but no plans are found for mining within the MMC. Therefore, mining is not taken into account in the model.

Data on other industrial water users in the MMC are scarce. Dessu et al. (2014) and Hoffman (2007) for instance only included the mining industry. WREM International (2008) mentioned few small-scale industries in the MRB, but did not provide their water use or other characteristics. Lilande (2016) listed only five industrial water users in the Kenyan share of the MMC. These included two tea factories in the Nyangores subbasin, which abstract 73 m^3/d from a pond respectively 78 m^3/d from the river; the remaining three industrial users combined abstract only 7 m^3/d (Lilande, 2016). Therefore, only the Tenwek dam and the tea factories are included in the model as industrial water use.

4.7.3 Commerce

Excluding services related to tourism (see Section 4.5), commercial activities in the MRB mainly consist of mining trade, agricultural trade and retail of general merchandise (WREM International, 2008). WREM International listed the amounts of registered shops, both providing goods and services, in the Tanzanian districts comprising the MRB. The MWI (2005) suggests a mean water use of 100 L/(shop · d). This results in 0.1 to 0.2 L/(capita · d), which is one to three orders of magnitude smaller than the domestic water use in each subbasin. Commercial water use is therefore assumed to be insignificant in the model calculations, even though many shops may not be registered, water use at for instance outdoor markets is not included and there may be spatial differences in commercial water use.

4.7.4 Uncertainty

Of the "other" daily water uses by user categories included in the model, most uncertainty is found in the water use for hydropower production. This especially amounts to future projections, as the implementation of large-scale hydropower projects is uncertain and data on associated structures and flows is limited. For future development, other main uncertainties are the development of water-consuming industries and the percentages of school-going populations for schools. In the total estimated "other" use, much uncertainty is also found in the possibly overlooked categories of water users. The water use at schools is also uncertain, as daily water use per student is unknown and most data is aggregated at district or even national level. For industries, the list of factories may be incomplete.

4.8 Environmental flows

Both the Kenyan Water Act 2002 Part III: 13 and the Tanzanian Water Resources Management Act 2009 Section 32 oblige relevant government bodies to determine the inclusive "reserve" of each river and to safeguard it. In Part I: 2(1) respectively Section 3, both acts define reserve as the "quantity and quality of water required (a) to satisfy basic human needs [...] and (b) to protect aquatic ecosystems". In compliance with these legislations, an environmental flow assessment (EFA) was undertaken for the Mara River under the Transboundary Water for Biodiversity and Human Health in the Mara River Basin (TWB-MRB) project (Global Water for Sustainability program – Florida International University [GLOWS-FIU], 2012). The reserve resulting from this EFA should be regarded the water demand with the highest priority (Tanzania National Water Policy, 2002).

For the EFA in the MRB, the building block methodology (BBM) was used (GLOWS-FIU, 2012). The BBM is based on the assumption that the characteristic features of the natural flow regime, called building blocks, are each important for the maintenance of the riverine ecosystem (King et al., 2000). At representative sites, the building blocks are identified and described in terms of water depth h_{EFR} (in m), discharge Q_{EFR} (in m^3/s and m^3/month), duration D_{EFR} (in days), maximum return period T_{EFR} (in years) and timing (King et al., 2000). This is done in a workshop setting by an interdisciplinary team of specialists; considered components are social use, hydrology, hydraulics, geomorphology, water quality, vegetation, aquatic invertebrates and fish (King et al., 2000). The BBM results in modified flow regimes at the selected sites for maintenance and drought conditions, which may be set as flow targets in water resources management (King et al., 2000; GLOWS-FIU, 2012).

For the EFA in the MRB, the team of specialists selected five representative sites throughout the river basin (see Appendix E). These include gauging stations 5H2 at Mara Mines and 1LB02 in the Amala River; all sites are located in the MMC. The sites were surveyed during low and high flows to recommend minimum water levels (see Appendix E). These were converted to discharges using the velocity-area method. Discharges were then extrapolated over the year to represent the average historical shape of the hydrograph (GLOWS-FIU, 2012). Over 58 years of rainfall records, 11 were classified as drought years and 9 as wet years (GLOWS-FIU, 2012). Not all indicators and components were critical for the EFRs (see Appendix E). For instance, water for basic human needs is considered to be automatically accommodated by larger flows required for other ecosystem services, such as riparian vegetation.

4.9 Overview

Water use and demand are estimated for the main water users in the MMC. Total demand was about $9.2 \cdot 10^{-3}$ mm/d during the dry season and $5.9 \cdot 10^{-3}$ mm/d during the wet season of 2016. This varies between 0.9% of wet season maintenance EFRs and 12% of dry season drought year EFRs. Demand is highest at irrigated farms, which contribute on average 49% to total demand. Following in decreasing order of magnitude of water demand are livestock, inhabitants, schools, tourists, wildlife and industry. Total demand is highest at rivers with 59%, but ponds are more important in the southeastern subbasins. However, these rankings and most values differ considerably per month, subbasin and year (see Table 4.11 and Table 4.12).

Table 4.11 – Comparison of estimated water demand for all users except EFRs in 2016 (in mm/d); water demand for hydropower generation is not included, as it is not evaluated in the scenarios

	Inhabitants	Livestock	Crops		Tourists		Wildlife		Other	Total	
			Aug	Apr	Aug	Apr	Aug	Apr		Aug	Apr
Nyangores	$6.2\cdot10^{-3}$	$2.9\cdot10^{-3}$	$2.1\cdot10^{-4}$	$8.4\cdot10^{-5}$	0	0	0	0	$1.3\cdot10^{-3}$	**$1.1\cdot10^{-2}$**	**$1.1\cdot10^{-2}$**
Amala	$4.4\cdot10^{-3}$	$2.5\cdot10^{-3}$	$1.1\cdot10^{-2}$	$1.4\cdot10^{-2}$	0	0	$1.0\cdot10^{-7}$	$3.6\cdot10^{-7}$	$9.2\cdot10^{-4}$	**$1.9\cdot10^{-2}$**	**$2.2\cdot10^{-2}$**
Mid-Mara	$1.1\cdot10^{-3}$	$2.2\cdot10^{-3}$	$4.4\cdot10^{-2}$	$4.6\cdot10^{-3}$	$6.7\cdot10^{-4}$	$1.5\cdot10^{-4}$	$7.6\cdot10^{-5}$	$4.9\cdot10^{-5}$	$1.1\cdot10^{-4}$	**$4.8\cdot10^{-2}$**	**$8.2\cdot10^{-2}$**
Lemek	$1.8\cdot10^{-4}$	$1.3\cdot10^{-3}$	0	$7.0\cdot10^{-6}$	$1.3\cdot10^{-4}$	$2.8\cdot10^{-5}$	$6.3\cdot10^{-5}$	$8.1\cdot10^{-5}$	$6.8\cdot10^{-5}$	**$1.7\cdot10^{-3}$**	**$1.6\cdot10^{-3}$**
Talek	$1.9\cdot10^{-4}$	$1.1\cdot10^{-3}$	0	$7.1\cdot10^{-6}$	$3.4\cdot10^{-4}$	$7.4\cdot10^{-5}$	$1.2\cdot10^{-4}$	$9.0\cdot10^{-5}$	$5.3\cdot10^{-5}$	**$1.8\cdot10^{-3}$**	**$1.5\cdot10^{-3}$**
Sand	$2.0\cdot10^{-4}$	$9.9\cdot10^{-4}$	0	$8.4\cdot10^{-6}$	$2.8\cdot10^{-4}$	$6.1\cdot10^{-5}$	$1.4\cdot10^{-4}$	$7.1\cdot10^{-5}$	$6.9\cdot10^{-5}$	**$1.7\cdot10^{-3}$**	**$1.4\cdot10^{-3}$**
Low-Mara	$1.1\cdot10^{-3}$	$1.8\cdot10^{-3}$	$1.0\cdot10^{-5}$	$6.1\cdot10^{-5}$	0	0	$2.3\cdot10^{-4}$	$6.3\cdot10^{-5}$	$1.5\cdot10^{-4}$	**$3.3\cdot10^{-3}$**	**$3.1\cdot10^{-3}$**
Total	**$1.6\cdot10^{-3}$**	**$1.7\cdot10^{-3}$**	**$5.4\cdot10^{-3}$**	**$2.3\cdot10^{-3}$**	**$1.8\cdot10^{-4}$**	**$4.0\cdot10^{-5}$**	**$1.2\cdot10^{-4}$**	**$5.6\cdot10^{-5}$**	**$3.1\cdot10^{-4}$**	**$9.2\cdot10^{-3}$**	**$5.9\cdot10^{-3}$**

Table 4.12 – Comparison of water demand from different sources in each subbasin (in %) and comparison of total water demand per subbasin as percentage of total demand in the MMC (in %), for all users except EFRs and hydropower generation in 2016

	River	Spring	Pond	Shallow well	Borehole	RRH	Total
Nyangores	28	6	26	4	13	23	**13**
Amala	73	1	11	1	6	8	**39**
Mid-Mara	85	4	9	0	2	0	**26**
Lemek	13	2	69	0	12	4	**2**
Talek	14	7	63	2	12	2	**4**
Sand	14	8	62	2	12	2	**4**
Low-Mara	26	5	52	3	12	2	**12**
Total	**59**	**3**	**23**	**2**	**7**	**6**	**100**

Measures for uncertainty are difficult to calculate, as these are usually not provided by the available data sources. “Maximum” values at the end of the design period (see Subsection 6.3) are therefore estimated, taking the most important sources of uncertainty into account (see Appendix F). As an indication of uncertainty for future projections, the difference between “best guess” and maximum water use is estimated for each user and subbasin (see Table 4.13). Both absolute and relative uncertainty are greatest for irrigation, followed by livestock and inhabitants.

Table 4.13 – Estimated maximum water use at the end of the design period minus estimated actual water use, as indicator of the absolute uncertainty of future projections (in mm/d); water demand for hydropower generation is not included, as it is not evaluated in the scenarios

	Inhabitants	Livestock	Crops		Tourists		Wildlife		Other	Total	
			Aug	Apr	Aug	Apr	Aug	Apr		Aug	Apr
Nyangores	$2.1\cdot10^{-2}$	$1.3\cdot10^{-2}$	$4.4\cdot10^{-5}$	$1.7\cdot10^{-5}$	-	-	-	-	$3.1\cdot10^{-3}$	$3.7\cdot10^{-2}$	$3.7\cdot10^{-2}$
Amala	$1.5\cdot10^{-2}$	$1.0\cdot10^{-2}$	$4.4\cdot10^{-2}$	$6.0\cdot10^{-2}$	-	-	$8.2\cdot10^{-7}$	$1.2\cdot10^{-6}$	$2.3\cdot10^{-3}$	$7.1\cdot10^{-2}$	$8.7\cdot10^{-2}$
Mid-Mara	$7.2\cdot10^{-3}$	$5.5\cdot10^{-3}$	$4.6\cdot10^{-1}$	$4.7\cdot10^{-2}$	$1.2\cdot10^{-3}$	$9.2\cdot10^{-4}$	$8.5\cdot10^{-4}$	$2.6\cdot10^{-4}$	$1.0\cdot10^{-3}$	$4.8\cdot10^{-1}$	$7.0\cdot10^{-2}$
Lemek	$2.6\cdot10^{-3}$	$8.1\cdot10^{-3}$	0	$1.5\cdot10^{-6}$	$2.4\cdot10^{-4}$	$1.7\cdot10^{-4}$	$6.3\cdot10^{-4}$	$4.0\cdot10^{-4}$	$2.3\cdot10^{-4}$	$1.2\cdot10^{-2}$	$1.2\cdot10^{-2}$
Talek	$2.5\cdot10^{-3}$	$7.1\cdot10^{-3}$	0	$1.6\cdot10^{-6}$	$6.3\cdot10^{-4}$	$4.6\cdot10^{-4}$	$1.2\cdot10^{-3}$	$3.8\cdot10^{-4}$	$1.8\cdot10^{-4}$	$1.2\cdot10^{-2}$	$1.1\cdot10^{-2}$
Sand	$3.3\cdot10^{-3}$	$6.4\cdot10^{-3}$	0	$1.8\cdot10^{-6}$	$5.2\cdot10^{-4}$	$3.8\cdot10^{-4}$	$1.4\cdot10^{-3}$	$3.0\cdot10^{-4}$	$2.2\cdot10^{-4}$	$1.2\cdot10^{-2}$	$1.1\cdot10^{-2}$
Low-Mara	$3.1\cdot10^{-3}$	$2.3\cdot10^{-3}$	$5.1\cdot10^{-1}$	$5.2\cdot10^{-2}$	-	-	$2.3\cdot10^{-3}$	$2.0\cdot10^{-4}$	$8.5\cdot10^{-4}$	$5.2\cdot10^{-1}$	$5.8\cdot10^{-2}$
Total	$\mathbf{6.3\cdot10^{-3}}$	$\mathbf{6.5\cdot10^{-3}}$	$\mathbf{1.8\cdot10^{-1}}$	$\mathbf{2.6\cdot10^{-2}}$	$\mathbf{3.3\cdot10^{-4}}$	$\mathbf{9.8\cdot10^{-4}}$	$\mathbf{1.2\cdot10^{-3}}$	$\mathbf{2.3\cdot10^{-4}}$	$\mathbf{9.6\cdot10^{-4}}$	$\mathbf{1.5\cdot10^{-2}}$	$\mathbf{1.4\cdot10^{-2}}$

5 | Hydrological modelling

5.1 Introduction

In this chapter, a FLEX-Topo model is made to provide insight into the rainfall-runoff mechanisms in the MMC and to predict the impact of water management interventions on the Mara River discharge. Firstly, the model choice is clarified. Subsequently, the MMC is classified into a limited number of HRUs. Their model structures are described and several parameter values are estimated. Next, the quality of meteorological and hydrological input data (see also Appendix H) is analysed. Parameter and process constraints are applied to the calibration with the Multiobjective Shuffled Complex Evolution Metropolis (MOSCEM-UA) algorithm. Lastly, the model is validated.

5.2 Model choice

5.2.1 Modelling process and model types

Beven (2001b) described the modelling process loop. It starts with the formulation of a perceptual model, which includes identification of hydrological processes and scientific principles governing them. This perceptual model is simplified in a mathematical description: the conceptual model. The latter is translated into computer code: the procedural model. Next, parameters are calibrated and the model is validated. If success is not declared, all steps should be revised (see also Fenicia et al., 2008; Savenije, 2009). Due to dissimilarities between both basins and modellers, resulting models may vary. In general, hydrological models are classified based on three aspects (Refsgaard, 1996; Zhang, 2007):

- ***Lumped or (semi-)distributed.*** Lumped models regard basins as uniform units, i.e. these models do not use any spatial distribution in input, model structure, parameters or output. Fully distributed models on the other hand try to represent heterogeneities and process complexities at the smallest possible level (McDonnell et al., 2007). Semi-distributed models are an intermediate option, using at least some spatial distributed information (Savenije, 2010).

- ***Empirical, conceptual or physically-based.*** Empirical models are black-box models, linking input to output without considering underlying processes (Zhang, 2007). Conceptual models represent dominant processes and storages by interrelated reservoirs with closed water balances (Shaw et al., 2010). Physically-based models solve partial differential equations derived from conservation laws (Zhang, 2007).

- ***Deterministic or stochastic.*** In contrast to deterministic models, stochastic models contain inner operations with a random character, therefore producing varying outputs for the same input under identical initial and boundary conditions (Refsgaard, 1996).

In general, reducing the predictive uncertainty is a trade-off between representation of heterogeneity and process complexities on the one hand, and equifinality and correct representation of scale effects on the other hand (Beven, 1993; McDonnell et al., 2007; Savenije, 2010). For the MMC and the study aims, lumped and empirical models may be too simple, whereas fully distributed, physically-based and stochastic models may be too data-intensive, complex and time-consuming. At least, flexibility of the model structure is desired to allow for revision of all modelling steps (Fenicia et al., 2011; Savenije, 2009). For this thesis, a compromise is found in FLEX-Topo.

5.2.2 FLEX-Topo

FLEX-Topo is a topography-driven semi-distributed conceptual model (Savenije, 2010). It is based on the assumption that dominant hydrological processes depend largely on topographical characteristics, which are closely related to soil type, land cover, and climate (Gao et al., 2013; Savenije, 2010). Based on such characteristics, the river basin is classified into a limited number of HRUs, which each behave similarly for similar forcings. The dominant hydrological processes on each HRU can be represented by relatively simple equations, due to self-organization of the catchment (Dooge, 2005; Savenije, 2001). These processes are described conceptually for each HRU, not only with different parameter values but also with different model structures (Savenije, 2010).

In the FLEX-Topo modelling approach, the knowledge and understanding of the MMC and its processes are represented in a way that leads to great simplifications, without losing the most important information (Savenije, 2010). Therefore, it is more likely that the model gives the right results for the right reasons, which is important for its predictive certainty (Kirchner, 2006). In validation, FLEX-Topo models have indeed proven to perform better than lumped models under various circumstances (De Looij, 2014; Gao et al., 2013; Gijsbers, 2015; Gharari et al., 2013; Piet, 2014). This thesis builds upon these results by applying the FLEX-Topo modelling approach to a data-scarce African catchment, adding water use and demand in the process.

5.3 Classification

5.3.1 Method

For the classification of the MMC, topographical maps are combined with land cover maps and observations. Firstly, topography is a key characteristic in the identification of dominant hydrological processes at catchment scale (Savenije, 2010). For the MMC, SRTM data are used as DEM (see Section 2.3). As recommended by Gharari et al. (2011) for hydrological landscape classification, the height above the nearest drainage (*HAND*; in m) and local slope s (-) are derived from the DEM. Thresholds are selected for both, to distinguish between four landscape classes (see Table 5.1).

Table 5.1 – Distinguished landscape classes and associated slope and HAND (Gharari et al., 2011)

Landscape class	Associated slope and HAND
Plateau	$s < s_{threshold}$ and $HAND > HAND_{threshold}$
Hillslope	$s > s_{threshold}$ and $HAND > HAND_{threshold}$
Sloped wetland	$s > s_{threshold}$ and $HAND < HAND_{threshold}$
Flat wetland	$s < s_{threshold}$ and $HAND < HAND_{threshold}$

Furthermore, freely available land cover maps were obtained for mutual comparison (see Table 5.2). Mainly due to differences in classification algorithms, datasets are inconsistent and of variable quality. In the MMC, the greatest uncertainty is found in croplands, probably due to their highly heterogeneous and variable nature. Some map show for instance extensive agricultural fields in the protected MMNR or reforestation in the northern subbasins. All land cover maps of the MMC are compared with “natural colour” and NDVI maps produced from Landsat data (NASA Landsat Program, 2016).

The best results are obtained for the Africover map, which was made especially for eastern Africa and verified by the FAO with field work (FAO, 2002a).

Table 5.2 – Product specifications of the freely available land cover maps that are used for comparison in the MMC

Product name	Product source	Data source: satellite (sensor)	Product coverage years	Scale/ grid size
Africover	FAO (2002a)	Landsat (TM)	Kenya: 1995 Tanzania: 1997	1 : 200000
Global Land Cover 2000	European Commission Joint Research Centre (2003)	Satellite Pour l'Observation de la Terre (VEGETATION)	2000	1 km
Global Land Cover by National Mapping Organizations	Survey of Kenya (n.d.)	Terra and Aqua (MODerate resolution Imaging Spectrometer [MODIS])	Kenya: 2003	1 km
GlobCover	European Space Agency (2008/2010)	Envisat (MODIS)	2005, 2009	300 m
MODIS Land Cover	Oak Ridge National Laboratory Distributed Active Archive Center (2010)	Aqua and Terra (MODIS)	Yearly: 2001-2012	500 m
University of Maryland Department of Geography Land Cover Classification	Hansen et al. (2000)	National Oceanic and Atmospheric Administration [NOAA] satellites (Advanced Very High Resolution Radiometer)	Combined: 1981-1994	1 km

Lastly, field observations are used for ground truth and final selection, delineation and characterisation of HRUs. Together with Hulsman (2015), the Kenyan share of the MMC was visited in September and October of 2014. Georeferenced pictures and notes were taken at 1345 points along major roads. Fifteen characteristic locations were described in detail, using a checklist (see Appendix G).

5.3.2 Class boundaries

For the delineation of class boundaries, the Africover map is used as base map. Rules are established for the reduction of its 112 classes in the MMC into four HRUs (see Figure 5.1 and Table 5.3). For instance, Hulsman (2015) analysed the sensitivity of the classification of the MMC to topographical threshold values, resulting in $s_{threshold}$ = 0.15 and $HAND_{threshold}$ = 0 m. Indeed, the wetland area seems to be insignificant, as most rivers and streams cut deep into the landscape or adjoin steep slopes. In general, the correlation between topography and land cover is strong in the MMC. Steep and flat areas align well with forests and shrublands respectively grasslands, but crops are found on both steep and undulating areas. Examples of borderline cases are cleared hillslopes, woodlands, strips of trees along streams, scattered farms or patches of shrubs on flat grassland, pastoral farms, large-scale rainfed wheat fields and patches of grass and shrubs in agricultural areas.

Table 5.3 – Classification results: area percentages of the HRUs per subbasin

	Forest (%)	Shrubs (%)	Crops (%)	Grass (%)
Nyangores	46	53	0	1
Amala	23	63	7	7
Mid-Mara	3	20	74	2
Lemek	0	5	76	18
Talek	0	0	79	20
Sand	0	0	73	27
Low-Mara	0	35	62	3
Total	**7**	**12**	**24**	**57**

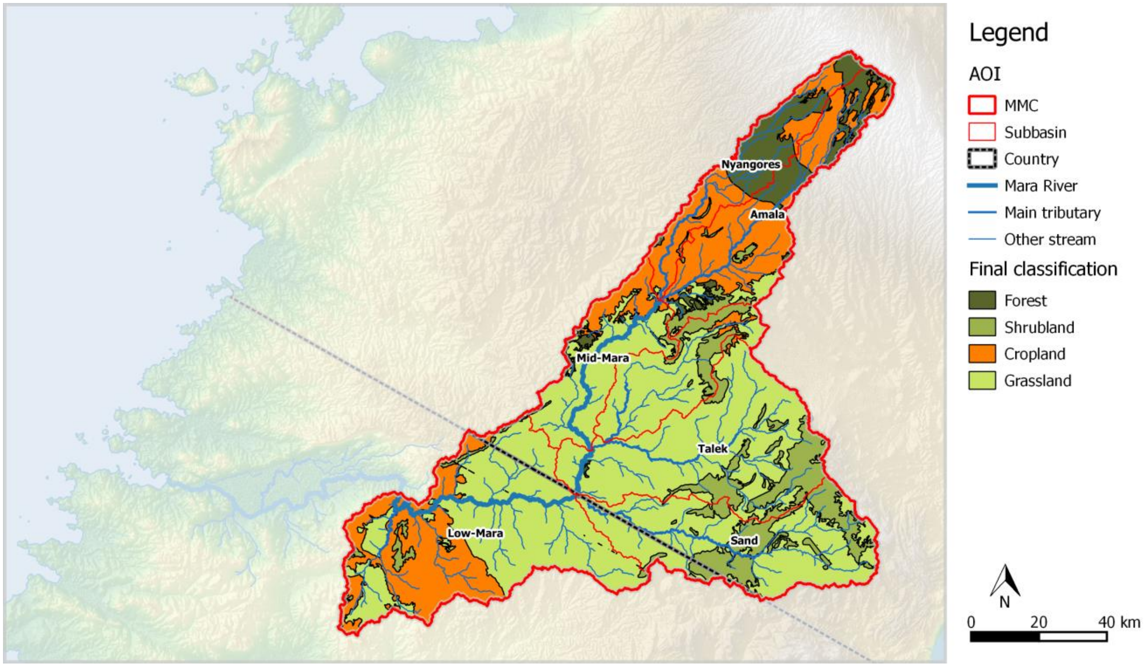


Figure 5.1 – Classification of the MMC into four HRUs

5.3.3 Class descriptions

5.3.3.1 Observations

The four distinguished HRUs are named after their dominant land cover, but there is a strong correlation between land cover, soil, and topography (see Figure 5.2):

- ***Forest.*** On the forested hillslopes, the vegetation is predominantly broadleaved and has a high density. Trees are up to 50 m tall; smaller trees, shrubs and standing plants are found underneath. The forest floor is covered by a dense mulch layer. The soil surface is loose and rough. The unsaturated zone is deep and probably has a high density of root channels, animal tunnels and burrows. The hillslopes are steeply inclined towards the river, with few open spot in the dense vegetation. Hardly any erosion features or other signs of overland flow were found.

- ***Shrubland.*** On the shrubbed hillslopes, the vegetation consists of multiple layers: broadleaved shrubs and standing plants are both abundant and the soil surface is covered by rocks and a mulch layer. Canopy height, vegetation density, soil depth and expected density of preferential flow paths are lower than in the forests, whereas erosion features are more abundant. The hillslopes rise abruptly from the surrounding grasslands.

- ***Cropland.*** On the croplands, the vegetation is characterized by its heterogeneity and variation over the year: fields with various crops in different stages are interspersed with strips and patches of grass, shrubs or trees. Soils are shallow, but may contain a substantial density of preferential flow paths. Cultivation takes place on both steep and undulating areas. Erosion was reported to have major impact on crop productivity.

- ***Grassland.*** Most grasslands are severely overgrazed, with average grass heights below 2 cm and visible bare soil. Dust layers form a crust during rainfall. The soil has a high clay content and is heavily compacted. The unsaturated zone is very shallow and probably contains few preferential flow paths. The grasslands are very gently inclined towards the river. Depressions of up to several tens of metres are found. Erosion features such as gullies are very abundant, both on the plains and along the river banks.

Figure 5.2 – From left to right, small-scale (above) and large-scale (below) characteristic views of forest, shrubland, cropland and grassland, i.e. the four distinguished HRUs in the MMC

5.3.3.2 Dominant runoff mechanisms

The four HRUs have different dominant runoff mechanisms (see Table 5.4). In the hillslopes, there are networks of preferential flow paths, which are created for instance by roots and animals. These channels become connected after a certain level of soil saturation has been reached. Storage excess or rapid sub-surface flow (SSF) is therefore perceived to be the dominant flow mechanism on the forested and shrubbed hillslopes. On the croplands and grasslands on the other hand, the infiltration capacity is much lower. This probably results in infiltration excess or Hortonian overland flow (HOF) as dominant flow mechanism. During the field work, HOF was observed in the Sand subbasin (see Figure 5.3).

A limited number of supporting runoff mechanisms is included in the model structure of each HRU. Some HOF probably takes place on the shrubbed hillslopes, whereas this process is barely expected in the densely vegetated forests. SSF is assumed to be a supporting runoff mechanism on the steep agricultural hillslopes, but not on the pastoral plains. Deep percolation (DP) is assumed to be a significant flux on every HRU, but its dominance is expected to differ. This probably also amounts to other hydrological processes such as interception and transpiration.

Table 5.4 – Summary of characteristics of the four HRUs

Land cover	**Forest**	**Shrubs**	**Crops**	**Grass**
Topography	Steep	Steep	Steep/undulating	Undulating
Soils	Very deep	Deep	Shallow	Very shallow
Dominant runoff mechanism	SSF	SSF	HOF	HOF
Supporting runoff mechanisms	DP	HOF and DP	SSF and DP	DP

Figure 5.3 – HOF on grassland in the Sand subbasin (left) and subsequent incoming peak flow in the Sand River (right)

5.3.3.3 Water use

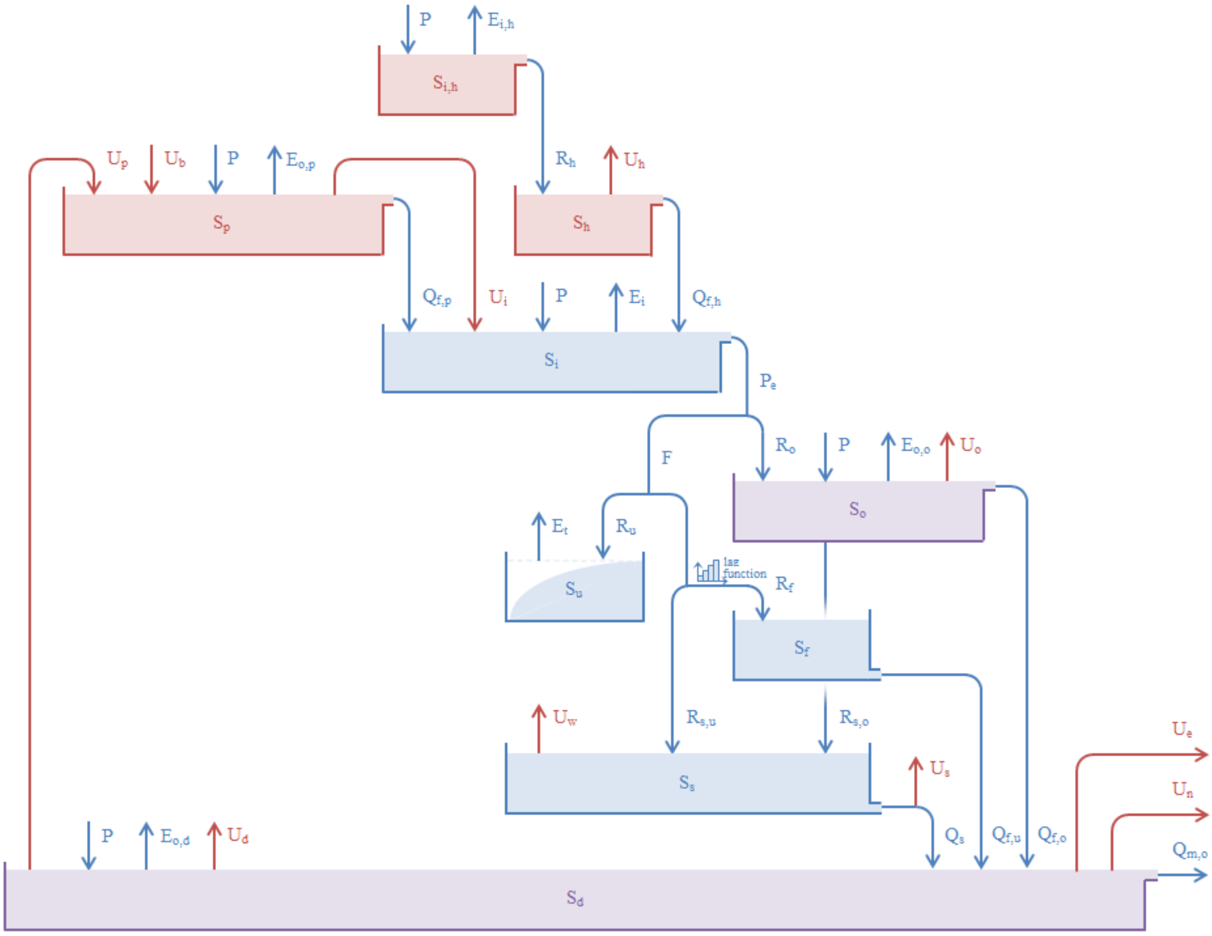
The main water users also differ between HRUs. Human activities are limited in the forests and shrublands, although extractions of fuelwood and timber are encountered. The biomass density of animals is also assumed to be insignificant on those HRUs, due to the impenetrable or ill-suited vegetation. Large wildlife and tourist facilities are almost exclusively found on the grasslands, although many tourist accommodations are found along the bases of shrubbed hillslopes. Households, livestock and institutions on the other hand are frequently encountered on both the grassland and croplands. Lastly, irrigation naturally takes place on the croplands.

Similarly, there is a strong correlation between HRUs and available water sources. In the forests and shrublands, no water abstractions were observed or reported during inventories (Hoffman, 2007; Lilande, 2016). Springs are however found abundantly along the bases of shrubbed hillslopes and both HRUs contribute substantially to groundwater and river flows – base flows in particular. The greatest variety in ponds is found on grasslands, which is partly due to the dominance of HOF. Boreholes are also more prevalent on the open and relatively dry plains. Springs are also found along the bases of agricultural hillslopes. Lastly, rooftop rainwater harvesting is less common among pastoral than agricultural water users.

5.4 Model structure

5.4.1 Overview

FLEX-Topo is a conceptual model (see Section 5.2). It consists of reservoirs representing storages and fluxes representing hydrological processes. The water balance is closed for each reservoir and subsystem. Fluxes are either measured or calculated by closure relations, and transfer functions are used for routing. The model structure for the MMC contains both “natural” and “artificial” building blocks (see Figure 5.4). The natural components are based on Fenicia et al. (2006), Gao et al. (2013) and Savenije (2010), and mostly designed together with Hulsman (2015). Depending on the characteristics of each HRU, some reservoirs and fluxes may be omitted and parameter values may differ. Per subbasin, the HRUs are connected by means of the fast and slow reacting reservoir and, if applicable, a reservoir in the river. Seven subbasins are distinguished, to allow for spatially distributed forcing and routing through the Mara River.



Storage (in mm)
$S_{i,h}$: in rooftop interception reservoir
S_h in rainwater harvesting reservoir
S_p: in ponds for irrigation
S_i: in interception reservoir
S_o: in open water reservoir
S_u: in unsaturated soil reservoir
S_f: in fast reacting reservoir
S_s: in slow reacting reservoir
S_d: in dam or river

Abstraction (in mm/d)
U_h: from rainwater harvesting reservoir
U_i: from pond for irrigation
U_o: from other ponds
U_w: from shallow wells
U_s: from springs
U_b: from boreholes for irrigation
U_p: from dam or river for irrigation
U_e: from dam for hydropower generation
U_n: from dam or river for regulation
U_d: from dam or river for other uses

Other external flux (in mm/d)
P: rainfall
$E_{i,h}$: rooftop interception
$E_{o,p}$: open water evaporation from ponds for irrigation
$E_{o,o}$: open water evaporation from other ponds
$E_{o,d}$: open water evaporation from dam or river
E_i: interception
E_t: transpiration
$Q_{m,o}$: overflow from dam

Other internal flux (in mm/d)
R_h: inflow or rainwater harvesting reservoir
$Q_{f,h}$: overflow from rainwater harvesting reservoir
$Q_{f,p}$: overflow from ponds for irrigation
P_e: effective rainfall
F: infiltration
R_u: recharge to unsaturated zone
R_f: recharge to fast reacting reservoir
R_o: overland flow to open water reservoir
$R_{s,o}$: recharge to slow reacting reservoir from open water reservoir
$R_{s,u}$: recharge to slow reacting reservoir from unsaturated zone
$Q_{f,o}$: very fast discharge from open water reservoirs
$Q_{f,u}$: fast discharge from unsaturated zone
Q_s: slow discharge

Figure 5.4 – General model structure of the HRUs in the MMC, including artificial (red), natural (blue) and combined (purple) storage reservoirs and fluxes; reservoirs and fluxes depending on the characteristics of the HRU

5.4.1 Natural components

5.4.1.1 Interception

A considerable proportion of the rainfall P (in mm/d) may be intercepted by the canopy, mulch layer, other objects on the surface and uppermost layer of the soil. This water evaporates within a timespan of about a day, without contributing to transpiration or runoff (Savenije, 2004). For a modelling time step of Δt = 1 d, the interception E_i (in mm/d) is limited by P, the potential evaporation E_p (in mm/d) and the daily storage capacity of the interception reservoir I_{max} (in mm/d) (Gao et al., 2013):

$$E_i = \min\left(P, E_p, I_{max}\right) \qquad \text{(Eq. 5.1)}$$

E_p is estimated by the simplified Hargreaves model (Duffie & Beckman, 1980). The effective rainfall P_e (in mm/d) is the rainfall that is not intercepted (Savenije, 2004):

$$P_e = P - E_i \qquad \text{(Eq. 5.2)}$$

It is assumed that the interception reservoir is only replenished by rainfall, i.e. that it is not connected to the deeper soil moisture. Hence, the total water balance of the interception reservoir becomes:

$$\frac{\Delta S_i}{\Delta t} = P - E_i - P_e = 0 \qquad \text{(Eq. 5.3)}$$

in which S_i is the storage in the interception reservoir (in mm). This reservoir is included in the model structure of every HRU. However, different time series are used per subbasin for both P and E_p. Furthermore, different values of I_{max} are used for the HRUs.

5.4.1.2 Unsaturated zone

In the forests, it is assumed that all P_e infiltrates into the soil. In all other HRUs, the infiltration F (in mm/d) may be limited by the infiltration capacity F_{max} (in mm/d):

$$F = \max(P_e, F_{max}) \qquad \text{(Eq. 5.4)}$$

Whenever $P_e > F_{max}$, HOF takes place. In the absence of ponds (see Subsubsection 5.4.2.2), it is assumed that the generated overland flow $R_{f,o}$ (in mm/d) equals the contribution of surface runoff to the river flow $Q_{f,o}$ (in mm/d), i.e. all HOF reaches the river within one modelling time step. F is partitioned into three fluxes. Firstly, the soil moisture content S_u (in mm) may be replenished by R_u (in mm/d), up to a maximum of $S_{u,max}$ (in mm). Secondly, networks of preferential flow paths may become connected after a certain level of soil saturation has been reached, resulting in SSF or R_f (in mm/d). Lastly, there may be percolation to the groundwater $R_{s,u}$ (in mm/d). Two splitters are used for this partitioning (Gao et al., 2013; Fenicia et al., 2006):

$$R_u = (1 - C_r) \cdot F \qquad \text{(Eq. 5.5)}$$

$$R_f = C_r \cdot F \cdot D \qquad \text{(Eq. 5.6)}$$

$$R_{s,u} = C_r \cdot F \cdot (1 - D) \qquad \text{(Eq. 5.7)}$$

in which C_r is the effective runoff coefficient (-) and D is a splitter to separate percolation from SSF (-). C_r is calculated with the beta-function of the Xinanjiang model (Zhao, 1992):

$$C_r = 1 - \left(1 - \frac{S_u}{S_{u,max}}\right)^{\beta} \qquad \text{(Eq. 5.8)}$$

in which β indicates the heterogeneity of the soil depth (-). From the unsaturated zone, vegetation withdraws water for transpiration E_t (in mm/d):

$$E_t = \min\left(E_p - E_i, \frac{(E_p - E_i) \cdot S_u}{S_{u,max} \cdot C_e}, \frac{S_u}{\Delta t}\right) \qquad \text{(Eq. 5.9)}$$

in which C_e is the fraction of $S_{u,max}$ above which E_t is limited by the potential evaporation (Gao et al., 2013; Fenicia et al., 2006). Hence, the total water balance of the unsaturated soil reservoir becomes:

$$\frac{\Delta S_u}{\Delta t} = R_u - E_t \qquad \text{(Eq. 5.10)}$$

This reservoir is included in the model structure of every HRU. However, it is assumed that D = 0 on the grasslands and a different value of D is used for the croplands than for the forests and shrublands. Furthermore, a different value of $S_{u,max}$ is used for each HRU and a different value of D is used for the forests and shrublands than for the croplands.

5.4.1.3 Fast and slow reacting reservoirs

The fast reacting reservoir is replenished by SSF and the slow reacting reservoir by DP. A lag function is used for routing of R_f (Gao et al., 2013):

$$R_{f,l}(t) = \sum_{q=1}^{T_{lag}} c(q) \cdot R_f(t - q + 1) \qquad \text{(Eq. 5.11)}$$

$$c(q) = \frac{q}{\sum_{p=1}^{T_{lag}} p} \qquad \text{(Eq. 5.12)}$$

in which $R_{f,l}$ is the inflow of the fast reacting reservoir (in mm/d), T_{lag} represents the time lag between R_f and $R_{f,l}$ (in d) and c is a weight factor (-). Linear reservoirs are assumed (Fenicia et al., 2006):

$$Q_{f,u} = \frac{S_f}{k_f} \qquad \text{(Eq. 5.13)}$$

$$Q_s = \frac{S_s}{k_s} \qquad \text{(Eq. 5.14)}$$

in which $Q_{f,u}$ and Q_s are the contributions of SSF respectively DP to the river flow (in mm/d), S_f and S_s are the storages in the fast respectively slow reacting reservoirs (in mm), and k_f and k_s are their respective reservoir coefficients (in d). Hence, the total water balances of the reservoirs become:

$$\frac{\Delta S_f}{\Delta t} = \sum_{i=1}^{n} R_{f,l,i} \cdot \frac{A_i}{A_{tot}} - Q_{f,u} \qquad \text{(Eq. 5.15)}$$

$$\frac{\Delta S_s}{\Delta t} = \sum_{i=1}^{n} R_{s,u,i} \cdot \frac{A_i}{A_{tot}} - Q_s \qquad \text{(Eq. 5.16)}$$

in which n = 4 is the number of HRUs (-), A_i is the surface area of HRU i (in m^2) and A_{tot} is the total surface area of the MMC (in m^2). All HRUs are connected by means of those reservoirs.

5.4.1.4 River routing

The total river discharge from each subbasin $Q_{m,j}$ (in mm/d) is the sum of fast and slow flows:

$$Q_{m,j} = \left(Q_{s,j} + \sum_{i=1}^{n} Q_{f,u,j} \right) \cdot \frac{A_j}{A_{tot}} \quad \text{(Eq. 5.17)}$$

in which A_j is the surface area of subbasin j (-). Retention by dams is described in Subsubsection 5.4.2.4. Under natural circumstances, a simple lag function is used for routing along the Mara River:

$$Q_m(t) = \sum_{j=1}^{z} Q_{m,j}(t - T_{r,j}) \quad \text{(Eq. 5.18)}$$

$$T_{r,j} = \frac{d_j}{\bar{u}} \quad \text{(Eq. 5.19)}$$

in which z = 7 is the number of subbasins (-), $T_{r,j}$ is the lag time for subbasin j (in d), d_j is the distance between the subbasin outlet and the Mara Mines gauging station (in m) and $\bar{u}$ is the mean flow velocity of the river (in m/d). More complex methods for routing would require more data or calibration parameters. To calculate the observed discharge Q_o (in mm/d) for each observed water level h (in m), the Manning formula is used as rating curve:

$$Q_o = \frac{k}{n \cdot A_{tot}} \cdot A \cdot R^{\frac{2}{3}} \cdot s^{\frac{1}{2}} = a \cdot A \cdot R^{\frac{2}{3}} \quad \text{(Eq. 5.20)}$$

in which n is the Manning coefficient (in $s/m^{1/3}$), k = 1000 mm/m · 86400 s/d is a conversion factor for the units, A is the cross sectional area (in m^2), R is the hydraulic radius (in m), s is the slope of the hydraulic grade line (-) and a is a calibration parameter (in $mm/(d/m^{8/3})$). Uniform flow is assumed, so s equals the channel bed slope. Assuming that both channel bed slope and n are constant over the modelling period, a is also constant. A and R are a function of h-h_0, in which h_0 is the water level at zero flow (in m).

5.4.2 Water use and demand

5.4.2.1 Rooftop rainwater harvesting

In the MMC, rainwater harvesting from suitable roofs takes place on the croplands and grasslands. P is intercepted by the presumably impervious roofs. It is assumed that all effective rainfall from the roofs $P_{e,h}$ (in mm/d) contributes to the inflow into the rooftop rainwater harvesting reservoir R_h (in mm/d):

$$R_h = \frac{A_r}{A_h} \cdot P_{e,h} \quad \text{(Eq. 5.21)}$$

in which A_r is the effective roof area (in m^2) and A_h is the surface area of the rainwater harvesting reservoir (in m^2). The storage in this reservoir S_h (in mm) is limited by its capacity $S_{h,max}$ (in mm), which may result in overflow $Q_{f,h}$ (in mm/d):

$$Q_{f,h} = \max\left(\frac{S_h - S_{h,max}}{\Delta t}, 0\right) \tag{Eq. 5.22}$$

The abstractions U_h (in mm/d) may be limited by the storage:

$$U_h = \min\left(\frac{S_h}{\Delta t}, U_{h,req}\right) \tag{Eq. 5.23}$$

in which $U_{h,req}$ is the water demand from the reservoir (in mm/d). It is assumed that $A_h << A_r$, so direct rainfall does probably not contribute significantly to the inflow nor open water evaporation to the outflow of the rooftop rainwater harvesting reservoir. Hence, its total water balance becomes:

$$\frac{\Delta S_r}{\Delta t} = R_h - Q_{f,o} - U_h \tag{Eq. 5.24}$$

To close the water balance of each subbasin, $A_{r,i}$ is abstracted from the original surface area A_i of HRU i (in m^2). Furthermore, $Q_{f,o}$ is added to the rainfall P_i (in mm/d) on the connected HRU:

$$P_i = P + \frac{A_r}{A_i} \cdot Q_{f,o} \tag{Eq. 5.25}$$

The latter assumption may not be justified for extreme scenarios with rainwater harvesting from large paved surfaces. Lastly, the same *de facto* descending order of priority is assumed for all water sources in the MMC, consisting of tourism, large-scale irrigated agriculture, piped supply to inhabitants, institutions, industry, manual supply to inhabitants, livestock, small-scale irrigated agriculture and wildlife. However, most users currently do not abstract water rooftop rainwater harvesting reservoirs.

5.4.2.2 Ponds

Both on the croplands and grasslands, HOF may contribute to the open water storage S_o (in mm). Only when the storage capacity $S_{o,max}$ (in mm) is exceeded, overland flow contributes to the river flow:

$$R_{f,o} = \frac{A_o}{A_i} \cdot (P_e - F) \tag{Eq. 5.26}$$

$$Q_{f,o} = \max\left(\frac{S_o - S_{o,max}}{\Delta t}, 0\right) \tag{Eq. 5.27}$$

in which A_o is the surface area of the ponds (in m^2). To close the total water balance, A_o is abstracted from the original value of A_i. Open water evaporation $E_{o,o}$ (in mm/d), infiltration $R_{s,o}$ (in mm/d) and water abstraction U_o (in mm/d) are all taken into account:

$$E_{o,o} = \min\left(\frac{S_o}{\Delta t}, E_p\right) \tag{Eq. 5.28}$$

$$R_{s,o} = \min\left(\frac{S_o}{\Delta t}, F_{max}\right) \tag{Eq. 5.29}$$

$$U_o = \min\left(\frac{S_o}{\Delta t}, U_{o,req}\right) \quad \text{(Eq. 5.30)}$$

in which $U_{o,req}$ is the water demand from ponds (in mm/d). It is assumed that all $R_{s,o}$ percolates to the groundwater. Hence, the total water balance of the ponds becomes:

$$\frac{\Delta S_o}{\Delta t} = R_{f,o} + P - Q_{f,o} - E_{o,o} - R_{s,o} - U_o \quad \text{(Eq. 5.31)}$$

It is assumed that HOF does not take place in the forests and that A_o = 0 m^2 on the shrublands.

5.4.2.3 Groundwater abstractions

Lilande (2014) identified the water types in the Kenyan share of the MMC, using environmental isotopes and hydrochemical tracers. She collected 156 samples in the study area, of which 95 from rivers and streams, 28 from shallow wells, 26 from springs, 5 from boreholes and 2 from rainfall events. The following conclusions may be drawn:

- ***River.*** Lilande concluded that the isotopic signature of the samples from the rivers and streams is derived from local precipitation. As these were collected during baseflow conditions, this supports the hypothesis that the groundwater reservoir in the FLEX-Topo model has a local recharge origin (see Subsubsection 5.4.1.3).

- ***Boreholes.*** The water from the boreholes shows a much more depleted signature. Lilande hypothesized that their recharge origin is located in areas with lower temperatures than those in the MRB. It is therefore assumed that boreholes abstract their water from a regional aquifer that is located beyond the spatial boundaries of the FLEX-Topo model.

- ***Shallow wells.*** At 95% confidence level, Lilande found no significant difference between the isotopic signature of the river water and the water from the shallow wells. It is therefore assumed that the shallow wells withdraw their water from the slow reacting reservoir in the model.

- ***Springs.*** Lastly, the isotopic signature of the spring water shows a much more scattered distribution. However, as this water is naturally part of the surface water, it is assumed that springs are connected to the groundwater reservoir included in the FLEX-Topo model.

Shallow wells are spread over the grasslands and croplands; developed springs on the other hand are mostly located along the bases of the shrubbed and agricultural hillslopes (Ecotourism Kenya, n.d.; Lilande, 2014/2016). Although there may be connectivity between the HRUs, especially between the grasslands and shrublands, parallel slow reacting reservoirs are assumed for water abstractions. The abstractions from shallow wells $U_{w,i}$ (in mm/d) are withdrawn directly from the slow reacting reservoirs:

$$U_{w,i} = \min\left(\frac{S_{s,i}}{\Delta t}, U_{w,i,req}\right) \quad \text{(Eq. 5.32)}$$

$$\frac{\Delta S_{s,i}}{\Delta t} = R_{s,i} - Q_{s,i} - U_{w,i} \quad \text{(Eq. 5.33)}$$

in which $U_{w,i,req}$ is the water demand from shallow wells on HRU i (in mm/d). The water abstractions from springs $U_{s,i}$ (in mm/d) are withdrawn from the slow runoff:

$$U_{s,i} = \min\left(Q_{s,i}, U_{s,i,req}\right) \qquad \text{(Eq. 5.34)}$$

$$Q_{s,j} = \sum_{i=1}^{n}\left(Q_{s,i} - U_{s,i}\right) \cdot \frac{A_i}{A_j} \qquad \text{(Eq. 5.35)}$$

in which $U_{s,i,req}$ is the water demand from shallow wells (in mm/d). A deep groundwater reservoirs is not included in the model. However, abstractions from boreholes for irrigation are taken into account, as these may contribute to return flows. It is assumed that borehole supply equals demand.

5.4.2.4 Dams

At each subbasin outlet, the total river discharge $Q_{x,j}$ (in mm/d) is the sum of the river discharge generated in the subbasin itself and the incoming discharge from the upstream subbasins:

$$Q_{x,j}(t) = Q_{m,j}(t) + \sum_{k=1}^{x} Q_{m,k}(t - T_{x,k}) \cdot \frac{A_k}{A_j} \qquad \text{(Eq. 5.36)}$$

$$T_{x,j} = \frac{d_{x,j}}{\bar{u}} \qquad \text{(Eq. 5.37)}$$

in which x is the number of subbasins upstream of subbasin j (-), and $T_{x,k}$ and $d_{x,k}$ are the time lag (in d) respectively distance (in m) between the outlets of subbasin k and j. Direct abstractions from the river U_d (in mm/d) may be limited by this combined river flow, but if dams are constructed to retain river water, U_d may be limited by the storage in the created reservoir S_d (in mm):

$$U_d = \begin{cases} \min\left(U_{d,req}, Q_x\right) & S_{d,max} = 0\ mm \\ \min\left(U_{d,req}, \dfrac{S_d}{\Delta t}\right) & S_{d,max} > 0\ mm \end{cases} \qquad \text{(Eq. 5.38)}$$

in which $U_{d,req}$ is the water demand from the river or dam (in mm/d). Only for large surface dams, the surface area of the reservoir A_d (in m^2) is varied with S_d. This requires unit conversions to m^3 and m^3/d. For small dams on the other hand, stocks and fluxes of the reservoir are averaged over the entire subbasin. Natural processes take place at these reservoirs, including direct inflow of rainfall P_d (in mm/d) and open water evaporation $E_{o,d}$ (in mm/d):

$$P_d = \frac{A_d}{A_j} \cdot P \qquad \text{(Eq. 5.39)}$$

$$E_{o,d} = \min\left(\frac{S_d}{\Delta t}, \frac{A_d}{A_j} \cdot E_p\right) \qquad \text{(Eq. 5.40)}$$

It is assumed that all surface reservoirs are located in effluent rivers. Hence, infiltration from the dams is not included in the model. Leakage underneath and around the dam is also assumed to be insignificant. The limited storage capacity may however result in overflow $Q_{m,o}$ (in mm/d), and there may be abstractions for hydropower production U_e (in mm/d) and other controlled outflows by reservoir operation U_n (in mm/d):

$$Q_{m,o} = \max\left(\frac{S_d - S_{d,max}}{\Delta t}, 0\right) \quad \text{(Eq. 5.41)}$$

$$U_e = \min\left(U_{e,req}, \frac{S_d}{\Delta t}\right) \quad \text{(Eq. 5.42)}$$

$$U_n = \min\left(U_{n,req}, \frac{S_d}{\Delta t}\right) \quad \text{(Eq. 5.43)}$$

in which $U_{e,req}$ is the water demand for hydropower (in mm/d), $U_{n,req}$ is the desired allowance for regulation (in mm/d) and $S_{d,max}$ is the storage capacity of the reservoir created by the dam (in mm). Hence, the total outflow from the subbasin $Q_{m,d,j}$ (in mm/d), the total water balance of the dam and the total discharge at the basin outlet become:

$$Q_{m,d,j} = Q_{m,o} + U_e + U_n \quad \text{(Eq. 5.44)}$$

$$\frac{\Delta S_d}{\Delta t} = Q_{x,j} + P_d - E_{o,d} - U_r - Q_{m,d,j} \quad \text{(Eq. 5.45)}$$

$$Q_m = Q_{m,d,z} \cdot \frac{A_{tot}}{A_z} \quad \text{(Eq. 5.46)}$$

Eq. 5.36 to Eq. 5.46 are also valid for rivers without dams. In such cases, it is assumed that A_d = 0 m^2 and $S_{d,max}$ = 0 mm: although processes such as open water evaporation take place at rivers, these fluxes are normally assumed to be insignificant compared to the total river flow. Subsurface storage in rivers, i.e. sand dams, also requires adjustments of the equations (Quilis et al., 2009). Hellwig (1973) showed that evaporation from sand decreases drastically with the depth of the water table d_s (in mm). Exponential regression of the measured values for coarse sand results in:

$$E_{o,d} = E_p \cdot 0.996^{d_s} \quad \text{(Eq. 5.47)}$$

$$d_s = \frac{S_{d,max} - S_d}{n} \quad \text{(Eq. 5.48)}$$

in which n is the drainable porosity of the sand (-). This porosity is taken into account in the calculation of $S_{d,max}$. Lastly, reservoir operation is not applied to sand dams in the MMC, so $U_p = U_n = 0$ mm/d.

5.4.2.5 Irrigation

The small- and large-scale irrigated areas are regarded as additional HRUs. To estimate the irrigation water supply $U_{i,s}$ respectively $U_{i,l}$ (in mm/d), it is assumed that the farmers attempt to achieve maximum transpiration $E_{t,req}$ (in mm/d). This requires a minimum storage in the unsaturated zone $S_{u,req}$ (in mm):

$$E_{t,req} = E_p - E_i \quad \text{(Eq. 5.49)}$$

$$S_{u,req} = C_e \cdot S_{u,max} \quad \text{(Eq. 5.50)}$$

As the farmers apply overhead irrigation, the interception reservoir has to be filled before any irrigation water reaches the subsurface:

$$E_{i,req} = \begin{cases} 0 & P_{req} = 0 \\ \min(E_p, I_{max}) & P_{req} > 0 \end{cases} \quad \text{(Eq. 5.51)}$$

in which $E_{i,req}$ is the required interception (in mm/d) and P_{req} is the required rainfall for maximum transpiration (in mm/d). During a first iteration, it is assumed that $P_{req} > 0$ mm/d; an additional iteration may be required to calculate the actual interception. To calculate P_{req} and the required irrigation water supply $U_{i,req}$ (in mm/d), the required infiltration F_{req} (in mm/d) has to be calculated first:

$$F_{req} = \min\left(F_{max}, \max\left(\frac{S_{u,req} - S_u}{(1 - C_r) \cdot \Delta t}, 0\right)\right) \quad \text{(Eq. 5.52)}$$

$$P_{req} = \begin{cases} 0 & F_{req} = 0 \\ F_{req} + E_{i,req} & F_{req} > 0 \end{cases} \quad \text{(Eq. 5.53)}$$

$$U_{i,req} = \max(P_{req} - P, 0) \quad \text{(Eq. 5.54)}$$

Due to F_{max}, $S_{u,req}$ may not always be reached. At the small-scale farms, $U_{i,s}$ may be further limited by the availability of labour, resulting in a daily maximum irrigation water use $U_{i,max}$ (in mm/d), or by the availability of water at the source $U_{i,a}$ (in mm/d):

$$U_{i,s} = \min(U_{i,req}, U_{i,max}, U_{i,a}) \quad \text{(Eq. 5.55)}$$

Large-scale farmers use ponds to cope with fluctuations in river discharge and less labour-intensive irrigation methods. It is assumed that their ponds are not completely refilled after each abstraction, to prevent frequent overflowing due to rainfall and because river flows are not always sufficient:

$$U_p = \min\left(\frac{f_p \cdot S_{p,max} - S_p}{\Delta t}, \frac{A_j}{A_p} \cdot Q_{x,j}\right) \quad \text{(Eq. 5.56)}$$

in which U_p is the water pumped to the irrigation ponds (in mm/d), f_p is the maximum fraction (-) of the storage capacity $S_{p,max}$ (in mm) up to which the ponds are filled by pumping, S_p is the actual storage in the ponds (in mm) and A_p is their surface area (in m^2). It is assumed that there are no conveyance losses, that A_p is independent of S_p and that the ponds are lined. The ponds are however uncovered, so that there is open water evaporation $E_{o,p}$ (in mm/d) from their surface and rainfall may result in overflow $Q_{f,p}$ (in mm/d), which is added to the rainfall on the connected HRU:

$$E_{o,p} = \min\left(\frac{S_p}{\Delta t}, E_p\right) \quad \text{(Eq. 5.57)}$$

$$Q_{f,p} = \max\left(\frac{S_p - S_{p,max}}{\Delta t}, 0\right) \quad \text{(Eq. 5.58)}$$

$$P_i = P + \frac{A_p}{A_i} \cdot Q_{f,p} \quad \text{(Eq. 5.59)}$$

$$U_{i,l} = \min\left(U_{i,req} \cdot \frac{A_l}{A_p}, \frac{S_p}{\Delta t}\right) \quad \text{(Eq. 5.60)}$$

in which A_l is the large-scale irrigated area (in m^2). The connected HRU is usually cropland, but grassland in the southeastern subbasins. Hence, the total water balance of these ponds becomes:

$$\frac{\Delta S_p}{\Delta t} = P - Q_{f,p} - E_{o,p} + U_p - U_{i,l} \quad \text{(Eq. 5.61)}$$

5.5 Parameter estimation

5.5.1 Natural reservoirs and processes

Vegetation uses the unsaturated soil reservoir as buffer for dry periods. Hypothesizing that ecosystems "design" their own root zones, Gao et al. (2014) showed that the mass curve technique, which is usually applied for reservoir design by engineers, can be used to estimate $S_{u,max}$. Required for the calculations are P_e and the mean water demands of the plants during dry periods, which can both be estimated using available satellite and station data series (Gao et al., 2014). Hulsman (2015) applied this method to the HRUs of the MMC, resulting in:

- Forests: $S_{u,max,1}$ = 122 mm
- Shrublands: $S_{u,max,2}$ = 89 mm
- Croplands: $S_{u,max,3}$ = 94 mm
- Grasslands: $S_{u,max,4}$ = 83 mm

For the unsaturated zone, it is also assumed that C_e = 0.5 (Gao et al., 2013; Gharari et al., 2013; Savenije, 1997). Groundwater reacts relatively slowly to forcing, providing baseflow to rivers. Due to the seasonality of rainfall in the MMC, depletion curves can easily be distinguished in the hydrograph. Combining the linear reservoir equation (Eq. 5.14) with the water balance equation of the slow reacting reservoir (Eq. 5.16), assuming that $R_{s,u}$ = 0 mm/d during dry periods, yields an exponential relation between Q_m and t:

$$Q_m(t) = Q_m(t_0) \cdot e^{-\frac{t-t_0}{k_s}} \qquad \text{(Eq. 5.62)}$$

Hence, k_s can be derived from the slope of the depletion curves on semi-logarithmic paper. For the MMC, this results in k_s = 28 d (Hulsman, 2015). For routing, it is assumed that $\bar{u} = 4 \cdot 10^4$ m/d, based on measurements by Rey et al. (2015). Furthermore, the cross-sectional profile of the Mara River at Mara Mines was measured during the EFA (see Figure 5.5), so both A and R can be calculated as function of $h - h_0$. As simplification, a trapezoidal cross section is assumed in the model calculations.

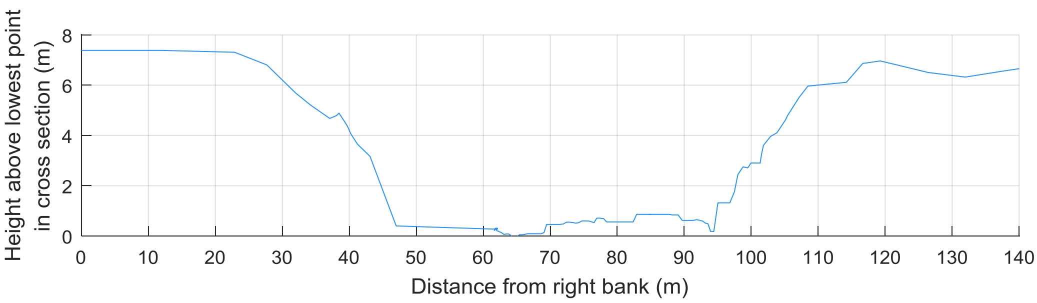


Figure 5.5 – Cross-sectional profile of the Mara River at Mara Mines (GLOWS-FIU, 2012)

5.5.2 Water use and demand

5.5.2.1 Rooftop rainwater harvesting

The model parameters of the rooftop rainwater harvesting component are $I_{h,max}$, A_r, A_h and $S_{h,max}$. As the occurring threshold processes lead to non-linearity, using averaged or summed parameter values may lead to gross inaccuracies. However, modelling each user individually would increase the calculation times and give a false sense of accuracy. For households, by far the greatest statistical variability is found in the reservoir volumes. Some only collect water in pots and cans, with a combined volume of 20 to 150 L, whereas tanks of up to 10000 L are found in the northern subbasins. It is assumed that the same exponential relation between the cumulative fraction of households f_r (-) and their maximum storage size for rainwater harvesting V_h (in L) applies to every subbasin:

$$V_h = A_h \cdot S_{h,max} = a \cdot e^{b \cdot f_r} \qquad \text{(Eq. 5.63)}$$

in which a = 20 L and b = 9.3 are empirical constants, obtained by regression analysis using the method of least squares (R^2 = 0.99). Minimum and maximum encountered or reported volumes of rainwater harvesting reservoirs per subbasin are used as data points. In the model, households are grouped for representative volumes. The value of A_h on the other hand is assumed to be uniform for households throughout the MMC. According to interviewees, the roof of a households' main dwelling is usually constructed of around 20 corrugated iron sheets, resulting in a floor area of roughly 50 m^2. Other dwellings in homesteads may also have iron sheet roofs, but these are typically much smaller.

Data on rainwater harvesting by schools is limited. Associated parameter values are therefore estimated with a guideline of the MWI (2005). It is assumed that the minimum recommended values for A_h and V_h apply to schools. These depend on rainfall statistics and are directly proportional to U_h. Per unit water use of U_h = 1 m^3/d, this results in $A_h = 4 \cdot 10^2$ to $8 \cdot 10^2$ m^2 and $V_h = 1 \cdot 10^5$ to $8 \cdot 10^5$ L, depending on the subbasin. Furthermore, the MWI suggests a runoff coefficient of 0.8 for corrugated iron sheet or similar roofs. This results in $I_{h,max}$ = 1.9 mm, with insignificant correlation to the mean annual rainfall of different stations. This value is used for all suitable roofs in the MMC.

5.5.2.2 Ponds

The model parameters of ponds are A_o and $S_{o,max}$. There are many pond types in the MMC (see Figure 5.6 and Table 5.5). Due to the high data uncertainty, ponds are lumped for each HRU. Moreover, A_o is assumed to be independent of S_o, although cross-section shapes are taken into account in the parameter estimates. The calculations are mainly based on observations, measurements and interviews:

- ***Private and communal ponds.*** It is assumed that every agricultural household reporting ponds as main water source (see Subsection 4.2.3) owns a private pond. On the grasslands, communal ponds are more common. It is assumed that each communal pond serves the same amount of pastoral households. Mean pond sizes are estimated per category.

- ***Road ponds.*** Two types of road ponds are distinguished: elongated and shallow or small with an almost square cross-section.These have roughly the same mean volume but different mean areas. Counts per subbasin are based on road maps (FAO, 2002b) and estimates of the mean spacing of ponds along the different road classes. The amounts of road ponds in the MMNR and SNP are assumed to be insignificant.

- ***Large ponds.*** Exceptionally large ponds are regarded separately. These can be identified on NDVI maps derived from Landsat imagery (NASA Landsat Program, 2016); other ponds cannot be distinguished due to the grid size. Most large ponds are visited or mentioned by Lilande (2016); the surface area of the rest is measured from satellite imagery (Google, n.d.).

- ***Natural off-stream ponds.*** Natural ponds are ubiquitous on the grasslands, especially in the Mara Triangle. The surface area of small and isolated waterholes is assumed to be insignificant compared to the wetland area. Boundaries on a hardcopy map (Watson & Watson, 2013) are compared with observations. On average, natural ponds are relatively shallow.

- ***Ephemeral streams.*** For ephemeral streams on the grasslands, mean volumes and areas per unit stream length are estimated for representative stretches. The results are combined with flow accumulation and stream segment maps derived from the DEM (USGS, 2006).

Not included in the model are for instance potholes, ephemeral streams on the croplands and soil and water conservation measures such as contour trenches, as their volumes and areas are assumed to be insignificant.

Figure 5.6 – Typical examples of the different pond and wetland types in the MMC, from left to right: private pond, communal pond, elongated and shallow road pond, small road pond with almost square cross-section (top), large artificial pond, extensive natural wetland, small and isolated natural off-stream pond, and ephemeral stream (bottom)

Table 5.5 – Estimated volumes of different pond types in the subbasins of the MMC around 1990, averaged over the subbasin areas or, for the total results, over the entire MMC for the total counts (in mm)

Volume (mm)	Private ponds	Communal ponds	Road ponds	Large ponds	Natural off-stream ponds	Ephemeral streams	Total
Nyangores	$3 \cdot 10^{-1}$	0	$7 \cdot 10^{-2}$	$4 \cdot 10^{-1}$	0	0	$\mathbf{8 \cdot 10^{-1}}$
Amala	$2 \cdot 10^{-1}$	$2 \cdot 10^{-2}$	$7 \cdot 10^{-2}$	$2 \cdot 10^{-1}$	$2 \cdot 10^{-3}$	$8 \cdot 10^{-3}$	$\mathbf{4 \cdot 10^{-1}}$
Mid-Mara	$1 \cdot 10^{-1}$	$1 \cdot 10^{-2}$	$5 \cdot 10^{-2}$	$2 \cdot 10^{-1}$	$4 \cdot 10^{-1}$	$7 \cdot 10^{-2}$	$\mathbf{9 \cdot 10^{-1}}$
Lemek	0	$6 \cdot 10^{-2}$	$4 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$1 \cdot 10^{-2}$	$1 \cdot 10^{-1}$	$\mathbf{2 \cdot 10^{-1}}$
Talek	0	$6 \cdot 10^{-2}$	$3 \cdot 10^{-2}$	$6 \cdot 10^{-3}$	$1 \cdot 10^{-2}$	$9 \cdot 10^{-2}$	$\mathbf{2 \cdot 10^{-1}}$
Sand	0	$7 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	0	$3 \cdot 10^{-2}$	$8 \cdot 10^{-2}$	$\mathbf{2 \cdot 10^{-1}}$
Low-Mara	$5 \cdot 10^{-2}$	$3 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$3 \cdot 10^{-2}$	$2 \cdot 10^{-1}$	$7 \cdot 10^{-2}$	$\mathbf{4 \cdot 10^{-1}}$
Total	$\mathbf{7 \cdot 10^{-2}}$	$\mathbf{5 \cdot 10^{-2}}$	$\mathbf{4 \cdot 10^{-2}}$	$\mathbf{8 \cdot 10^{-2}}$	$\mathbf{9 \cdot 10^{-2}}$	$\mathbf{7 \cdot 10^{-2}}$	$\mathbf{4 \cdot 10^{-1}}$

5.5.2.3 Dams

The model parameters of surface dams are A_d and $S_{d,max}$. Only the Tenwek dam is included in the model (see Subsection 4.7.2). According to engineers working at its hydropower plant, the maximum depth of its reservoir decreases yearly from 6 to 3 m; desilting takes place in April. Using $A_d = 6 \cdot 10^3$ m^2 (Google, n.d.) and the cross sectional profile of the Nyangores discharge station, it is estimated that $S_{d,max} = 2 \cdot 10^{-2}$ mm after desilting, of which $1 \cdot 10^{-2}$ mm is unavailable hydropower abstractions.

The Sand River bed is modelled as sand dam: water is stored in the sand upstream of constructed walls and natural rock outcrops. Abstractions currently take place at scoop holes, but shallow wells may also be constructed (Maddrell & Neal, 2012). A mean depth of 2 m is estimated using interviews and observations in the river and nearby gullies. The widths and lengths of representative river sections are obtained by field measurements and stream segment maps derived from the DEM (USGS, 2006). Infiltration in the banks probably increases the effective storage capacity (Maddrell & Neal, 2012; Quilis et al., 2009). The coarse sand has an estimated n = 0.27 (Johnson, 1967). These figures result in $A_d = 1 \cdot 10^6$ m^2 and $S_{d,max} = 1 \cdot 10^{-3}$ mm.

5.5.2.4 Irrigation

The additional model parameters due to irrigation are A_p, $S_{p,max}$, f_p and $U_{i,max}$. According to Jimmy Naritoi (personal communication, 4 October 2014), a storage volume of $1 \cdot 10^3$ m^3 is used to irrigate 137 ha at Olerai Mara Farm. The surface area of this reservoir is $4.5 \cdot 10^2$ m^2 (Google, n.d.), resulting in a mean depth of 2.2 m. It is assumed that the pond is filled up to 0.2 m below the rim. For all other large-scale irrigated farms, the same values of $S_{p,max} = 2.2 \cdot 10^3$ mm, f_p = 0.9 and A_p/A_l = 3.3 m^2/ha are used. For daily bucket irrigation of private gardens in South-African rural areas under unlimited water availability, mean uses of 2.5 mm/d (Perez de Mendiguren & Mabelane, 2001) and 2.88 mm/d (Ladki et al., 2004) were found. As data from the MMC or even Kenya are not available, an average of $U_{i,max}$ = 2.7 mm/d is applied to the MMC.

5.6 Time varying input

Apart from water demand (see Chapter 4), additional time varying input is required. Data were obtained from stations in and around the MMC (see Appendix H). Station selection was based on location, data quality and data availability during the modelling period. For instance, data gaps were only accepted in the water level series. Data series of rainfall, temperature, water level and water demand from 1980 to 1992 were used for calibration and data from 1970 to 1976 for validation:

- ***Rainfall.*** Daily rainfall series were obtained from 28 stations. Hulsman (2016) assessed their quality using double mass curves. For some subbasins, two series with similar statistics were combined to increase the temporal coverage. Satellite data (e.g. Novella & Thiaw, 2013), were not used, as these may incorrectly represent rainfall statistics in the MMC (Dessu & Melesse, 2013; Ochieng, 2009) and have little overlap with the water level data.

- ***Temperature.*** Daily minimum, maximum and mean temperature series were collected from 9 stations. Data quality control included checks for both temporal and spatial outliers (Hulsman, 2016). Gaps shorter than one week were filled by linear interpolation and longer gaps by long term averaged daily temperatures. As temperature in the troposphere usually decreases with elevation, environmental lapse rates were estimated from the station data and mean subbasin elevations were calculated from the DEM (USGS, 2006).

- ***Water level.*** Daily water level and discharge series were obtained from 4 stations in the MMC. Hulsman (2016) compared multiple versions for each station and removed erroneous data, including outliers, prolonged constant water levels and apparent duplications. Furthermore, the data were corrected for datum shifts. As there is considerable uncertainty about the rating curve at Mara Mines (Hulsman, 2016), the model is calibrated on stage.

5.7 Calibration method

5.7.1 Objective functions

Calibration is the adjustment of parameter values until the hydrological behaviour of the observed and modelled output are sufficiently similar (Beven, 2001b). For this thesis, the MOSCEM-UA algorithm is applied for automatic calibration. An advantage of this effective and efficient calibration algorithm is the possibility to apply multiple performance measures to define optimal parameter sets (Vrugt et al., 2003). In traditional objective functions, hydrographs or logarithmic hydrographs are used. However, because of the many drawbacks of this approach (Westerberg et al., 2011), flow duration curves are used in this study. The Nash-Sutcliffe efficiency (NSE) is applied (Nash & Sutcliffe, 1970). As the NSE of the flow duration curves NSE_{FDC} (-) emphasizes high flows, the NSE of the logarithmic flow duration curve NSE_{logFDC} (-) is also used:

$$NSE_{logFDC} = 1 - \frac{\sum\left(\log Q_{o,FDC} - \log Q_{m,FDC}\right)^2}{\sum\left(\log Q_{o,FDC} - \overline{\log Q_{o,FDC}}\right)^2} \qquad \text{(Eq. 5.64)}$$

$$NSE_{FDC} = 1 - \frac{\sum\left(Q_{o,FDC} - Q_{m,FDC}\right)^2}{\sum\left(Q_{o,FDC} - \overline{Q_{o,FDC}}\right)^2} \qquad \text{(Eq. 5.65)}$$

Because of the uncertainty about the rating curves in the MMC (Hulsman, 2016), the model is calibrated on stage. Observed and modelled water levels are converted to discharges by Eq. 5.20, with a as calibration parameter. A spin-up time of 1 year is excluded from the objective function calculations. Dates without stage observations of sufficient quality are also removed from the model results, as their occurrence may be biased. Although as many parameters as possible are estimated using measurements, calculations or literature to prevent equifinality (see Section 5.5), calibration remains required, which is mainly due to scale issues and “uniqueness of place” (Beven, 2001a).

5.7.2 Parameter constraints

Parameter and process constraints are applied to discard unfeasible parameter sets based on expert knowledge. Parameter constraints are applied *a priori*: parameter combinations that are deemed unrealistic are discarded before model evaluation runs (Gharari et al., 2013). For instance, the highest value of I_{max} is expected in forests, followed in decreasing order by shrublands, croplands and grasslands. Furthermore, the value of D is expected to be lower in the forests and shrublands than in the croplands:

$$I_{max,1} > I_{max,2} > I_{max,3} > I_{max,4} \qquad \text{(Eq. 5.66)}$$

$$D_{1,2} < D_3 \qquad \text{(Eq. 5.67)}$$

The remaining parameters are calibrated freely, within reasonable ranges. These ranges are based on assumptions, water balances, literature, measurements and iterations. For instance, the fast reacting reservoir should drain faster than the slow reacting reservoir, so 0 d < k_f < 28 d (see Subsection 5.5.1). Furthermore, the range for a is estimated using empirical Manning coefficients (Chow, 1959) and measurements from the DEM (USGS, 2006), but the possible influence of rapids is also taken into account (Hulsman, 2015). Ranges for I_{max} are inferred from Breuer et al. (2003).

5.7.3 Process constraints

Process constraints are applied *a posteriori*: parameter sets that result in unexpected internal fluxes are discarded after the model evaluation runs (Gharari et al., 2013). For example, mean percolation rates are assumed to be higher in the forests and shrublands than in the croplands and grasslands. Similarly, it is expected that the grasslands generate on average more overland flow per unit area than croplands and shrublands, whereas overland flow is not included in the model structure of forests:

$$\overline{R_{s,u,1}}, \overline{R_{s,u,2}} > \overline{R_{s,u,3}}, \overline{R_{s,u,4}} \qquad \text{(Eq. 5.68)}$$

$$\overline{R_{s,o,2}}, \overline{R_{s,o,3}} < \overline{R_{s,o,4}} \qquad \text{(Eq. 5.69)}$$

Furthermore, mean annual evaporation E_b (in mm/yr) and runoff Q_b (in mm/yr) can be estimated using the Budyko curve, requiring meteorological input only (Arora, 2002). For each subbasin, the modelled annual evaporation and runoff are compared with these estimates:

$$\frac{\overline{Q_b}}{\overline{\sum P}} = 1 - \frac{\overline{E_b}}{\overline{\sum P}} = \exp\left(-\frac{\overline{\sum E_p}}{\overline{\sum P}}\right) \qquad \text{(Eq. 5.70)}$$

$$\overline{Q_b} - 5 \cdot \sigma_{Q_b} < \overline{\sum Q_m} < \overline{Q_b} + 5 \cdot \sigma_{Q_b} \qquad \text{(Eq. 5.71)}$$

$$\overline{E_b} - 5 \cdot \sigma_{E_b} < \overline{\sum E} < \overline{E_b} + 5 \cdot \sigma_{E_b} \qquad \text{(Eq. 5.72)}$$

Additionally, the NDVI ratio $r_{i,i+k}$ (-) can be used to estimate the transpiration ratios of HRUs, assuming a directly proportional relation between NDVI and transpiration (Gharari et al., 2013; Szilagyi et al., 1998). For each pair of HRUs, the modelled ratio of transpirations is compared with these estimates, using the MOD13Q1 product (Didan, 2015) for the NDVI:

$$\frac{E_{t,i}}{E_{t,i+k}} \approx \frac{\overline{NDVI_i}}{\overline{NDVI_{i+k}}} = r_{i,i+k} \qquad \text{(Eq. 5.73)}$$

$$\overline{r_{i,i+k}} - 5 \cdot \sigma_{r_{i,i+k}} < \frac{\overline{E_{t,i}}}{\overline{E_{t,i+k}}} < \overline{r_{i,i+k}} + 5 \cdot \sigma_{r_{i,i+k}} \qquad \text{(Eq. 5.74)}$$

Lastly, the yearly number of peak flows in the Sand River N_{peak} (-) is limited due to infiltration of river flow into the river bed. Flow in the Sand River is considered to be peak flow if $Q_{m,o,6}$ > 2 mm/d; peak flows on subsequent days are only counted once. The average number of observed peak flows in the Sand River is not more than 5 per year:

$$\overline{N_{peak}} \leq 5 \qquad \text{(Eq. 5.75)}$$

5.8 Calibration and validation results

The resulting flow duration curves and hydrographs at Mara Mines are plotted for both the calibration and validation periods (see Figure 5.7 respectively Figure 5.8). The model performs well during both, with NSE_{logFDC} = 0.990 and NSE_{FDC} = 0.937 during calibration and NSE_{logFDC} = 0.991 and NSE_{FDC} = 0.932 during validation. Moreover, the shapes of the observed and modelled hydrographs are similar: most peaks are captured, their timings usually match and both the rising and falling limbs have about the same shapes. Moreover, the balance between water demand and supply corresponds to observations (see Subsubsection 6.3.1.2). These are all requirements for a high predictive certainty.

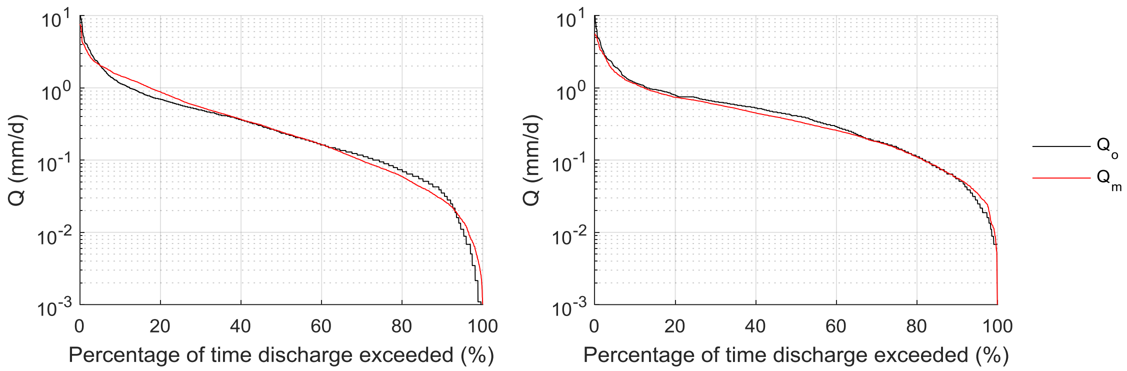


Figure 5.7 – Flow duration curves resulting from calibration (left) and validation (right)

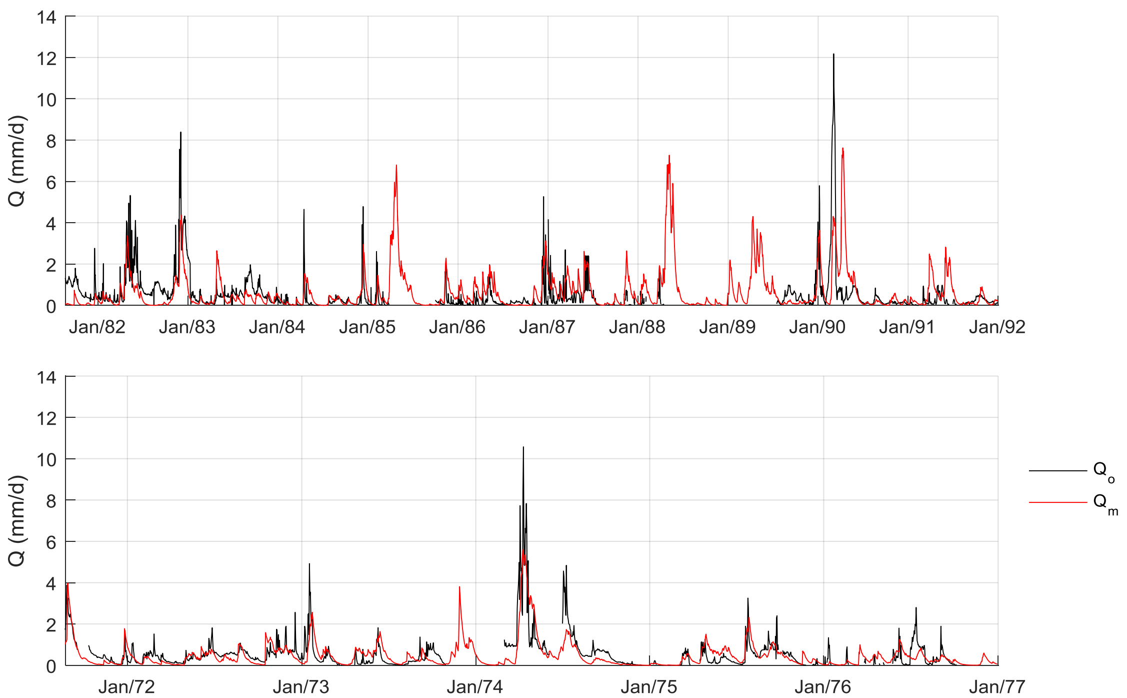


Figure 5.8 – Hydrographs resulting from calibration (top) and validation (bottom)

Due to the inclusion of water demand, the model performance during calibration did not improve significantly, but the validation performance increased with $\Delta NSE_{logFDC} = 0.035$ and $\Delta NSE_{FDC} = 0.021$. Moreover, improvements were clearly visible in the flow duration curves: especially the low flows became more realistic (see Figure 5.9). These results may support the hypothesis that the inclusion of artificial water abstractions improves the model's representation of reality.

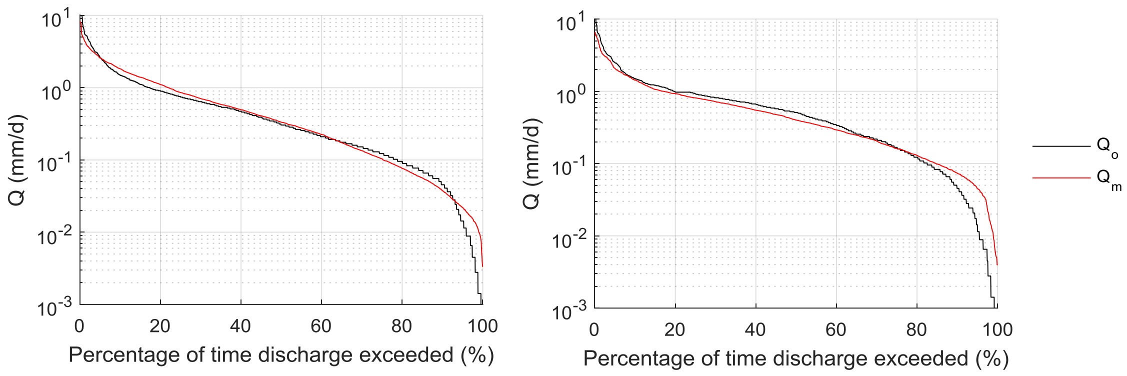


Figure 5.9 – Flow duration curves resulting from calibration (left) and validation (right) of the model without inclusion of water demand

Lastly, most parameters are well-defined (see Figure 5.10). Increasing the parameter ranges makes some peaks even more clearly visible, which indicates that appropriate ranges were selected. As T_{lag} could be fixed anywhere in its range without affecting the model performance, the lag function for SSF was removed from the model structure to avoid compensation of errors by automatic adjustment of other parameters. However, another lag function might be more appropriate. For F_{max}, field observations and its relatively low correlation suggest that its value may differ significantly between HRUs and subbasins. Distributing this parameter may improve model performance, but might also increase equifinality.

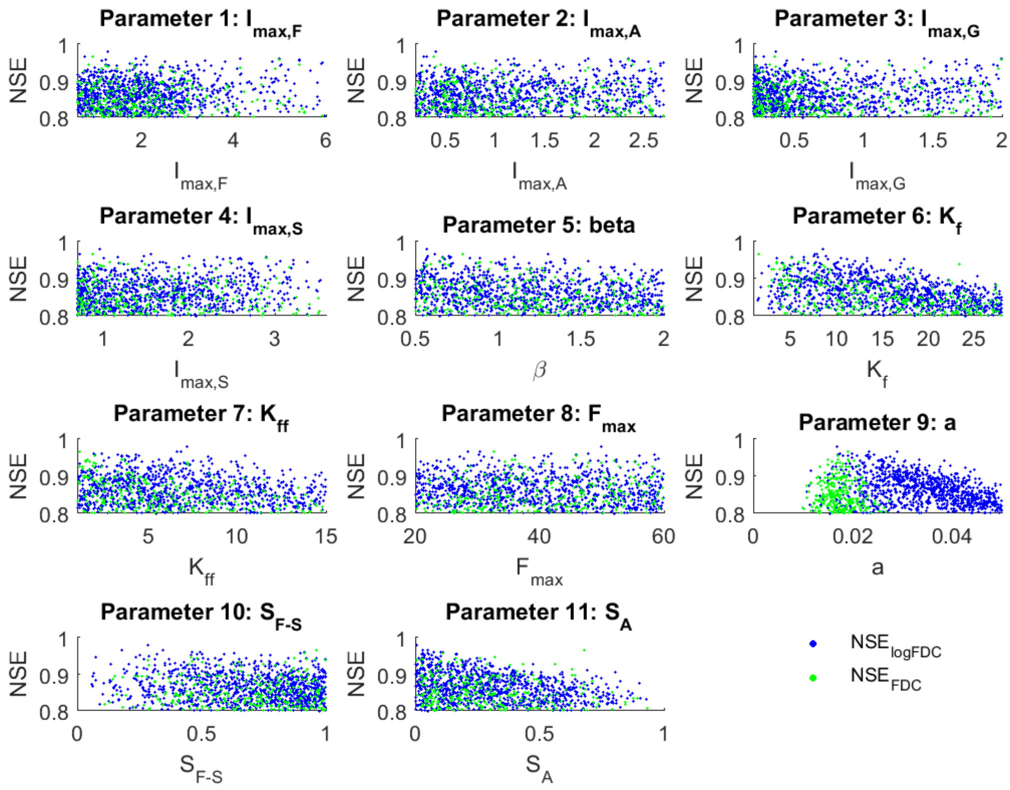


Figure 5.10 – Scatter plots in which all tested values of the calibration parameters are plotted against their score on both objective functions

6 | Water management scenarios

6.1 Introduction

Scenario selection was based on predicted changes in the study area, concerns of interviewed stakeholders and potential solutions for experienced water scarcity. The MWI (2005) and WRMA (2009) prescribe a design period of 20 years in their design manuals on water supply for Kenya. Selected scenarios therefore include predicted changed water demand at each source, water demand of each user, land use and climate in 20 years. Standardization of scenario evaluation included the creation of a reference model and the establishment of performance measures. The assessment was based on changes in balances between water demand and supply at the various water source types in the MMC. This evaluation was mostly done at subbasin level, although the performance regarding EFRs was only evaluated at Mara Mines.

6.2 Scenario selection

6.2.1 Change in water demand

Each water user may have different impacts on the balances between demand and supply in the MMC, which is due to differences in abstracted quantities and in partitioning between sources. For each user, “best guess” scenarios were therefore selected to estimate their most likely influences at the end of the design period. “Extreme” scenarios were also included, to estimate the boundaries for other scenarios. For each user, modelled demands were therefore no demand, “expected” demand and “maximum” demand at the end of the design period. The extrapolations and uncertainty estimations were based on Chapter 4; the assumptions for the scenarios of maximum demand are listed in Appendix F. Uncertainties in the partitioning between water sources were not taken into account, as scenarios on water sources were regarded separately (see Appendix I).

Water use from different sources may have different impacts on the flow regimes of the rivers and the balances between water supply and demand at other sources in the MMC. For controlled comparisons, separate scenarios were included for an increase in demand from each source of $1 \cdot 10^{-4}$ mm/d over the entire MMC. Extreme scenarios were also selected, each consisting of the partitioning of all demand to a source. Furthermore, the allocation of all demand from boreholes to shallow wells was modelled, because of the uncertainty about the recharge origin of borehole water in the MMC (see Subsubsection 5.4.2.3). Lastly, the water availability at some sources may be enhanced by enlarging their storage sizes. This was tested for both ponds and rooftop rainwater harvesting, as these are considered to be ideal solutions for water scarcity affecting inhabitants respectively livestock (see Subsection 3.4.4).

6.2.2 Land use change

Interviewees listed deforestation as a major problem in the MMC (see Section 3.3). Previous studies suggested that deforestation may indeed have affected the hydrological regime of the Mara River significantly (Mango et al., 2011; Mati et al., 2008; Melesse et al., 2008; Mutie et al., 2006). Moreover, reforestation is often included in the Sub-Catchment Management Plans (SCMPs) by WRUAs (see

Appendix A) and mentioned by interviewees as an ideal solution for perceived increases in Mara River flow fluctuations. Lastly, shrubland protection is a main activity of WRUAs in the southeastern subbasins to prevent reduction of spring discharges (see Section 3.4). For these reasons, deforestation and reforestation scenarios are included for both forest and shrubland (see Appendix I). These scenarios are derived from literature and land cover maps:

- ***Forests.*** Forests in the MMC are almost exclusively found in the northern subbasins (see Subsection 5.3.2). According to analysis of Landsat imagery by Mati et al. (2008) and Mutie et al. (2006), the forest cover in the MMC declined by 32% between 1973 and 2000 due to agricultural encroachment. As extreme scenarios, reforestation of this area and conversion of the entire HRU to cropland are therefore modelled.

- ***Shrublands.*** Shrublands in the MMC are mostly found in the pastoral areas. It is assumed that only grasslands with $s > s_{threshold}$ may have been converted from shrublands (see Subsection 5.3.3). An increase in shrubland area of about 1% is deemed representative for these small areas. As extreme scenarios, reforestation of these hillslopes and conversion of the entire HRU to grassland are therefore modelled.

All scenarios are implemented both without and with changes in water demand and storage facilities; these changes are assumed to be proportional to the area changes of croplands respectively grasslands. Furthermore, it is assumed that the characteristics of the reforested areas equal those of the remaining indigenous forests or shrublands.

6.2.3 Climate change

Most interviewed stakeholders believed that climate change negatively has affected the water availability in the MMC during the past decades and that these negative impacts will worsen in the future. For agriculture, climate change is even considered to be the main cause of growing water scarcity (see Subsection 3.3.1). Recent studies found that future climate change may indeed have significant impact on the hydrological regime of the Mara River (Dessu & Melesse, 2012; Mango et al., 2011). To compare this impact with the output of the other scenarios and to assess the influence of climate change on water availability from different sources, predicted changes in temperature and rainfall are included as scenarios (see Appendix I).

Most global circulation models (GCMs) project increasing temperatures and precipitation in East Africa (Anyah & Qiu, 2012). Dessu and Melesse (2012) compared predictions for the MRB of sixteen GCMs, two downscaling methods and three Special Report for Emission Scenarios (SRESs; Nakicenovic et al., 2000). To facilitate comparisons with other scenarios, their results are linearly interpolated to a 20 year design period (see Table 6.1). Furthermore, SRES A2 is discarded and the numbers of scenarios of the other SRESs are reduced based on similarities. Lastly, whereas for instance Mango et al. (2011) assumed constant percentage changes in rainfall over the year for the MMC, Dessu and Melesse found significant seasonal variations. The influence of yearly averaging is tested for both SRES A1B and B1, assuming the same changes in total rainfall volumes as in the original scenarios.

Table 6.1 – Climate change projections under different SRES at the end of a 20 year design period, interpolated from the analysis of Dessu and Melesse (2012)

SRES	Season	Temperature increase (°C)			Rainfall increase (%)		
		Mean	Min	Max	Mean	Min	Max
A1B	Mar – May	0.8	0.5	1.4	6.7	-5.1	20.3
	Jun – Aug	0.7	0.4	1.4	0.0	-7.2	10.9
	Sep – Nov	0.7	0.5	1.2	-2.9	-6.7	0.8
	Dec – Feb	0.7	0.5	1.2	7.7	-8.5	28.0
B1	Mar – May	0.6	0.3	1.4	10.7	0.8	19.7
	Jun – Aug	0.5	0.3	1.3	8.0	-5.1	37.3
	Sep – Nov	0.5	0.3	1.1	1.1	-3.5	8.0
	Dec – Feb	0.5	0.3	1.2	18.7	5.1	43.2

6.3 Evaluation criteria

For the evaluation of scenarios, a reference model was created first. As discharge or water level data were not required for this model, a total series length of 22 years could be selected for the meteorological time varying input; this modelling time included the calibration and validation periods. The model structure, parameter values (see Chapter 5) and all other inputs were kept constant over the years, although some varied between months. For instance, monthly water use estimates of 2016 were used (see Chapter 4). For scenario evaluation, scenario outputs were compared with the output of the reference model. As such, the impacts of any changes in the MMC could be assessed individually, under various meteorological circumstances.

The assessment was based on changes in balances between water demand and supply at the various water source types in the MMC. To facilitate comparison, various statistics were calculated. For instance, the changes in monthly mean evaporative and runoff fluxes were determined at subbasin level. Furthermore, the three widely used criteria proposed by Hashimoto et al. (1982) were applied. These are reliability, resilience and vulnerability.Their respective dimensionless metrics are the probability α that a predefined system variable X_t at time t is in a satisfactory state S (see Eq. 3.76), the average probability γ of recovery from failure F in a single time step (see Eq. 3.77), and the expected maximum severity ν during a sojourn into F (see Eq. 3.78):

$$\alpha = \mathrm{P}(X_t \in S) \qquad \text{(Eq. 3.76)}$$

$$\gamma = \mathrm{P}(X_{t+1} \in S \mid X_t \in F) \qquad \text{(Eq. 3.77)}$$

$$\nu = \sum_{j \in F} s_j \cdot e_j \qquad \text{(Eq. 3.78)}$$

in which s_j is the severity of discrete outcome x_j for X_t and e_j is the probability that x_j is the most severe outcome during a sojourn into F (Hashimoto et al., 1982). For this thesis, failure or unsatisfactory outcome is defined as insufficient water supply to meet demand. Therefore, s_j is defined as 1 for no supply, with a linear increase to 0 for just sufficient supply. As such, the values of all indices range between 0 and 1; improvements are indicated by higher values of α and γ and lower values of ν.

For scenario evaluation, distinction was made between different users, sources, subbasins, years and months. EFRs were only compared with modelled flows at EFA Site 5, i.e. Mara Mines, as the rating curves of the upstream EFA sites were not available. As the EFRs were provided for both drought and maintenance years (see Section 4.8), all modelling years were classified using the Standardized Precipitation Index (Kumar et al., 2009) and the Effective Drought Index (Byun & Kim, 2010), which were also used during the EFA (GLOWS-FIU, 2012). Although monthly EFRs were provided, daily output were used to calculate performance measures, to better detect small changes. The supply to all other water users was also compared with the demand at each source. As rivers are assumed to be the last alternative sources for all users, the performances of the rivers equal the total performance for reliability and resilience.

6.3.1 Reference model

6.3.1.1 EFRs

In the reference model, mean monthly flows exceed EFRs at EFA Site 5 from the onset of the short rains until the first months of the long dry season, during both drought and maintenance years (see Figure 6.1). During the rest of the long dry season however, EFRs are not met during maintenance years and flows are critical during drought years. Reliability is highest and vulnerability is lowest in May (see Figure 6.2); this is at the end of the long rains, when the mean storage levels, rainfall intensities and rainfall frequencies are all relatively high. At the end of the dry season on the other hand, when storages are depleted and rainfall is relatively low, reliability is lowest and vulnerability highest.

Despite the lower mean flows during drought years, reliability is lower and vulnerability higher during maintenance years (see Figure 6.2). This is to the disproportionally higher EFRs. Only in November, maintenance year reliability is higher than drought year reliability, as the short rains usually arrive later than average during drought years. Similarly, small peaks are visible in the performance in March, due to the erratic timing of the onset of the long rains. Resilience on the other hand is slightly higher during maintenance years, which is due to higher frequency and intensity of rainfall events. However, the uncertainty in resilience is high due to the low mean values.

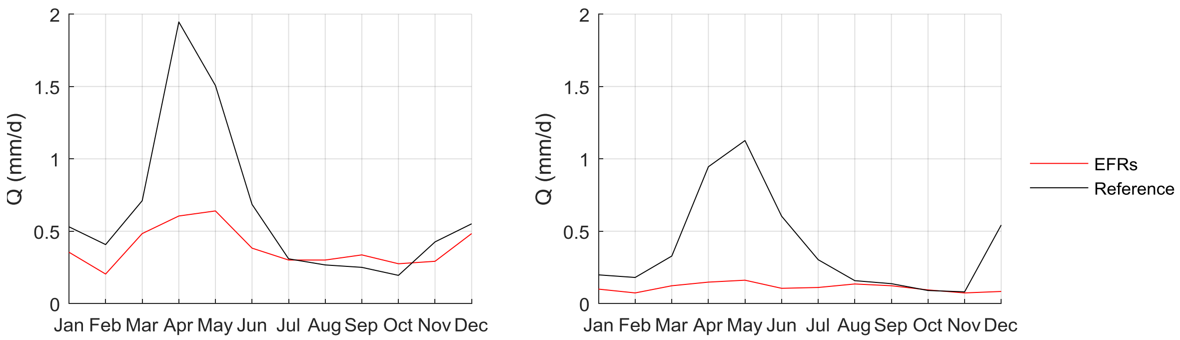


Figure 6.1 – Comparison of reference flows with EFRs at EFA Site 5, during maintenance years (left) and drought years (right)

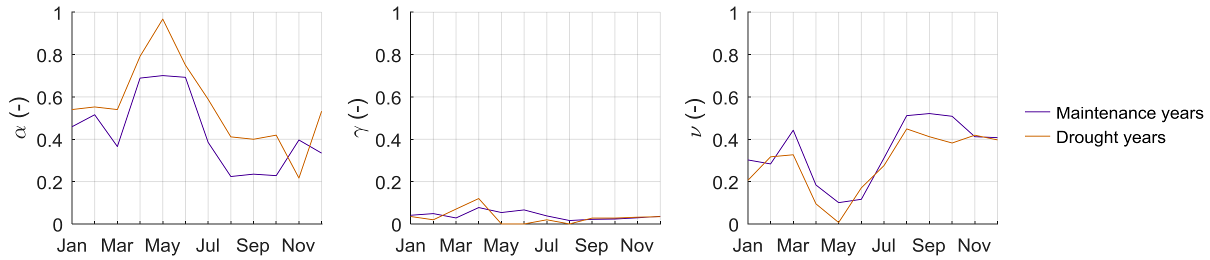


Figure 6.2 – Performance regarding EFRs at EFA Site 5 during drought and maintenance years: reliability (top left), resilience (top right) and vulnerability (bottom); the

6.3.1.2 Water sources

The performance of all water sources in the reference model is calculated at subbasin level and their performance over the year is plotted for the entire MMC (see Appendix J). The performances corresponds to observations and interview results. For boreholes, this is due to the modelling assumption that boreholes abstract water from an aquifer beyond the spatial boundaries of the model, for which supply always equals demand. This assumption might be incorrect, so the actual performance of boreholes may be worse; the results for boreholes should therefore be treated with caution. For all other water sources, the water supply in most subbasins does not always meet demand.

On average, rivers are the second-most reliable water sources in the MMC. In the Sand subbasin for instance, the water supply from the Sand River is almost always sufficient to meet demand. This is due to the storage in sand dams, in combination with the relatively low demand from rivers per unit area – the latter is inter alia due to the very low score on accessibility (see Appendix D). The reliability of all other rivers in the MMC is lowest at the end of the dry season, when water demands are highest and river flows lowest. In the northern subbasins, the rivers are most under pressure due to large-scale irrigated agriculture. In the Mid- and Low-Mara subbasins, the reliability of the Mara River is relatively high, due to the inflow from the upstream subbasins.

On average, shallow wells are the third-most reliable sources in the MMC. The reliability of shallow wells is highest during periods with high groundwater levels, i.e. from the end of the long rains to the first months of the long dry season. Moreover, their reliability is highest in the southeastern subbasins, which is mainly due to the relatively low demand per unit area in these subbasins. The mean percolation to the slow reacting reservoir at subbasin level is up to 67 mm/yr. For an average year, this leads a difference between minimum and maximum storage levels of up to 27 mm. The difference with observed water level fluctuations in shallow wells may for instance be caused by delayed discharge to rivers or shallow wells, but also by the filling of shallow wells through other runoff processes. Hence, the results for shallow wells should be treated with caution.

On average, springs are the fourth-most reliable sources in the MMC. In the southeastern subbasins, their reliability is even higher than the reliability of shallow wells and sometimes even rivers. This is due to the relatively large area percentages of shrublands (see Section 5.3) in combination with the relatively low demands from springs per unit area in these subbasins. Moreover, springs in forests are currently not accessible. Similar to shallow wells, the reliability of springs is highest during the end of the long rains and the first months of the long dry season, as groundwater responds relative slowly to forcing. For both source types, this results in a relatively low resilience compared to rivers. Lastly, as spring flow generation may be a threshold process, the actual reliability of springs may be lower; the results should therefore be treated with caution.

The water availability from ponds and rooftop rainwater harvesting mirrors the rainfall pattern more closely than for other sources in the MMC. This is due to their low storage sizes, in combination with the relatively high demands. Therefore, these sources have the lowest scores on reliability. The reliability of ponds is highest in the Lemek and Lemek subbasins, due to the relatively large pond sizes in the pastoral areas. The vulnerability of ponds is however highest in the Sand subbasin, due to the high infiltration losses in its sandy soils (see Subsubsection 5.4.2.2). Rooftop rainwater harvesting has a reliability of zero in every subbasin, with the highest vulnerability in the subbasins with the smallest tank sizes for households (see Subsubsection 5.5.2.1).

6.4 Change in water demand

6.4.1 Shallow wells

There is still considerable potential for increased water use from shallow wells (see Figure 6.3), especially during the last months of the long rains and the first months of the long dry season, when storage levels in the slow reacting reservoir are relatively high. For instance, if all demand is allocated to shallow wells, the mean use from this source type increases on average by a factor 8. In the southeastern subbasins, where the abstractions from shallow wells per unit area are relatively low in the reference model, the mean use even increases by a factor 27 to 48. However, as the water use from shallow wells is abstracted directly from the saturated zones, the abstractions are limited by the storages in the slow reacting reservoirs. For instance, if all demand is allocated to the source type, this results in a total mean performance of shallow wells of only $\alpha = 0.00$, $\gamma = 0.00$ and $\nu = 0.95$.

Furthermore, as water use from shallow wells is abstracted directly from the slow reacting reservoirs, use affects groundwater flows. For small increases of $1 \cdot 10^{-4}$ mm/d over the entire basin, the overall mean reduction in groundwater flows is 0.73%, with monthly means of up to 1.6% during the dry season. However, due to the small contribution of groundwater flows to the total discharge of the Mara River, the mean reduction in total flows is negligible for small changes in water demand from shallow wells. For the allocation of all demand to the source, the performance regarding EFRs reduces slightly for reliability and vulnerability; resilience on the other hand is hardly affected. At downstream springs, the water availability also decreases slightly due to the lower groundwater levels. For instance, allocating all demand to shallow wells results in $\Delta\alpha = -0.05$ and $\Delta\nu = 0.05$ at springs in the Low-Mara subbasin.

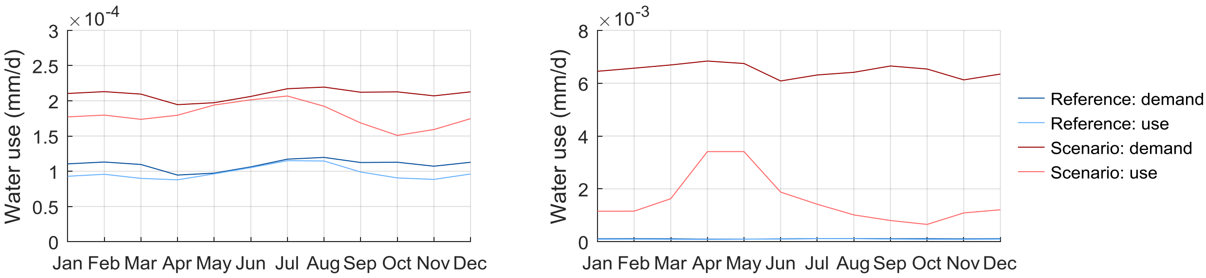


Figure 6.3 – Comparison of the total mean water use and demand from shallow wells in the MMC for an increase in demand of $1 \cdot 10^{-4}$ mm/d (left) and the allocation of all demand to shallow wells (right)

6.4.2 Springs

For springs, there is also considerable potential for increased water use (see Figure 6.4), especially during the last months of the long rains and the first months of the long dry season. As water use from springs is abstracted from groundwater flow emerging at the bases of agricultural and shrubbed hillslopes, water use from springs does not affect the storage levels in the slow reacting reservoirs. Therefore, the water use from springs under maximum demand is smoother than for shallow wells (see Figure 6.3 and Figure 6.4). In the southeastern subbasins, the relatively low demands from springs per unit area in the reference model and the relatively large area percentages of shrublands result in an increase in mean use at springs by a factor 11 to 24 due to the allocation of all demand to springs. This is capped to a factor 3 to 7 in the northern subbasins. Allocating all demand to springs results in a total mean performance of springs of only $\alpha = 0.00$, $\gamma = 0.00$ and $\nu = 0.61$.

Furthermore, the water use from springs is abstracted directly from groundwater emerging at the bases of agricultural and shrubbed hillslopes. For small increases of $1 \cdot 10^{-4}$ mm/d over the entire basin, the overall mean reduction in groundwater flows is 0.85%, with monthly means of up to 2.8% during the dry season. Therefore, the impacts of increased spring water demand are even more negative than the effects of similar increases in demand from shallow wells. Again, the resilience is hardly affected.

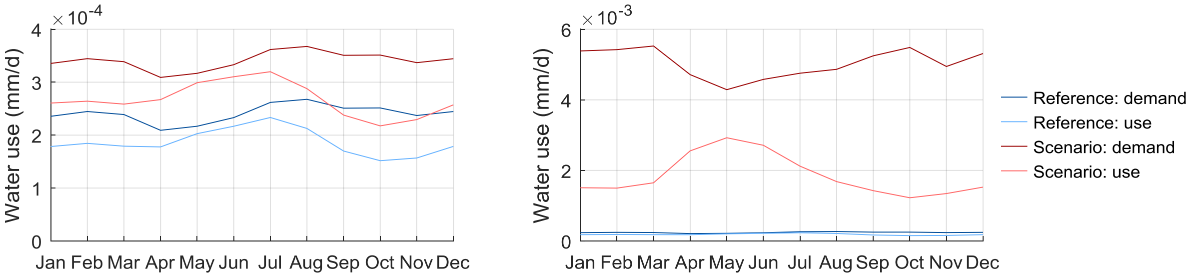


Figure 6.4 – Comparison of the total mean water use and demand from springs in the MMC for an increase in demand of $1 \cdot 10^{-4}$ mm/d (left) and the allocation of all demand to springs (right)

6.4.3 Boreholes

It is assumed that all boreholes in the MMC withdraw their water from an aquifer beyond the spatial boundaries of the model (see Subsubsection 5.4.2.3). Furthermore, it is assumed that the supply from this aquifer always equals demand. Therefore, borehole performance is not affected by changes in demand (see Figure 6.5). However, the total incoming fluxes of the system increase with enhanced use from boreholes. This "additional" water may leave the system by increased discharge, evaporation or consumption. For instance, if boreholes are applied by all users in the MMC, total mean river flows at Mara Mines increase by 0.53%, evaporation by 0.02% and water use by 13%. This is even more during drought years, with 0.71%, 0.03% respectively 17%. Furthermore, mean transpiration on large-scale irrigated farms increases by 6% and becomes more constant over the years.

Even more important for the performance regarding EFRs are the changes in the contributions of the different runoff processes. The increase in river flows is mostly due to an increase in mean groundwater flows of 4%. Due to the enhanced baseflows and because water demand is highest at the end of the dry season, the mean increase in river flows is even 20% in October during drought years. Increasing the demand from boreholes without changing the demand from other sources or allocating all demand in the MMC to boreholes slightly improves the performance regarding EFRs. From a hydrological perspective, constructing boreholes as solution for water scarcity may therefore be recommended. Moreover, boreholes are considered to be an ideal solution for water scarcity by most interviewed stakeholders (see Subsection 3.4.4).

However, caution is advised for an increased use of boreholes. Firstly, the assumption that boreholes abstract their water from an aquifer beyond the spatial boundaries of the model may be incorrect. Abstracting their water from the slow reacting reservoir instead considerably reduces their potential for expansion of borehole water use and has negative impacts on river flows (see Subsubsection 6.4.1). Secondly, the assumption that the supply from the regional aquifer always equals the demand may also be incorrect. Hence, the actual performance of boreholes might be worse and, if the regional aquifer is prone to depletion, enhancement of the water use from boreholes might have negative long-term effects. Lastly, water abstractions from boreholes in the MMC might exacerbate any water scarcity downstream.

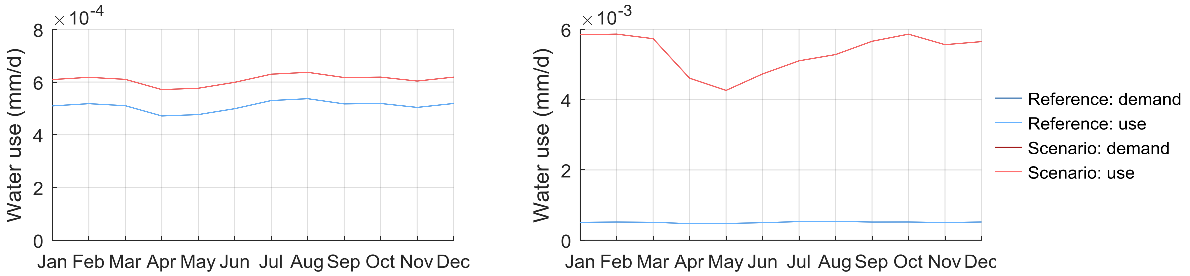


Figure 6.5 – Comparison of the total mean water use and demand from boreholes in the MMC for an increase in demand of 1 · 10^{-4} mm/d (left) and the allocation of all demand to boreholes (right); as use and demand are assumed to be equal for boreholes, not all lines are visible

6.4.4 Rooftop rainwater harvesting

Increasing the demand from rooftop rainwater harvesting tanks without increasing their mean storage sizes, catchment areas or amounts only leads to a mean total increase in use from these tanks of up to 7%. During the wettest months, when the storage levels are relatively high, the total mean monthly use may increase up to 24%. However, this reduces the water availability from the tanks during the drier months. The reduction is most significant in the southeastern subbasins, where the tanks are currently relatively small (see Subsubsection 5.5.2.1). In the Sand subbasin for instance, the mean monthly use from tanks in October during drought years even decline up to 56%.

However, if the minimum catchment areas and tank sizes recommended by the MWI (2005) are applied, the performance of rooftop rainwater harvesting increases considerably (see Table 6.2). The effects on river flows are either insignificant or positive, despite the total mean increase in water use of 3.6%. This is mainly due to the reduced demand at rivers, springs and shallow wells, which have relatively more impact on the low flows. From a hydrological perspective, implementing rooftop rainwater harvesting as a solution for water scarcity may therefore be recommended. This is also considered to be an ideal solution for water scarcity for inhabitants and, if facilities are adequate, for livestock (see Subsection 3.4.4). However, the impacts on high flow EFRs should be investigated.

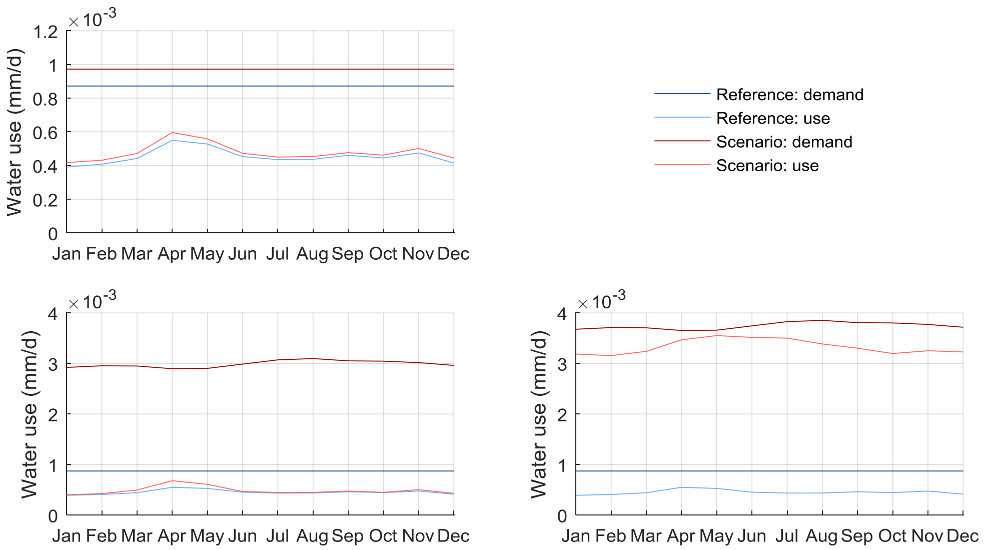


Figure 6.6 – Comparison of the total mean water use and demand from rooftop rainwater harvesting in the MMC for an increase in demand of 1 · 10^{-4} mm/d (top), the allocation of all demand to rooftop rainwater harvesting (bottom right) and increasing the catchment areas and reservoir volumes according to recommended by the MWI (2005; bottom left); irrigated areas are excluded, as iteration is required for the design of their facilities

Table 6.2 – Change in mean performance at subbasin level of rooftop rainwater harvesting facilities and river flows at EFA Site 5 due to an increase in catchment areas and tank sizes recommended by the MWI (2005) for all users except irrigated agriculture, for which iteration is required

	Rooftop rainwater harvesting		EFRs	
	Maintenance	**Drought**	**Maintenance**	**Drought**
$\Delta\alpha$	0.62 to 0.80	0.49 to 0.63	$2 \cdot 10^{-3}$	$3 \cdot 10^{-3}$
$\Delta\gamma$	0.09 to 0.13	0.04 to 0.12	$1 \cdot 10^{-4}$	$2 \cdot 10^{-4}$
Δv	-0.19 to -0.64	-0.10 to -0.57	$-3 \cdot 10^{-3}$	$-6 \cdot 10^{-3}$

6.4.5 Ponds

At ponds, total mean use increases only by 14% if all demand is allocated to ponds (see Figure 6.7). This is due to the limited pond sizes. In the Lemek and Talek subbasins, mean pond volumes per unit demand are much larger, which results in mean increases of 31% respectively 38% in water use from ponds. In the Sand subbasin, the increase is even 56%: as the infiltration losses from ponds are high in this subbasin due to the sandy soils, emptying the ponds faster reduces these losses. However, increasing the demand from ponds without increasing their amounts or storage sizes results in a mean decline in water availability from ponds of up to 28% during the dry season.

To make more abstractions from ponds possible, the volume of open water storage may be increased. Although for instance doubling the amount of ponds does not double the water use from ponds (see Figure 6.7), due to infiltration and evaporation losses and overflow, the total mean vulnerability of ponds reduces by Δv = -0.11 due to this intervention. At subbasin level, the vulnerability of ponds reduces even up to Δv = -0.18 and the reliability increases from up to $\Delta\alpha$ = 0.06 at subbasin level. In the Sand subbasin however, the effects of increasing the amounts of ponds on their performance are insignificant due to the high infiltration "losses". However, baseflows in the Sand subbasin increase by 5% on average and even by 11% in October.

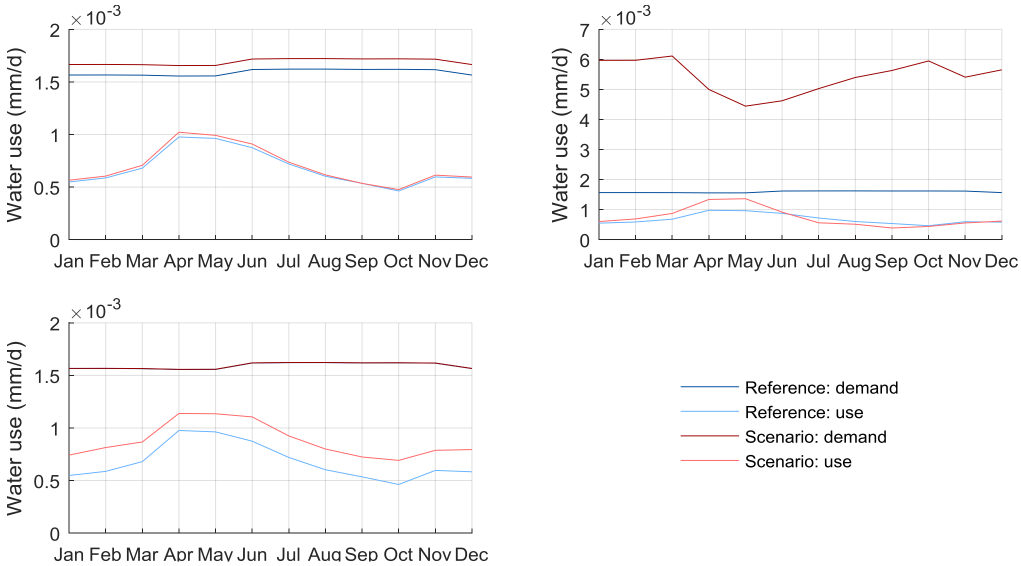


Figure 6.7 – Comparison of the total mean water use and demand from ponds in the MMC for an increase in demand of $1 \cdot 10^{-4}$ mm/d (top left), the allocation of all demand to ponds (top right) and doubling the pond volumes (bottom)

Doubling the pond volumes does not significantly affect the performance regarding low flow EFRs, despite the mean resulting increase in water use of 4% and the increase in open water evaporation of

6%. This is mainly due to the negligible influence of HOF on the performance: the ponds are filled by overland flow. From a hydrological perspective, constructing ponds as solution for water scarcity may therefore be recommended in all subbasins but the Sand. This is also considered to be one of the ideal solutions for water scarcity for livestock (see Subsection 3.4.4). However, the impacts on high flow EFRs should be investigated, as might the potential for enhanced groundwater recharge in the Sand subbasin.

6.4.6 Rivers

In most subbasins, increased demand from the rivers almost directly translates into increased use (see Figure 6.8). In the Sand subbasin for instance, the water supply from the Sand River even remains sufficient if all demand is allocated to this source. This is due to the storage in sand dams and the relatively low demand per unit area in this subbasin. In the Low-Mara subbasin, supply also always meets demand in this scenario, due to the high inflow from upstream subbasins. In all other subbasins however, the performance of the rivers declines slightly with increased demand. On average, the change in use as fraction of the increase in demand of $1 \cdot 10^{-4}$ mm/d is 0.91 for rivers in the MMC. Except for boreholes, this is the highest result of all water sources in the MMC (see Figure 6.9).

However, increased water use from rivers has same negative impacts on performance regarding EFRs as increased water use from springs. Indeed, abstractions from both rivers and springs are withdrawn directly from the river flows. As the rivers are assumed to be the alternative sources for springs, use from both sources results in the same reduction in river flows. For both source types, the proportional reductions in flows are greatest during low flows, whereas these are critical for the performance regarding EFRs. For dams however, the type and regulation may influence the impacts on EFRs. As there are plans for the construction of hydropower dams (see Subsubsection 4.7.2.1), assessing their influences before implementation is recommended.

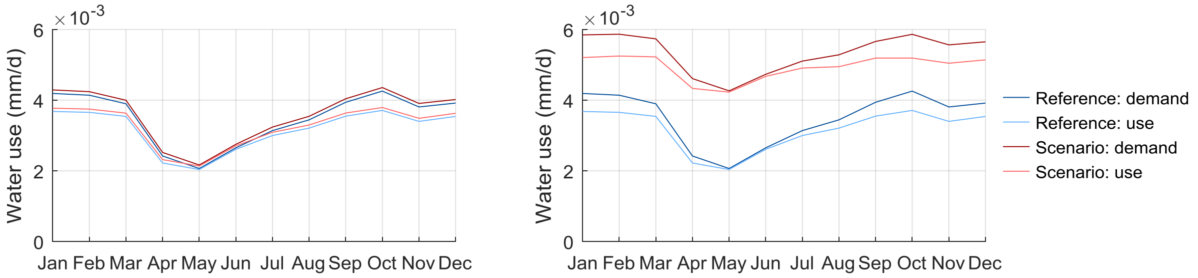


Figure 6.8 – Comparison of the total mean water use and demand from rivers in the MMC for an increase in demand of $1 \cdot 10^{-4}$ mm/d (left) and the allocation of all demand to rivers (right)

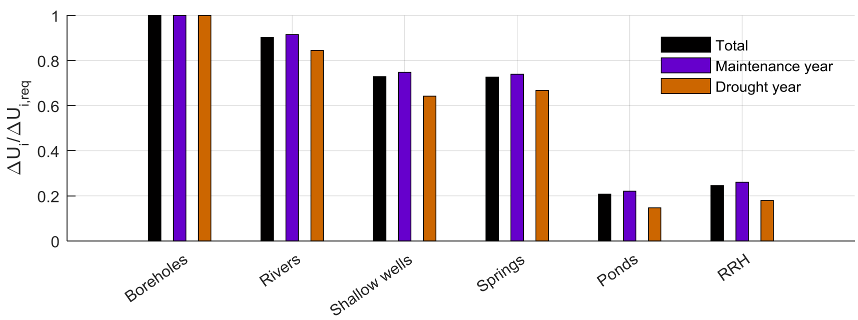


Figure 6.9 – Change in water use divided by change in water demand for an increase in demand of $1 \cdot 10^{-4}$ mm/d per source (RRH = rooftop rainwater harvesting); as the relation is non-linear, results cannot be extrapolated

6.4.7 Water users

The total difference between no use, expected use and maximum use has significant impact on the performance regarding EFRs (see Figure 6.10). For maximum use at the end of the design period, the impact is $\Delta\alpha$ = -0.04, $\Delta\gamma$ = -0.001 and $\Delta\nu$ = 0.06. This increases to $\Delta\alpha$ = -0.06, $\Delta\gamma$ = -0.004 and $\Delta\nu$ = 0.09 during drought years, which is mainly due to the greater sensitivity of drought years to absolute changes in discharges and the higher irrigation water demands during those years. For no use, performance increases only by $\Delta\alpha$ = 0.004, $\Delta\gamma$ = 0.0005 and $\Delta\nu$ = 0.008.

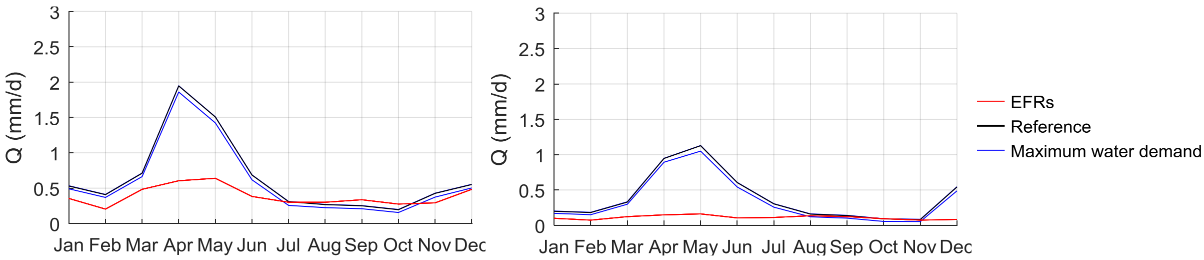


Figure 6.10 – Comparison between the reference model and the scenario of maximum demand for the hydrographs at EFA Site 5 during maintenance years (left) and drought years (right)

The impact of each water user on the Mara River flows depends on the abstracted quantities, the partitioning between sources and the timing of abstractions. Of all users in the MMC, irrigated agriculture has the highest water demand and absolute uncertainty for future predictions (see Subsection 4.9). Furthermore, more than 99% of all irrigation water is abstracted from rivers (see Subsection 4.4.3). Therefore, the impact on low flows is highest for irrigated agriculture (see Figure 6.11). The impacts of water use by tourists, wildlife and "other" users are insignificant compared to the influences of irrigation, inhabitants and livestock.

Although irrigation slightly enhances the groundwater contributions to the river flows, the total flows at Mara Mines decline on average by 1.8% if all irrigation projects are implemented. During drought years, the mean reduction is 2.5%, with a monthly maximum of 16% at the end of the dry season. Small-scale irrigated farms only contributes 1% to the changes in river flows, which is mainly due to their relatively low water use per area. Mean transpiration on the large-scale irrigated farms on the other hand is up to 80% higher than on the rainfed croplands in the same subbasin. As the implementation of all irrigation project may not be recommended, investigating the use of alternative sources for large-scale irrigation, such as boreholes or rooftop rainwater harvesting, is suggested.

For livestock, the total maximum demand is only about 6% higher than for inhabitants and the absolute estimated uncertainty is only about 3% higher. However, the performance regarding EFRs reduces disproportionally: for instance, the reduction in mean reliability is twice as high. This may be due to nonlinearities in the relation between performance and river flows, but may also be due to differences in partitioning between sources. As current pond sizes cannot support much higher livestock numbers, most pastoralists have to resort to the rivers. Inhabitants on the other hand use more alternative water sources such as boreholes and rooftop rainwater harvesting. As interviewees considered ponds to be the ideal solution for water scarcity affecting livestock (see Section 3.4) and the impact of ponds is less negative than the impact of rivers, increasing pond sizes for livestock is recommended.

For inhabitants, the uncertainty in population numbers for future projections is relatively low compared to the uncertainty in water demand per person. Increased accessibility of water sources may lead to an increase in water demand by inhabitants of up to a factor 5 (see Subsection 4.2.2). The use of for instance boreholes and rooftop rainwater harvesting for the required – and desired – improvements in accessibility is recommended: these sources are preferred by inhabitants (see Section 3.4) and have the least negative impact on performance regarding EFRs and water availability for other users. The use of for instance pipelines from rivers or springs is not recommended. For boreholes, uncertainties about the modelling assumptions should be solved first (see Subsection 6.4.3).

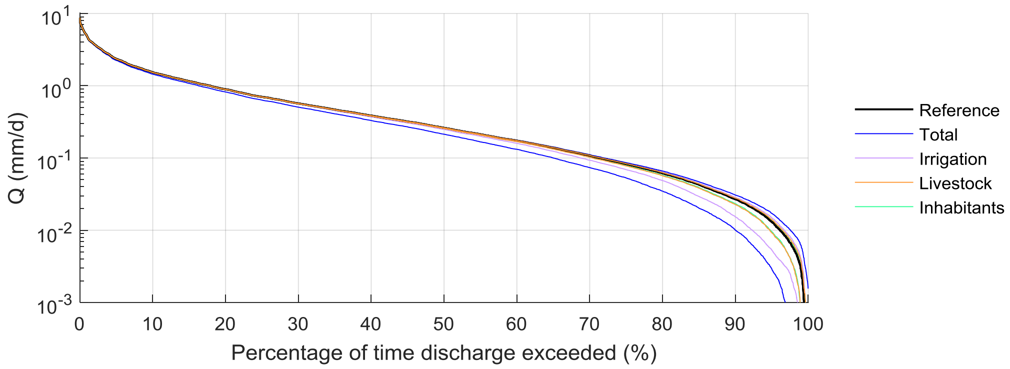


Figure 6.11 – Flow duration curve of the reference model at EFA Site 5, including the band widths of the demand of all users, irrigation, livestock and inhabitants; other users are not included separately in the figure because of their small influence on the flow duration curve

6.5 Land use change

6.5.1 Forests

For forests, complete removal of the HRU results in a total mean reduction in evaporation of 0.29%; this is 1.8% in the Nyangores and 0.68% in the Amala subbasin. These changes are mainly caused by interception, as the annual mean interception rates are a factor 2.9 to 3.0 higher in the forests than on the rainfed croplands in the same subbasins. As the HRUs operate in parallel, the relation between forested areas and mean interception rates are linear. For transpiration and discharges on the other hand, the relations with forested areas are non-linear. This is due to water abstractions. For instance, the total mean discharge at Mara Mines increases by 1.2% due to complete deforestation and declines by 1.0% due to complete reforestation.

However, more important for the performance regarding EFRs are the changes in the contributions of the different runoff processes. For instance, complete deforestation increases the total mean discharge by HOF by 15% and reduces the total mean groundwater flow by 47%. Hence, the baseflows decline and the peak flows increase due to deforestation. Although these effects dampen out in downstream direction (see Figure 6.12), complete deforestation still reduces the performance regarding EFRs at EFA Site 5 by $\Delta\alpha$ = -0.005 and $\Delta\nu$ = 0.009. Resilience on the other hand increases by $\Delta\gamma$ = 0.001, due to the enhanced peak flows. At the upstream EFA sites, the impact of deforestation on river flows is larger, which may result in greater declines in performance regarding EFRs.

Potential water sources in the forests are currently not accessible for users (see Subsubsection 5.3.3.3), whereas deforestation increases the contributing areas of most sources on the croplands. This results in improved performance of especially springs and shallow wells. However, water demand is also likely to increase if there is more land available for settling. Therefore, proportional changes in demand are assumed in additional scenarios. The resulting performances of most sources are similar to those of the reference model. However, the resulting changes in water use significantly amplify the effects of deforestation and reforestation (see Figure 6.12). The strongest amplification effects are found in the Nyangores subbasin, where the water demand per unit area is relatively high.

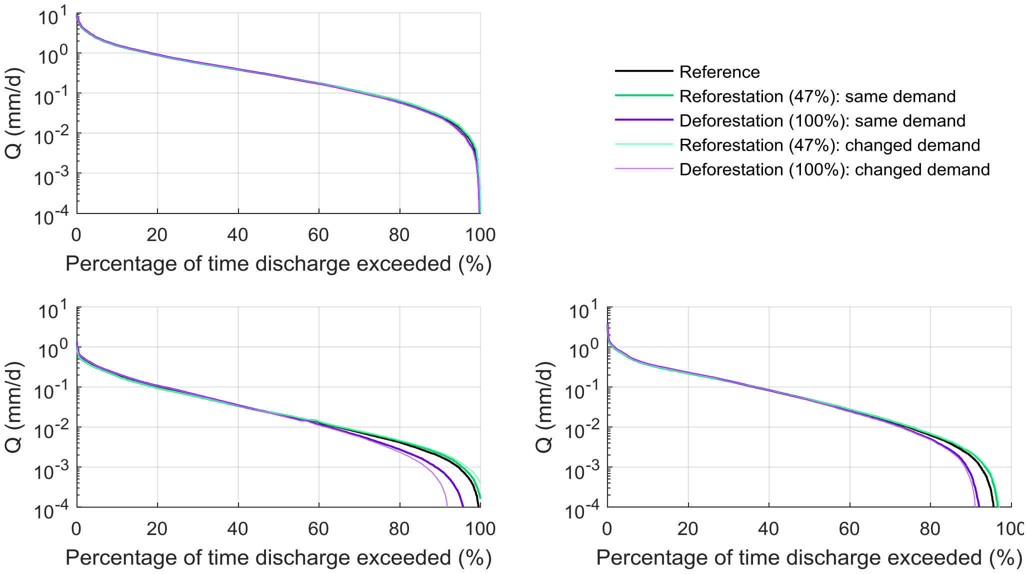


Figure 6.12 – Comparison of the flow duration curves of the reference model and re- and deforestation scenarios for forests at EFA Site 5 (top) and at the outlet of the Nyangores (bottom left) respectively Amala (bottom right) subbasins; in the increase in water use, large-scale irrigated agriculture is not taken into account as its water use is only increased incidentally on project basis

6.5.2 Shrubs

For shrubs, the impacts of complete reforestation on the different evaporation and discharge fluxes are insignificant (see Figure 6.13). This is due to the small area potential for reforestation of shrublands. Complete removal of the HRU on the other hand results in a total mean reduction in evaporation of 0.20%. Compared to the complete removal of forests, the changes are more evenly distributed over the MMC, with the greatest reduction in evaporation of 0.61% in the Sand subbasin. Again, these changes are mainly caused by interception: the annual mean interception rates are a factor 2.5 to 2.6 higher on the shrublands than on the grassland in the same subbasins. Due to the complete removal of the shrublands, the total mean river flows increase by 0.87%

Again, more important for the performance regarding EFRs are the changes in the contributions of the different runoff processes. Complete removal of the HRU increases the total mean discharge by HOF by 11% and reduces the total mean groundwater flow by 42%, increasing the peakedness. The resulting reduction in performance regarding EFRs at EFA Site 5 is $\Delta\alpha$ = -0.003 and $\Delta\nu$ = 0.007. The resilience on the other hand increases by $\Delta\gamma$ = 0.001, due to the enhanced peak flows. These changes are of the same order of magnitude as for complete removal of the forests. For shrubs however, the effects on the river flows and therefore possibly on the performance regarding EFRs are greater in the south-eastern subbasins, with the greatest change in the Sand subbasin. Lastly, amplification effects due to changes in demand are smaller for the removal of shrublands than forests (see Figure 6.13). This is mainly due to the relatively low water demand per unit area and great importance of ponds in the pastoral areas.

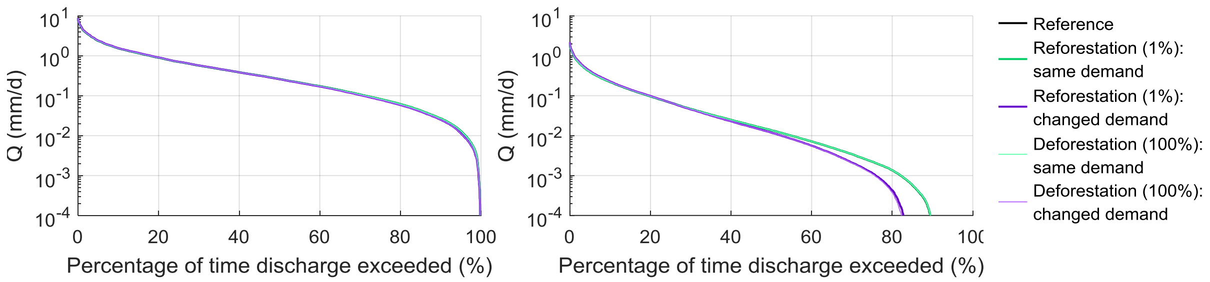


Figure 6.13 – Comparison of the flow duration curves of the reference model and re- and deforestation scenarios for shrubs at EFA Site 5 (left) and at the outlet of the Sand subbasin (right); in the increase in water use, large-scale irrigated agriculture is not taken into account as it is uncommon in the southeastern subbasins

Moreover, reforestation of shrublands significantly reduces the water availability at springs (see Figure 6.7). In all pastoral areas, the reliability of springs reduces to zero by complete reforestation of the shrublands, i.e. the supply becomes insufficient to meet the demand during the entire modelling period. Furthermore, the total mean vulnerability of the springs increases by $\Delta v = 0.30$. In the southeastern subbasins, spring protection is considered to be an important activity for WRUAs. The model results confirm this perception.

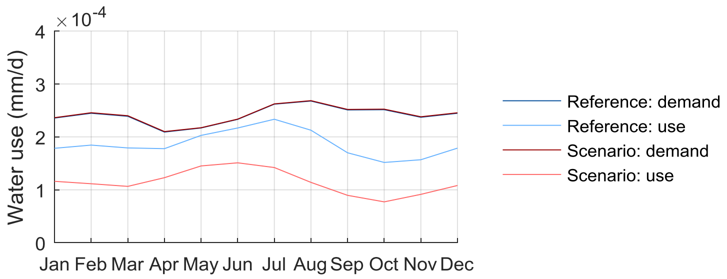


Figure 6.14 – Comparison of the total mean water use and demand from springs in the MMC for complete removal of the shrublands; the reference demand from springs equals the demand during the scenario

6.6 Climate change

6.6.1 Temperature

Due to the predicted temperature rises, the total mean monthly potential evaporation increases up to 3.0% during the dry season and up to 3.7% during the wet season, when the mean temperatures are lower and the predicted changes in temperature slightly higher. As interception throughout the MMC is usually limited by the interception capacity or the rainfall instead of the potential evaporation, the temperature rises do not significantly affect the interception. The total mean monthly transpiration on the other hand increases up to 2.8% in 20 years. The yearly mean increase however is only 0.9%, as transpiration during the dry season is usually limited by the storage in the unsaturated zone. Lastly, the total mean open water evaporation increases up to 1.7%, with a maximum of 3.3% for April, which is the wettest month.

The changes in the evaporation fluxes affect the discharges in the Mara River. For instance, the total mean discharge by HOF decreases due to increased open water evaporation. Due to the small areas of the ponds however, the mean reduction is only up to 0.07%. The other distinguished runoff processes are affected more by the increased transpiration. SSF and groundwater flow decline on average up to 4.4% respectively 4.7%, with up to 3.4% in April and up to 7.1% respectively 6.8% in July. Furthermore, the water demand from the river increases, due to the reduced water availability at most sources and especially increased irrigation water requirements. In total, the temperature rise results in an overall decline in Mara River flows of up to 4.1%, with up to 3.2% during the long rains and up to 6.9% at the start of the dry season. The relation between the mean decline and the temperature changes is approximately linear (R^2 = 0.998).

The mean performance regarding EFRs declines up to $\Delta\alpha$ = -0.02, $\Delta\gamma$ = -0.001 and Δv = 0.02. The highest reduction in reliability takes place in July with $\Delta\alpha$ = -0.10, but this leads to an increase in resilience of $\Delta\gamma$ = 0.13 due to the small difference between modelled flows and EFRs during this month. Vulnerability on the other hand increases most in May with Δv = 0.02. Lastly, the impact of climate change is greatest in subbasins with large area percentages of large-scale irrigation and forests, due to their high contributions to transpiration and SSF. Amala River flows for instance decrease up to 5.3%, with 3.1% in April and 8.0% in July. Hence, performance regarding EFRs may decline even more in the northern subbasins.

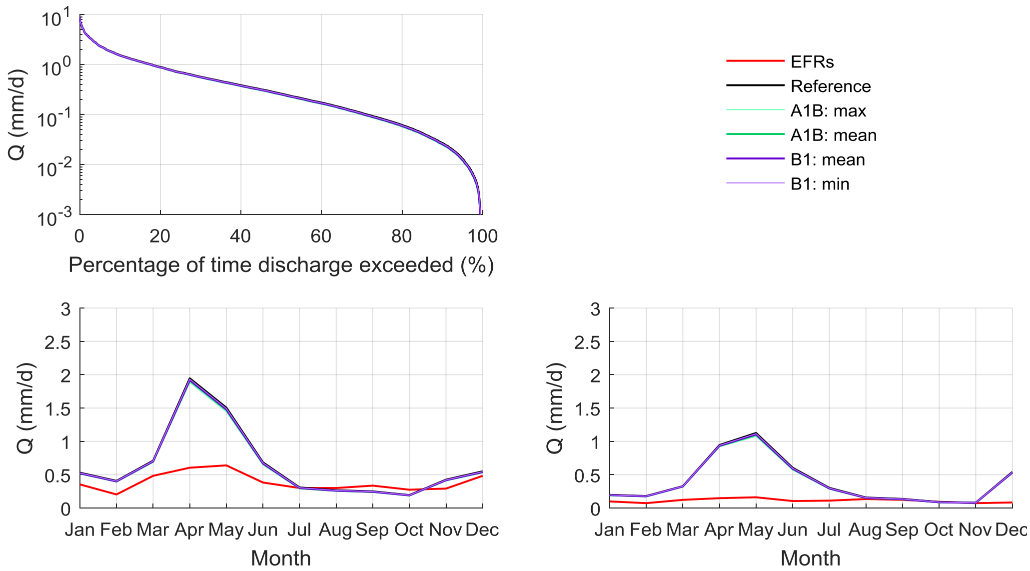


Figure 6.15 – Comparison of the reference model and several temperature scenarios at EFA Site 5 for the flow duration curves (top) and the hydrographs during maintenance years (bottom left) and drought years (bottom right)

6.6.2 Rainfall

Total mean annual interception changes between -0.3% and +0.9% for different SRESs and GCMs, whereas transpiration changes between -4.7% and 15% and open water evaporation changes between -4.6% and 16%. The relatively low impact on interception is due to the relatively low values of I_{max} compared to the average rainfall intensity, in combination with the assumption of a constant number of rainy days. The relatively high increase in open water evaporation is also due to the use of relative percentage changes for rainfall, in combination with the perception of infiltration as a threshold process. This results in a total mean annual change in HOF of -16% to 195%, whereas the changes in SSF and groundwater flows are -15% to +70% respectively -16% to 78%. These changes are not linear to the increase in rainfall, due to the occurring threshold processes. Resulting changes in total mean annual discharges at Mara Mines differ between -16% and 79%.

Regarding EFRs, the performance changes between $\Delta\alpha$ = -0.06 to 0.21, $\Delta\gamma$ = -0.006 to 0.018 and Δv = 0.06 to -0.15 for different SRESs and GCMs. Hence, despite the moderate influence of temperature increase, climate change will probably have most impact on Mara River flows compared to all other modelled changes in the MMC. Contrary to common belief among all interviewed stakeholders, future changes in rainfall may significantly increase both peak flows and base flows in the Mara River and its main tributaries, as most GCMs predict rainfall increases (see Table 6.1). However, the actual influences are very uncertain, as changes in rainfall differ strongly between SRESs and GCMs (see Figure 6.16) and the impact of climate change on other rainfall statistics than the means are unknown.

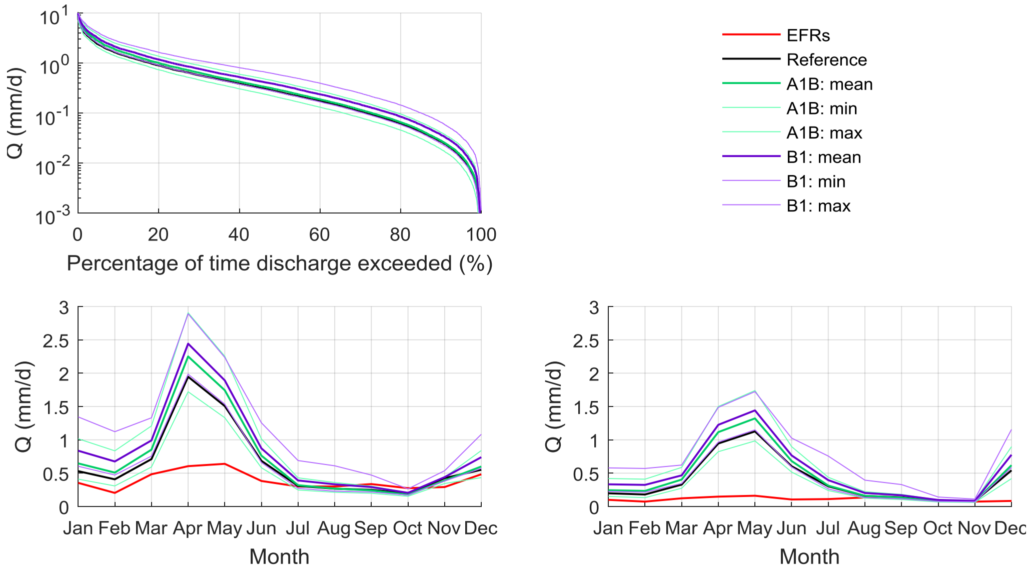


Figure 6.16 – Comparison of the reference model and several temperature scenarios at EFA Site 5 for the flow duration curves (top) and the hydrographs during maintenance years (bottom left) and drought years (bottom right)

Furthermore, the water availability at almost all distinguished sources increases with higher rainfall (see Figure 6.17). Boreholes are the only exception, which is due to the assumption that boreholes abstract water from an aquifer beyond the spatial boundaries of the model. Overall, water levels in ponds are most affected by changes in rainfall. This is due to the relatively high increase in HOF. At most sources, increased availability leads to higher use. At boreholes however, use decreases slightly as less users resort to boreholes as alternative water source. Rivers are an even more common alternative in the MMC; river water use therefore decreases during the rainy seasons, although use still increases in months with a worse balance between supply and demand.

The timing of changes in rainfall influences the model output, including the performance measures for EFRs and water supply to other users. Most GCMs show a higher increase or lower decrease in rainfall during the wet season than during the dry season (see Table 6.1). Averaging the total volume change over the year therefore leads to overestimations of storages and flows during the dry season (see Figure 6.18). As the performance during dry months is most critical, it is important to take the seasonality into account. Moreover, the influence of other changes in rainfall statistics is not investigated, but these may also affect the results. Examples are changes in rainfall frequencies and differences in rainfall changes between maintenance drought and years.

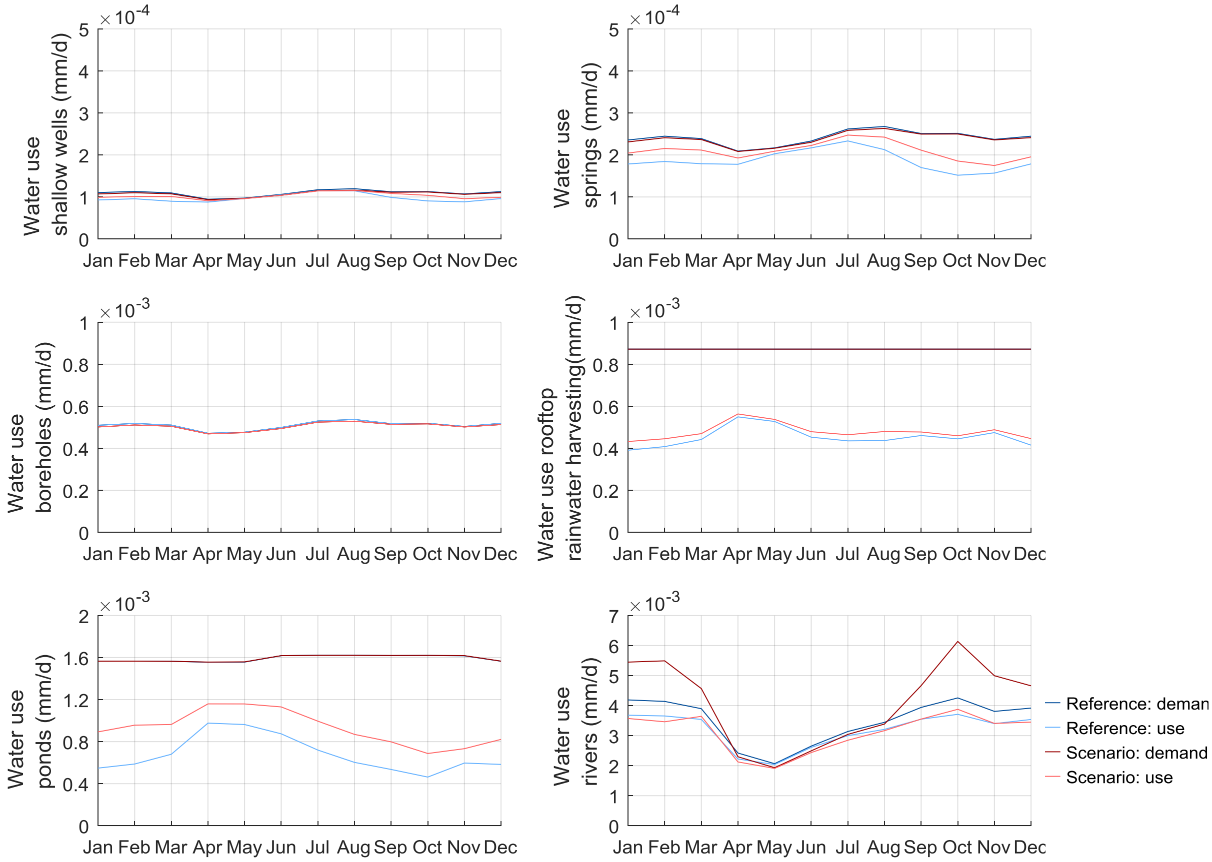


Figure 6.17 – Comparison between mean water use and demand at different water sources in the MMC over the year for the reference model and SRES B1 Max, sorted in increasing order of magnitude of water use; from left to right: shallow wells, springs (top), boreholes, rooftop rainwater harvesting (middle), ponds and rivers (bottom)

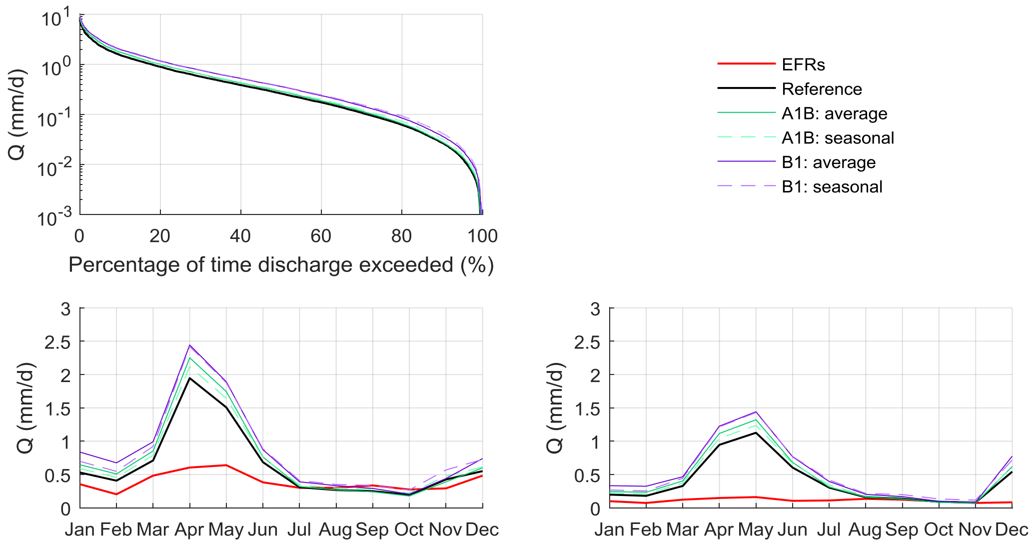


Figure 6.18 – Comparison of flow duration curves and flows at EFA Site 5 between the reference model and Scenario 1, 4, 9 and 12 during maintenance years (left) and drought years (right)

7 | Conclusions

The objective of this study is to predict the impact of changes in water demand, land cover and climate on the balance between water demand and supply at the different water sources in the Kenyan share of the Mara River Basin (MRB). As such, this thesis aims to contribute to water resources planning and management in the study area. To achieve this goal, water-related problems, potential solutions and ideal solutions were identified first, using surveys and observations in the study area. Next, water use and demand were estimated as input for a hydrological model. This model was used to evaluate the reliability, resilience and vulnerability of each water source at subbasin level and the performance of the system regarding environmental flow requirements (EFRs) at Mara Mines. This evaluation was done for the current situation and for scenarios of water demand, climate and land use.

Water scarcity turned out to be the main livelihood issue for all stakeholders in the study area, except for wildlife. However, the severity of the water scarcity increased in southeastern direction. Deforestation and climate change were perceived to be major causes of increased water scarcity. Interviewees considered the construction of boreholes, pipelines, spring protection and enhanced rooftop rainwater harvesting to be ideal solutions for domestic water insecurity. For irrigation and livestock water supply, ideal water sources were considered to be rivers respectively boreholes and ponds. For wildlife, be reforestation and reduced competition with other users were desired. Lastly, shallow wells were also prevalent in the study area; although shallow wells and boreholes both withdraw their water from saturated zones, the recharge origins of these aquifers are assumed to be different.

Literature review and surveys resulted in a total current water demand in the Mara Mines Catchment (MMC) of $9.2 \cdot 10^{-3}$ mm/d during the dry season and $5.9 \cdot 10^{-3}$ mm/d during the wet season. This varies between 0.9% of wet season maintenance EFRs and 12% of dry season drought year EFRs. The water demand is highest at irrigated farms, with 49% to the total demand. Following in decreasing order of magnitude of water demand are livestock, inhabitants, institutions, tourists, wildlife and industry. The total demand is highest at rivers with 59%, but ponds are more important in the southeastern subbasins. For future projections, both absolute and relative uncertainty are greatest for irrigation. However, all values and rankings differ between months, subbasins and years.

For the creation of a hydrological model, the semi-distributed conceptual FLEX-Topo modelling concept was used. Due to the strong correlation between topography and land use in the MMC, four hydrological response units (HRUs) could be identified: forests, shrublands, croplands and grasslands. The resulting model performed well during both calibration and validation. Moreover, the model performance improved due to the inclusion of water use and demand, especially during validation and low flows. This supports the hypothesis that the inclusion of artificial water abstractions improves the model's representation of reality.

Using there results, a reference model was created, which is assumed to be representative for the current situation. In this reference model, the EFRs at Mara Mines exceed the mean monthly flows during the last three months of the long dry seasons of both drought and maintenance years. Moreover, the performances of the water sources in this model correspond to observations. The reliability is greatest for boreholes, followed in decreasing order by rivers, shallow wells, springs, ponds and rooftop rainwater harvesting. The conceptualization of especially boreholes, shallow wells and springs is however uncertain.

Scenarios were selected for a 20 year design period. These included no water demand, expected demand and maximum demand by each main water user, an increase in demand at each water source by $1 \cdot 10^{-4}$ mm/d and the allocation of all demand to each distinguished source. Furthermore, complete reforestation and deforestation were included as scenarios for both forests and shrublands; this amounts to changes in their areas of -100% to 47% respectively -100% to 1%. Lastly, climate change scenarios were derived from literature, resulting in predicted temperature rises from 0.3°C to 1.4°C and seasonal changes in rainfall from -7.2% to 43.2%, with -6.7% to 8.0% during the driest months.

In 20 years, climate change will probably have the greatest impact on the water availability for all water users in the study area, including EFRs. For instance, the mean annual discharges at Mara Mines may change between -16% and 79% due to the predicted changes in rainfall. Compared to all other sources, the water availability from ponds will probably increase the most due to higher rainfall intensities, with mean monthly increases in water use from ponds of up to 63%. Contrary to common belief among interviewees in the study area, climate change will most likely have positive effects on the water availability from all sources. However, the rainfall predictions are very uncertain. Lastly, including the seasonality of climate change is important for the results, as using annual means probably leads to overestimations of the dry season flows in the MRB.

Furthermore, deforestation of forests and shrublands would increase the peakedness in the Mara River and its main tributaries. For instance, complete clearance of the forests would increase mean annual overland flow by 15% and reduce mean groundwater flows by 47%. Increased water use on the cleared lands would significantly amplify these effects. In the affected subbasins, the impacts on river flows are comparable to those of climate change, but the effects dampen out in downstream direction. At Mara Mines, the impacts on the river flows of complete shrubland clearance would be of the same order of magnitude as for complete clearance of forests. Moreover, complete deforestation of shrublands would significantly affect spring flows in the southeastern subbasins, reducing their mean reliability and resilience to zero and their vulnerability by factor 2.4.

Lastly, the difference in water use between the scenarios of no demand, expected demand and maximum demand in 20 years is significant for the performance regarding EFRs at Mara Mines. Of all investigated water users, large-scale irrigated agriculture will probably have most impact on Mara River flows, followed by livestock and inhabitants. For instance, if all planned irrigation projects would be implemented, mean monthly flows at Mara Mines would reduce up to 16% during drought years. For maximum demand by all water users, the reduction would be 30%. The influences of the water demands of tourists, wildlife, institutions and commercial enterprises are relatively insignificant.

As reducing the low flows would negatively affect the performance regarding EFRs, increased water use from rivers and springs is least desirable of all water sources, followed by shallow wells. Boreholes on the other hand may even have positive impacts on performance regarding EFRs, although caution is needed because of the uncertainties in the model conceptualization. For ponds and rooftop rainwater harvesting, enhanced water use requires larger storage sizes. These interventions hardly affect low flows and therefore performance regarding EFRs.

8 | Recommendations

This thesis is part of the Mau Mara Serengeti (MaMaSe) Sustainable Water Initiative. The thesis aims to contribute to the water resources planning and management in the Kenyan share of the Mara River Basin (MRB). To achieve this goal, water-related problems, potential solutions and ideal solutions were identified first, using surveys and observations in the study area. Subsequently, the results of the field work were compared to hydrological model outputs, both for the current situation and for scenarios of water demand, climate and land use. This results in recommendations for the MaMaSe Initiative.

Because of the relatively high severity of water scarcity in the Sand subbasin, this is the most recommended target area for MaMaSe project actions. However, as water scarcity turned out to be the main livelihood issue throughout the project area, enhancing water availability in the other subbasins is also desirable. Interviewees considered increasing rooftop rainwater harvesting tank sizes and catchment areas to be ideal solutions for domestic water insecurity, and increased pond sizes for livestock water supply. Because of the insignificant or even positive impacts of these interventions on the Mara River flows, these solutions are recommended. Only in the Sand subbasin, ponds are not feasible. Furthermore, the importance of protection of the catchment areas of springs is stressed.

Most water users also considered boreholes to be ideal solutions for water scarcity. Indeed, boreholes perform best of all distinguished sources on reliability, resilience and vulnerability. Moreover, their influence on the performance regarding EFRs may even be positive. However, before enhanced use from boreholes would be advised, it should be confirmed that the borehole water is indeed abstracted from a regional aquifer and that increased abstractions from boreholes do not have negative impacts on downstream or future users. Lastly, rivers, springs and shallow wells were not considered to be ideal solutions for water scarcity by interviewees and these sources have negative impacts on water availability for other users. Therefore, increased use from these sources is not recommended.

In further research, the analysis might be improved most by improving the hydrometeorological input data of the model, reducing the uncertainty in planned irrigated areas, reducing the uncertainty in the climate change predictions, checking the model conceptualization of especially boreholes, assessing the performance regarding EFRs at multiple sites throughout the river basin and increasing the sample sizes of the surveys. In further research, the impacts of other planned projects may also be investigated, such as large-scale hydroelectric dams or enhanced groundwater recharge in the Sand subbasin. Furthermore, the model may be expanded with for instance water quality and erosion, which are both important for the performance of water sources.

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Appendices

Appendix A | Institutional framework

As the MaMaSe project focusses on the Kenyan share of the MMC, the institutional framework of the Kenyan water management sector is briefly described in this appendix. The sector used to be highly centralized. Reforms took place under the Water Act 2002 but are not yet fully realized (Institute of Economic Affairs [IEA], 2007). At the national level, the MWI is responsible for policy formulation, including data collection on water resources (Water Act 2002). At the lower levels, water resources management and water supply and sewerage are separated between different authorities, companies and associations, as are day to day regulation and service provision (see Figure A.1). Other related government institutions are for instance the Ministry of Agriculture, Livestock and Fisheries and similar departments of the counties.

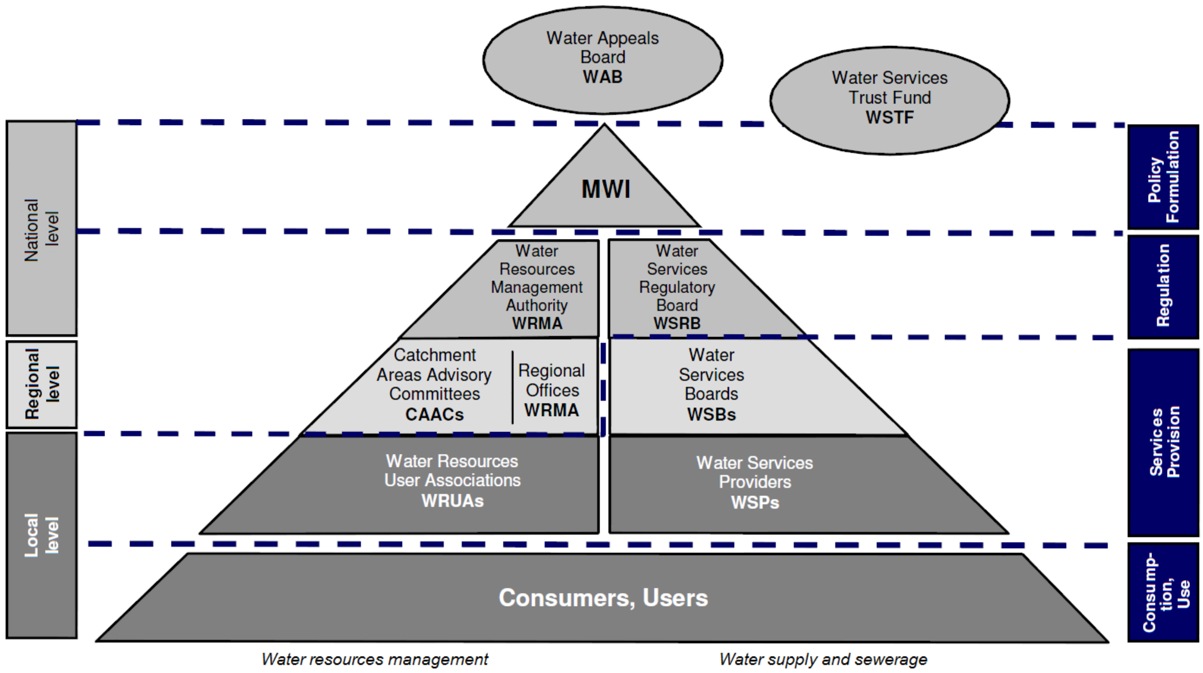

Figure A.1 – Institutional framework of the Kenyan water sector under the Water Act 2002 (IEA, 2007)

For this thesis, the WRMA and WRUAs are the most relevant water-related institutions, although for instance Water Service Providers were also contacted for the calculation of piped water supply. The MMC is located in the Lake Victoria South Catchment Area, which is governed by the regional WRMA office in Kisumu; the subregional office responsible for the MMC is located in Kericho (LVBC & WWF-ESARPO, 2010). WRUAs are community groups consisting of water users and other voluntary stakeholders, such as non-governmental organizations and companies; the Water Resource Users Development Cycle was established to support the WRUAs both financially and technically (Water Services Trust Fund & WRMA, 2009). In the MMC, at least 13 WRUAs had been established by 2014 but especially the Lemek, Talek and Mid-Mara subbasins were not yet fully covered.

Many relevant policy documents are published by the institutions. The MWI develops National Water Resource Management Strategies as one of its main instruments (Water Act 2002). Each regional WRMA office develops a Catchment Management Strategy (CMS). The CMS covers inter alia the water balance, water allocation, resource protection and conservation and infrastructural development (WSTF & WRMA, 2009). Each WRUA develops a SCMP for three to five years, with a similar structure as the CMS. Examples of planned activities in SCMPs are data collection, resource monitoring and assessment, infrastructure development for water storage and irrigation and land cover rehabilitation (WSTF & WRMA, 2009).

Since 2002, integrated water resources management is pursued in Kenyan water policies (IEA, 2007). A proposed instruments is the treatment of water as an economic good, with "socially responsible commercialisation" and cost-recovery (Kenya Water for Health Organisation, 2009). Transboundary cooperation has also been introduced during the reforms (Hoffman, 2007). Furthermore, decentralized decision making and stakeholder involvement and participation are officially promoted and human rights based approaches are adopted (IEA, 2007; Kenya Water for Health Organisation, 2009; WSTF & WRMA, 2009).

Appendix B | Limitations

During the field work, most stakeholders were asked about their main limitations for solving their problems related to water insecurity:

- ***WRUAs.*** 8 out of 11 WRUA board members ranked limited financial resources as their main limitation. According to the interviewees, government funds are usually not received or insufficient. Member contributions are the main source of income, but these are deemed low and unreliable. Other listed limitations are conflicting policies and legislations, limited manpower, remoteness of the Sand subbasin, political interference, limited awareness, vastness of the covered areas and limited expertise.

- ***Small-scale farmers and pastoralists.*** Many small-scale farmers and pastoralists believe that there are no solutions for their water-related problems, since they depend on rain. However, 8 out of 9 small-scale farmers and 4 out of 5 pastoralists ranked limited financial resources as their main limitation. Some attribute the lack, delay or malfunctioning of water-related projects to poor governance. Other mentioned limitations are collective land ownership in some pastoral areas and limited awareness.

- ***Large-scale farmers.*** Financial constraint are much less important for large-scale farmers than for most other stakeholders in the MMC, although they are affected by market fluctuations. Their main limitation is however land tenure. Most lease or rent land on former group ranches, where fragmentation and instability of leaseholds or rental agreements impede long-term investments.

- ***Wildlife.*** For the management of the MMNR, limited cooperation or conflict with politicians and inhabitants, due to conflicting interests, is considered to be the main limitation; this is also mentioned as a major challenge for conservancies. The main limitation of conservancies is however limited financial resources. Their incomes fluctuate considerably, as they depend mostly on tourism. Tourist accommodations did not list any major limitations for solving their own water-related issues.

Appendix D | Water source comparison

Table D.1 – Current relative average scores (very high / high / low / very low) for the main selection criteria of water sources for domestic use, based on the survey results; brief explanations with perceived main advantages and disadvantages or costs are included

	Accessibility	Reliability	Water quality	Costs
Rooftop rainwater harvesting	*Very high* Located at homesteads, widely used, some shared	*Very low* Unpredictable rainfall, depends on size: usually small	*Very high* No treatment required, best quality of all sources	*Low* Low investment costs, long service life
Ponds	*High* All pond types combined: many, well distributed	*Low* Unpredictable rainfall, depends on size, often high losses	*Very low* Depends on pond type and pollution by animals	*High* Depends on type; durability affected by sedimentation and wildlife
Wetland	*Very low* Few, usually small: only substantial in the MMNR	*High* Not only overland but also groundwater flow	*Low* Polluted by overland flow and animals, but naturally filtered	*Very low* Free: natural source
Springs	*Low* Few, unevenly distributed, some obstructed by camps	*Low* Usually dry or low discharges during several months	*Low* No treatment required, some salty or polluted	*Very low* Free, although low investment costs if protection is applied
Shallow wells	*Very high* Located at homesteads, widely used, sometimes shared	*Low* Depends on location, often dry during several months	*Low* No treatment required, some salty or polluted	*Low* Low investment costs, long service life
Boreholes	*Very low* Few, unevenly distributed, often private	*Very high* Water availability considered completely independent of rainfall	*High* No treatment required, often salty	*Very high* High investment and operational costs, often needs repairs
Rivers	*Low* Most subbasins: only one permanent river	*Very high* Always water available, sometimes in river bed only	*Very low* Especially during dry months or peak discharges, diseases	*Very low* Free, but low costs if pumping is applied
Surface dams	*Very low* Almost none, highly centralized	*Very high* Depends on size; some dry up during very dry years	*Very low* Similar to river water quality	*Very high* High investment costs, sedimentation
Sand dams	*Very low* Almost none, only in Sand subbasin, highly centralized	*High* Depends on stream order	*High* Filtered through sand, no further treatment required	*Low* Depends on type, long service life
Pipelines	*Very low* Very few connections, taps in or near house	*High* Frequent breakdowns solved with storage	*High* Drinking water treatment usually applied	*Very high* Very high investment, maintenance and operational costs

Appendix E | EFRs

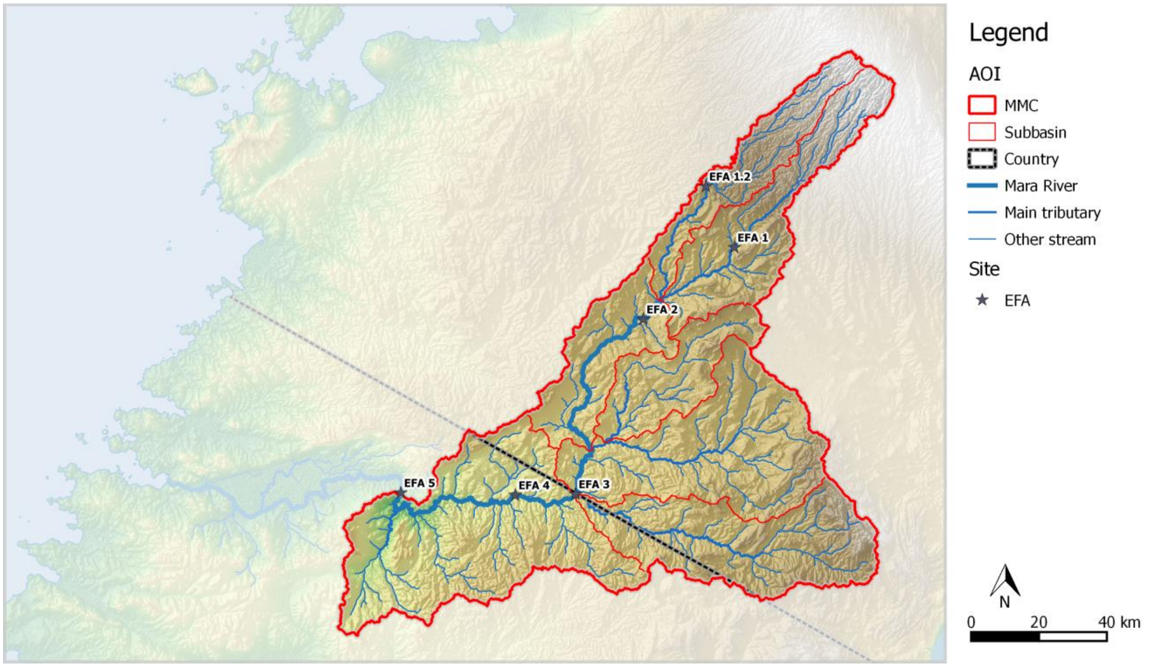

Figure E.1 – EFA sites in the MMC; at Site 1.2 in the Nyangores River, no flow recommendations were developed as no full EFA was conducted (GLOWS-FIU, 2012)

Table E.1 – Critical indicators used during the TWB-MRB project to determine the reserves (GLOWS-FIU, 2012)

Critical indicator	
Functioning of natural sediment generation processes	• Presence of stable river banks • Intact riparian zones • Absence of large-scale erosion denuding landscapes • Absence of excessive fine-scale sediment deposition in river channel
Occurrence of a variety of instream and riparian habitats to provide habitat for diverse species	• Adequate distribution of pools, runs and riffles • Presence of lateral and channel bars • Vegetated riparian zones that receive periodic inundation
Presence of sensitive species that reflect suitable water quality levels	• Rare or threatened fish species that depend on appropriate timing of variable flows for feeding and reproduction • Sensitive invertebrate species that indicate subtle fluctuations in water quality and pollution levels • Important riparian plant species that depend on seasonal inundation for germination
Adequate provision of human needs by water resources	• Year-round accessibility of water for domestic purposes • High water quality to reduce the occurrence of disease • Maintenance of tourism-dependent processes, such as water for wildlife habitats

Table E.2 – Environmental flow building blocks used during the TWB-MRB project (GLOWS-FIU, 2012)

Flow building blocks	Definitions	Functions
Drought year – low flows	The low flow requirements during the driest month of a drought year	• Maintain hydrological connectivity in the system • Maintain inundation of critical habitats (e.g. riffles) • Sustain flow-sensitive species • Provide natural variability to maintain diverse species assemblage
Drought year – high flows	The low flow requirements during the wettest month of a drought year	• Maintain active channel flows to inundate benches and sustain emergent vegetation • Permit fish passage over obstacles
Maintenance year – low flows	The low flow requirements during the driest month of a maintenance year	• Provide natural variability to maintain diverse species assemblage
Maintenance year – high flows	The low flow requirements during the wettest month of a maintenance year	• Cue migration and spawning in fishes • Inundate macrophytes and emergent vegetation along banks • Displace dominant competitors and allow drift of species into new habitats, promoting increases in species diversity • Maintain groundwater recharge for riparian species
Small annual floods	Small pulses of higher flow that occur in the drier months	• Cue spawning and migration in fishes • Inundate surrounding floodplains to facilitate lateral migration of fauna • Facilitate nutrient transfer between floodplains and the river • Allow germination and seed dispersal of riparian vegetation • Prevent sediment build-up on river bed, thus increasing habitat variability for invertebrates • Maintain active channel features • Flush out organic matter, thus improving water quality
Major flood events	Major peaks in the river's flow level that occur at a given recurrence interval	• Maintain macro channel features and provide diversity of physical habitats • Scour bed of sediment deposits • Inundate and recharge larger floodplain, allowing for nutrient transfer

Table E.3 – EFRs for Site 5 (GLOWS-FIU, 2012)

Building blocks		Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
Maintenance year – low flows	Q (m^3/s)	9.28	10.02	17.85	12.43	6.50	17.80	23.50	24.92	13.80	10.34	10.34	11.79
	h (m)	0.55	0.57	0.77	0.64	0.46	0.77	0.88	0.91	0.67	0.58	0.58	0.62
Maintenance year – high flows	Q (m^3/s)	-	-	367	-	-	-	535	-	-	-	-	-
	h (m)	-	-	3.60	-	-	-	4.37	-	-	-	-	-
	D (days)	-	-	1	-	-	-	1	-	-	-	-	-
	T (years)	-	-	1.8	-	-	-	2.3	-	-	-	-	-
Drought year – low flows	Q (m^3/s)	2.59	2.00	2.35	2.48	2.00	3.62	4.50	5.00	2.99	3.17	4.14	3.64
	h (m)	0.29	0.25	0.27	0.30	0.25	0.34	0.38	0.40	0.31	0.32	0.36	0.34
Drought year – high flows	Q (m^3/s)	-	-	-	-	-	-	-	10	-	-	-	-
	h (m)	-	-	-	-	-	-	-	0.57	-	-	-	-
	D (days)	-	-	-	-	-	-	-	1	-	-	-	-
	T (years)	-	-	-	-	-	-	-	1	-	-	-	-

Appendix F | Uncertainty of water demand

Table F.1 – Assumptions for extreme scenarios of maximum water use for each user

User	Assumptions
Inhabitants	• Human population densities are assumed to be lower outside the river basin than inside • Rural water demand per capita is increased to use during intermediate access • Urban water demand per capita is increase to use during optimal access • The highest observed mean population growth rate of two data intervals is used per subbasin
Livestock	• The largest cattle counts are selected from all available data sources per subbasin • Shoat populations are extrapolated exponentially • All cattle is assumed to be improved • The design demands are used instead of estimated actual use
Large-scale irrigation	• Large-scale irrigation takes place on all previous locations • Small-scale irrigated areas are increased with higher rates and maximum population counts • All known planned projects are in an operational phase; all planned irrigation projects just downstream of Mara Mines are also relocated to and operational in the Low-Mara subbasins • Unsaturated zones are filled up to maximum soil moisture content instead of the minimum require-ments for maximum transpiration • Daily water supply at small-scale farms not constrained by the availability of labour
Tourists	• The probability of reduced visitor numbers due to incidents is assumed to be zero during extrapolation • Monthly BORs during the low season are not reduced according to the MMNR visitor numbers • All tourist accommodations are assumed to be luxury • The water demand per tourist is assumed to be “excessive”
Wildlife	• Wildlife populations are assumed to be restored to their numbers of 20 years earlier • The upper confidence limits are used for the wildlife counts • The maximum unit weights of the species are used to calculate the unit water demand
Other	• School attending population percentages are assumed to be lower outside the river basin • School attending populations per subbasin are calculated with maximum population counts • For daily water use per student, the guideline value for schools with toilets is used for every day school • Estimated maximum water use by other institutions, such as health facilities, is included • Estimated maximum commercial water use is included • Industrial water use is assumed to increase faster

Appendix G | Field observations

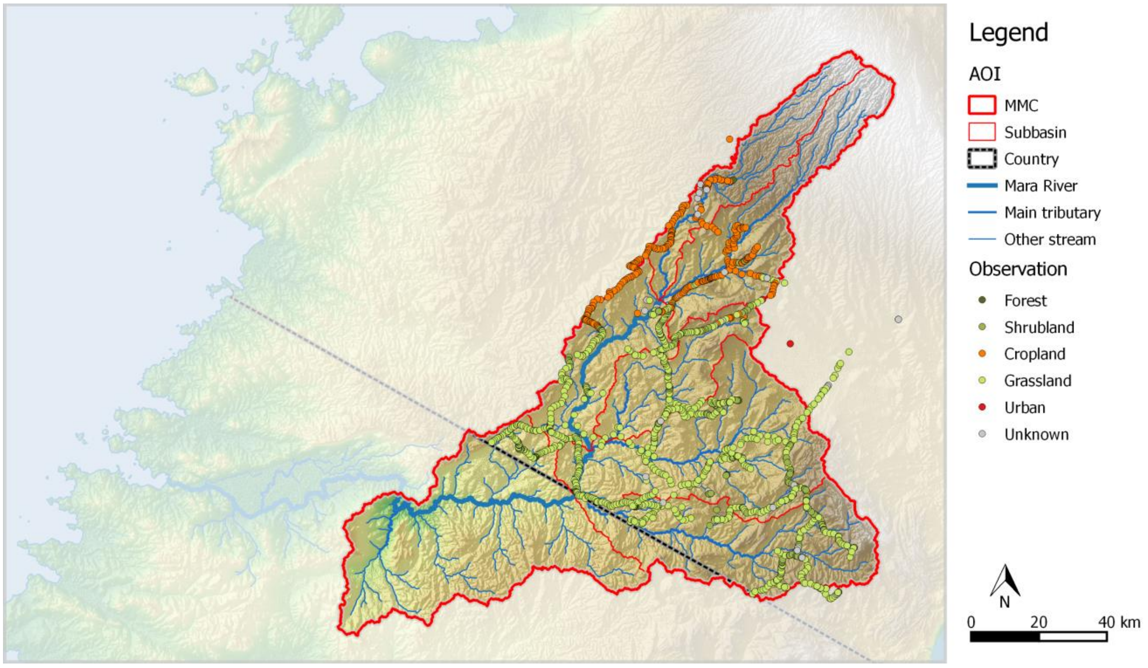

Figure G.1 – Field observation locations including their classifications; due to the low accessibility of some HRUs, these are not equally represented but could often be observed from a distance

The field observations had the following goals:

- to obtain ground truth for satellite data;
- to distinguish or lump classes;
- to refine the model structure;
- to estimate parameters or their ranges;
- to establish parameter and process constraints;
- to identify and characterize water sources.

A checklist for detailed observations is provided in Table G.1.

Table G.1 – Checklist for detailed observations

Category	Observations	Questions
Start	Date; time; coordinates; closest village; special features; rainfall: current, previous days, intensity, duration and timing	Closest village; special features
Vegetation	Density; layers; heights; rooting depths; leaves; trunks; roots; fruits; flowers; smells; evergreen/deciduous; natural/exotic; land use	Names; start seed production; evergreen/deciduous; natural/exotic; change in density, colours and other indicators of dryness over yes; land use change
Soil type	Type; crusts; cracks; trampling; profile; macro pores; root channels; animal burrows; dark stains; decomposing plant material; smell; colour	Profile; changes over months and years in trampling
Erosion / sedimentation	Dust clouds; gullies or rills; stones on top of land surface; pedestals of soil supporting stones and plants; exposed tree roots; soil accumulation along boundaries; sediment deposition on pavements, at bases of slopes and in depressions; exposure of lighter coloured subsoil at surface; different elevation fields compared to paths; clumps of grass in streams; water colour; overhanging tops stream banks; collapsed banks	Ephemeral gullies or rills: dimensions, variation over year, response; turbidity: darkness, location in stream, variation over year and after rainfall; consequences; origins sediments; changes over years; solutions
Flow of water	Current overland flow; water marks on trees or objects; debris or sediment lodged on trees, objects and soil surface; puddles; depressions; stream dimensions, currently and just before bank overflow; flow velocities; groundwater level; location of roads; steepness	Stream: timing completely dry, highest and lowest water levels, steepness of rise and decline; overland flow: depth, concentration in streams, flow velocity; puddles or depressions: water depth; wetlands: depth standing water, boundaries; for all: variation over year and after rainfall, difficulty to cross
Water sources	Type; dimensions; maximum and minimum water level or discharge; water colour; smell; protection; devices: diversion, conveyance, supply, measurement, hydropower production	Water body name; users; timing completely dry; highest and lowest water levels or discharges; steepness of rise and decline; owner; users; permits; variation over year and after rainfall; costs

Appendix H | Data availability

Figure H.1 – Stations measuring rainfall, temperature and/or water level in the MMC

Table H.1 – Temperature data availability in and around the MMC in 2014 (e.g. NOAA, 2014); only stations with at least one year of daily minimum, maximum and mean temperature records are included

Station ID	Location				Data coverage			Data source
	Country	Description	Coordinates	Elevation (m)	First year	Last year	Coverage (%)	
637090	Kenya	Kisii	0.67°S, 34.78°E	1771	1984	2014	43	NOAA
637100	Kenya	Kericho	0.37°S, 35.27°E	1976	1973	2014	36	NOAA
637140	Kenya	Nakuru	0.27°S, 36.10°E	1901	1957	2014	73	NOAA
637330	Tanzania	Musoma	1.50°S, 33.80°E	1147	1957	2014	30	NOAA
637370	Kenya	Narok	1.13°S, 35.85°E	1890	1957	2014	33	NOAA
9035279	Kenya	Hail Research Station Kericho	0.37°S, 35.25°E	1972	1992	2003	100	Other
9135001	Kenya	Narok Meteorological Station	1.10°S, 35.87°E	1856	1992	2003	99	Other
9135012	Kenya	Talek Camp Narok	1.45°S, 35.25°E	1591	1998	2007	97	Other
9135030	Kenya	Mara Serena Lodge	1.25°S, 35.12°E	1668	2004	2007	97	Other

Table H.2 – Water level data availability in and around the MMC

Station ID	Location				Data coverage		
	Country	River	Description	Coordinates	First year	Last year	Coverage (%)
1LA03	Kenya	Amala	Kapkimolwa Bridge	0.90°S, 35.44°E	1955	2008	73
1LB02	Kenya	Nyangores	Bomet Bridge	0.79°S, 35.35°E	1963	2008	86
1LA04	Kenya	Mara	Kichwa Tembo	1.23°S, 35.04°E	1970	1992	37
5H2	Tanzania	Mara	Mara Mines	1.55°S, 34.55°E	1969	2013	69

Table H.3 – Precipitation data availability in and around the MMC; only stations with daily data are included

Station ID		Location			Data coverage		
		Country	Description	Coordinates	First year	Last year	Coverage (%)
9035031	**-**	Kenya	Danson K.Ngugi, Saw Mill, Elburg.	0.38°S, 35.80°E	1959	1987	75%
9035079	**60579**	Kenya	Sotik, Tenwik Mission	0.75°S, 35.37°E	1970	1983	98%
9035085	**-**	Kenya	Oleguruoe D.O's Office	0.58°S, 35.68°E	1959	1984	95%
9035241	**60652**	Kenya	Elburgon Baraget Forest Station	0.42°S, 35.73°E	1969	1992	100%
9035264	**60670**	Kenya	Sotik Water Supply	0.68°S, 35.12°E	1965	2004	84%
9035265	**60671**	Kenya	Bomet Water Supply	0.78°S, 35.35°E	1965	2008	72%
9035284	**60682**	Kenya	Mulot Police Post	0.93°S, 35.43°E	1969	1988	85%
9035302	**60698**	Kenya	Nyangores Forest Station	0.70°S, 35.43°E	1979	1990	99%
9035303	**60699**	Kenya	Narotia Forest Station	0.77°S, 35.53°E	1979	2003	66%
9133000	**90045**	Tanzania	Musoma Met.	1.50°S, 33.80°E	1970	1974	8%
9133004	**90049**	Tanzania	Nyabangi Mission	1.55°S, 33.87°E	1970	1994	92%
9134011	**60727**	Kenya	Sotik Div Agri Office	1.00°S, 34.88°E	1970	1988	93%
9134012	**60728**	Kenya	Taranganya Sec. School	1.23°S, 34.60°E	1983	1990	85%
9134016	**90173**	Tanzania	Kisaka Nguruime	1.57°S, 34.47°E	1970	1979	64%
9134019	**60731**	Kenya	Ntimaru Chief's Office	1.33°S, 34.68°E	1959	2000	88%
9134026	**90062**	Tanzania	Tarime Hydromet	1.33°S, 34.33°E	1970	1994	66%
9134027	**60734**	Kenya	Lolgorien Police Post	1.23°S, 34.82°E	1981	1987	56%
9134029	**90172**	Tanzania	Buhemba Tr. Centre	1.77°S, 34.08°E	1970	1997	90%
9134033	**90063**	Tanzania	Mugumu Primary School	1.87°S, 34.72°E	1970	1997	96%
9135008	**60745**	Kenya	Sotik, Kaboson Gospel Mission	1.00°S, 35.23°E	1970	1986	86%
9135010	**60747**	Kenya	Sotik, Aitong Vet. House	1.18°S, 35.25°E	1981	1997	70%
9135012	**60749**	Kenya	Talek Camp Narok	1.45°S, 35.25°E	1988	2011	99%
9135013	**60750**	Kenya	Narok, Keekorok Game Lodge	1.58°S, 35.23°E	1970	1997	97%
9135020	**60753**	Kenya	Entasekera Chief's Camp	1.83°S, 35.83°E	1986	1992	53%
9135022	**60754**	Kenya	Naikara Africa Gospel Church	1.55°S, 35.63°E	1970	1988	90%
9135026	**60756**	Kenya	Governor's Camp	1.28°S, 35.08°E	2011	2011	100%
9135030	**60758**	Kenya	Mara Serena Lodge	1.25°S, 35.12°E	2008	2011	99%
9135035	**60761**	Kenya	Kichwa Tembo Camp	1.23°S, 35.02°E	1988	2002	68%

Appendix I | Overview of scenarios

Table I.2 – Scenario for water sources (RRH = rooftop rainwater harvesting)

No.	Source	Use
S1	River	$+1 \cdot 10^{-4}$ mm/d
S2	Boreholes	$+1 \cdot 10^{-4}$ mm/d
S3	Shallow wells	$+1 \cdot 10^{-4}$ mm/d
S4	Springs	$+1 \cdot 10^{-4}$ mm/d
S5	Ponds	$+1 \cdot 10^{-4}$ mm/d
S6	RRH	$+1 \cdot 10^{-4}$ mm/d

No.	Source	Use
S7	River	All
S8	Boreholes	All
S9	Shallow wells	All
S10	Springs	All
S11	Ponds	All
S12	RRH	All

No.	Source	Storage
S13	Boreholes	Shallow wells
S14	Ponds	Doubled
S15	RRH	Recommended

Table I.3 – Scenarios for water users (LSI = large-scale irrigation, SSI = small-scale irrigation)

No.	User	Use
U1	Inhabitants	No
U2	Livestock	No
U3	LSI	No
U4	SSI	No
U5	Tourists	No
U6	Wildlife	No
U7	Other	No

No.	User	Use
U15	Inhabitants	Expected
U16	Livestock	Expected
U17	LSI	Expected
U18	LSI	Expected
U24	Tourists	Expected
U25	Wildlife	Expected
U26	Other	Expected

No.	User	Location
U15	Inhabitants	Max
U16	Livestock	Max
U17	LSI	Max
U18	SSI	Max
U24	Tourists	Max
U25	Wildlife	Max
U26	Other	Max

Table I.4 – Land use change scenarios

No.	HRU		Change forest	Different water use
	From	To		
L1	Cropland	Forest	+47%	No
L2	Forest	Cropland	-100%	No
L3	Cropland	Forest	+47%	Yes
L4	Forest	Cropland	-100%	Yes

No.	HRU		Change shrubland	Change water use
	From	To		
L5	Grassland	Shrubland	+1%	No
L6	Shrubland	Grassland	-100%	No
L7	Grassland	Shrubland	+1%	Yes
L8	Shrubland	Grassland	-100%	Yes

Table I.5 – Climate change scenarios

No.	Input	SRES	Amount	Seasonal
C1	Rainfall	A1B	Mean	Yes
C2	Rainfall	A1B	Min	Yes
C3	Rainfall	A1B	Max	Yes
C4	Rainfall	B1	Mean	Yes
C5	Rainfall	B1	Min	Yes
C6	Rainfall	B1	Max	Yes

No.	Input	SRES	Amount	Seasonal
C7	Rainfall	A1B	Mean	No
C8	Rainfall	B1	Mean	No
C9	Temperature	A1B	Max	Yes
C10	Temperature	A1B	Mean	Yes
C11	Temperature	B1	Mean	Yes
C12	Temperature	B1	Min	Yes

Appendix J | Water sources in the reference model

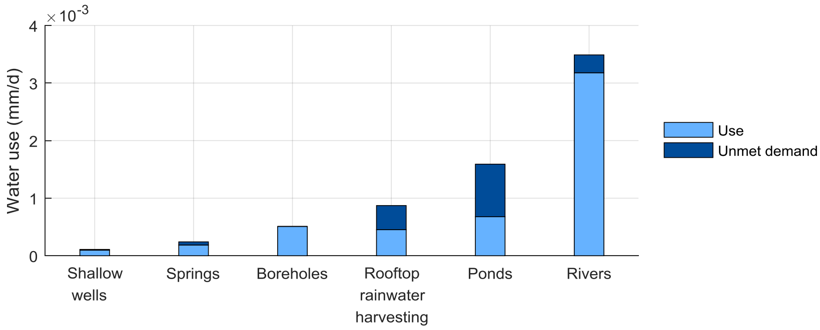

Figure J.1 – Comparison between mean water use and demand at different water sources in the MMC in the reference model, sorted in increasing order of magnitude of water use

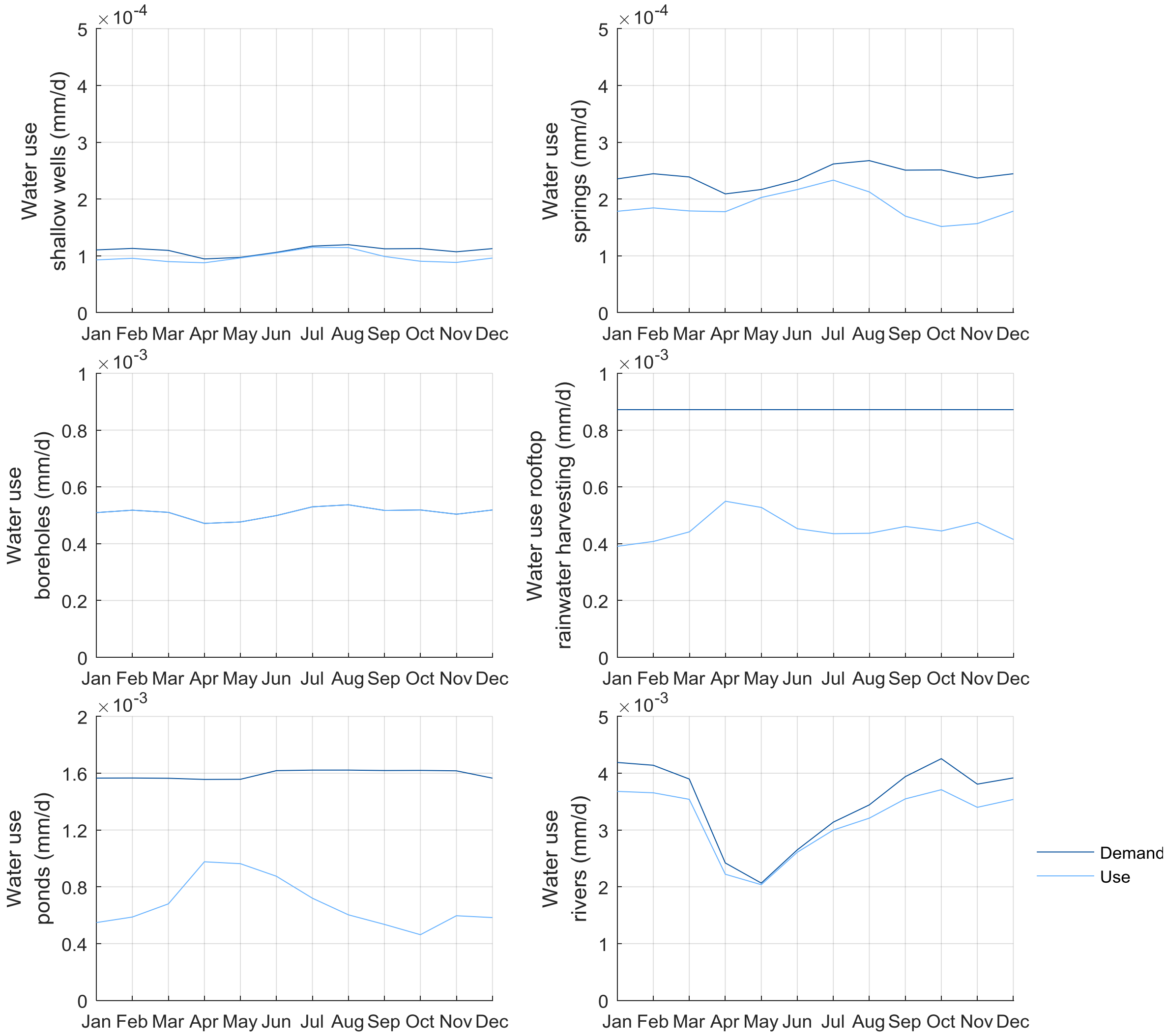

Figure J.2 – Comparison between mean water use and demand at different water sources in the MMC over the year in the reference model, sorted in increasing order of magnitude of water use; from left to right: shallow wells, springs (top), boreholes, rooftop rainwater harvesting (middle), ponds and rivers (bottom)

Table J.1 – Percentage of water demand met at the different water sources in each subbasin in the reference model, for all users except EFRs (in %)

	Shallow wells	Springs	Boreholes	Rooftop rainwater harvesting	Ponds	Rivers	Total
Nyangores	84	70	100	57	64	97	**99**
Amala	90	82	100	55	42	92	**94**
Mid-Mara	89	64	100	24	42	97	**98**
Lemek	99	100	100	60	46	94	**97**
Talek	99	100	100	47	51	97	**99**
Sand	99	100	100	45	2	100	**100**
Low-Mara	90	79	100	22	42	100	**100**
Total	**89**	**78**	**100**	**52**	**43**	**97**	**98**

Table J.2 – Performance of the different water sources in each subbasin in the reference model, for all water demand except EFRs (in %)

		Nyangores	Amala	Mid-Mara	Lemek	Talek	Sand	Low-Mara
Shallow wells	α	0.86	0.91	0.84	0.99	0.99	0.80	0.89
	γ	0.06	0.06	0.04	0.10	0.09	0.13	0.05
	ν	0.13	0.08	0.10	0.01	0.01	0.01	0.10
Springs	α	0.61	0.78	0.30	1.00	0.90	0.79	0.70
	γ	0.05	0.05	0.01	0.20	0.15	0.13	0.03
	ν	0.28	0.16	0.35	0.00	0.00	0.00	0.20
Boreholes	α	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	γ	-	-	-	-	-	-	-
	ν	-	-	-	-	-	-	-
Rooftop rainwater harvesting	α	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	γ	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	ν	0.44	0.45	0.76	0.40	0.53	0.55	0.78
Ponds	α	0.00	0.00	0.00	0.16	0.18	0.01	0.00
	γ	0.00	0.00	0.00	0.04	0.04	0.00	0.00
	ν	0.36	0.58	0.58	0.55	0.49	0.98	0.58
Rivers	α	0.96	0.84	0.89	0.91	0.95	1.00	1.00
	γ	0.06	0.07	0.07	0.05	0.05	-	-
	ν	0.02	0.07	0.04	0.05	0.02	-	-