THE DYNAMICS OF INTER-BASIN WATER TRANSFER UNDER INCREASING WATER DEMANDS AND CLIMATE VARIABILITY: A CASE OF WATER TRANSFER FROM UPPER TANA BASIN TO ATHI BASIN

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The Dynamics of Inter-basin Water Transfer under Increasing Water Demands and Climate variability: A Case of Water Transfer from Upper Tana Basin to Athi Basin.

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other university

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DEDICATION

This thesis is dedicated to my family and friends. Much gratitude to my loving daughter Tumi, my parents Munjiru & Nyingi, Kariuki & Njeri for their love, support, and encouragement throughout the study. Special thanks to my siblings Mwangi, Wanjiru, Wanjira, Mwihaki and Wambui for being there for me throughout the entire period.

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ACRONYMS AND ABBREVIATIONS

AfDB	African Development Bank
ASAL	Arid and Semi-Arid Land
BFI	Base Flow Index
CHIRPS	Climate Hazards Group Infrared Precipitation With Stations
DEM	Digital Elevation Model
ET	Evapotranspiration
FAO	Food and Agriculture Organization
FDC	Flow Duration Curve
FI	Flashiness Index
HEC HMS	Hydrologic Modelling System
HFB	Horizontal Flow Barrier
IBWTs	Inter-Basin Water Transfers
ICID	International Commission on Irrigation and Drainage
IHA	Indicators of Hydrological Alteration
ISRIC	International Soil Reference and Information Centre (ISRIC)
KENSOTER	Kenya Soil and Terrain Database
KNBS	Kenya National Bureau of Statistics
MODFLOW	Modular Finite-Difference Flow

NASA	National Aeronautics and Space Administration
NCT	Northern Collector Tunnel
NDWI	Normalized Difference Water Index
RCM	Regional Climate Model
RCMRD	Regional Centre for Mapping Resource for Development
RVA	Range of Variability Approach
SDI	Streamflow Drought Index
SMA	Soil Moisture Accounting
SNAP	Sentinel Application Platform
SOTER	Soil and Terrain Database
SRTM	Shuttle Radar Topography Mission
VES	Vertical Electrical Sounding
WAPOR	Water Productivity Open-Access Portal
WCD	World Commission on Dams
WEAP	Water Evaluation and Planning System

ABSTRACT

Universal and equitable access to adequate, safe and affordable drinking water by all is one of the Sustainable Development Goals (SDGs). However, this goal is far from being achieved as issues of water scarcity remain a big challenge especially in sub-Saharan Africa due to growing population, urbanisation, and climate variability. There have been several interventions to cope with the rising water demands, among them inter-basin water transfers (IBWTs). IBWTs link two or more basins resulting in complex economic, social, and environmental inter-dependencies among the donor and recipient basins. A proper understanding of these inter-dependencies requires a multi-disciplinary approach and in-depth scientific analysis, which may vary for different river systems. The aim of this research was thus to evaluate the hydrological and socio-economic implications of inter-basin water transfer systems under growing water demand and climate variability with a focus on the Northern Collector Tunnel (NCT I) in Upper Tana basin, Kenya. First, the study evaluated the reliability of Maragua, Irati and Gikigie streams to meet the proposed water transfers to Nairobi City under different climatic conditions using hydrological modelling system (HEC HMS) and stream flow variability indices. An innovative methodology that uses evapotranspiration (ET) from water productivity open access portal (WaPOR) as input to the model was used to improve the hydrological model performance and limit model uncertainty. The results showed that during the dry years, the reliability of Maragua, Irati, and Gikigie to meet the water transfer was 15%, 23%, and 33% respectively. In normal years, the reliability increased to 45%, 60%, and 62%; and to 83%, 98%, and 94% in the wet years. This implies that the project will not meet its objective of achieving over 70% supply coverage during the dry and normal years for which the dry years have a 5-year cycle of occurrence. In addition, Maragua stream showed a higher flow variability thus lower reliability whilst envisioned to contribute the highest amount among the three streams. Thus, it is recommended that the technical viability of large IBWTs should emphasis on the reliability of water sources taking into account climate variability. Using the water evaluation and planning model (WEAP), the study evaluated optimal urban water allocation strategies for Nairobi city with the current and planned IBWTs. While the government's objective is to increase the supply coverage in Nairobi city to over 70%, this will only be achievable during the wet years. From the results of this study, even with demand management measures, NCT 1 will still not meet the desired supply coverage in the normal and dry years. However, from the results, with additional water sources (NCT phase II and Maragua dam), demand management measures provide opportunities of alleviating water shortages by achieving the desired supply coverage under all climatic conditions. For flood based IBWT systems, it would be vital to incorporate storage reservoirs to enhance supply reliability. There were concerns about the possible impacts of the Northern Collector Tunnel (NCT) I project on groundwater flow in the Upper Tana Basin. Therefore, this study investigated the barrier effect of the project on groundwater flow in the basin using vertical electrical sounding (VES) survey and modular finite difference flow (MODFLOW) modelling. Results showed the recharge zones are on the upstream side of the tunnel where many shallow springs of a maximum depth of 50m are located. The tunnel increased the local hydraulic head on the upstream side by up to 10% with a 2% decrease observed in boreholes located on the downstream side. Lastly, the study evaluated the distribution of risks and benefits in IBWTs among stakeholders in the

NCT 1 using the stakeholder analysis technique. Athi Water Works Development Agency (AWWDA) and the Ministry of Water and Irrigation (MoWI), which are national institutions, played a key role in the project. However, most stakeholders consider the devolved units; Water Services Providers (WSPs), Water Resources Authority (WRA) and Water Resources Users Associations (WRUAs) and Murang'a County as the most critical institutions. Major risks of the project emerged as reduced river flows, drying up of springs and local community's inability to meet their water needs. Increased water supply to Nairobi City was perceived as the major benefit of the recipient basin. Thus, NCT I project presents both risks and benefits to the donor and recipient basins, however, without a specific framework to balance them. This calls for a water levy that covers the full costs of water abstraction, socio and environmental externalities (risks) and catchment conservation.

CHAPTER ONE

INTRODUCTION

1.1 Background

Water is increasingly becoming a scarce resource due to population growth, urbanisation, and climate change especially in the arid and semi-arid regions (ASAL). Supply-oriented strategies such as desalination of seawater, inter-basin water transfers and reservoir storage have continued to offer solutions to address this water scarcity (Gohari et al., 2013). Inter-basin water transfers (IBWTs), have over the years, been developed to augment water supply in recipient basins in many countries. Worldwide, IBWTs account for 14% of the total water abstractions and this is projected to increase to 25% by 2025 (ICID, 2007). If properly planned and managed, IBWTs could be an effective way of improving water access in water scarce regions. However, in most of the regions, IBWTs have not only temporarily solved the water scarcity problem in the recipient basin but have also caused severe long-term impacts in the donor basin (J. Gupta & van der Zaag, 2008). Among the reasons is because development of most IBWTs is based on long term water balance studies where regions deemed to have "surplus" water donate to regions perceived to be water "scarce" (Gohari et al., 2017). Gupta & van der Zaag (2008) in their review of inter-basin water transfers gave a set of criteria for evaluating IBWTs projects, among them, being a real and verifiable surplus in the donor basin and a deficit in the recipient basin. For instance, over-exploitation of the water resources in the donor basin in the Ixtlahuaca groundwater transfer to Mexico City critically reduced groundwater levels in the basin which affected the local community water needs (Dyrnes & Vatn, 2005). Often, IBWTs water allocation studies seldom consider flow variability (Khadem et al., 2021) which leads to an overestimation of the available water (Pittock et al., 2009). For instance, in Australia, the snow mountainous scheme was developed to reduce flooding from snowmelt in spring and rainfall in winter in the regions downstream of the Snow River. The scheme in the 1950s to 1970s diverted 99% (approximately 1,130 Mm^3/year) of flow to Murray basin for irrigation and hydropower. This had severe consequences to the river ecology and downstream water users and an agreement was reached to restore the environmental flow to 21 % (approximately 212 Mm^3/year) and ultimately to 28% of the mean annual flow (approximately 294 Mm^3/year) (Ghassemi & White, 2007b; NSW, 2010). In India, surplus in a basin is considered when the difference between Q_{75} and the projected water demand is positive, otherwise it is considered water deficient. As such only flood water would be diverted whose variability is high (Ghassemi & White, 2007a). Although knowledge of water balance is essential in inter-basin water transfers, it is not sufficient on its own for making decisions to divert water from one basin to another.

Globally, urban population is expected to grow by 2.9 billion by 2050, with most of the people residing in cities of the developing countries (Nagendra et al., 2018; WWAP, 2022). Thus, water demand in regions with fast economic development and high population growth is predicted to increase while the available freshwater resources remain constant. Arguably, these are often the urban cities, which subsequently become strategic regions politically (Bischoff-Mattson et al., 2020). In most urban cities, water scarcity solutions have been supply-driven, for instance the IBWTs, which are popularized by technocrats to increase water availability (J. Gupta & van der Zaag, 2008).Such projects are what Kumar et al., (2021) terms as critical infrastructure as they are at the core of a society’s survival. There have been concerns on the increasing water scarcity in urban cities which contribute greatly towards the countries’ economic growth. With the expansion of urban cities, and the development of informal settlements, the demand for water is expected to increase while the supply remains uncertain due to climate variability (Daloğlu Çetinkaya et al., 2022). In the recent past, a number of urban cities have faced major water crisis, Cape town in 2018, San Paulo in 2015 and Southeast Queensland in 2007 where residents experienced unprecedented water shortages (Head, 2014; Rodina, 2019). Thus, water security in urban cities is becoming a challenge of the 21st century (Ahmadi et al., 2020; Empinotti et al., 2019; Sahin et al., 2017; WWAP, 2022). As such, evaluating optimal water allocation from IBWTs is vital for the schemes to achieve their objective of alleviating water shortages in the recipient basins which are often urban cities (Zhou et al., 2017).

IBWTs often involve connecting two or more river basins hydraulically, and with that a new dependency between communities in the donor and recipient basin is created evoking interests from different stakeholders (J. Gupta & van der Zaag, 2008). In most IBWTs, the socio-economic risks are often borne by the poor and vulnerable communities in the donor basin while benefits accrue at higher social level. Therefore, some IBWTs systems have been met with resistance from the local communities in the donor basin (Carvalho & Magrini, 2006; Dyrnes & Vatn, 2005; Gohari et al., 2013; Roman, 2017). The local community in Ixtlahuaca basin in Mexico, who depended on groundwater for their livelihoods, were forced to pay a higher price to access the resource because of the reduced groundwater levels in the basin which resulted in increased pumping costs (Dyrnes & Vatn, 2005). In the Lesotho Highlands Water Project, distribution of benefits was at state level while the local community continued to experience water scarcity (J. Gupta & van der Zaag, 2008). Unlike dams where in 2000, the World Commission on Dams (WCD) proposed a framework in which benefits are shared equitably '*We believe that an equitable and sustainable approach to development requires that a decision to build a dam or any other options must not, at the outset, sacrifice the rights of any citizen or group of affected people'*(WCD, 2000). IBWTs have no such explicit provisions and maybe complex especially where the donor and the recipient basins are in different administrative units. Several researchers have attempted to expound on the basic principles of IBWT include the issue of integrated water resources management (IWRM) which encourages public participation and equitability in water management (Kibiiy & Ndambuki, 2015; Sinha et al., 2020). Gupta & van der Zaag (2008) proposed a set of five (5) guidelines which in essence promote ecological, social and economic sustainability of IBWTs to in that *"No person will be worse off because of the IBWT scheme".* Although this issue has attracted a lot of concern, there is no clear framework on sharing water under IBWTs and how benefits and risks are distributed amongst the stakeholders.

IBWTs are large infrastructural works often consisting of reservoirs and channels where the channels are either surface or underground (tunnels) systems. Tunnelling has been found to cause piezometric drawdowns when the tunnel is permeable as groundwater flows into the tunnel (Boukhemacha et al., 2015). If the tunnel has an impermeable lining, the flow of groundwater is constrained and depending on the aquifer properties a barrier effect may be experienced which may lead to detrimental effects (Font-Capo et al., 2015; Pujades et al., 2012).

Although there has been substantive research on the impacts of IBWT, most of the studies have only been on the ecological impacts on the donor basins (Quan et al., 2016; Sadegh et al., 2010; Tian, Liu, Guo, Pan, et al., 2019; H. Yang & Zehnder, 2005) while stream flow variability which influences the reliability of the system to meet the anticipated water demand in the recipient basin is seldomly addressed. Further, limited research has been done on IBWTs water allocation especially when the system relies on flood water which is highly variable. Most of the research on IBWTs water allocation has been on normal flow under certain climatic conditions (Sinha et al., 2020). In addition, issues of distribution of risks and benefits among stakeholders in IBWTs schemes have not received a lot of attention by researchers and practitioners. Therefore, for sustainable water development and management, an integrated approach needs to be adopted in the planning of inter-basin water transfers schemes (Berger et al., 2007).

1.2 STATEMENT OF THE PROBLEM

Most of the infrastructural development for inter-basin water transfer has been undertaken in Upper Tana Basin diverting water from the Chania and Thika rivers, which are tributaries of the Tana River accounting for 96% of the domestic water supply to Nairobi (Table 1.1) (AWWDA, 2012).

Table 1.1: Summary of the Sources of Water for Nairobi City

Source	Location	Completion year	Storage Capacity Mm^3	Amount in %	Amount in m^3/d	Remarks
Thika Dam	Tana river basin	1994	70	84%	440,000	Inter-basin transfer from Tana Basin
Sasumua	Tana river basin	1968	15.9	12%	62,500	Inter-basin transfer from Tana Basin
Ruiru Dam	Athi river basin	1950	2.9	4%	22,000	Intra-basin transfer (Athi)
Kikuyu Springs	Athi river basin	1913	-	0.1%	5,500	Intra-basin transfer (Athi)

Source (AWWDA, 2012)

The Kenya government has implemented the Northern Collector Tunnel (NCT) I; a water transfer project intended to alleviate this water shortage and meet the growing water demand for Nairobi city and its environs. The project involved construction of a 12 km impervious underground tunnel to convey approximately 140,000 m^3/day from Maragua, Gikigie and Irati streams to the already existing Thika Dam. However, from the projected water demands, the project needs to be augmented with other sources of water to meet the future and ultimate water requirements (Figure 1.1 and Table 1.2) (AWWDA, 2012).

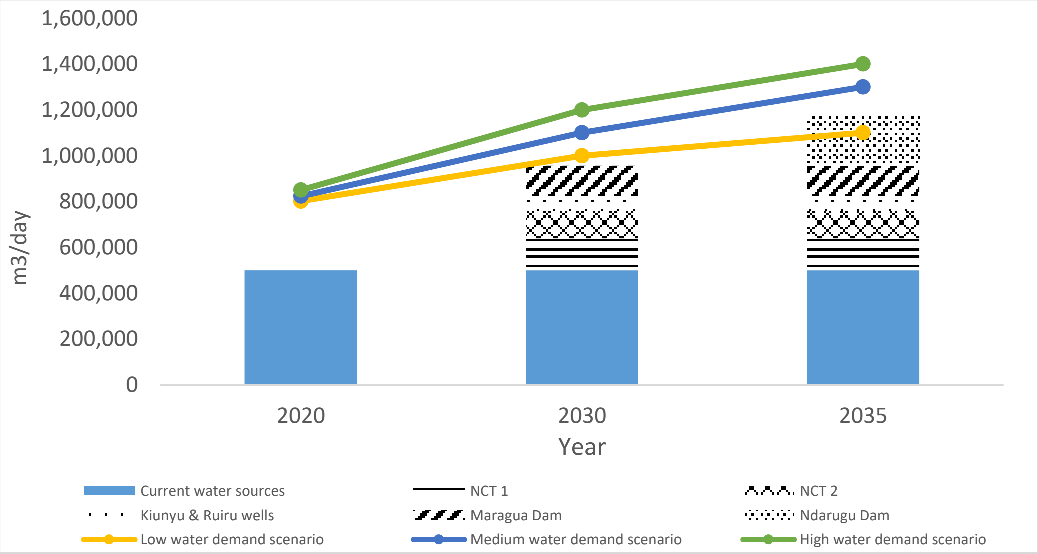


Figure 1.1: Water Demand and Supply for Nairobi City

Table 1.2: Planned Water Sources for Nairobi City

Source	**Expected Completion date**	**Amount in m^3/d**	**Remarks**
Kiunyu and Ruiru Wells	2015	64,800	Intra-basin transfer (Not in operations)
Northern Collector Phase 1	2016	120,960	Irati, Gikigie and Maragua rivers (inter-basin transfer-completed in 2022)
Maragua Dam	2020	132,192	Inter-basin transfer (not done)
Northern Collector Phase 2	2026	120,096	South Mathioya, Hembe, Githugi & North Mathioya rivers (inter-basin transfer)
Ndarugu Dam	*2029*	*216,000*	*Ndarugu river with Chania & Komu river Inter-basin transfer*

Assessment of the available water from three streams (Maragua, Gikigie and Irati) was based on a hydrological assessment of 2010 that estimated the mean annual flow less the required reserve flow and present abstractions from the streams (AWWDA, 2016). Further, the engineering design of NCT 1 is that only the normal flow (Q_{80}) and flood flow (Q_{68}) will be abstracted from the respective streams using regulated height-dependent water diversion structures. As such, water availability and reliability will be highly dependent on the temporal variability of flow in Maragua, Gikigie and Irati streams (AWWDA, 2012; MCG, 2015; World Bank Group, 2017). However, there is limited scientific studies on stream flow variability and reliability of the tributaries of Tana River and many river systems in Africa. In addition, most IBWTs water allocation strategies have been on normal flows unlike in the NCT I project which targets flood flows for the diversion. This may result in varied levels of unknown reliability thus affecting the overall objective of the project.

The NCT I project faced significant resistance from the local community during its construction stage who raised concern about their water resources being diverted to Nairobi with no tangible benefits to them. There is consensus among scholars that IBWTs systems introduce both benefits and risks which are borne differently among stakeholders (Hernández-Mora et al., 2014; W. Zhuang, 2016). This study therefore sought to explore the distribution of risks and benefits in IBWTs through stakeholder analysis of the NCT I project.

There were concerns on the impacts of NCT I project on groundwater flow in the area and possible drying up of their springs and wells since the conveyor system is an underground impervious tunnel (World Bank Group, 2017). Proper assessments of the impacts of tunnel on groundwater can inform decisions on how to compensate those relying on groundwater for their livelihoods (Raposo et al., 2010).Thus, sound scientific research on the hydrological and socio-economic dynamics of inter-basin water transfers under uncertainties is thus key in decision making. This research, therefore aimed at providing information on how to manage the interdependency in inter-basin water transfers systems using multi-disciplinary approaches.

1.3 Justification

Nairobi City has over the years relied on IBWTs from the Upper Tana basin to meet its urban water demands. Further majority of the planned and future water sources will be IBWTs as there are plans to extend NCT I to NCT II abstracting from three streams upstream of the NCT I. The Upper Tana basin has been experienced extreme hydrological events which impact the availability of the water resources to meet the growing water demands. However, with proper planning and management, the NCT I and planned NCT II offers a solution to water scarcity in Nairobi City. According to a feasibility study done for NCT I, the water balance assessment was done based on the mean annual flow to estimate the yield from Maragua, Gikigie and Irati streams under normal climatic conditions (AWWDA, 2012). However, a good understanding of the variability of stream flows especially when the IBWT is relying on flood flows is necessary. In addition, IBWTs are large infrastructural projects that require huge investments, thus, there is need to ensure their viability. NCT I project faced a lot of resistance from the Muranga residents (donor communities), as they claimed the Environmental and Social Impact Assessment (ESIA) for NCT1 was not comprehensive and lacked adequate geotechnical studies, water supply and demand analysis and the environmental and social impacts study (World Bank Group, 2017). NCT I will introduce hydraulic interdependency between Nairobi City in Athi basin and the Upper Tana basin therefore it is vital to balance between the risks in the Upper Tana basin and the benefit accrued at Nairobi City for the project to be socially acceptable and sustainable. The study has provided variable insights that will guide the policy makers on the current and future IBWTs in Upper Tana basin and in other similar river basins in the region and the world.

1.4 Research Objectives

1.4.1 Main Objective

The main objective of this study was to evaluate the hydrological and socio-economic implications of the water transfer from Upper Tana River basin to the Athi river basin under growing water demand and climate variability

1.4.2 Specific Objectives

1) To assess the streamflow variability of the proposed inter-basin water transfers, (Northern Collector Tunnel I) under different climatic conditions in the Upper Tana basin.
2) To determine the optimal water allocation strategies for Nairobi city under different climatic conditions and variable water demands.
3) To assess the barrier effect of the underground tunnel (Northern Collector Tunnel I) on groundwater flow in the Upper Tana River basin
4) To assess the distribution of risks and benefits among different stakeholders in the donor and recipient basins.

1.5 Research Questions

Question 1

How will the stream flow variability affect the reliability and availability of water for the Northern Collector Tunnel I project under different climatic conditions?

Question 2:

What are the optimal water allocation strategies for Nairobi city under varying climate and water demands?

Question 3:

What is the barrier effect of the Northern Collector Tunnel I underground tunnel on groundwater flow in the basin?

Question 4:

What is the distribution of risks and benefits in the Northern Collector Tunnel I project among various stakeholders?

1.6 Scope of the Study

The study was carried out in the Upper Tana basin located in Muranga County, Kenya, and focused on the Northern Collector Tunnel (NCT I), an inter basin water transfer project. It entailed hydrological modelling and streamflow analysis for the period 1982-2017. The study further evaluated the distribution of risks and benefits among the various stakeholders in the project and the effects of tunnelling on the local community's water supply sources.

1.7 Limitations of the Study

Limitations of this study was the lack of long-term monitored groundwater levels in the study area. This might have limited some accuracy of the field borehole measurement analysis, however, to validate the results numerical modelling using MODFLOW was done.

CHAPTER TWO

LITERATURE REVIEW

2.1 Development of Inter-Basin Water Transfers (IBWTs)

Globally, water resources are unevenly distributed among regions and catchments, such that while some regions and catchments are water scarce others are water abundant. However, in many regions of the world, water shortage is not only a water scarcity issue, but also because of high water demands. It is for this reason that inter-basin water transfers have been used for ages to redistribute water from water abundant regions to water scarce regions (Shumilova et al., 2018)

The first inter-basin water transfers to be recorded were in Egypt, Mesopotamia and Israel which are all water scarce regions. These diversions were mainly for agriculture and were done using gravity canals (Snaddon et al., 1999). It is during the 19th century, that most of the now developed countries constructed majority of their inter-basin water transfers. It was associated with the concept of hydraulic civilization where water was considered a resource to be exploited in order to drive economic growth (Pittock et al., 2009). For this reason, issues of environmental integrity and public participation were hardly considered in the development of these projects. This resulted in severe negative environmental impacts, loss of social welfare and in some cases water conflicts (Rinaudo & Barraqué, 2015; Roman, 2017; W. Zhuang, 2016). In recent years, there has been a lot of emphasis on upholding the ecological health of both the donor and recipient basins and involving the public with the aim of ensuring sustainable projects (J. Gupta & van der Zaag, 2008). Nevertheless, inter-basin water transfers continue to attract a lot of controversy despite their benefits because of the unintended negative effects associated with the systems (Gohari et al., 2013).

2.2 Controversies Involved in Inter-Basin Water Transfers (IBWTs)

The controversies around inter-basin water transfers involve environmental (geomorphological, geological and hydrological), social-economic, legal, administrative and political aspects (Giacomoni & Berglund, 2015; Gohari et al., 2013, 2013; Sinha et al., 2020; Y. Wang et al., 2016).

2.2.1 Environmental Impacts

Inter-basin water transfers are anchored on the basis of donor basins having abundant water supplies to divert some to basins with insufficient supplies or otherwise water scarce. Although there are regions which are wetter than others, Mehta (2007) argues that water scarcity is sometimes socially created in order to drive projects that are key to governments of the day. These projects are promoted as solutions to water scarcity in regions that are often of interest to the government politically and /or economically (J. Gupta & van der Zaag, 2008). In addition, these projects often have the support of epistemic groups of engineers, politicians and financiers who promote them as the best possible solutions to water scarcity (Gohari et al., 2013)

There are no international standards for assessing the “surplus” which is to be diverted to the recipient basin. This often leads to over estimation of the water available in the donor basin, the results of overestimation not only affect the water resources in the donor basin but the reliability of the inter-basin system to meet the recipient’s water demands(Tian et al., 2019). Water availability is predicted to be influenced by uncertainties of climate change and the rate of development of a region. Since the inter-basin water transfer are usually designed for a long-life span, such uncertainties can lead to undesirable environmental effects (de Andrade et al., 2011).

Research has shown that inter-basin water transfers alter the hydrological regimes of both the donor and the recipient basins. The flow in the donor basin reduces while that in the recipient basin increases. The reduction of the flow in the donor basin is not only because of the possibility of over-estimation of water availability but also due to over-exploitation (Yevjevich, 2001).Generally, inter-basin transfers are justified by the fact that essentially only the overflow “excess water” will be diverted. However, as the water demand in the recipient basins rises, diversion of water may exceed the limits set for environmental flow and other uses downstream (Dyrnes & Vatn, 2005) .The decrease in flow regime in the donor basin, has subsequent consequences for instance saltwater intrusion in the estuary as in the case of North-South water transfer, China and California water transfer project (W. Zhuang, 2016). In other cases, springs and wetlands downstream dry up, leading to loss of ecosystem services offered by the resources to the local communities. In the recipient basin, the environmental concerns include increase in the grey water and its disposing mechanisms (Pittock et al., 2009).

Although, Environmental Impact Assessments (EIA), for such projects are normally done, they mostly address components of the specific project and seldom address the holistic impacts of the projects. In most cases, the EIA studies are done when a decision to implement the project has already been made and therefore only serve as a check box to access funds for the project (Matete & Hassan, 2005).

2.2.2 Socio-Economic Impacts

Most inter-basin water transfers have been met with resistance especially from the donor basin local communities (Carvalho & Magrini, 2006) (Fraj et al., 2019). The communities are usually concerned about the possibility of water shortages because of the diverted water (Roman, 2017). In response to the local communities' concerns, they are promised other development projects e.g., roads, water supply projects for them to cooperate and allow the projects to be implemented. However, these projects are often not done to completion and even then, do not solve the concerns of the communities (J. Gupta & van der Zaag, 2008).As mentioned earlier water resources are often overexploited leaving the local communities to suffer from water shortages. In cases of groundwater that would mean higher pumping costs as the water levels reduce significantly. The costs of over-exploitation are normally borne by local communities in the donor basin, despite them not benefitting from the water transfer (Dyrnes & Vatn, 2005). The key issue is how the interests and right of use of the existing water users are considered in the inter-basin water transfers. Research has shown that inter-basin water transfer projects require a lot of investment in terms of funding. Since these funds could have been used for other development projects, it is important that IBWTs be economically and socially sustainable (de Andrade et al., 2011)

Some of the inter-basin water transfers result in inequalities where people in the donor basin are displaced when the large infrastructure are built for instance dams and canals or tunnels (Shumilova et al., 2018). This issue if not properly addressed can cause long term land compensation and displacement disagreements just like the case of Thika dam built in 1970s for water transfer to Nairobi City (Syagga & Olima, 1996). There are also indirect costs to the projects they stall or prolong as a result of resistance from the local communities (Purvis & Dinar, 2020).

IBWTs have been seen to increase water supply in recipient basins which may lead to agricultural development in an agricultural region or industrial boost an urban area. However, this diverted water leads to deterioration of the water sources in the donor basin affecting their income. In some instances, the residents have been forced to involuntary migrate or resettle in other areas. Groundwater transfer from the Sahara to the Mediterranean coasts in Libya caused migration of people to the desert further increasing the demand for water (Shumilova et al., 2018).

2.2.3 The Case of Northern Collector Tunnel (NCT I) in the Upper Tana basin, Kenya

Since the 1970s, Upper Tana basin has been considered as the primary source of water for Nairobi city located in the Athi river basin. A water resources study done in 1986 (Third Nairobi Project), proposed the development of Thika dam (Ndakaini), and the diversion of water from rivers upstream of the dam through a tunnel which came to be known as the Northern Collector Tunnel (NCT I & II) projects (NCC, 1986).

Since then, there has been various studies done on the feasibility of the NCT I. The main concern has been on the compensation flow downstream of the project especially during the dry spells. The water demand for Muranga county by 2035, was estimated at 111,100m^3/day for the rural water supply water schemes and 97, 946m^3/d for water services providers (WSPs). The sources will be Maragua, Irati and Kahaywe streams, thus Maragua catchment will account for more than 50% of the water supply in the county (MCG, 2015). The county has 20,000 hectares of arable land that can potentially be under irrigation, however, only about 2947 hectares has been developed whose water requirements is 193, 620m^3/day. Of this, 1120 hectares is in Maragua catchment with a water demand of 43,377 m^3/day of water (AWWDA, 2016). The county estimates that the livestock water demand projection by 2035 will be 35,677 m^3/day. There are various small dams for tea farms and major hydropower plants in the basin. Wanjie and Mesco power stations of 7.4 Megawatts (MW) AND 0.38 MW respectively are located downstream of Maragua stream. In addition, the NCT I stream are all tributaries of Tana River which is the source of the chain of hydropower stations; Masinga, Kamburu, Gitaru, Kindaruma and Kiambere with a capacity of approximately 500MW. Taking the Muranga county water requirements into account the recommendation was that the abstraction should be of flows above Q_{50}. In addition, the studies recommended a system that will ensure diversion of water is stopped once Thika reservoir is full. This would avoid unnecessary water losses from the diverting rivers during the wet seasons. The studies noted that a holistic water resources development plan of the two basins i.e. Upper tana and Athi river basin was necessary for sustainable water resources management (MCG, 2015; NCC, 1998).

Subsequently, the local community expressed the same concerns arising from the studies. According to an inspection panel report by the World Bank, a section of Muranga residents, were concerned about several issues on the NCT I:

a) Interference of underground tunnelling on groundwater flow which would lead to the drying of their wells, springs and boreholes.
b) Water shortages because of the diversion of water from the rivers especially during the dry spells.
c) Insufficient reservoir capacity at Thika (Ndakaini) dam that would lead to unnecessary losses through spillage during the wet season.
d) Poor community engagement at all steps of the project formulation and implementation (World Bank Group, 2017).

To address these concerns a joint consensus was reached in December 2015 between Muranga County government and Athi Water Works Development Agency (AWWDA) where the design of NCT I was amended to increase the compensation flows in the three streams (Maragua, Gikigie and Irati) and thus reduce the likelihood of reduced river flows. To reduce the risk of interference with groundwater levels, the NCT I tunnel was to be made impervious. In addition, a water abstraction survey was to be conducted and a water master plan for Muranga county where the construction of Maragua dam and other multipurpose dams for downstream users was to be undertaken. Accordingly, Muranga County would benefit from the project through community water projects, increased employment opportunities, formation of a bulk water utility to supply bulk water within and outside county and financing of conservation activities in the Aberdare Forest. However, in November 2016, a group of Muranga County residents submitted to the project financiers a request for re-evaluation of the short and long-term impacts of the project on their water sources. However, their request was denied as the financiers referenced an Environmental Impact Assessment (EIA) report approved by NEMA and the Consensus agreement made with the county government then on the project.

2.3 Hydrological Modelling

A hydrological model is a simplified representation of the hydrological processes of a region, basin, or catchment. The suitability of a model is based on the accuracy of results using minimal data and the ease of use of a model. A hydrological model estimates runoff using a set of equations that are a function of the basin characteristics (Devia et al., 2015). However, by simplifying a complex process, hydrological models entail a certain level of uncertainties and errors even from the process of inputting the data. Fortunately, over the years, developers and researchers have devised ways of anticipating these errors and uncertainties and correcting or minimising them (Bourdin et al., 2012).

Hydrological modelling can be classified into:

a) Empirical – oriented approach which are data driven models which implicitly simulate the hydrological processes. These include statistical and soft computing methods. The major limitation of these models is that they do not consider uncertainties or changes in hydrological processes. The effects of climate change are also not adequately addressed by these models.
b) Process - oriented models -These models explicitly simulate the hydrological processes which include evapotranspiration (ET), interception, ground, and surface water. Simulation of the hydrological processes is done using mathematical equations. These types of models have gained popularity since they are able to simulate uncertainties like climate change. These models can

further be classified based on their spatial distribution and complexity of simulation (Devia et al., 2015).

Most used process - oriented models are lumped, semi-distributed and fully distributed hydrological models. Lumped models involve simulating the hydrological processes without changing the parameters within the basin. Semi-distributed models usually split the basin into sub-basins which have similar characteristics. In fully distributed models the hydrological process parameters change depending on the user's resolution requirements. However, fully distributed models are data intensive and require large computational time (Bourdin et al., 2012). Various models have been used for hydrological modelling including HEC-HMS (hydrologic modelling system), SWAT (soil and water assessment tool), STREAM (spatial tool for river basin environmental analysis), MIKE SHE, HBV and TOPMODEL (Arnold et al., 2012; Feldman, 2000; Jaber & Shukla, 2012). Some of the models are open source while others are commercial, however open-source models are the most recommended for research.

2.3.1 Soil and Water Assessment Tool (SWAT)

SWAT is a physically based model that is used to estimate discharge and sediments to assess the effects of land management system in a basin over a long period of time (Arnold et al., 2012). SWAT divides the entire basin into hydrological response units (HRUs) with similar land use, vegetation and soil characteristics. SWAT model requires weather parameters of the basin, soil, land cover data and digital elevation model (DEM) as input data for simulation. For evapotranspiration, the model uses Penman Monteith, Priestly- Taylor and Hargreaves methods using the weather time series. Thus the model is data intensive and also require skilled training (Bourdin et al., 2012; Devia et al., 2015).

2.3.2 Hydrologiska Byrans Vattenavdelning (HBV)

HBV is a semi-distributed model where the basin is divided into sub-basins and further into elevation and vegetation zones. This model uses either daily or monthly climatic weather parameters including temperature to simulate the hydrological process of a basin (Bergström, 1976). Although, HBV has limited data requirements and is easy to use, the generalization of parameters is a challenge in achieving quality simulation results. However, to address this challenge, the developers have introduced new versions with improved calibration process and also incorporating new sub models (Devia et al., 2015).

2.3.3 MIKE SHE (Systeme Hydrologique European)

MIKE SHE model is a physically based model developed in the 1990s. The model encompasses hydrological processes such as precipitation, evapotranspiration, interception, river flow, saturated groundwater flow and unsaturated groundwater flow (Ma et al., 2016). MIKE, SHE simulates run off, sediments and water quality issues in a basin. The model uses SHE code for pre-processing and post-processing modules which are explained in detail in the user manual for ease of use (Jaber & Shukla, 2012). The model is data intensive and requires an advanced computer to run the code.

2.3.4 Hydrological Modelling System (HEC-HMS)

The Hydrological Modelling System (HEC-HMS) was developed by the Hydrologic Engineering Centre for the U.S. Army Corps of Engineers for continuous and event based hydrologic modelling (Feldman, 2000). Event modelling is simulations that have small time span for instance, the beginning of a storm and shortly after a storm. Continuous modelling involves modelling over a long time even several years and includes evapotranspiration and groundwater seepage processes unlike in the event modelling (Scharffenberg & Fleming, 2016).

HEC HMS consists of four components namely, basin, meteorological, time series and control specifications model for each sub-basin. The meteorological component consists of rainfall and evapotranspiration data. The model uses two loss methods to include the representation of evapotranspiration which are deficit-constant and soil moisture accounting (SMA)(Ouédraogo et al., 2018). Evapotranspiration can be estimated using the physical-based energy balance (Penman-Monteith) or independently outside the model and imported into the HEC HMS software. The control component involves specified simulation period and time step to be used in the simulations (Feldman, 2000). SMA method simulates the movement of water through vegetation, surface interception, soil profile and two groundwater layers. Output from the SMA algorithm is precipitation excess (surface runoff), groundwater flow and deep percolation (Figure 2.1) (Rabi & Watkins, 2013).

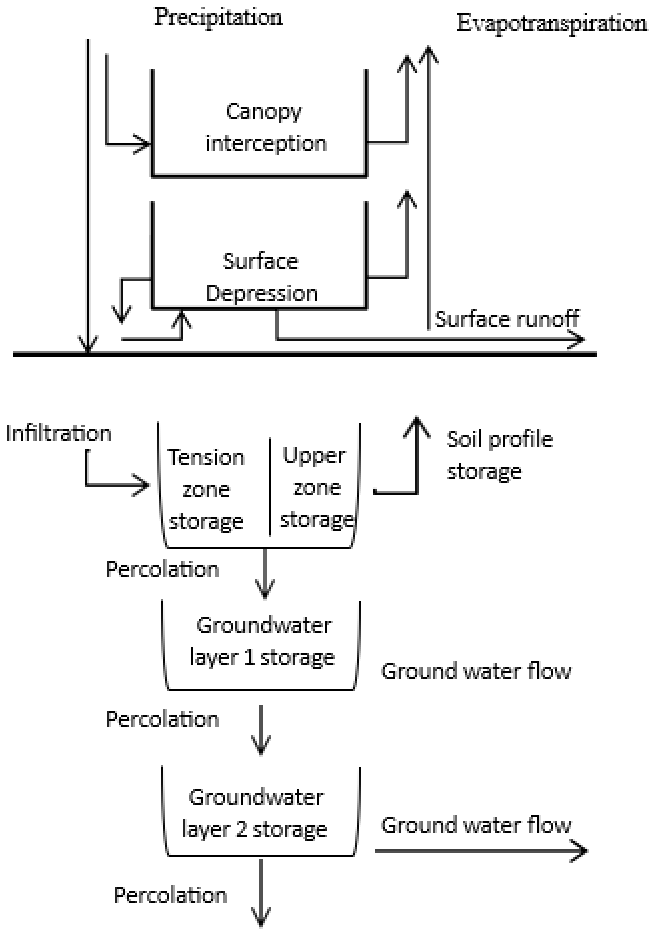


Figure 2.1: HEC HMS Soil Moisture Accounting (SMA) Algorithm

Source: (Feldman, 2000)

Canopy interception and surface depression values are based and influenced by land use and elevation of a catchment guided by Table 2.1 and Table 2.2 (Holberg, 2014).

Table 2.1: Canopy Interception Values

Vegetation type	Interception (mm)
General vegetation	1.3
Deciduous trees and grasses	2.0
Trees	2.5

Source: (**Holberg, 2014)**

Table 2.2: Surface Depression Values

Surface type	Slope (%)	Depression (mm)
Paved impervious	N/A	3.2-6.4
Farrowed and Flat	0-5	50.8
Gentle -Moderate slope	5-30	6.4-12.7
Steep-smooth slope	Over 30	1.0

Source: **(Fleming, 2002)**

Soil profile storage is based on the soil analysis of a catchment, which involves the hydraulic conductivity, slope, density and porosity of specific soils to determine the soil infiltration and storage (Fleming, 2002).

HEC HMS provides various methods to model ground water flow which include bounded recession, linear reservoir, non-linear boussinesq and recession method. (Fleming & Doan, 2010).

The channel routing methods available in HEC HMS are given in Table 2.3.

Table 2.3: Channel Routing Parameters in HEC HMS

Methods	Parameter
Kinematic Wave	Manning’s n
Lag	Lag
Modified Plus	Sub reaches. Initial flow
Muskingum	K X Sub reaches
Muskingum Cunge	Manning’s n
Straddle Stager	Lag Duration

ET and P are highly variable in tropical African landscapes and a model that can use validated external data would result in less model uncertainty (Kiptala et al., 2014). HEC-HMS has successfully been used to predict river discharges in many river basins in the tropical climate including in Kenya (Gebre, 2015; Halwatura & Najim, 2013; Ouédraogo et al., 2018; Sampath et al., 2015). It is also a public domain free software.

Gebre (2015) used HEC HMS to simulate daily stream flows in the Upper Blue Nile River basin, Ethiopia. The results were satisfactorily, and the author recommended use of the model in tropical climate basins. Ouédraogo et al., (2018) results showed that soil moisture accounting (SMA) loss method in HEC-HMS was able to estimate continuous daily stream flow in the Mkurumudzi catchment in Kwale County, Kenya. The authors noted that the simulation results were more sensitive to groundwater storage coefficient and the infiltration rate. Sampath et al., (2015) successfully used HEC HMS to evaluate stream flows variations in a basin with water diversions in Sri-Lanka and validated the model capabilities of simulating flows in tropical catchments with IBWTs.

2.3.5 Remote sensing and Hydrological Modelling

Hydrological modelling is often a challenge in a data scarce basin, however, over time satellite datasets with finer spatial resolutions have become available. Research in remote sensing has resulted in improved quality of a variety of spatial data (Cheng et al., 2011). For instance, using actual evapotranspiration (ET) data from Water Productivity through Open access of Remotely sensed derived data (WaPOR) database is available for most parts of the world at a good spatial and temporal scale. The method of calculating evaporation (E) and transpiration (T) is based on the ETLook model which uses the Penman-Monteith (P-M) equation, adapted to remote sensing input data (FAO, 2020). The ETLook model uses optical and passive microwave sensors to obtain information on actual evaporation (E) and transpiration (T) over a land surface even under adverse conditions (Bastiaanssen et al., 2012).

Blatchford et al., (2020) evaluated the use of actual ET-WaPOR datasets and the results showed that the quality was satisfactory to contribute in understanding the hydrological processes at local and global spatial scales. ET-WaPOR database was commissioned in

2009 thus it has data ranging from 2009 to present and is limited in historical data prior to 2009 (FAO, 2020). However, for the missing historical data, ET can be estimated using its relationship with precipitation for the existing period. For tropical climate, evapotranspiration can be correlated with precipitation using the linear relation $ET = \beta PET + \alpha P$ (where ET is evapotranspiration, PET is potential evapotranspiration and P is precipitation) using historical data (Cheng et al., 2011). In tropical climate, the effect of variability of potential evapotranspiration on a daily time scale is minimal (Woodroffe & Falkland, 2004) therefore βPET can be assumed to be constant (Thornthwaite, 1951). The slope α indicates the variability of ET with respect to P (precipitation).

Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) datasets were developed by the University of California-Santa Barbara and the U.S. Geological Survey (USGS) scientists with a resolution of 0.05° × 0.05° providing rainfall estimates based on infrared Cold Cloud Duration (CCD) observations from 1981 to the present (Funk et al., 2015). CHIRPS datasets have been used extensively worldwide and have provided acceptable estimates when validated with limited ground observations from local rain gauges (Shen et al., 2020). CHIRPS datasets like other satellite estimates are susceptible to systematic errors which influence the results of hydrological modelling by either under or overestimating the simulated discharge. Thus it is paramount to correct the bias by using techniques such as; Linear, non-linear, gamma distribution and empirical distribution methods (Luo et al., 2018).

Linear correction method involves comparing simulated means with observed means. The difference between the simulated data and observed data is then used to obtain the correction factor (Equation 2.1-2.4). Further, the projected data is corrected using the obtained correction factor.

$$\boldsymbol{P^{*}_{chirps}\,(d) = P_{chirps}\,(d)[\frac{\mu m\,(P_{obs}\,(d))}{\mu m\left(P_{chirps}\,(d)\right)}]}$$

Equation 2.1

$$\boldsymbol{P^{*}_{prj}\,(d) = P_{prj}\,(d)\left[\frac{\mu m\,(P_{obs}\,(d))}{\mu m\left(P_{chirps}\,(d)\right)}\right]}$$

Equation 2.2

$$\boldsymbol{T^{*}_{chirps}\,(d) = T_{chirps}(d) + \mu m\,(T_{obs}\,(d)) - \mu m\left(T_{chirps}\,(d)\right)}$$

Equation 2.3

$$\boldsymbol{T^{*}_{prj}(d) = T_{prj}(d) + \mu m\left(T_{obs}(d)\right) - \mu m(T_{chirps}(d))}$$ **Equation 2.4**

Delta Change method involves using the mean monthly ratio of the simulated projections and observed output. The ration is further applied on the observed data to represent future projections. This correction technique requires at least 30 years of observed quality data to improve its accuracy. The advantage of this method is that it is simple and requires monthly data. However, monthly data might not show the inter-monthly variability of rainfall thus distorting the daily precipitation (Diaz-Nieto & Wilby, 2005). Due to the limitations of the linear correction method, the nonlinear correction method was introduced such that;

$$\boldsymbol{P^{*} = aP_{o}^{b}}$$ **Equation 2.5**

Where $P^{*}$is the biased corrected CHIRPs data, P_O is the original CHIRPS data (uncorrected) and a and b are correcting factors (Goshime et al., 2019; Lafon et al., 2013).

2.3.6 Calibration and validation of hydrological models

To improve the accuracy of simulated results, HEC HMS offers deterministic and stochastic optimizations. Deterministic optimisation uses an initial single parameter to adjust the simulated flows to match the observed flows. Stochastic optimization creates a set of parameters and creates an uncertainty analysis where the difference in simulated and observed flows are minimised as much as possible (Scharffenberg & Fleming, 2016).

There are several statistical methods of evaluating model performance among them: Coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE) and PBIAS (percentage bias) (Table 2.4). The Coefficient of determination (R^2) (Equation 2.6) represents the proportion of variation of the simulated data *(P)* from the observed data *(O)*. R^2 values range from 0 to 1, where values greater than 0.5 indicate that the model results are acceptable (Moriasi et al., 2015)

$$\mathbf{R}^2 = \left[\frac{\sum_{i=1}^{n}(O_i-\underline{O})(P_i-\underline{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\underline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\underline{P})^2}}\right]^2 \qquad \textbf{Equation 2.6}$$

Nash-Sutcliffe Efficiency (NSE) estimates the accuracy of the model by assessing the relative magnitude of the residual variance to the observed data variance (Equation 2.7)(Nash & Sutcliffe, 1970). According to Moriasi et al., (2015) NSE values greater than 0.5 are considered satisfactory.

$$\mathbf{NSE} = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\underline{O})^2} \qquad \textbf{Equation 2.7}$$

PBIAS (percentage bias) which represents the average tendency of the simulated data to be greater than or less than the observed data (Equation 2.8). Negative PBIAS values show an underestimation of the model results while positive values show an overestimation. PBIAS values of 0 would show a perfect fit (V. H. Gupta et al., 1999).

$$\mathbf{PBIAS} = \frac{\sum_{i=1}^{n} O_i-P_i}{\sum_{i=1}^{n} O_i} \times 100 \qquad \textbf{Equation 2.8}$$

Table 2.4: Model Performance Guidelines Used for Hydrological Modelling

Performance	**NSE**	**PBIAS**	**R^2**
Very good	0.75 <NSE≤1.00	PBIAS≤ ±10	>0.85
Good	0.65 <NSE≤0.75	±10 <PBIAS≤ ±15	0.75< R^2 ≤0.85
Satisfactory	0.50 <NSE≤0.65	±15<PBIAS≤ ±25	0.60<R^2 ≤0.75
Not Satisfactory	NSE≤0.50	PBIAS≤ ±25	$R^2 \leq 0.60$

Source: (Moriasi et al., 2015)

2.4 Stream Flow Variability Indices

For inter-basin water transfers especially those that are flood dependent, it is paramount to understand the changes in the hydrological regimes of streams in the transfers (Khadem et al., 2021). There are a various techniques for evaluating the variability of streamflow that include slope of flow duration curve, trend analysis, rapidity, and frequency of changes /variations in flow i.e., the flashiness index and the reliability of flow (De Girolamo et al., 2008; Leong & Yokoo, 2021).

2.4.1 Flashiness Index-Richard-Baker (FI)

Flashiness index (FI) can be used to show the recurrence and speed of short-term changes in flow thus evaluating stability of rivers and streams. The FI index shows the changes in the stream flow using the ratio of absolute day to day fluctuations with the total annual (Equation 2.9) as defined by (Baker et al., 2004):

$$\boldsymbol{RB\ (FI) = \frac{\sum_{i=1}^{n}\ q_i - q_{i-1}}{\sum_{i=1}^{n}\ q_i}} \qquad \textbf{Equation 2.9}$$

Where *RB(FI)* is the flashiness index, q_i is the mean daily discharge, q_{i-1} is the mean daily discharge of the previous day and $\sum_{i=1}^{n}\ q_i$ is the total flow for the year. Long term changes (annual) in river discharge can be estimated using this index (Baker et al., 2004; Holko et al., 2011).

FI has been used to quantify the variations in stream flow and the relationship between the flashiness of the stream with catchment characteristics. De Girolamo et al.,(2008) used FI to evaluate flow regimes in the Mediterranean region and observed that generally streams showed an increase in flashiness with the seasonal streams having higher values that the permanent ones. Dow (2007) analysed the streamflow regime of nine New Jersey streams and found both decreasing and increasing trends of flashiness for four streams. The results suggested that they were related to an apparent slowdown in urbanization and to potential changes in wetland agricultural practices.

2.4.2 Flow Duration Curve

Flow Duration Curve (FDC) is a stream flow variability index that shows the percentage of time (duration) a flow is exceeded over a period for a river basin (Equation 2.10) (Boscarello et al., 2016). FDC is a representative of low and flood flows for a given river system (Smakhtin, 2001) estimated as;

$$\boldsymbol{P = 100 * \frac{Rank}{N+1}} \qquad \textbf{Equation 2.10}$$

Where P is the percentile, N is the number of data points and Rank is the rank order (from1-N) (Leong & Yokoo, 2021). Flow duration curves have been used extensively in water resources planning, development and management (Castellarin et al., 2007).

2.4.3 Base Flow Index

Base Flow Index (BFI) is a non-dimensional ratio obtained by dividing the volume of base flow by the total stream flow (Smakhtin, 2001). BFI can be used to estimate the flow stability of rivers and streams. A BFI closer to 1 shows a high groundwater recharge to stream flow while that closer to 0 indicates a seasonal stream (Sapač et al., 2019). BFI can also be estimated using the BFI index software (http://hydrooffice.org/) using Equation 2.11.

$$\boldsymbol{BFI = \frac{Baseflow}{Streamflow}} \qquad \textbf{Equation 2.11}$$

The relationship between baseflow and streamflow is an important indicator of streamflow variability and its characteristics (Han et al., 2018).

2.4.4 Monthly Trend analysis

Linear regression model is among the parametric methods of estimating patterns in data series (Ahn & Merwade, 2014; Ye et al., 2003) using Equation 2.12.

$$\boldsymbol{y = m * X + C} \qquad \textbf{Equation 2.12}$$

Where y is the dependent variable (streamflow), X is the independent variable (time), m is the slope and C is the intercept. Negative (-) slope sign indicates a decreasing trend while a positive (+) sign indicates an increasing trend. Further, a p value of < 0.05 in a linear regression model shows statistically significant correlation in the stream flow.

2.4.5 Hydrological Alteration of Streams Flows

Indicators of Hydrological Alteration (IHA) software developed by the US Nature Conservancy in the 1990s is used to estimate changes in streams flows resulting from water developments (Mathews & Richter, 2007). The program calculates 33 hydrological parameters that characterize seasonal flow variability based on the magnitude, frequency, duration, timing and rate of change of flows or water levels. IHA enables evaluation of impacts of a development on a river or stream like the construction of dams and inter-basin water transfers and also changes on the hydrological regimes as result of land use changes (Mathews & Richter, 2007). The indicators are categorized into five groups of magnitude of monthly flows, magnitude of extreme flows, timing of extreme flows, flow pulses and rise and fall rate. Degree of hydrological alteration is estimated using the Range of Variability Approach (RVA). RVA divides the pre impact data into three categories based on percentile values and computes the expected frequency with which the post impact values should fall within the categories (Pumo et al., 2018). As such, degree of hydrological alteration is defined as: (Equation 2.13).

$$\boldsymbol{HA} = \frac{\boldsymbol{observed\,frequency - expected\,frequency}}{\boldsymbol{expected\,prefquemcy}}$$ **Equation 2.13**

Where the expected frequency is the number of years which annual statistics fall within the RVA limits in the pre-impact period and observed frequency is the number of years which annual statistics fall within the RVA limits in the post-impact period. Pumo et al., (2018) used the RVA concept to come up with a general global hydrological alteration indictor to assess the pre and post impacts of anthropogenic activities on two rivers in Sicilian, Italy. Fang et al.,(2023) used RVA to assess the change of flow regime in Liujiaping River in Hunan Province, China, and found significant changes in the hydrological regime after the construction of dams in the river. An evaluation of the impacts of climate change on Nakong river in Southeast Korea using IHA revealed rapid and extreme high and low flows which would cause stress on the aquatic ecosystems in the river (Lee et al., 2014). Similarly, Brouziyne et al., (2021) analysed the influence of climate variability in Mediterranean basin using IHA and found that a number of the rivers would experience both an increase and decrease in the magnitude of monthly flow, however, flash floods and low flow events increased.

2.5 Reliability of stream Flows under Different Climatic Conditions

2.5.1 Characterization of Climatic Conditions

Studies in East Africa have shown an increase in drought events and climate variability. Upper Tana basin has been experiencing frequent and more severe droughts over the last decades (Okal et al., 2020). Proper IBWT planning and management requires comprehensive understanding of the variability and reliability of flows under different climatic conditions. Streamflow Drought Index (SDI) method can be used to characterize drought seasons as it defines the severity and frequency of hydrological drought in a river basin (Jahangir & Yarahmadi, 2020) (Equation 2.14).

$$\boldsymbol{SDI_{i,k} = \frac{V_{i,k} - \underline{V}_k}{S_k}} \ \textbf{......i=1,2,3..... k=1,2,3} \qquad \textbf{Equation 2.14}$$

Where $V_{i,k}$ cumulative streamflow volume for the k month of the i th hydrological year. $\underline{V}_k$ and S_k are the mean and standard deviation of the streamflow of the k th month in the study period. SDI can be calculated using the Drought Indices Calculator (DrinC) software at a 12- (annual), 6 and 3 months timesteps (Tigkas et al., 2015) and drought categories identified based on the guidelines in Table 2.5.

Table 2.5: Description of Climatic Condition Based on SDI Value and Corresponding Drought Category

SDI Value	Drought Category
2.00 or greater	Extremely wet
1.50-1.99	Severely wet
1.00-1.49	Moderately wet
0-0.99	Near normal (mildly wet)
0 to -0.99	Near normal (Mild drought)
-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
-2.00 or lower	Extreme drought

Source: (Tigkas et al., 2015)

SDI has been used extensively over the years to evaluate the magnitude and spatial distribution of drought events for water planning and development purposes. Abbas & Kousar, (2021) characterised the spatial pattern and intensity of drought in Indus Basin using SDI calculated from DrinC software. The results informed strategies to minimize the effects and risks in the northern eastern side of the basin. Malik et al.,(2019) analysis of drought frequency using SDI showed that the Upper Yangtze river basin had been experiencing wet and dry years successively with spring being the driest and that strategies needed to be put in place to ensure reduction of the effects of drought on the community (Hong et al., 2015).

2.5.2 Supply Reliability Index

There are several indicators used to analyse the performance of a water system. The commonly used are the deficit of water in volume (shortages) and the supply reliability (Digna et al., 2018). These two indicators have been used successfully in many studies (Mersha et al., 2018). Supply reliability can be used to analyse the performance of inter basin water transfer systems (IBWTs) under different climatic conditions (Sandoval-Solis et al., 2011) using Equation 2.15 where;

$$\boldsymbol{Reliability}\ (\%) = \frac{\boldsymbol{Number\ of\ times\ demand\ is\ fully\ met}}{\boldsymbol{Time\ interval\ under\ consideration}\ (\boldsymbol{daily\ ,monthly,yeary})} \qquad \textbf{Equation 2.15}$$

The use of reliability indicators in water allocation studies has gained momentum recently as it enables water managers to evaluate the performance of a water system taking into consideration uncertainties. They show to what extent failure may occur and how well a system is likely to perform under a failure (Pedro-Monzonís et al., 2015; van der Zwaan et al., 2018).

2.6 Optimal Urban Water Allocation Strategies in Inter-Basin Water Transfers Systems (IBWTs)

2.6.1 Water Allocation

Water allocation models simulate the water balance between supply and demand. They enable water managers to evaluate possible trade-offs in water allocation in a river system. Through optimization, the model provides the best possible option that maximizes user defined benefit while minimising loses (Mutiga et al., 2010). Water allocation becomes challenging because the resources occurs in various forms i.e. white, blue , grey and green water and most of the uses are consumptive in nature (Savenije & Van der Zaag, 2008). Water allocation, has historically followed the principles of;

i. Res nullis which meant water was for everybody,
ii. Res communis omnium which implied that water was communally owned,

iii. Regulated riparianism which involved riparian rights and required abstraction permits,
iv. Prior appropriation which meant first some first serve,
v. Correlation involved water allocation based on special water needs,
vi. Proportional meant all uses had equal proportion of water(Jaspers, 2003) .

However, over time, water allocation process has shifted from a path dependent strategies to include scenario allocation planning at a river basin level (Speed et al., 2013)as shown in Figure 2.2

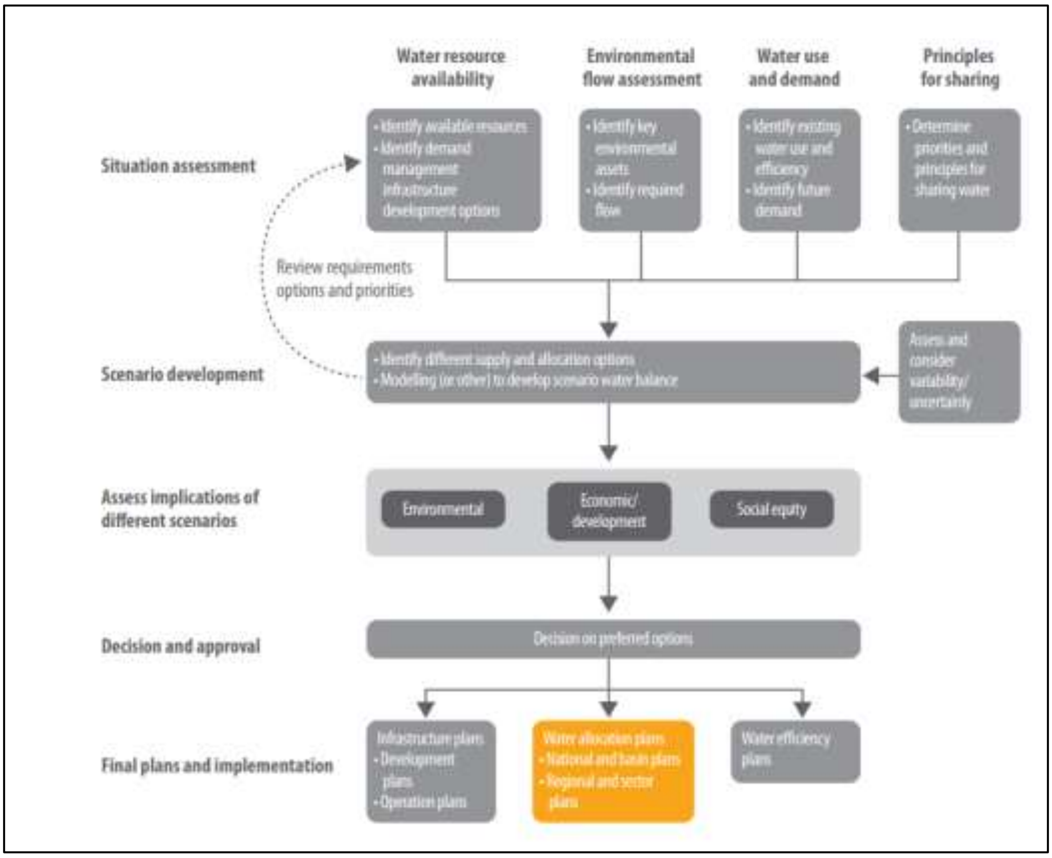


Figure 2.2: A Water Allocation Plan Process at a River Basin Level

Source: (Speed et al., 2013)

Situation assessment involves water supply and demand assessment in a water supply system. A vital component in the planning process , is the scenario development stage, which enables water managers to evaluate impacts of several strategies on a water system while taking into account uncertainties (Speed et al., 2013). There are two types of scenario development as identified by Mahmoud et al.,(2009); Exploratory and Anticipatory scenarios (Figure 2.3). Exploratory scenarios involve investigating the future using known past trends to anticipate impacts and changes in the system. Anticipatory scenarios involves a water manager using past and future strategies to achieve the best and desired outcome in a water system (Mahmoud et al., 2009).

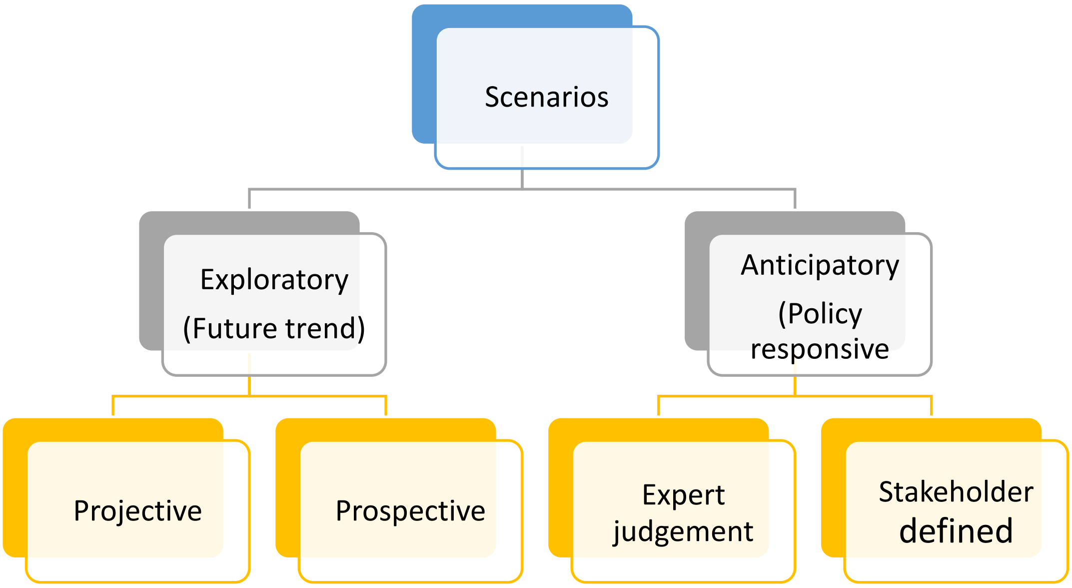


Figure 2.3: Types of Scenarios

Source: (Mahmoud et al., 2009)

Several models have been used for simulation-optimization, for example WEAP, RIBASIM, HEC-ResSIM among others (Demertzi et al., 2014; Mourad & Alshihabi, 2016) .

2.6.1.1 Water Evaluation and Planning System (WEAP) Model

WEAP model has gained popularity over the years for modelling water development, allocation and monitoring for proper decision making. It was developed by the Stockholm Environment Institute (SEI) to investigate optimal water strategies based on the development, management and allocation of water resources (Sieber et al., 2005; WEAP, 2005). The model uses the principal of water mass balance for simulation at every link and node (river and reservoirs) for a specified period. It also enables creation of scenarios to answer the 'What if' questions which is very helpful when it comes to planning and management of water resource (Hamlat et al., 2013). Mutiga et al (2010) used WEAP model to assess several water allocation strategies among various water users in the Ewaso Ngiro basin, Kenya, with an aim of reducing water conflicts. In western Algeria, Hamlat et al., (2013) simulated water resources management scenarios using WEAP model and the results showed demand management strategies were needed for sustainable water management of both domestic and agricultural water demands in the region. Mourad & Alshihabi, (2016) used WEAP to assess the balance between the future and present water demand in Syria. The results indicated that climate change and regional conflicts would have a major effect on the water resources in the region and the need for improved cooperation and use of technology to bridge the gap between water supply and demand.

WEAP uses the "water year method" to create scenarios of future changes in stream flow / stream variability. A water year characterizes the stream flow variations from the normal year thus creating drought and wet climatic conditions for which the performance of a water system is evaluated against (Demertzi et al., 2014). The water years are categorized into very dry, dry, normal, wet, and very wet years. A value is assigned to each category based on the deviation of flow from the normal year (WEAP, 2005). This method has been used successfully in various studies to assess the performance of water systems under different climatic regimes (Demertzi et al., 2014; M Al-Mukhtar & S Mutar, 2021; Mounir et al., 2011).

2.6.1.2 River Basin Simulation (RIBASIM)

Ribasim is a **Ri**ver **Ba**sin **Sim**ulation model that allows the user to simulate the interaction between water sources and water demands in a river basin. The model uses nodes to represent water sources (variable and fixed inflows), reservoirs and water demands (irrigation, public water) (Loucks, 2005). The water sources nodes are connected to the water demand nodes by links where the flow of water is guided by the source priority rules. RIBASIM model enables users to evaluate the effects of new developments for example irrigation expansion, new hydropower on the availability of water in a river basin (Demertzi et al., 2014). In addition, trade-offs among users can easily be identified by assigning uses different levels of allocation priority. If all uses have priority 1, then the downstream users are disadvantaged because their demand is only satisfied after all the upstream users' demands are satisfied (Digna et al., 2018).

2.6.1.3 Reservoir System Simulation (HEC-ResSim)

The Reservoir System Simulation (HEC-ResSim) software developed by the U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (CEIWR-HEC) is used to model reservoir operations. The software is mostly used for reservoir operation simulations where it enables incorporation of multiple reservoirs with the operating rules (Babazadeh et al., 2007). It represents the reservoirs and river channels using junctions, reaches and diversions. The model simulates the operations of the water system using a mass balance equation to analyses flood control and water planning requirements (Kim et al., 2020).

2.6.2 Sentinel Imagery

Remote sensing data is increasing gaining popularity in water resources development and management studies. Monitoring of surface water resources e.g., reservoirs has been done using traditional ways of ground survey, however, use of satellite data has shown to be a valuable tool due to its cost effectiveness (Kansara & Lakshmi, 2022). In the past hydrologists have avoided using remote sensing data because of the high cost of acquisition and course resolution. However, with advancement in technology, products like Sentinel 2 with spatial resolutions of 10m, 20m and 60m revisiting every five days has catalysed its use in hydrological studies (Bhaga et al., 2021). Normalized Difference Water Index (NDWI) is among the widely used indices in mapping and detecting water bodies given by Equation 2.16.

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR}$$ **Equation 2.16**

Where GREEN and NIR represent green and near-infrared red bands, respectively. The values of NDWI ranges from -1 to 1 where water bodies have values of between 0.2 to 1(Kansara & Lakshmi, 2022). The index has been used widely and successfully in mapping and detecting water bodies (Benzougagh et al., 2022; Bhaga et al., 2021; Ghansah et al., 2022; Sekertekin et al., 2018).

2.7 Influence of Tunnelling on Groundwater in Inter-Basin Water Transfers

Underground structures interfere with groundwater either by seeping into the tunnel if it is a pervious structure or by interfering with the hydraulic head and flow direction if the structure is impervious. The latter effect has been referred to as the barrier effect of underground structures on groundwater flow. Barrier effect results into the groundwater level increasing in the upstream of the structure and decreasing in the downstream of the structure (Attard et al., 2017). There are several ways to assess the barrier effect caused by underground structures which include numerical modelling and analytical methods (Pujades et al., 2012).

Pujades et al., (2012) came up with an analytical method to assess the barrier effect where the authors express the barrier as:

$$S_B = \Delta h_B - \Delta h_N \qquad \textbf{Equation 2.17}$$

Where S_B = Barrier effect

Δh_B = head drop across a barrier

Δh_N = head drop between the same point under natural conditions

The barrier effect can be categorized into localised (S_{BLO}) and regional(S_{BRO}), where barrier effect localised is the maximum head loss or rise which is near the structure. Regional barrier effect is the minimum head loss or rise at a distance from the underground structure as expressed in Equation 2.18 and 2.19 respectively.

$$\mathrm{S}_{BRO} = \int_{\frac{2i_N b}{3\pi}}^{0} \ln\left(\frac{1}{5\pi b_{bD}(1-b_{bD})^6}\right) \text{ if } b_{bD} \leq 0.1 \qquad \textbf{Equation 2.18}$$

$$\text{if } b_{bD} > 0.1$$

$$\mathrm{S}_{BLO} = \int_{i_N b}^{2 b_{bD} i_N b} \sqrt{\frac{3}{8}} \ln\left(\frac{2 {b_{bD}}^{0.29}}{{b_{aD}}^{2}}\right) \text{ if } b_{bD} < 0.28 \qquad \textbf{Equation 2.19}$$

$$\text{if } b_{bD} \geq 0.28$$

$$\mathrm{S}_{BI} = i_N L_B \left(\frac{\boldsymbol{b}}{\boldsymbol{b_a}} - \mathbf{1}\right) \qquad \textbf{Equation 2.20}$$

Where S_{BI} is the barrier effect, L_B is the width of the barrier, i_N is the natural groundwater gradient perpendicular to the barrier (measured before the construction), b is the thickness of the aquifer (or width, depending on the length cut, b_a and b_b are the open and cut fractions of the aquifer, respectively. b_{bD} = $(b_b|b)$ and b_{aD} =$(b_a|b)$. If the groundwater flows through heterogeneous soil through the barrier then, the distances ($b_{a,}b_b$and b) must be corrected using anisotropy factor. Groundwater flow is antistrophic when the vertical flow is different from the horizontal flow which is because of vertical heterogeneity. The anisotropy factor is a ratio of the vertical and horizontal hydraulic conductivity of the aquifer.

The above equations assume a constant flow within the aquifer thus the equations are not adequate in accounting for external factors affecting the groundwater flow like the changes in rainfall and abstraction rates. In addition, the geometrical properties of the underground structure causing the barrier effect are a square. The main limitation is when the i_N is too small which is hard to estimate from the piezometer measurements (Font-Capo et al., 2015; Pujades et al., 2012).

Many of the studies have been done using numerical modelling which have successfully quantified the head loss / gain of groundwater through the influence of underground structures. It is also possible to assess the barrier effects from observed piezometric measurements taken across the underground structure. To quantify the change in hydraulic head, measurements of pre-construction and post-construction must be taken into account (Font-Capo et al., 2015). For analytical and numerical modelling, aquifer and underground structure characteristics need to be assessed. These would include mapping the aquifer, groundwater levels, and the geometry of the underground structure cutting across the aquifer (Bello et al., 2019). This entails a geophysical and groundwater exploration survey which can be done using electrical resistivity methods such as the vertical electrical sounding (VES) (Pujades et al., 2012).

2.7.1 Vertical Electrical Sounding (VES)

VES is a subsurface investigation method that uses resistivity imaging to provide information on the geological formation of the subsurface. With this method, one can obtain images of bedrock, water bearing areas with their thicknesses (Chauhan et al., 2019)**.** Thus, electrical sounding, can successfully map and detect aquifers in a river basin. The method involves measuring the potential difference in the ground from the flow of current in the ground surface (Farid et al., 2013). As the current flows through the ground, the resultant voltage difference is recorded as a resistivity determined by Equation 2.21 where V is voltage and I is current (Kasidi & Victor, 2019; Soomro et al., 2019).

$$R = \frac{V}{I}$$ **Equation 2.21**

Geo-electrical method has gained popularity in sub surface exploration because it is less demanding in terms of time and resources as compared to traditional methods like the pumping tests (Oudeika et al., 2021).

2.7.2 Numerical Modelling Using MODFLOW

Modular finite-difference flow model (MODFLOW) software was introduced by the U.S Geological Survey (USGS) (Langevin et al., 2017) and uses finite-difference in groundwater flow simulation and contaminant modelling. Finite difference implies that the grid developed is rectangular, other models like Finite Element subsurface FLOW (FEFLOW) uses finite -element which means the grid is created is triangular (C. P. Kumar, 2019). MODFLOW is widely used because is a public software which uses several graphical user interfaces both non-commercial and commercial and it is easy to set up (Hariharan & Shankar, 2017).

Several studies have successfully used MODFLOW to simulate ground water flow in their regions. Golian et al., (2020) successfully used MODFLOW to predict the drawdown of wells because of tunnelling in Iran. Yang et al., (2009) used MODFLOW to examine the impact of tunnelling on local hot springs and hydrogeology of Tseng-Wen reservoir water transfer in Taiwan. The results showed that, during excavation of the tunnel, groundwater flowed into the tunnel. The authors noted that MODFLOW can be used successfully to estimate, regional and local effects of tunnelling on groundwater resources in a water diversion project. This can be done using the Horizontal Flow Barrier (HFB) package in MODFLOW to represent the impervious barrier as in a study in Italy. The authors noted that the tunnel created two scenarios in which the groundwater levels upstream of the tunnel were at maximum while on the downstream of the tunnel a barrier was created causes a drop in the groundwater levels (Bonomi & Bellini, 2003).

2.8 Distribution of Benefits and Risks in Inter-Basin Water Transfers (IBWTs)

2.8.1 Stakeholder Analysis

A stakeholder is defined as a person, group or organization who has an interest with an issue either by being affected by it, or having influence, knowledge, or experience over it or about it. Based on this definition, Mitchell et al.,(2015) expresses the importance of categorizing stakeholders on the bases of their power (influence), legitimacy (having a relationship with) and urgency (claim). Stakeholder analysis has gained popularity in water resources studies and management because of the shift from a solely technocratic view of water challenges. In addition, stakeholders' analysis provides an opportunity to evaluate how risks and benefits are distributed in a water system (Chevalier, 2001). Thus, stakeholders analysis is a vital and necessary tool for sustainable water resources management and development (Stanghellini, 2010).

The interaction of stakeholders and their intervention on a water resource which is usually driven by their interest results in both benefits and risks distributed differently among a society (Fraj et al., 2019). Theoretical dimensions of stakeholder analysis include **Network** which is when stakeholders with the same interest come together to drive their agendas concerning a policy. **Perception** which involves the beliefs that stakeholders have towards a certain policy. **Values** which refer to the norms that stakeholders have which guide them towards making decisions. **Resources** are the ways which enables the stakeholders to achieve their goals (Hermans & Thissen, 2009). Reed et al., (2009) proposes a methodology (Figure 2.4) for conducting a stakeholder analysis.

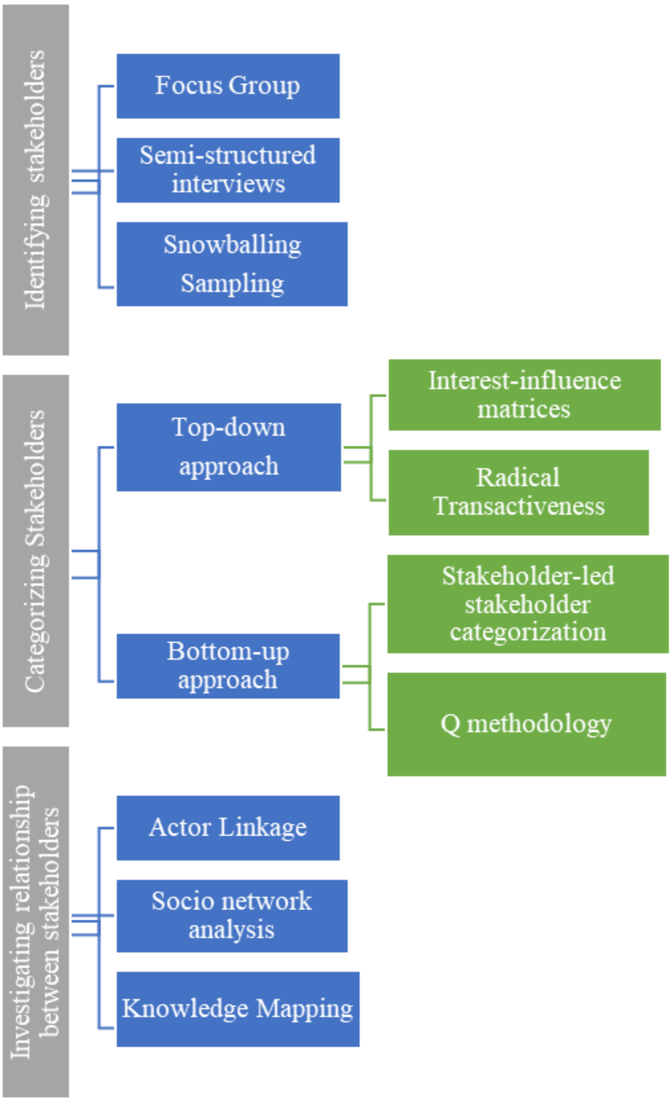


Figure 2.4: Stakeholder Analysis Approach

Source: (Reed et al, 2009)

The first step is to identify the stakeholders through interviews and snowballing. This involves conducting interviews to a section of perceived stakeholders to gather more information on the subject matter. The main disadvantage is that it is time consuming and thus maybe costly to conduct. Snow balling involves the initial stakeholders in the interviews identifying other actors and their contacts (Reed et al., 2009).

The second step involves categorizing the stakeholders into four group using an influence and importance matrix (Figure 2.5) (Stanghellini, 2010). This can be done using a top-down or bottom-up approach. Top-down approach is where categorisation is done by the researcher based on their sound knowledge of the system under analysis. The main set back of this method is that the categorization might be influenced by the researcher biasness and thus fail to represent the stakeholders' perception of the system. Bottom-up approach is a stakeholders-led categorization, where they are directly involved in the grouping of the stakeholders. This includes techniques such as card-sorting and Q methodology (L. E. Yang et al., 2018).

Stakeholders grouped as Subject include those with high interest but low influence on decision making. They are often the marginalised who may form coalitions that become very influential in the long term. Key players have high influence and interest in the decision making. Crowd are those stakeholders who have very little interest and influence while the Context Setter have high influence with low interest in the decision making of a project (Reed et al., 2009).

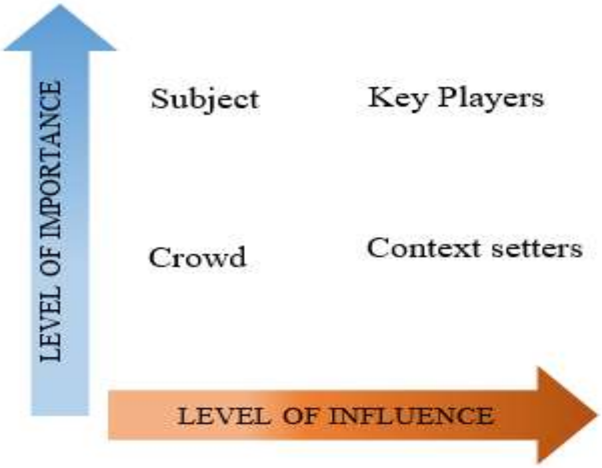


Figure 2.5: Influence-Importance Matrix

The third step involves investigating the interaction and interest among stakeholders using actor-linkage matrices and socio network analysis while knowledge mapping is used to show how information is conveyed among the stakeholders(Hermans & Thissen, 2009; Reed et al., 2009).

Over the past decade, studies have increasingly emphasized stakeholder analysis in water and environmental resource management decisions. However, there has been limitations some being that the number of stakeholders might hinder conclusive dialogues. Secondly, stakeholders' analysis is site specific thus results of studies in one area might differ from results in another area. Additionally, even within a stakeholder's group, there may be differentiated perceptive and views making the process complicated (Bendtsen et al., 2021; Mutekanga et al., 2013). In Phanang river basin, stakeholders' analysis revealed that small-scale farmers were more disadvantaged and incurred more loses because of the changing ecosystem and degradation of the water resources in the basin (Mumtas & Wichien, 2013). Wang et al.,(2013) evaluated stakeholders in the drinking water supply system in Shenzhen, China where water companies, governments and consumers emerged as the most important stakeholders however their interest and influence in the systems was quite limited.

2.9 Research Gap

2.9.1 Summary of Literature

Table 2.6: Summary of Literature Review

Author	Title of article	Review
(Yevjevich, 2001)	Water Diversion and Inter-basin transfers	Author notes that most IBWTs have been mired by controversies because of their complex linkages between the physical and sociological components which calls for a multidisciplinary approach in their studies and planning.
(Quan et al., 2016)	Impact of Inter-Basin Water Transfer Projects on Regional Ecological Security from a Tele coupling Perspective	The authors used tele coupling technique to analyse the ecological impacts of IBWTs. The results showed that a single index can be used to analyse the ecological health of IBWTs, and that information sharing was vital for the security of the systems.

(J. Gupta & van der Zaag, 2008)	Inter-basin water transfers and integrated water resources management: Where engineering, science and politics interlock	The authors note that IBWTs introduce rights, risks and interest of different groups of stakeholders in the recipient and donor basins. However, they note that such studies have not received a lot of attention, and that multi-disciplinary research is required especially in light of climatic uncertainties.
(Gohari et al., 2013)	Water transfer as a solution to water shortage: A fix that can Backfire	Authors emphasizes the need for policy makers to assess and control the dynamics that IBWTs introduce and especially the risks that emanate from the systems. Authors argue that, without taking the complex interaction of these systems, the systems might not achieve their intended objective of elevating water shortages.
(W. Zhuang, 2016)	Eco-environmental impact of inter-basin water transfer projects: a review	Author notes that IBWTs cause huge ecological risks and that it is important to ensure these risks are mitigated or in some cases alternative solutions to IBWTs such as water use efficiency and rainwater harvesting technology. In the recommendations, the author calls for a wholistic review that considers the societal, economic and ecological impacts of IBWTs to realize the maximum benefits.
(Rollason et al., 2022)	Inter basin water transfer in a changing world: A new conceptual model	The authors reviewed approaches used to assess IBWTs since the 1980s to date and noted that IBWTs continue to offer supply-oriented solutions at the expense of socio and environmental considerations. The authors emphasize the need for understanding these kinds of projects in light of their socio-ecological impacts to ensure sustainability of the projects and equality in access to water resources.

Authors note that inter-basin water transfers introduce complex socio-economic, hydrological, ecological and institutional impacts that require multi-disciplinary approach (Carvalho & Magrini, 2006; Dyrnes & Vatn, 2005; Gohari et al., 2013; J. Gupta & van der Zaag, 2008; Roman, 2017; Snaddon et al., 1999; Yevjevich, 2001). However, there is limited multi-disciplinary research on the subject as compared to other developments like dams. Furthermore, there has been no scientific study on the Upper Tana basin to assess such implications which are important for efficient, equitable and sustainable management of the water resources in the basin.

2.10 Conceptual Framework of IBWTs

Inter-basin water transfers bring about the linking of river basins that were naturally / originally not linked. The recipient basin relies on the donor basin to cater for their growing water demand due to growing population. However, the donor basin also faces climatic uncertainties that affect the availability of the water resources. This hydrological interdependency also introduces complex socio-economic, and institutional inter-relationship between the donor and recipient basins. Thus, making it very challenging for the systems to achieve sustainable water development and management (Figure 2.6)

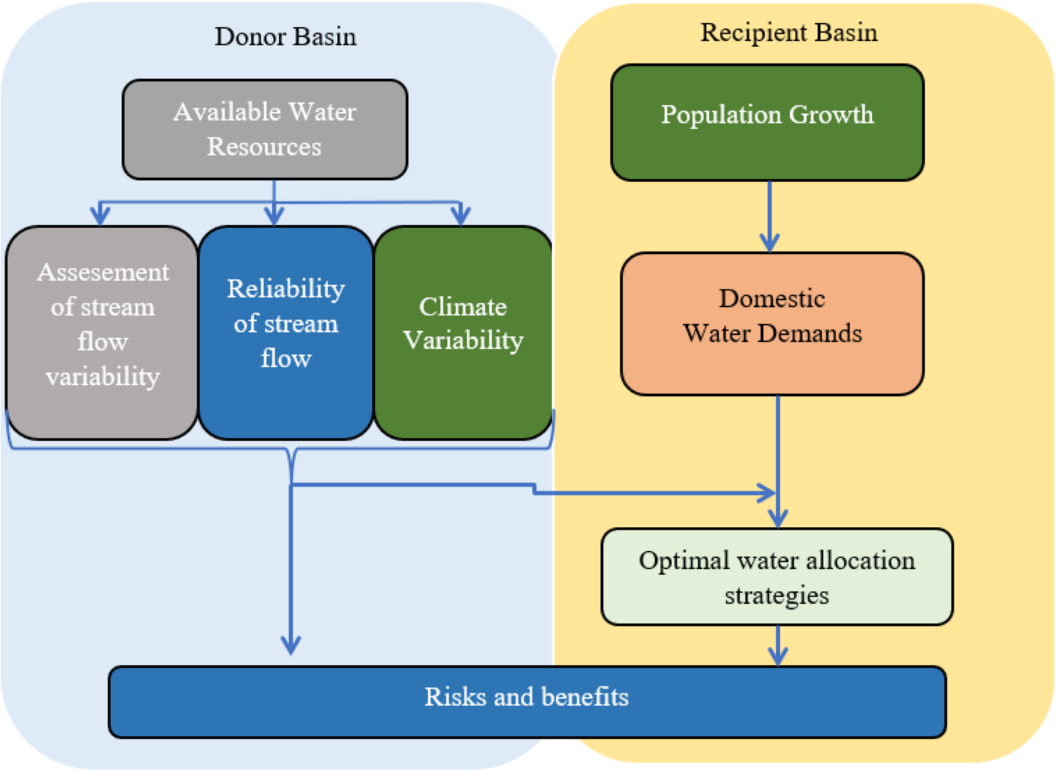


Figure 2.6: Conceptual Framework of the Study of IBWTs

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

3.1.1 Geographical Description

The Upper Tana River Basin covers an area of 19,000 km^2 with a population of approximately 5.2 million people according to the 2019 census report (KNBS, 2019). The basin covers the counties of Nyeri, Meru, Kirinyaga, Muranga, Embu, Tharaka Nithi and parts of Thika which is in Kiambu County (Figure 3.1)

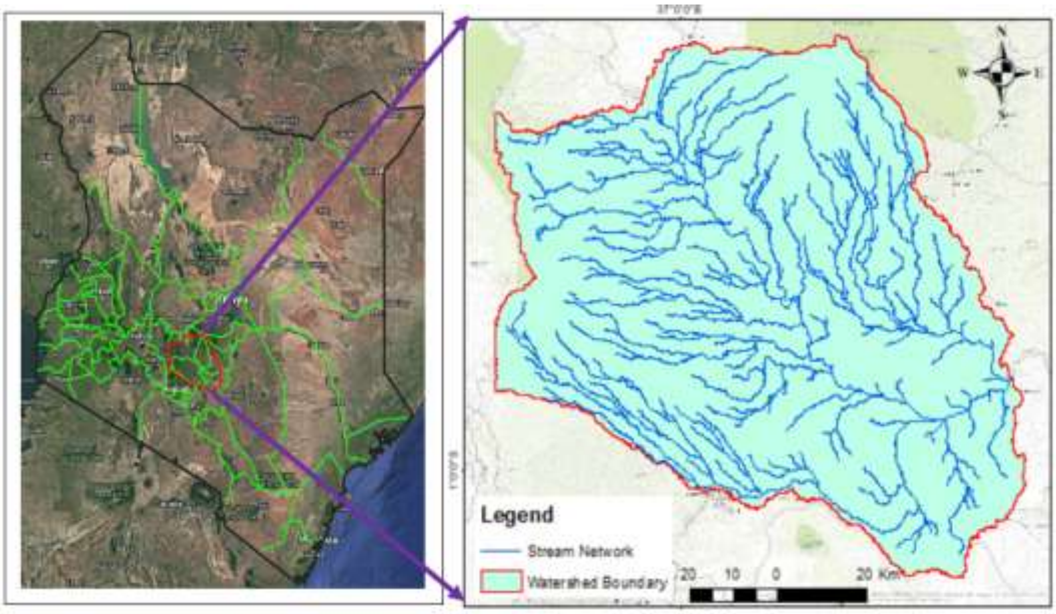


Figure 3.1: Geographical Location of The Upper Tana Basin

3.1.2 Precipitation

The Upper Tana basin has an average annual rainfall of 1200 mm in the upper altitudes and as low as 700 mm in the lower altitudes (Figure 3.2) .The major water towers in the basin are Mount Kenya and the Aberdare highlands at an elevation of 4,900 m.a.s.l. Rainfall is bimodal which falls in two seasons, long rains spanning between the months of March to June and short rains from October to December. The potential evapotranspiration is estimated at 1000 mm annually (Hunink et al., 2013).

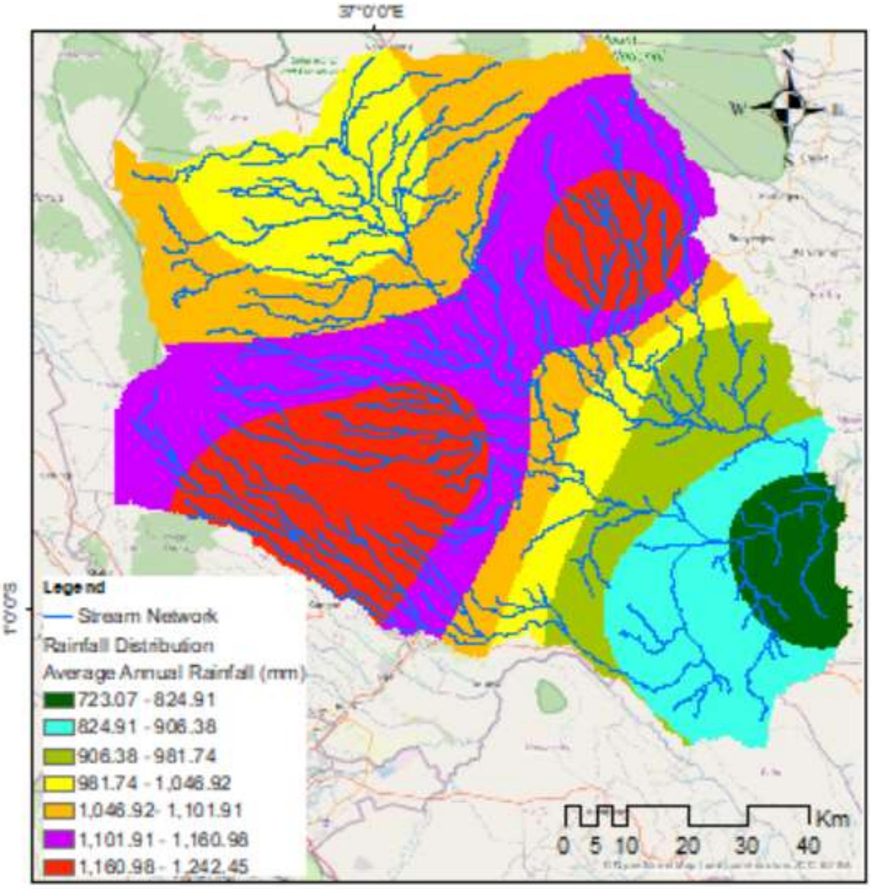


Figure 3.2: Upper Tana Precipitation Range Using FAO, WAPOR Datasets, 2016

3.1.3 Land Use

The land use zones are the forests in the high-altitude region, fodder crops for livestock, tea, and coffee in the middle altitude and maize cultivation in the lower altitudes area (Figure 3.3). Majority of the population in the region depends on rain-fed agriculture.

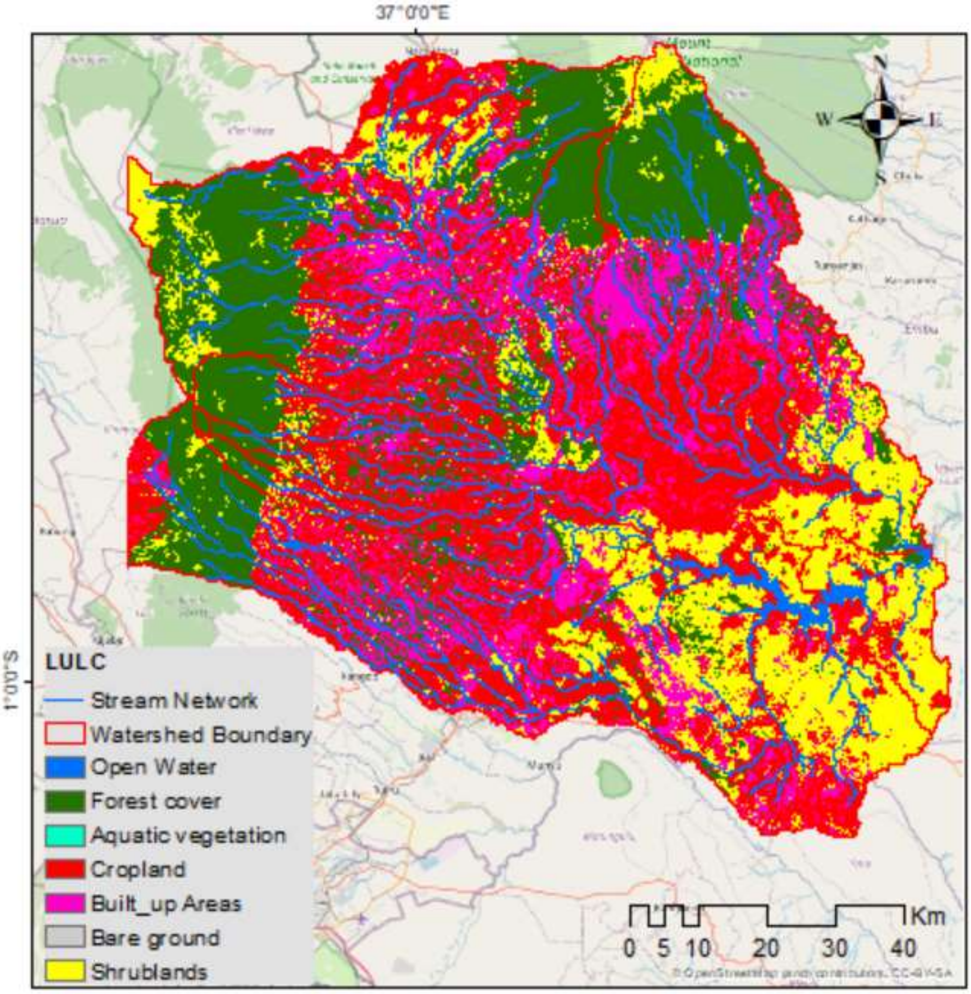


Figure 3.3: Land Use Distribution in the Upper Tana Basin

Source: (Kenya Sentinel 2 2016)

3.1.4 Elevation

Upper Tana basin consists of Mount Kenya and the Aberdares with the elevation ranging from 4900 to 979 m above sea level Figure 3.4.

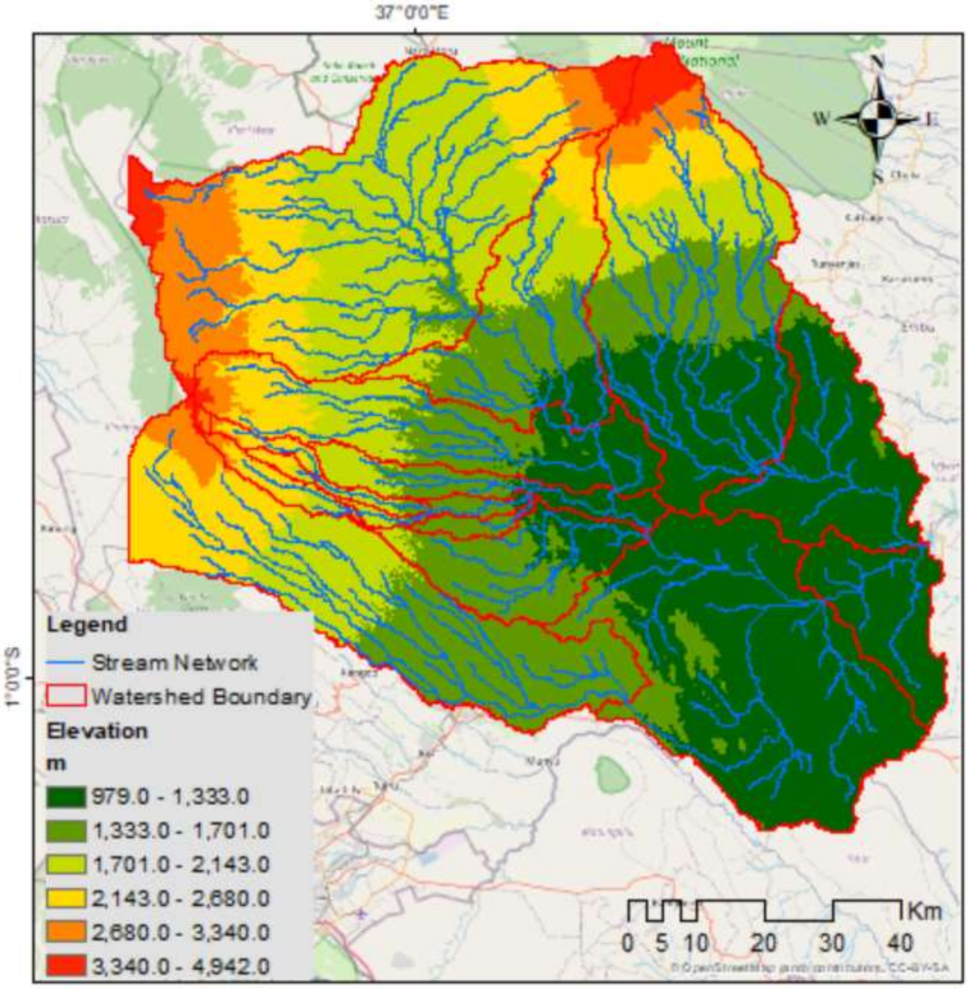


Figure 3.4: Topography of the Upper Tana basin (Regional Centre for Mapping Resource for Development

Source: (RCMRD, 2016)

3.1.5 Existing and Planned Upper Tana Inter-Basin Water Transfers

Tana River basin is the most developed basin in the country, with 40% of the country's total energy produced from hydropower through dams located in the basin. The dams are namely Masinga, Kamburu, Gitaru, Kindaruma and Kiambere power stations. There are also large irrigation schemes being the Mwea-Tebere, Bura, Hola and Tana Delta and small-scale farmers along the river thus high demand for irrigation water (Maingi & Marsh, 2002) . The upper zone is also the source of water for domestic water demand in the basin including inter-basin transfers to Nairobi city through Sasumua and

Ndakaini dams drawing water from Chania and Thika rivers respectively as shown in Figure 3.5 (Apse et al., 2014).

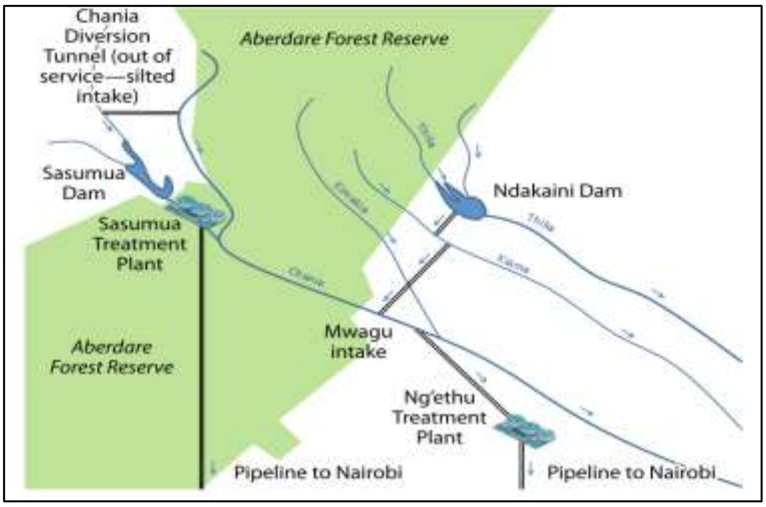


Figure 3.5: The existing Upper Tana Inter-Basin Water Transfer System

Source: (Apse et al., 2014)

The government is currently implementing the Northern collector tunnel 1 project which is expected to divert approximately 1.5 m^3/s of water from three more tributaries of the Tana River namely Maragua, Gikigie and Irate streams. The proposal is to expand the project further to divert water from more tributaries namely Hembe, Githugi, S Mathioya and N Mathioya (MCG, 2015) (Figure 3.6).

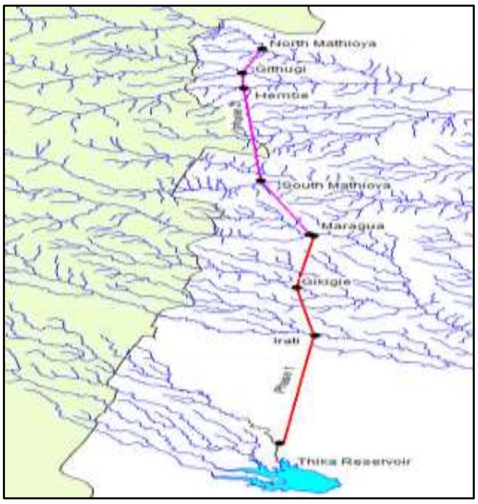


Figure 3.6: The Northern Collector Tunnel Phases I AND II Inter-Basin Water Transfer System

Source: (MCG, 2015).

3.2 Hydrological Modelling and Stream Flow Variability Analysis

3.2.1 Conceptualisation

The hydrological modelling followed the framework shown in Figure 3.7. HEC HMS model was used to simulate Maragua, Gikigie and Irati stream flows while FDC, trend analysis, FI and BFI were used to evaluate the stream flow variability. Reliability index was used to estimate the service reliability of the system under different climatic conditions. Further, Indicators of Hydrological Alteration (IHA) were applied to investigate the magnitude of stream flow alteration caused by the NCT phase I.

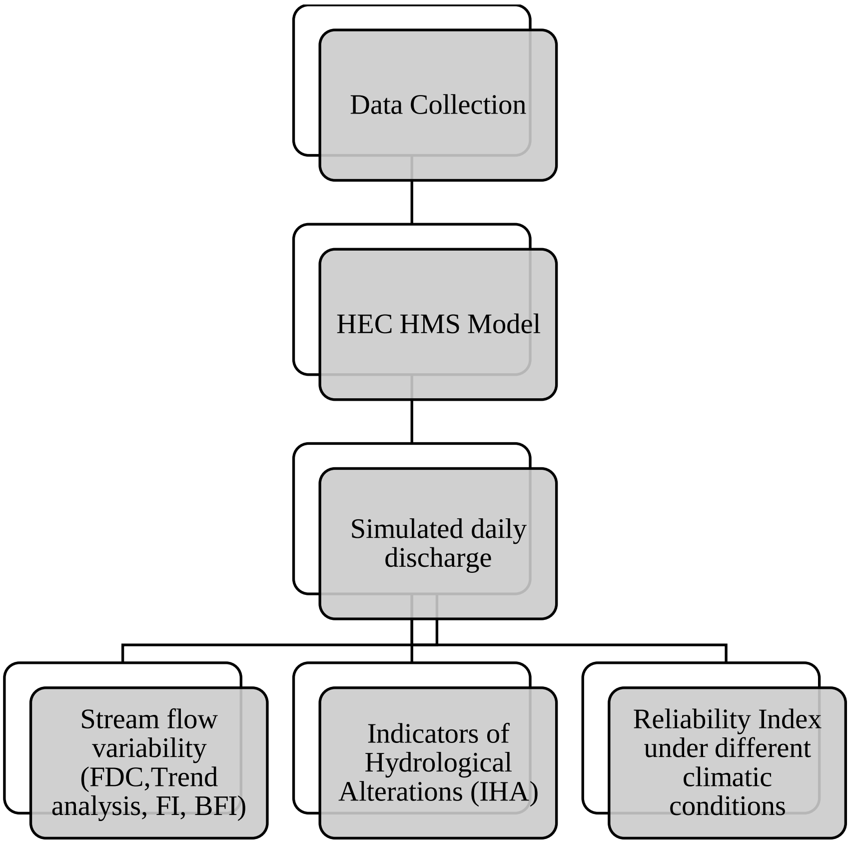


Figure 3.7: A Systematic Methodological Framework for the Hydrological Modelling

Hydrological modelling is often a challenge in a data scarce basin, however, over time satellite datasets with finer spatial resolutions have become available. Recent research in remote sensing has resulted in improved quality of a variety of spatial data. This research presents a novel method of using actual ET data from Water Productivity through Open access of Remotely sensed derived data (WaPOR) database. Arc GIS was used for map preparation which involved watershed and stream delineation and extraction of watershed properties. This process prepared input for the HEC HMS model**.**

3.2.2 Data Requirements

3.2.2.1 Precipitation

The study used daily precipitation data from three stations namely Ndakaini, North Mathioya and DWO collected from Muranga County Meteorological department located in Maragua watershed for the period 1982-2017. Further, four (CHIRPS) (PG1, 2, 4, 5) were used in areas that were not sufficiently covered by the observed rainfall stations for the same period (1982-2017) (Figure 3.8). CHIRPS datasets were corrected using the power transformation method with the three observed stations. River gauging station 4BE01 was used for HEC HMS calibration and validation with data from the Water Resources Authority (WRA) for the period 1983- 1987 and 2012-2015 respectively.

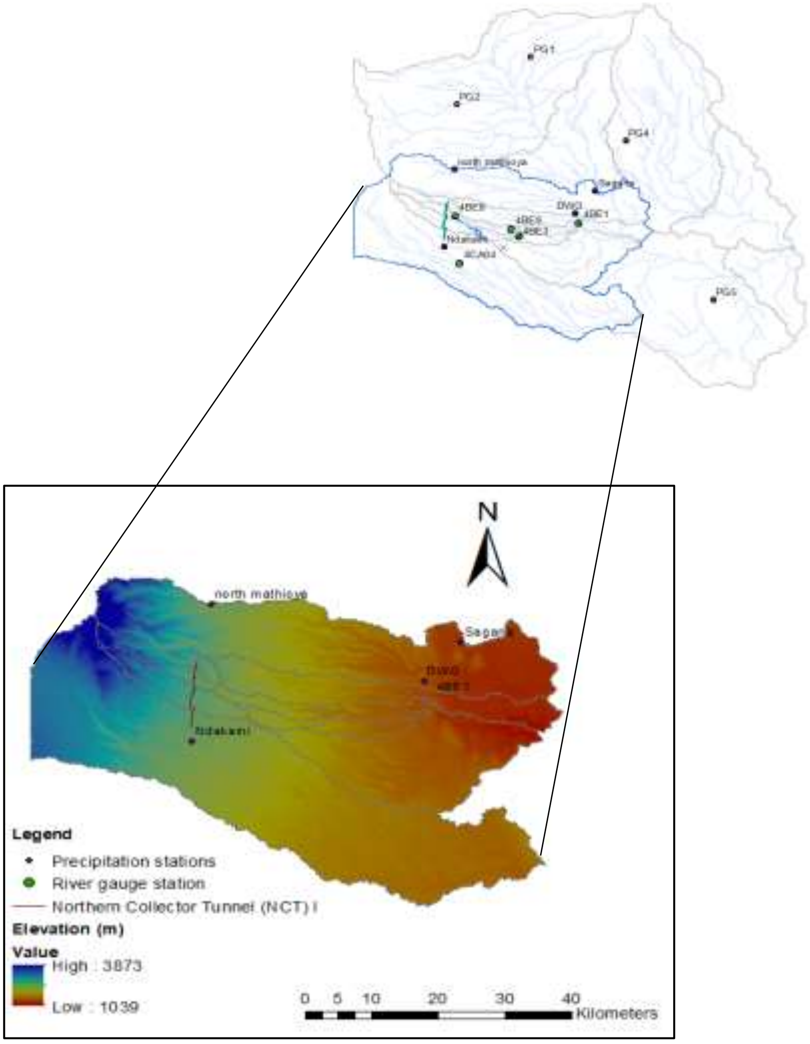


Figure 3.8: Maragua Watershed in Upper Tana Basin and the Location of Observation (Rainfall and Streamflow) and Chirps Stations

3.2.2.2 Soil and Land Use/Land Cover Data

Soil Type Data was downloaded from the Upper Tana KENSOTER database with a resolution of 1:1 m. The land use / land cover data was obtained from Kenya Sentinel 2 2016 at a resolution of 10 m.

3.2.2.3 A Digital Elevation Model (DEM)

A digital elevation model (DEM) was downloaded from the Regional Centre for Mapping Resource for Development (RCMRD) website at a resolution of 30m.

3.2.2.4 Actual Evapotranspiration

This research used actual ET data from Water Productivity through Open access of Remotely sensed derived data (WaPOR) database for the period 2010-2017 in decadal (10 days) time steps. The method to calculate E and T is based on the ETLook algorithm which uses the Penman-Monteith (P-M) equation, adapted to remote sensing input data (FAO, 2020) . The evaluation of actual ET-WaPOR datasets showed that the quality is satisfactory to contribute to understanding the hydrological processes at a local and global spatial scale (Blatchford et al., 2020). The evapotranspiration points were identified based on the land cover of the basin. To estimate evapotranspiration data for historical years (1982-2009), this study correlated 2010-2017 evapotranspiration with precipitation using the linear relation $ET= \beta PET+\alpha P$ (Cheng et al., 2011). For a tropical climate, the effect of variability of potential evapotranspiration on a daily timescale is minimal (Woodroffe & Falkland, 2004) therefore βPET was assumed to be constant. The slope α indicates the variability of ET with respect to P (precipitation).

The main advantage of using ETLook algorithm is that it uses passive microwave sensors Advanced Microwave Scanning Radiometer (AMSRE) to estimate soil moisture as the main parameter of the algorithm. Although , AMSRE data is not influenced by clouds, it is too coarse and is therefore downscaled by use of Moderate Resolution Imaging Spectroradiometer (MODIS) sensor which is the surface albedo and land cover (Pelgrum et al., 2010). Previous remote sensing techniques of estimating actual evapotranspiration like Surface Energy Balance Algorithm for Land (SEBAL), Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) and Remote Sensing Energy Balance (RSEB) use surface energy balance where actual evapotranspiration is estimated as latent heat flux. The limitation of these techniques is that, they are influenced by clouds (Bastiaanssen et al., 2012). ETLook algorithm has been used in Australia, China, Indus in Pakistan, and Iran to estimate ET values and the results compared with the observed ET values (Bastiaanssen et al., 2012; Javadian et al., 2019; Pelgrum et al., 2010).

3.2.3 HEC HMS Application

HEC HMS consists of four components namely, basin, meteorological, time series, and control specifications model for each sub-basin. The basin model consists of the basin map prepared and derived from ArcGIS. as shown in Figure 3.9. The meteorological component consists of rainfall and evapotranspiration data (Feldman, 2000). Evapotranspiration was imported to HEC HMS software as in the ET datasets from WaPOR (Scharffenberg & Fleming, 2016). The control component involves the simulation period and time step to be used.

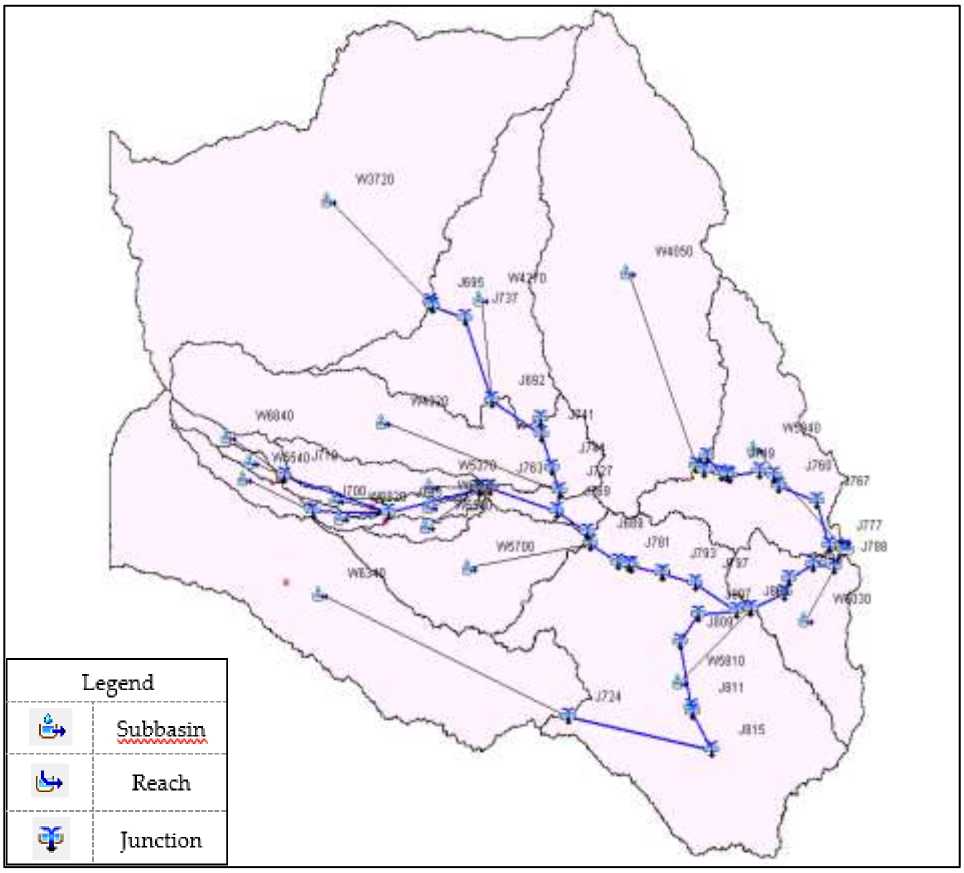


Figure 3.9: HEC HMS Schematization of the Upper Tana Basin

In this study, SMA (Soil Moisture Accounting) was used as the loss rate method for each basin. SMA method simulates the movement of water through vegetation (canopy), surface interception, soil profile and two groundwater layers which requires the parameters shown in Table 3.1.

Table 3.1: Soil Moisture Accounting (SMA) Parameters

	Initial canopy storage (%)
Canopy	Maximum canopy storage (mm)
	Crop coefficient
Surface	Initial surface storage (%)
	Maximum surface storage (mm)
SMA	Soil (%)
	Groundwater 1 (%)
	Groundwater 2 (%)
	Max infiltration rate (mm/hr)
	Impervious (%)
	Soil storage (mm)
	Tension storage (mm)
	Soil percolation (mm/hr)
	GW 1 storage (mm)
	GW 1 percolation (mm/hr)

The canopy component in the model represents the presence or not of vegetation. So, the rainfall is trapped in the vegetation until the canopy storage is filled. The excess precipitation falls on the surface of the soil (soil surface) where it fills the soil field capacity and the ground depression before surface run off begins as shown in Figure 3.10.

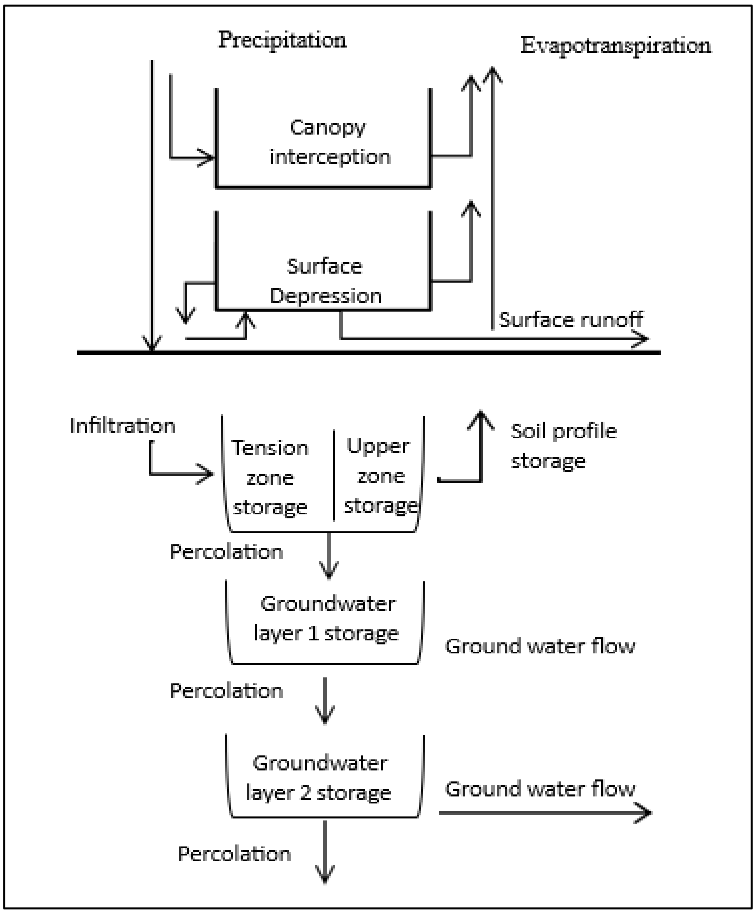


Figure 3.10: Soil Moisture Accounting (SMA) Conceptualization Framework

Canopy interception and surface depression values were obtained from the analysis of land use and elevation of a catchment using ARCGIS guided by Table 3.2 and Table 3.3 (Holberg, 2014).

Table 3.2: Values Used for the Canopy Interception in the Upper Tana Basin

Vegetation type	Interception (mm)
General vegetation	1.3
Deciduous trees and grasses	2.0
Trees	2.5

Source: **(Holberg, 2014)**

Table 3.3: Value Used For Surface Depression in the Upper Tana Basin

Surface type	Slope (%)	Depression (mm)
Paved impervious	N/A	3.2-6.4
Farrowed and Flat	0-5	50.8
Gentle -Moderate slope	5-30	6.4-12.7
Steep-smooth slope	Over 30	1.0

Source: **(Fleming, 2002)**

Soil profile storage is based on the soil analysis of a catchment, which involves the hydraulic conductivity, slope, density and porosity of specific soils to determine the soil infiltration and storage (Table 3.4).

Table 3.4: Upper Tana Basin Soil Properties

	Soils					**Bulk**	
Sub Basins	**Name**	**Percentage(%)**	**Slope (%)**	**Texture**	**Saturated Hydraulic Conductivity (cm/h)**	**Density (g/cm^3)**	**Porosity (cm^3/cm^3)**
	Humic Andosols	15		Sandy Loam	6.11	1.55	0.44
W3720	Terric Histosols	0	16.3	Clay	0.55	1.35	0.55
	Ferric Luvisols	8		Loamy Sand	1.96	1.60	0.55
	Humic Nitisols	52		Clay Loam	1.11	1.50	0.44
W6840, W5540, W6820, W5370,W4920,W5700,W5500,W6860,W6340,W6830,W6850	Humic Nitisols	70.0	13.7	Loamy Sand Clay	1.11	1.50	0.44
	Humic Andosols	30.0		Sandy Loam	6.11	1.55	0.55
	Humic Nitisols	60		Loamy Sand Clay	1.11	1.50	0.44
W4270	Humic Andosols	20	7.9	Sandy Loam	6.11	1.55	0.55
	Terric Histosols	20		Clay	0.55	1.35	0.55
	Humic Nitisols	40		Loamy Sand Clay	1.11	1.50	0.44
	Humic Andosols	30	13.0	Sandy Loam	6.11	1.55	0.55
W4050, W5040, W6030							
	Eutric Vertisols	30		Loamy Sand Clay	1.11	1.50	0.44
	Rhodic Ferralsols	70		Loamy sand	1.96	1.60	0.55
	Eutric Vertisols	20		Loamy Sand Clay	1.11	1.50	0.44
W5810	Ferralic Arenosol	10	7.0	Sand	21.00	1.56	0.437

For the maximum infiltration rate, the values depended on the soil analysis in each basin and were represented by the saturated hydraulic conductivity of the given soils (Table 3.4). The soil water storage values were determined based on the porosity of the soils and their percentage in each basin. The tension storage was considered as the filed capacity of the soils based on their texture values.

For this study, linear reservoir method was used which requires groundwater initial flow in m^3/s and the storage coefficient in hours. This study used the lag method to estimate river routing using Equation 2.1(Subramanya, 2008)

$$T_{lag} = L^{0.8} \frac{(S+1)^{0.7}}{1900} \qquad \textbf{Equation 3.1}$$

Where; T_{lag}= lag time (hours)

L = Hydraulic length of the catchment (m)

S = Maximum retention at the catchment given by: $s = \frac{25400}{CN} - 254$

CN= Soil Conservation Service curve number

Y= Slope (%)

Hydrologic Engineering Centre- the Hydrologic Modelling System (HEC HMS) was adopted as the hydrological modelling tool for this research study because of its ease of use, low data requirement as well as its ability to use external data as input data (Feldman, 2000; Fleming & Doan, 2010; Munyaneza et al., 2014)

3.2.3.1 Calibration and Validation

The HEC HMS model was calibrated and validated using daily streamflow data for a period of 5 years (1983-1987) and 4 years (2012-2015) respectively for river station 4BE01 (Maragua river). To improve accuracy of the simulated results, calibration was done using the optimization tools in the HEC HMS model. Further, manual calibration was done using basin input parameters estimated from watershed characteristics such as the percolation rate of the groundwater through the second layer (GW2), Initial canopy storage and surface storage %. The model performance was evaluated using three objective functions: Coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE) and PBIAS (percentage bias).

3.2.3.2 Sensitivity Analysis

Sensitivity analysis of the model was performed to identify the most sensitive parameters that needed to be estimated precisely for accurate simulations. Thus, the model was first run using the parameters estimated by the methods presented in section 3.2.3 (base run). Next, the model was run while varying the value of each parameter from -30% to 30% in increments of 10% while keeping the other parameters constant. The results were then compared with the base run output to determine the variations and hence identify the most sensitive parameters.

3.2.4 Stream Flow Variability Indices

Stream flow variability was analysed using Flashiness index (FI), flow duration curve (FDC), base flow index (BFI) and monthly trend analysis.

3.2.4.1 Flashiness Index

Flashiness index was used to show the recurrence and speed of short-term changes in flow thus evaluating stability of the three streams

3.2.4.2 Flow Duration Curve (FDC)

FDC was chosen for this study because the Northern Collector Tunnel (NCT) 1 abstractions are based on flow exceedance at any given time. The project is expected to only abstract flood flows exceeding Q_{80} for Maragua and Gikigie and Q_{68} for Irati stream (MCG, 2015). The study used the FDC software (from http://hydrooffice.org/) to plot the curves using average daily discharge flows for each of the streams.

3.2.4.3 Base Flow Index

BFI was estimated using the BFI index software (http://hydrooffice.org/) using average daily discharge of the study period (1983-2017).

3.2.4.4 Monthly Trend Analysis

In this study, linear regression model was used to describe the monthly trend of Maragua, Gikigie and Irati streams using Equation 2.12.

3.2.4.5 Hydrological Alteration of Streams Flows in the NCT Phase I

Changes in stream flows because of the NCT I were estimated using Indicators of Hydrological Alteration (IHA) software developed by the US Nature Conservancy (Mathews & Richter, 2007). The study used the magnitude of monthly flows and extreme flows as the indicators of hydrological alterations in the three NCT I stream. The degree of hydrological alteration was estimated using the Range of Variability Approach (RVA) as defined in Equation 2.13.

3.2.5 Reliability of NCT Phase I under Different Climatic Conditions

Streamflow Drought Index (SDI) was calculated using the DrinC software at a 12-month time step (annual) (Tigkas et al., 2015). The dry, normal and wet years were identified based on guidelines of drought categories as shown in Table 3.5 For this study supply reliability at daily time step (Equation 2.15) was used to analyse the performance of NCT I under the dry, normal and wet years.

Table 3.5: Description of Climatic Condition Based on SDI Value and Corresponding Drought Category

SDI Value	Drought category	Climatic year
2.00 or greater	Extremely wet	
1.50-1.99	Severely wet	
1.00-1.49	Moderately wet	Wet years
0-0.99	Near normal (mildly wet)	
0 to -0.99	Near normal (Mild drought)	Normal years
-1.00 to -1.49	Moderate drought	
-1.50 to -1.99	Severe drought	
-2.00 or lower	Extreme drought	Dry years

3.3 Sentinel Imagery to Detect Changes in Thika Reservoir from NCT I Inflows

3.3.1 Sentinel Data Acquisition and Processing

3.3.1.1 Sentinel Data Acquisition

The datasets were acquired for the months of April, May and June 2022 which was based on the availability of data and because NCT 1 started operating in May 2022. The data was downloaded from Copernicus Data Access Service (https://finder.creodias.eu/). The atmospheric correction for the data set was done using the Sen2Cor processing tool in sentinel application platform (SNAP).

3.3.1.2 Calculation of Water Index

Normalized Difference Water Index (NDWI) was selected to map changes in Thika reservoir area from the NCT I inflows. This index has been used widely and successfully in mapping and detecting water bodies (Benzougagh et al., 2022; Ghansah et al., 2022; Kandekar et al., 2021; Sekertekin et al., 2018).

3.3.1.3 Validation with Observed Thika Reservoir Area

Estimates of Thika reservoir area from Sentinel imagery were validated with the observed reservoir area using the available elevation-area-volume graph. The observed volume and elevation datasets were obtained from Nairobi Water and Sewerage Company (NWSC) who oversee the operations of the reservoir.

3.4 WEAP Model for Optimal Allocation Strategies

3.4.1 The Water Evaluation Planning (WEAP) Model Conceptualisation

The first step in WEAP model was to define the water resources system by assessing the water supply sources (current and future) and water demands (current and projected) Second step was to define the time steps for the study area. The third step was to create scenarios and assess the performance of the water system using unmet demand and supply coverage indicators. In addition, WEAP model considers uncertainties of climate variability using water year method. The performance of these scenarios would determine the most desirable strategies for water supply to Nairobi city (Figure 3.11)

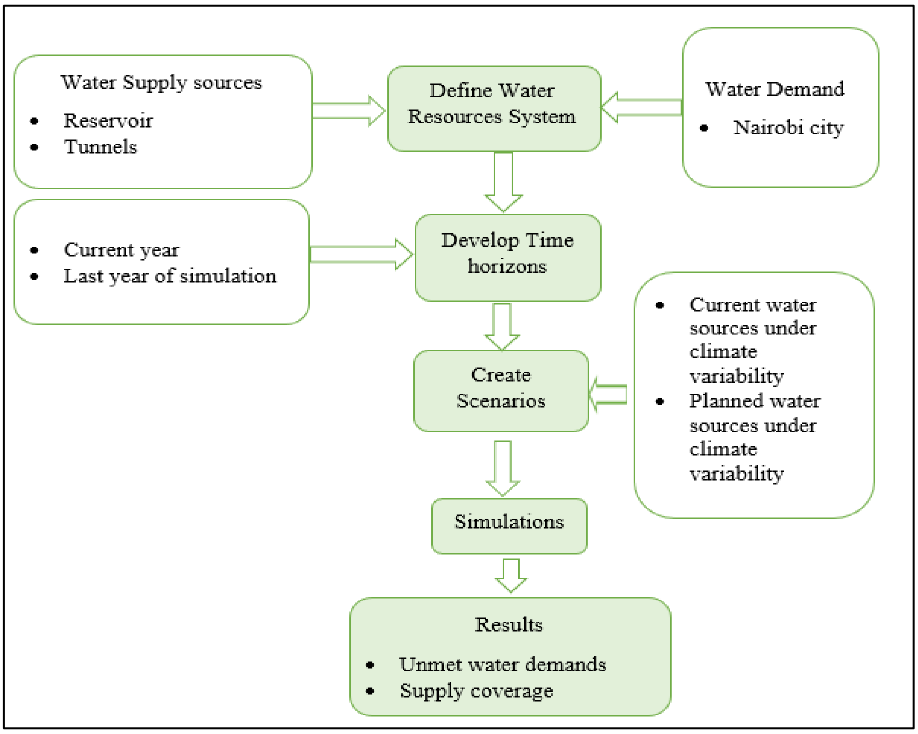


Figure 3.11: **WEAP Model Framework**

3.4.2 Data Requirements

3.4.2.1 WEAP Model Data Requirements

The model was developed using the data sets provided in Table 3.6

Table 3.6: WEAP Model Data Sets and Sources

	Data Requirements	Source	Period
Water Supply	NCT 1 Rivers (Gigike, Irati and Maragua)	Hydrological modelling (Nyingi)	1997-2017
	Thika Reservoir (physical dam characterises and operating rules)	Nairobi Water and Sewerage Company (NWSC)	1997-2017
	Thika, Chania, Kimakia and Kiama Rivers	Nairobi Water and Sewerage Company (NWSC)	1997-2017
	NCT II and Maragua dam	Athi Water Works Development Agency (AWWDA)	2035
Water Demand	Nairobi City and its environs	Athi Water Works Development Agency (AWWDA)	Projected water demand for 2022 & 2035
	Environmental flow requirements	Athi Water Works Development Agency (AWWDA)	1997-2017

3.4.2.2 Scenarios Development

B0 scenario: Water availability with the current water sources. This scenario was developed based on the current water supply as in Table 1.1. For the water demand, the study used the low water demands scenario for the year 2022 provided by AWWDA (Figure 1.1) of approximately $10.1m^3/s$. This is because according to the 2019 census (KNBS, 2019), the population growth rate reduced from 2.9 % to 2.2 % which represented the low water demand scenario.

B1 scenario: B0 + NCT 1. This scenario evaluated the effects of the new water source NCT 1. The water demand was the same as in B0 scenario.

***B2 scenario**:* B1 + 10% demand measures

From literature it is predicated that effective water saving strategies are likely to reduce domestic and industrial water demand by 10-30%. These strategies may include water savings home appliances (showers, WCs, urinals and washing machines), encouraging urban rainwater harvesting and re-use of grey water (Abu-Bakar et al., 2021; Cominola et al., 2015; Deverill et al., 2001; Lee et al., 2013; Lévite et al., 2003). Based on this information and following personal discussions with water managers in Kenya, the study opted for three options 10%, 20% and 30 % demand measures. Therefore, this scenario evaluated the impacts of a 10% demand measure on the water availability with NCT 1.

***B3 scenario**:* B1 + 20% demand measures

In this scenario, the effects of enforcing a 20% demand measure on water availability with the implementation of NCT 1 were evaluated.

***B4 scenario**:* B1 + 30% demand measures.

This scenario involved simulations of the effects of NCT 1 on water availability with a 30% demand measure.

***B5 scenario*:** B1+ NCT II and the projected low water demand scenario for the year 2035 being 13.0 m^3/s as provided by AWWDA (Figure 1.1)

B6 scenario: B5 + Maragua dam and the projected water demand for the year 2035.

For each of the scenarios, climate variability was included as water year method provided in WEAP model. Water year method involved variation of streamflow by defining five climatic conditions (very dry, dry, normal, wet and very wet). The climatic conditions were developed based on the Stream Flow Drought Index (SDI) categorization of drought in the river basin as per section 3.2.5. The normal year was given a value of 1 whereas the other years flows were a function of the normal years as in Table 3.7.

Table 3.7: Variations of Streamflow for WEAP Water Year Method in Upper Tana Basin

Very dry year	0.6
Dry year	0.8
Normal year	1
Wet year	1.8
Very wet year	2.2

3.4.3 Model Assumptions

The initial condition of Thika reservoir was assumed to be full at the beginning of simulation. Only domestic and industrial demands were considered, and the demands were taken as constant throughout the year but increased over the years as per the population growth rate. The study also assumed that the discharge series 1997-2017 represented the future discharge. Reservoir storage was assumed to be constant in that siltation effects on the reservoir were not considered.

3.5 NCT I Tunnel And Groundwater Flow Interactions in the Upper Tana River Basin

3.5.1 Scope of the Study

The NCT I is in Maragua sub-basin which is approximately 425 km$^{2.}$ NCT I is approximately 12km and will divert water from Maragua, Gikigie and Irati rivers to the existing Thika Reservoir (Figure 3.12). Residents of Maragua sub-county currently tap water from streams and springs for their livelihoods. The study area is characterized by many ridges and valleys where groundwater recharges rivers and streams. Further, the study focused on the intakes of the tunnel since at this level there is some interaction with the river level (Figure 3.13).

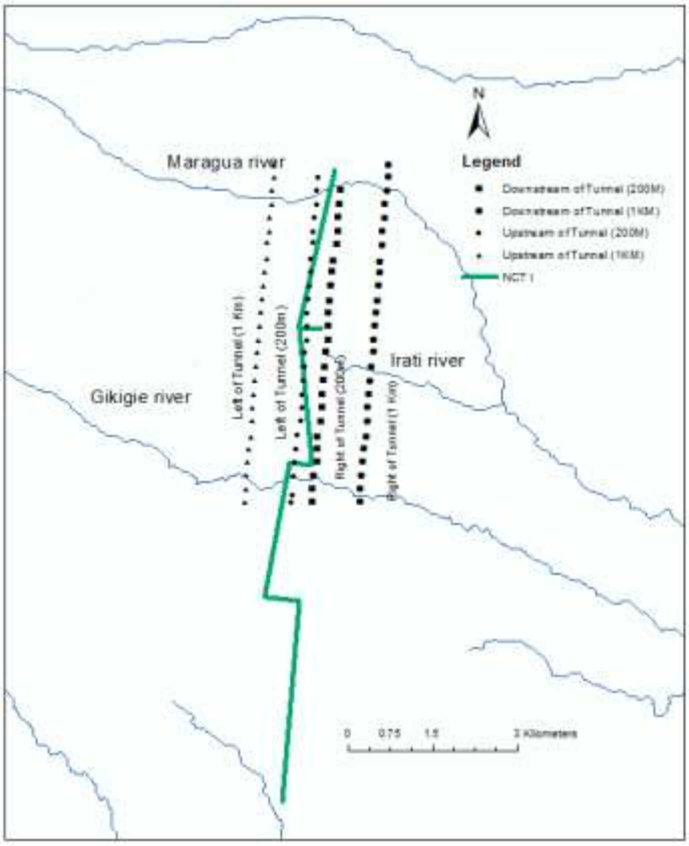


Figure 3.12: Study Area Map Showing the NCT I Profile, Borehole Locations and the VES Study Points

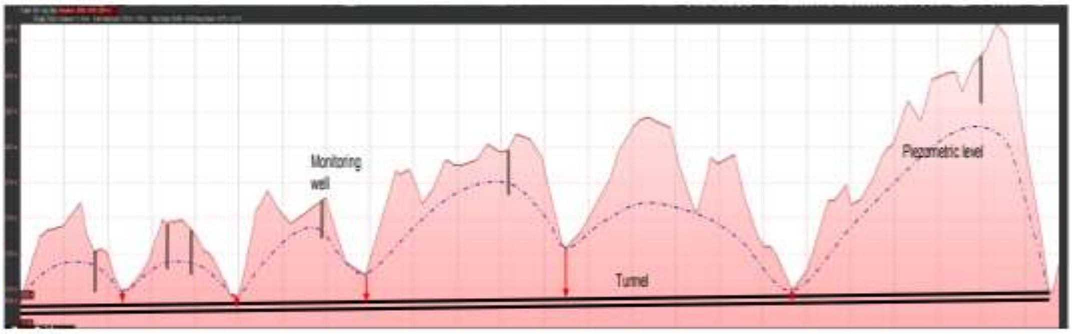


Figure 3.13: NCT I Tunnel Route with Groundwater Level Source

Source: (Geotechnical & Allied Ltd, 2016)

3.5.2 Geology of the Study Area

The principal rocks distinguished in the study area are basalts, basaltic agglomerates (autobreccias), trachytes, phonolites, pyroclastic rocks and lacustrine deposits (Veldkamp et al., 2012). The sequence in which these rocks were laid down was Younger Pleistocene volcanic rocks and Helocene sediments in thickness <30 meters, Pliocene to Middle Pleistocene Sattima Series and Laikipian Lavas with associated pyroclastics in thickness < 900 meters and Miocene Simbara Series in thickness > 900 meters (Bauernhofer et al., 2009)

3.5.3 Framework of the Study of the Interaction between NCT I and Groundwater Flow

MODFLOW software was used to simulate groundwater flow and the interaction with NCT I tunnel. The model required a good understanding of aquifer characteristics which was done using vertical electrical sounding (VES) survey (Figure 3.14).

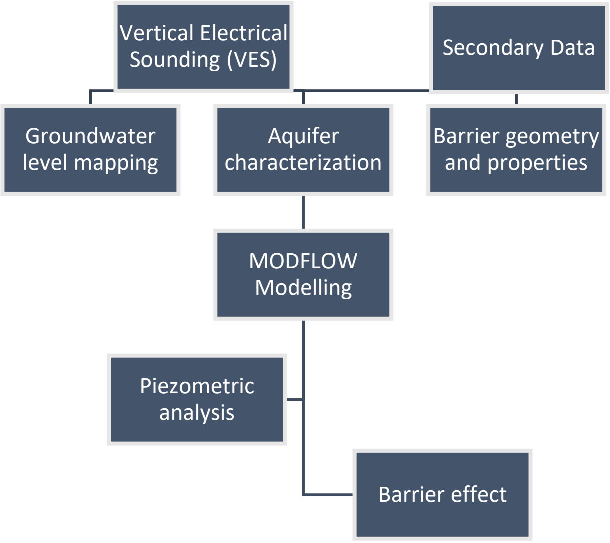


Figure 3.14: The Framework to Investigate the Barrier Effect on Groundwater Flow in NCT I Tunnel

3.5.4 Vertical Electrical Sounding (VES) Survey

The main elements of the NCT I system were the aquifer system and the underground tunnel. For sub-surface exploration, VES survey was carried out during the month of March 2023 just before the onset of the long rainy season using the PQWT-s500 machine. Four profile lines, two upstream and two downstream of the tunnels were done each 6 km long at a maximum depth of 500 m. A total of 104 points at intervals of 200 m were generated (Figure 3.12). The 6 km (50% of the total length) represented the NCT I tunnel from Maragua intake to Irati intake which was representative of the total tunnel length. Voxler 4 software was used to visualize the resistivity data in 3D model.

3.5.5 MODFLOW Model Formulation

To estimate the effect of NCT I on ground water levels, MODFLOW was used to simulate groundwater flows in the study area using Processing Modflow (PM) interface. Field measurement analysis was carried out using observed groundwater levels from eight boreholes (BH1, BH3, BH4, BH5, BH6, BH7, BH8, and BH9) obtained from Athi Water Works Development Agency (AWWDA). The borehole levels were validated using a water level dip meter. Abstraction rates were obtained from data records of Water Resources Authority in Muranga County. Groundwater flow was modelled in a steady-state condition covering a geographical area of 14 km (Y – axis, along the tunnel length) and 4 km (X-axis, across the tunnel breadth) within coordinates: X: 258000 – 262000 and Y: 9911000 – 9925000. The Northern boundary was modelled using No Flow cells to represent the basin divide and the Eastern, Western and Southern boundaries were modelled using General Head Boundary (GHB) to represent groundwater flow from the basin into the model area. The Horizontal Flow Barrier (HFB) package provided in MODFLOW represented the impervious NCT I tunnel (Figure 3.15).

The model was composed of two layers consisting of the upper vadose / unsaturated zone and the lower unconfined / water table aquifer. Aquifer parameters were obtained from the VES survey and from available literature. The borehole levels were interpolated to represent the upper boundary of the aquifer while the borehole total depths were interpolated to represent the lower level of the aquifer. GPS Visualizer and TCX Converter software was used to obtain ground elevations for the area of interest around the tunnel and interpolation done to obtain a DEM for the entire study area. The interpolated borehole water levels obtained from subtracting interpolated surface levels and the interpolated depth to water levels (in meters above sea level) were also assumed to be the initial prescribed heads for both the upper and lower layers.

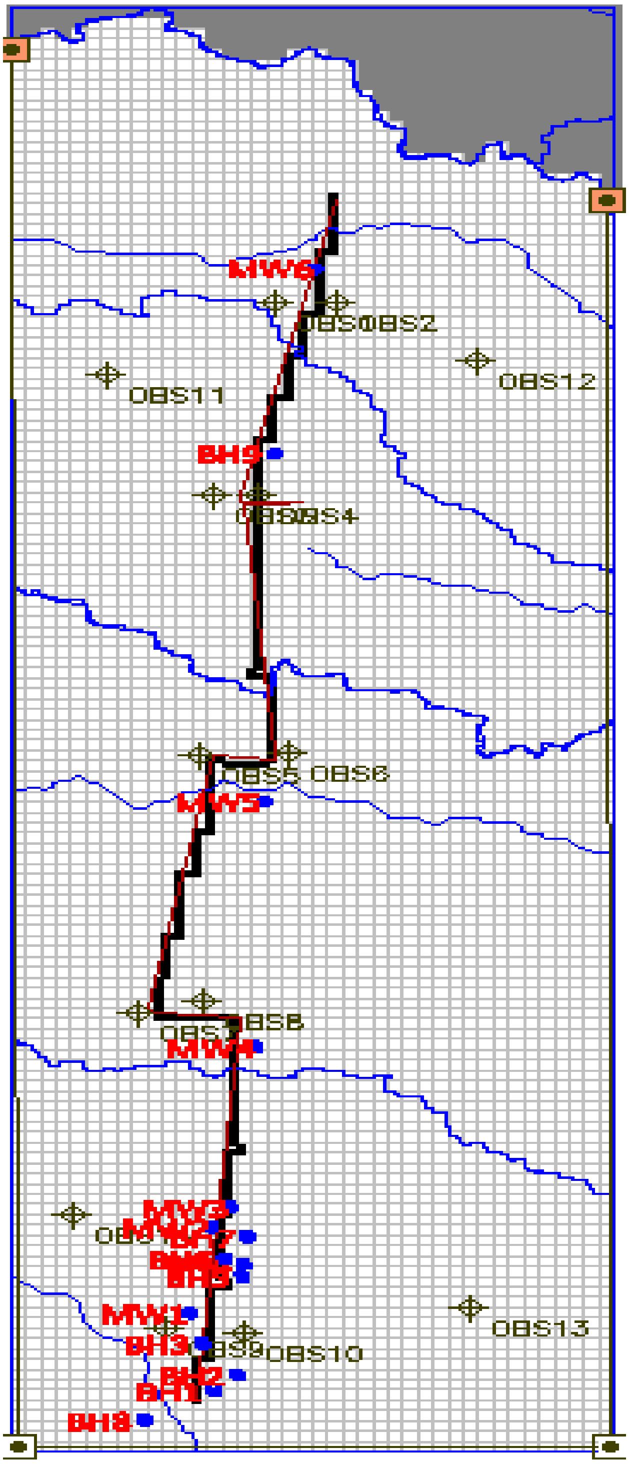


Figure 3.15: MODFLOW Grid Showing the Boreholes, Streams and the NCT 1 Tunnel as a Horizontal Flow Barrier (HFB)

3.5.5.1 Groundwater Recharge

Evapotranspiration datasets were obtained from FAO-WAPOR to estimate the recharge rate of the aquifer. Research in remote sensing has resulted in improved quality of a variety of spatial data (Bastiaanssen et al., 2012; FAO, 2020; Nyingi et al., 2023). The rate of evapotranspiration was obtained as 1060 mm/year. The average rainfall over the watershed was 1581 mm/year which was obtained from North Mathioya rainfall station data collected from Muranga County Meteorological Department. The aquifer recharge was estimated as a percentage of the local infiltration of the annual precipitation and replenishment from lateral inflows from other nearby areas using the groundwater estimation committee norms developed in 1987. Where ; Alluvial areas: recharge could be taken as 20–25% of rainfall for sandy areas, and 10–20% for areas with high clay content (more than 40 % clay), Semi-consolidated sandstones: 10–15% of rainfall is considered as recharge ,Granitic terrain: for weathered and fractured rocks, 10–15% of rainfall, Un weathered – 5–10% of rainfall, Basaltic terrain: 10–15% of rainfall and Weathered basalt: 4–10% of rainfall (Andualem et al., 2021).

3.5.5.2 Aquifer Characteristics

From the VES survey conducted during the study and borehole field measurements, borehole depths were found to range from 17.5 to 35 metres while static water level varied from 1.5m to 7m below ground level with an average aquifer thickness of 7 meters. The geology of the area along the tunnel comprises basalts and agglomerates of the Simbara Series. Thus, the hydraulic conductivity was 0.37m/day based on Foster et al., (2012) guidelines while aquifer transmissivity was 2.2 m^2/day. The horizontal hydraulic conductivity, K_h was 10m/day for the aquifer (agglomerates) and 0.01m/day for the vadose zone composed of basalts. The vertical hydraulic conductivity, K_v, adopted was 1m/day for the aquifer and 0.001m/day for the vadose zone. i.e., one order of magnitude lower than K_h. For the effective porosity a value of 20% for the aquifer and 15% for vadose zone was adopted based on the guidelines by Bower & Zyvoloski,(1997) (Table 3.8). Riverbed conductance describes the capacity of river water to be transmitted through the channel bed when the elevation of the river stage is higher than the elevation of groundwater under the riverbed. It is given by the following expression, Equation 3.2:

$$C_{riv} = \frac{K_{riv} \,.\, L \,.\, W_{riv}}{M_{riv}} = \frac{K_{riv} \,.\, A}{M_{riv}}$$ **Equation 3.2**

Where.

C_{riv} = riverbed hydraulic conductance (m^2/day)

K_{riv} = hydraulic conductivity of the riverbed sediments (m/day)

L = length of riverbed cell (m)

W_{riv} = width of the river cell (m)

A = area of river element (m^2)

M_{riv} = thickness of the riverbed (m)

Note: The average value of C_{riv} was calculated as 8,000m^2/day for a 100m x100m cell, K_{riv} = 0.4m/day and M_{riv} = 0.5m. Riverbed elevations were estimated from the interpolated surface topography (i.e., Elevations of Top surface of upper most layer).

Aquifers in the watershed area have an estimated average transmissivity value of 1.53 x 10^{-3} m^2/min with a standard deviation of 1.43 x 10^{-3} m^2/min. The storage coefficients for aquifers in this area have an average value of 6.50 x 10^{-3} with a standard deviation of 6.71 x 10^{-3} (Bower & Zyvoloski, 1997)

Table 3.8: Ranges of Effective Porosities for Different Rocks and Alluvial Sediments

	Total Porosity	Effective Porosity
Unconsolidated Sediments		
Gravel	0.25-0.44	0.13-0.44
Coarse sand	0.31-0.46	0.18-0.43
Medium sand		0.16-0.46
Fine sand	0.25-0.53	0.01-0.46
Silt, loess	0.35-0.50	0.01-0.39
Clay	0.40-0.70	0.01-0.18
Sedimentary and Crystalline rocks		
Karst and reef limestone	0.05-0.50	
Limestone, dolomite	0.00-0.20	0.01-0.24
Sandstone	0.05-0.30	0.10-0.30
Siltstone		0.21-0.41
Basalt	0.05-0.50	
Fractured crystalline	0.00-0.10	
Weather granite	0.34-0.57	
Unfractured crystalline rock	0.00-0.05	

Source: (Bower & Zyvoloski, 1997)

3.6 Distribution of Benefits and Risks in NCT Phase 1 Project

The study focused on stakeholders that played a role and / or were affected by the NCT 1 IBWT. The project's initial feasibility study was done in 1998 under the Third Nairobi Water Supply Project. In 2012, AWWDA did a Master Plan for developing water sources for Nairobi city and its satellite towns. The master plan further validated and recommended the NCT projects as a viable water source for Nairobi city. It is against this that AWWDA, through the MoWI sourced for financing of approximately KES 6.8 billion (USD 65 Million) (KES 104 = 1USD) from the World Bank and AFD to implement the NCT phase 1project (MCG, 2015).

3.6.1 Data and Method

The main method used was stakeholder analysis which involved (i) identifying (ii) categorizing stakeholders and (iii) investigating their relationships, benefits and risks following Reed et al., (2009) guidelines but adjusted to suit the case study. The process involved sub-methodological steps (Figure 3.16) of literature review, snowball sampling, semi-structured interviews, and focused group discussion (FGD) to identify and categorize stakeholders. Further, qualitative content analysis was used to investigate the stakeholder relationships and identify the perceived risks and benefits of the project to the stakeholders (Mohamadian et al., 2022; Schlund et al., 2022; Yeleliere et al., 2022).

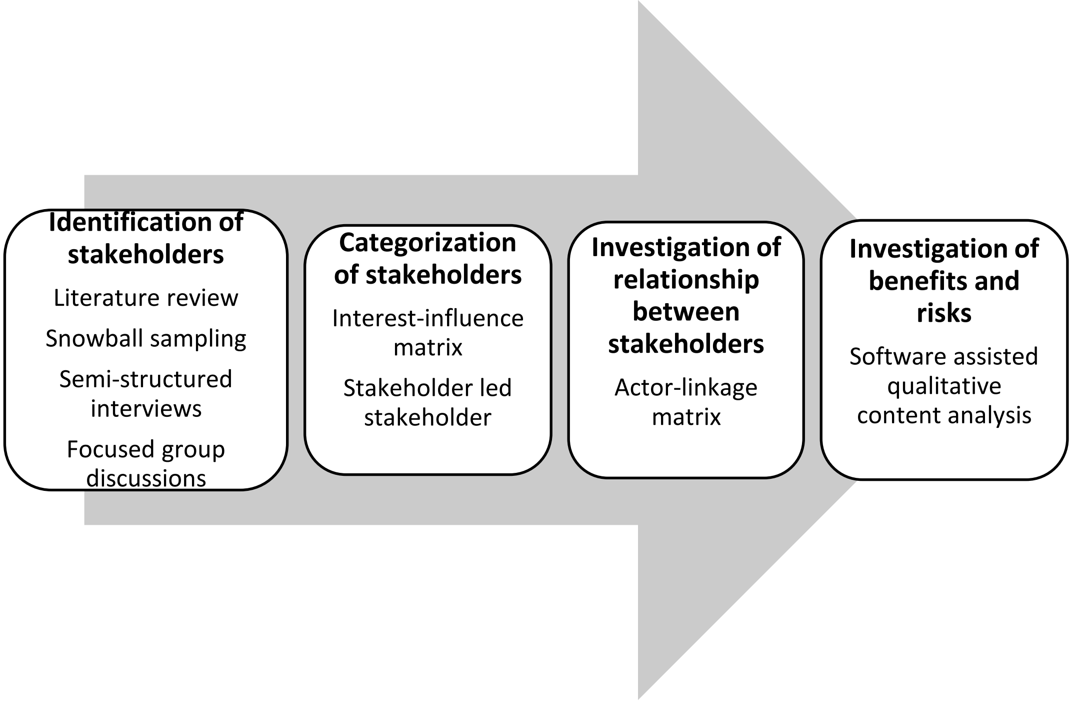


Figure 3.16: Methodology Steps for Undertaking Stakeholder Analysis in the NCT I Project - Upper Tana Basin, Kenya

First stakeholders were identified through review of policy documents, project design reports and academic papers (Table 3.9) derived from the various government websites and personal communication.

Table 3.9: NCT I Reviewed Policy Documents and Project Design Reports

Authors	Title
(AWWDA, 2016)	Feasibility Study and Master Plan for Developing New Water Sources for Nairobi and Satellite Towns: Northern Collector Tunnel Project Phase I. Athi Water Works Development Agency
(Geotechnical & Allied Ltd, 2016)	Study Location of Monitoring Wells along the Northern Collector Tunnel
(MCG, 2015)	Report of the Technical Committee on Northern Collector Tunnel Project, Muranga County Technical Committee
(NCC, 1986)	Regional studies 1986 Part 2
(NCC, 1998)	Northern Collector Scheme- Draft Report June 1998
(World Bank Group, 2017)	The inspection panel report and recommendation on a request for inspection, Northern collector project
(WRA, 2013)	The project on the development of the national water master plan 2030, Ministry of environment, water and natural resources, Kenya
(SMEC, 2013)	Consultancy Services for Detailed Design, Tender Documentation, Supervision and Coordination for Northern Collector Tunnel Phase 1
(Gibb, 2014)	Final-ESIA-study-Report-for-Northern-Collector-Tunnel-PHASE-1. Volume-2

Further, interviewees were requested to mention and give contacts where possible of other stakeholders relevant to the NCT I project (Snowballing). Further, semi-structured interviews were conducted to identify stakeholders’ roles, their relationships, risks and benefits in the project using an interview guide on the power dynamics and decision-making process. In addition, one focused group discussion was held to gather additional information and in-depth insights on the topics. In total 25 interviews were conducted and one focused group discussion with representatives of the identified stakeholders. Data collection was carried out during the months of February, March, and April of 2023.

3.6.2 Data Analysis

The interviews results were analysed using Nvivo software process that is commonly referred to as software-assisted qualitative content analysis (QCA). This method follows a guideline to ensure objective interpretation of the qualitative data which is mainly in text format (Kaefer et al., 2015; Mayring, 2004). The stakeholders were classified according to their level of importance-influence matrix to illustrate the stakeholders power interactions (Reed et al., 2009). Data from the interviews was coded in Nvivo and themes from the research questions were developed thus identifying the risks and benefits of the project as perceived by the stakeholders.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Hydrological Modelling Results

This section describes results of the HEC HMS simulation of Maragua, Gikigie and Irati stream flows, their variability using FDC, trend analysis, FI and BFI indices. The service reliability of flows from the three streams under different climatic conditions. Lastly, the probable Maragua, Gikigie and Irati flows alteration caused by the NCT I project using Hydrological Alteration (IHA) Indicators.

4.1.1 Calibration and Validation

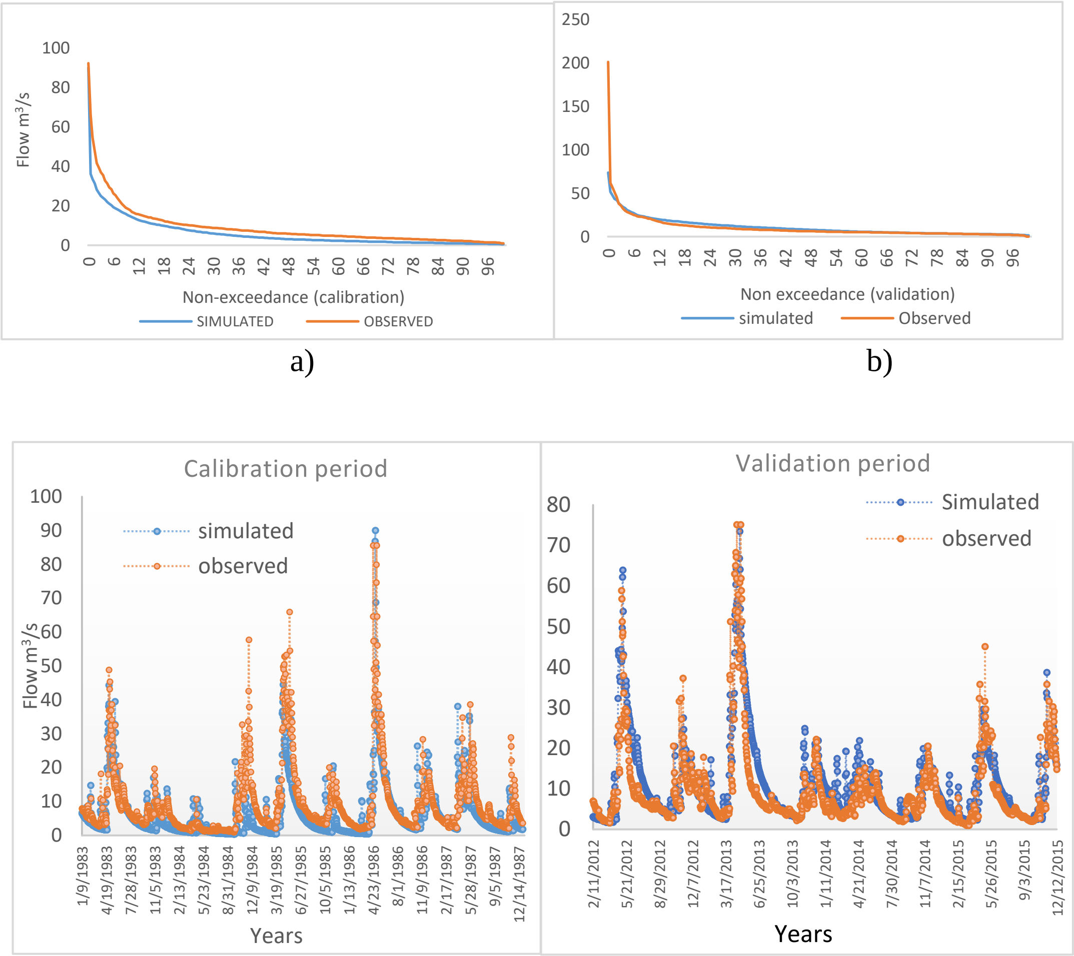
HEC HMS model was calibrated and validated using daily stream flow data and non-exceedance for a period of 5 years (1983-1987) and 4 years (2012-2015) respectively for river station 4BE01 (Maragua river) (Figure 4.1). Table 4.1 shows the optimized model parameters for the Upper Tana basin. The Coefficient of determination (R^2) for calibration and validation were 0.57 and 0.72 respectively while the Nash-Sutcliffe Efficiency (NSE) was 0.45 and 0.59 respectively (Table 4.2). Lower NSE values during calibration is widely experienced in data scarce basins mostly attributable to the uncertainty involved in the observed stream flow data. Hernandez-Suarez et al., 2018; Kiptala et al., 2014; Nyeko, 2015; Sirisena et al., 2020 obtained similar results where the NSE was lower than 0.50 in calibration (unsatisfactory) but above 0.50 in validation (satisfactory). As indicated by Kiptala et al., (2014) this uncertainty can be attributed to poorly maintained river gauging stations and outdated river rating curves especially in African landscapes. In addition, smaller streams are more prone to uncertainty of observed flows due to the short-term temporal variability of high flows in tropical climate (Hernandez-Suarez et al., 2018). Percentage bias (PBIAS) was -38% for calibration period and 14% for validation period. PBIAS during the calibration period was not within range because of underestimation of peak flows during this period (Figure 4.1). Underestimation of peaks is a common drawback in hydrological modelling and may be because of poor data collection and entry because the observed data is read and recorded manually (Zhang & Savenije, 2005). However, the results were acceptable since the model performance indices (Table 4.2) were within the stipulated ranges Table 2.4.The linear relation ET= βPET+αP showed that the value of α was 1.0 in January, 0.3 in April, and 1.5 in September showing that the value during the wet season is smaller than during the dry season.

Table 4.1: Optimized HEC HMS Parameters

Parameters	**W3720**	**W6840**	**W4270**	**W4050**	**W5810**
Max canopy storage (mm)	2.5	2.5	2.5	2.5	2.5
Max surface storage (mm)	12	15	9	28	32
Max infiltration rate (mm/h)	30	30	40	50	55
Impervious (%)	5	5	5	5	5
Soil storage (mm)	260	200	200	280	200
Tension storage (mm)	180	180	150	200	180
Soil percolation (mm/h)	50	50	50	50	50
GW1 storage (mm)	85	85	85	85	85
GW1 percolation (mm/h)	1.98	1.98	1.98	1.98	1.98
GW1 coefficient (h)	115	115	115	115	115
GW2 storage (mm)	200	200	200	200	200
GW2 percolation (mm/h)	1.35	1.35	1.35	1.35	1.35
GW2 coefficient (h)	1000	1000	1000	1000	1000

Table 4.2: Model Performance during Calibration and Validation at Station 4BE01

	Station 4BE01			
	Year	**R^2**	**NSE**	**PBIAS**
Calibration	1983-1987	0.57	0.45	-38 %
Validation	2012-2015	0.72	0.59	14%



a) b)

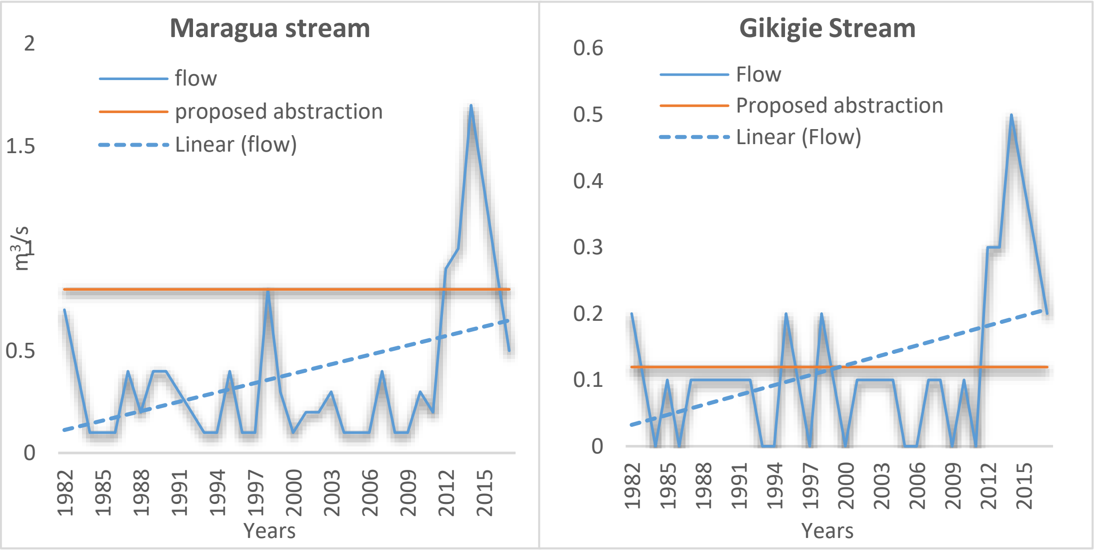
c) d)

Figure 4.1: Hec Hms Calibration and Validation Results at Station 4BE01

4.1.2 Stream Flow Variability

4.1.2.1 Flow Duration Curve (FDC) and Monthly Trend Analysis

The proposed plan of the NCT I is to abstract more than 0.843 m^3/s and 0.137 m^3/s (Q_{80}) for Maragua and Gikigie streams respectively and 0.481 m^3/s (Q_{68}) for Irati stream upon its completion (MCG, 2015). Based on that, this study analysed possible variations in flow in exceedance of Q_{80} and Q_{68} over the study period. The results given in Figure 4.2 showed the changes in Q_{80} for Maragua and Gikigie streams and Q_{68} for Irati stream over the period 1982-2017. All the three streams showed an increasing trend in Q_{80} and Q_{68} flows. Generally, for all the streams they were sudden peaks in flow between 2012-2015, this could have been attributed to the peak of rainfall in the same years as shown in Figure 4.3. Table 4.3 shows the results of linear regression model, where all the streams showed an increasing trend in monthly flows other than for the month of May where Maragua stream had a decreasing trend. For Irati stream, seven of the months had a *p-value* of less than 0.05 showing a high statistical significance compared to Maragua and Gikigie streams which had 4 and 5 months with *p-values* of less than 0.05 respectively. Langat et al., (2017) obtained similar results when investigating changes in Tana river flow and rainfall trends in the basin. Stream flow had an increasing trend, which they concluded was because of the upward trend of rainfall in the stations located in the highlands (Aberdare Ranges and Mount Kenya). Similarly, Figure 4.3, shows an upward trend in rainfall from North Mathioya and Ndakaini rainfall stations in the study area which could have resulted in the increasing trend in the stream flows observed. The results showed that although flows in the streams had an increasing trend, flow variability was significant where in some low flow years, the flows were significantly below the proposed abstractions. That would mean that, during these low flow years the water demands in Nairobi city for which the projected is intended to serve will not be met.



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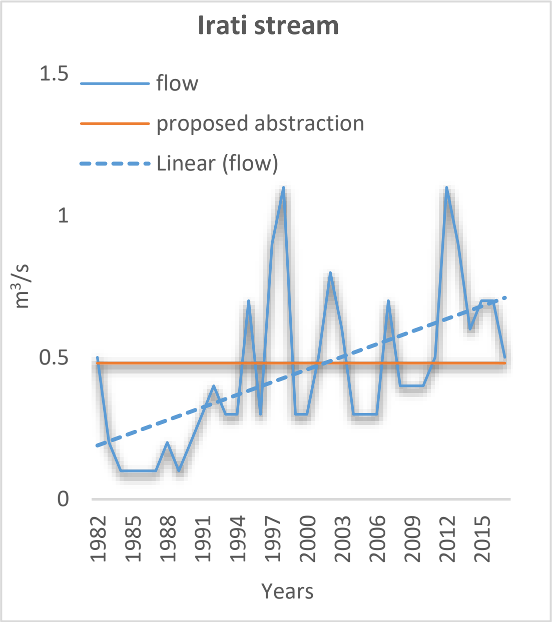


c)

Figure 4.2: Variability of Q_{80} for Maragua (a) and Gikigie (b) and Q_{68} for Irati Streams (C) Over the Period 1982-2017

Table 4.3: Monthly Flow Trend Analysis for Maragua, Gikigie and Irati Streams

Maraga	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**30-day min**	**30-day max**
Slope	0.03	0.02	0.01	0.02	-0.04	0.04	0.02	0.01	0.01	0.01	0.06	0.05	0.01	-0.02
Pvalue	0.05	0.10	0.25	0.50	0.50	0.25	0.25	0.25	0.05	0.50	0.03	0.05	0.05	0.50
Gikigie														
Slope	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.02	0.02	0.00	0.02
Pvalue	0.05	0.05	0.25	0.50	0.50	0.25	0.25	0.10	0.05	0.50	0.03	0.05	0.25	0.25
Irati														
Slope	0.02	0.02	0.02	0.06	0.07	0.03	0.02	0.01	0.01	0.02	0.08	0.06	0.01	0.10
Pvalue	0.25	0.25	0.03	0.01	0.10	0.05	0.05	0.03	0.01	0.25	0.03	0.05	0.00	0.01

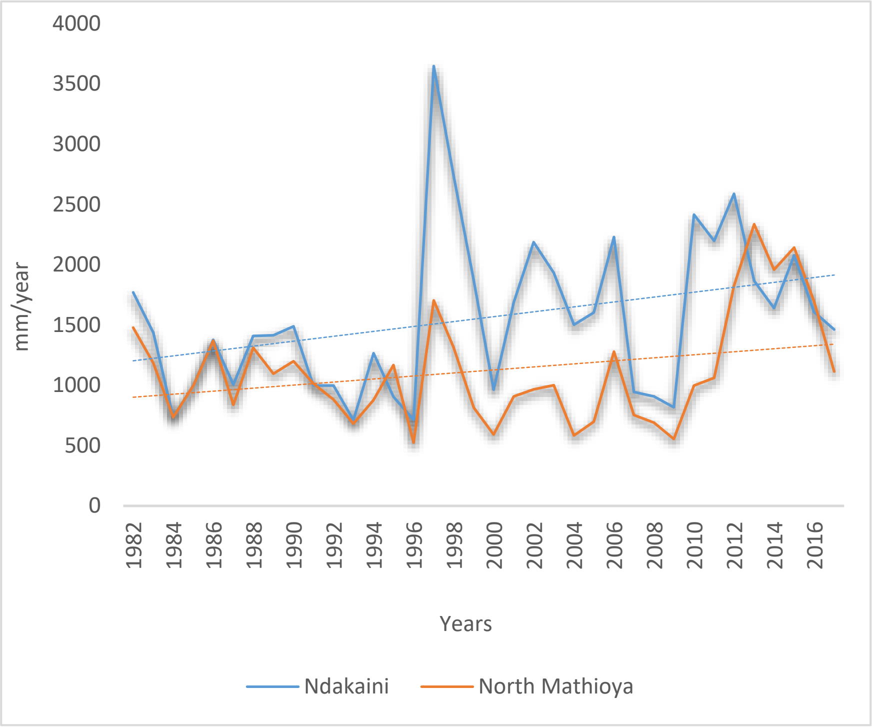


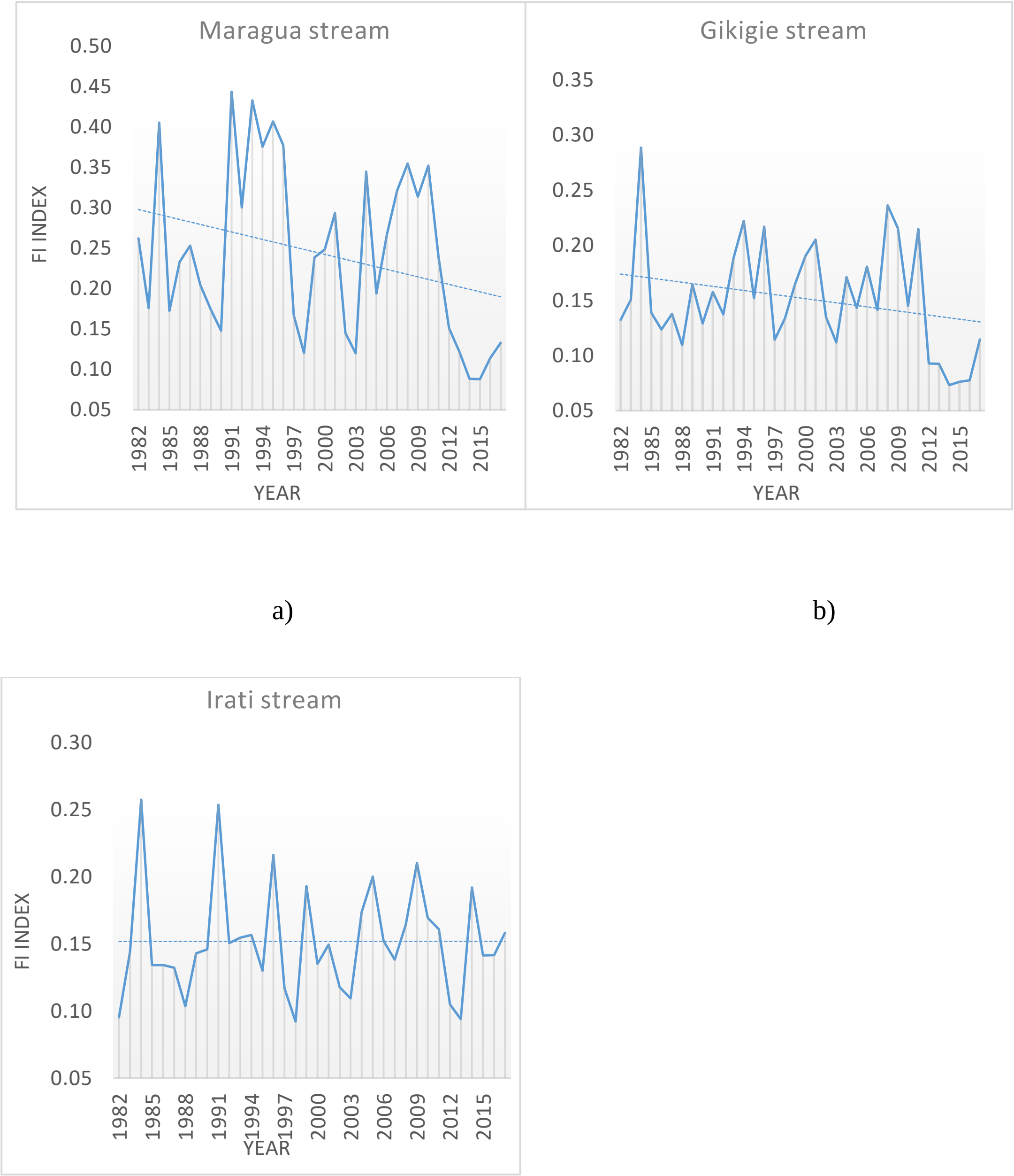
Figure 4.3: Annual Rainfall and Trend for North Mathioya and Ndakaini Rainfall Stations for the Period 1982-2017

4.1.2.2 Base Flow Index

Analysis of the BFI index showed a value of 0.5 in all three streams indicating that the groundwater component of streams is approximately 50%. This means that during the dry periods, users can rely on baseflow to meet their needs. This is vital as the streams show that 50% of their flow comes from the groundwater storage. So, to maintain this flow it is important to maintain and conserve the catchment to enhance groundwater recharge and hence base flow.

4.1.2.3 Flashiness Index

The annual flashiness index (FI) in Maragua stream varied from 0.07 to 0.44 indicating variations of 7% and 44% in stream flow. Gikigie stream showed a flashiness index of between 0.07 and 0.29 meaning the discharge varied between 7% and 29%. For the Irati stream the discharge varied between 9% and 26% (Figure 4.4)



a) b)

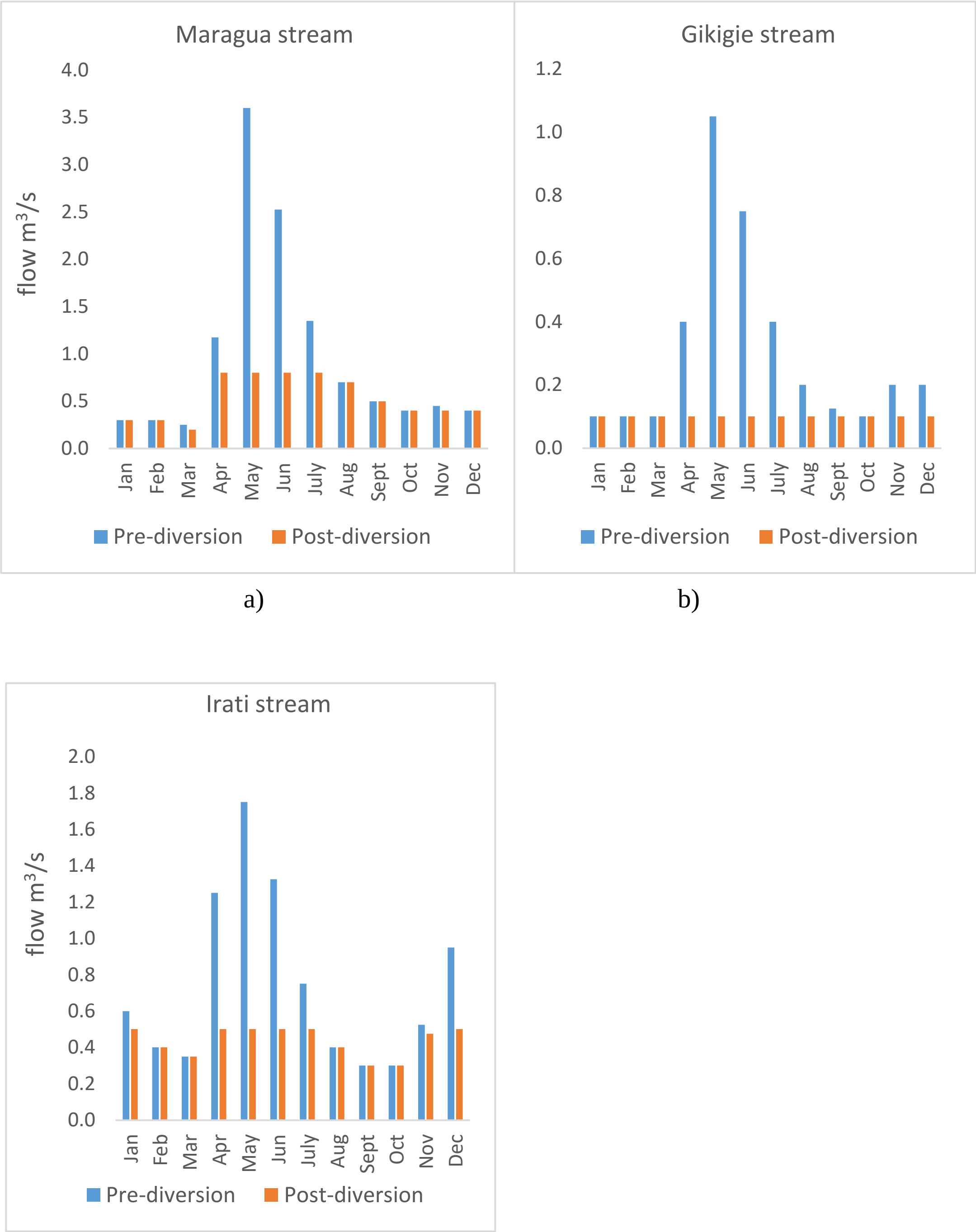
c)

Figure 4.4: Flashiness Index and Trend for Maragua (a), Gikigie (b) and Irati (c) Streams

From the results, Maragua stream is the least stable of the three streams with more variability of flow. However, it is expected to contribute the highest amount of water among the three streams. As such, it is vital for the NCT I project managers, to promote sustainable land uses practises as this will contribute towards reducing the flashiness of the streams thus less variability in flow. The flashiness index (FI) depends on catchment characteristics such as climate, soil, geology, size and largely on land use and land management practices (Holko et al., 2011). Irati stream had no changes in the trend analysis however, Gikigie and Maragua streams showed a decreasing trend. This may be due to a tributary that joins Irati stream at the abstraction point, thus attenuating the flow.

4.1.2.4 Hydrological Alteration Indicators

The degree of hydrological alteration will influence the risk of environmental damage for the streams in the NCT I project. Changes in the three streams were similar in that the median for monthly flow were lower during the wet season (April-July) after NCT I. The magnitude of the median monthly flow for Maragua, Gikigie and Irati streams decreased by an average of 55%, 66% and 56% respectively during the wet season while in the dry season the magnitude of the decrease was lower at 4%, 21% and 9% respectively (Figure 4.5). Similarly, all the three streams showed a downward trend for the annual 1, 3-, 7-, 30- and 90-day maximum flow. However, the annual 1, 3-, 7-, 30- and 90-day minimum flow showed a constant trend (Table 4.4).



a)

b)

c)

Figure 4.5: Magnitude of Median Monthly Flows for Maragua (a), Gikigie (b) and Irati (c) Streams

Table 4.4: Magnitude of Median Annual Maximum and Minimum Flows for Maragua, Gikigie and Irati Streams

	Maragua stream	**Gikigie stream**	**Irati stream**
	% change	% change	% change
1-day maximum	-23.6	-34.5	-21.2
3-day maximum	-30.3	-39.7	-26.5
7-day maximum	-27.7	-49.5	-35.6
30-day maximum	-43.2	-68.5	-51.6
90-day maximum	-51.9	-75.7	-58.1
	% change	% change	% change
1-day minimum	0.0	0.0	0.0
3-day minimum	0.0	0.0	0.0
7-day minimum	0.0	0.0	0.0
30-day minimum	0.0	-32.3	0.0
90-day minimum	-25.5	-27.7	-8.6

The results show that during the wet seasons all the streams will be affected when the flood flows are diverted. This means that all the users who depend on flood flows from the three streams for instance the riparian ecosystem and flood farming downstream will be affected. It is vital that the extent of the impacts assessed so that mitigation measures can be implemented. Studies have shown that alteration of the hydrological regime affects the quality of riparian conditions and decreases habitats in the stream ecosystem. A change in the flood intensity might cause the stream beds to be invaded by plants. In some streams, the spawning of fish is affected thus influencing the diversity and abundance of fish in the streams (Belmar et al., 2013; Eum et al., 2017; B. Yang et al., 2020)

4.1.3 Service Reliability of Maragua, Gikigie and Irati Streams under Different Climatic Conditions

4.1.3.1 Characterization of Climatic Conditions (Dry, Normal and Wet Years)

The SDI index was used to analyse stream discharge data to estimate the dry, normal and wet years for each stream in the study area. Table 4.5 and Figure 4.6 shows that the streams experienced extremely dry years in the periods 1984-1985, 1993-1994, 1996-1997, 2000-2001, 2004-2005 and 2008-2010 like a drought characterisation study done by Okal et al., (2020) who found drought years to have been in 1994, 2007-2009,2006,2000 and 2011. From the results, dry years had a cycle of occurrence of 5 years and lasted for two years. Normal years were 1989-1991, 1992-1993, 2002-2004, and 2007-2008 while wet years were 1997-1999, 2012-2016, which showed a 10-year cycle. The Upper Tana basin has experienced frequent and severe drought, especially during the dry seasons. As such strategies to cope with the effects of drought are paramount for proper water management (Agwata et al., 2015).

Table 4.5: Categorization of Climatic Years Based on Their Corresponding SDI Value

SDI Value	Years	Climatic year
1.6,1.4,1.5,1.8,1.6, 2.0	1997-1998,1998-1999,2012-2013,2014-2015,2015-2016,2013-2014	Wet years
-0.2,0.3,0.2, -0.07,0.41,0.10	1989-1990,1992-1993,2002-2004,2007-2008	Normal years
-2.0, -1.2, -1.3,-1.1,-1.4, -1.7,-1.6	1984-1985,1993-1994,2000-2001,2004-2005,2008-2009, 1996-1997,2009	Dry years

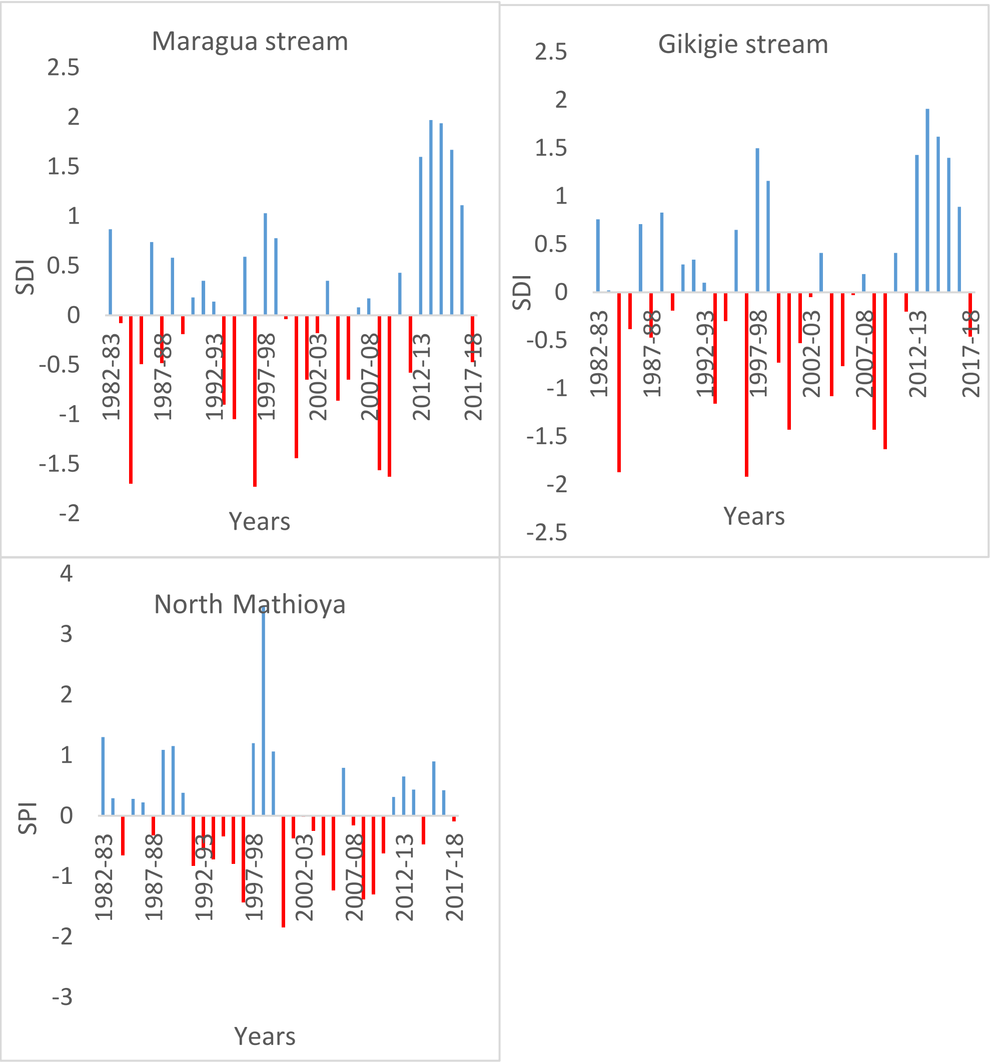


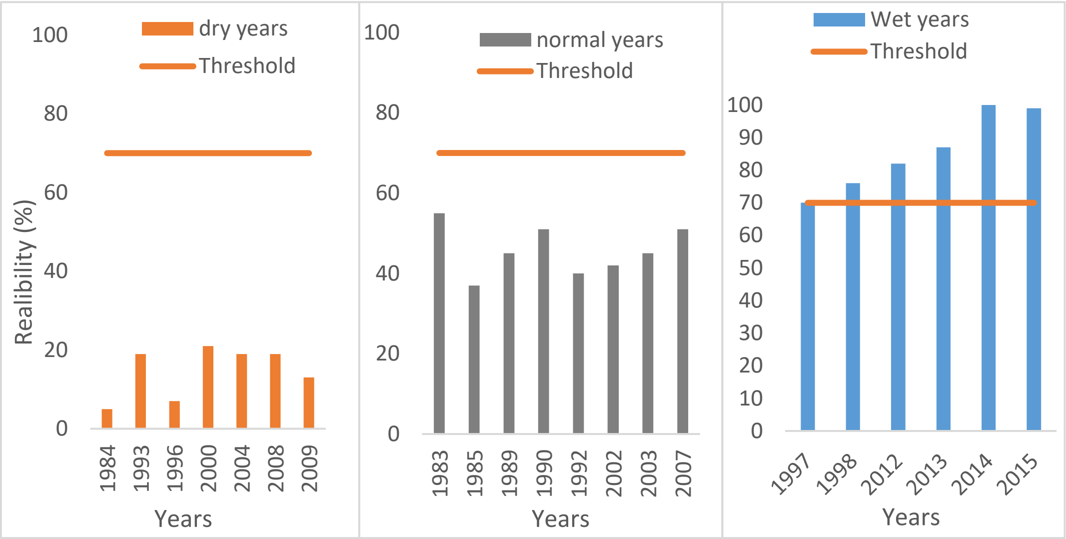
Figure 4.6: Stream Flow Drought Index (SDI) -12 Values for Maragua and Gikigie Streams with the Corresponding SPI 12 Values for North Mathioya Rainfall Station

4.1.3.2 Reliability Index

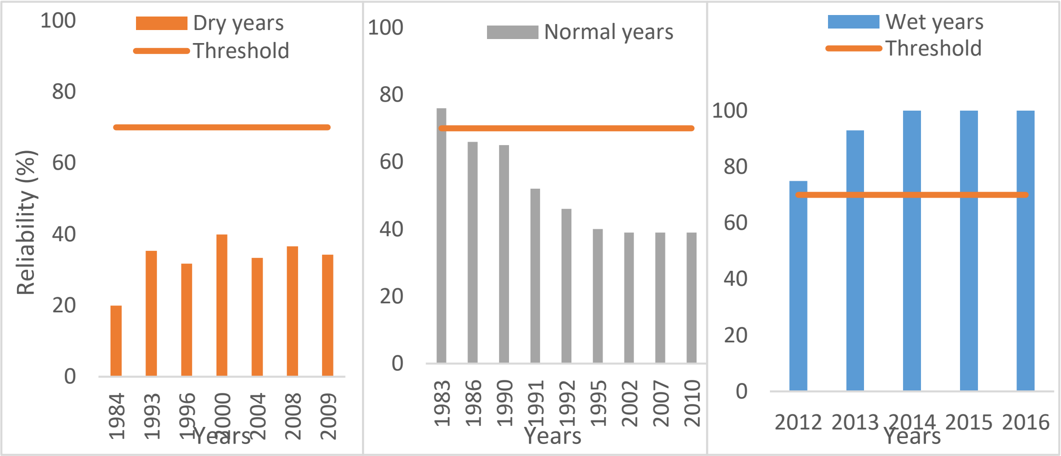
Hydrological variability was further evaluated using reliability of the three streams under dry, normal and wet years. The results showed that the reliability of supply in all the three streams was highest during the wet years, reduced in the normal years and was lowest during the dry years (Figure 4.7). On average, reliability of Maragua, Gikigie, and Irati streams during the dry years was 15%, 33% and 23% respectively. In the normal years, reliability increased to 45%, 62%, and 60% for Maragua, Gikigie and

Irati streams respectively. Reliability of the streams was highest during the wet years with 83% for Maragua, 94% for Gikigie, and 98% for Irati as shown in Figure 4.8.

a) Maragua stream



b) Gikigie stream



c) Irati stream

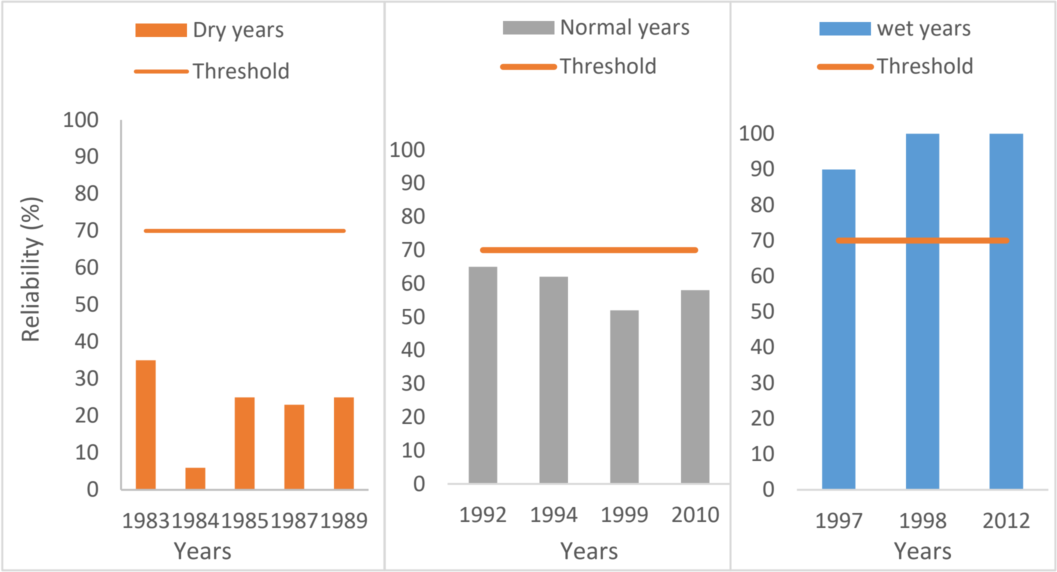


Figure 4.7: Reliability Level for Maragua, Gikigie and Irati Stream under Dry, Normal and Wet Years

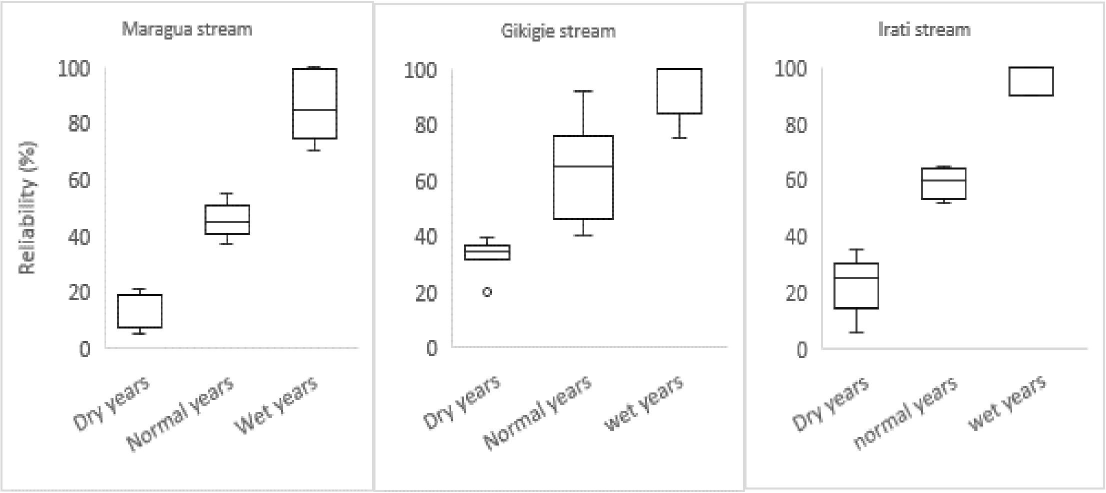


Figure 4.8: Box Plot of the Three Streams Showing the Quartiles of Reliability of the Streams at Dry, Normal and Wet Years

The objective of the NCT 1 project is to bridge the water demand gap in Nairobi city and its environs with over 70% reliability. However, from the above results, this objective will not be met during the dry and normal years due to the low reliability of the stream flows. Yet, the demand for water is highest particularly during these years in both the donor and recipient basins. From the study, it would be vital to explore ways of storing the water during the wet periods when the reliability is high for use during the dry and normal periods. Of the three streams, Maragua stream had the lowest reliability in both dry, normal and wet years, which could be attributed to its high variability in flow as indicated by the flashiness index (FI). In addition, competition for scarce water resources during dry periods may lead to conflicts in and between the basins. Further, water transfer projects tend to focus on increasing supply thus shifting attention from water demand management strategies. Thus, the water demand in the Nairobi city may increase further with time because of the new water transfer project.

Studies have shown similar results, that the expansion of IBWTs systems to meet growing water demand does not guarantee reduced shortages in the recipient basins. Tian et al., (2019) notes that in most water transfer projects, supply reliability in the donor basin is greatly reduced thus making it impossible to meet the water demands of the recipient basin. For instance, the hydrological risks of water transfers from the northeast of England to London were high and led to a supply deficit of 60%. To meet the water demands in London with minimal risks in the donor basin, large volumes of water would only be abstracted during the winter months. This water would be stored either as recharge to aquifers or in a small reservoir for use in the summer months (Khadem et al., 2021). Similar conclusions were made in Hanjiang River, China water diversion. The authors noted that shortages in supply were more likely to occur during the dry periods than during the wet periods (Tian, Liu, Guo, Pan, et al., 2019). Developing optimal water allocation strategies were key to improving reliability of the system which would mean coming up with measures to coordinate the inflow, storage and demand (Ming et al., 2017). Since flow uncertainty influences IBWTs supply reliability, use of a stochastic model when assessing water availability and developing reservoir operating rules would improve the performance of inter-basin water system (Li et al., 2014).

4.2 Simulation for Optimal Water Transfers Allocation Strategies

This section describes results of optimal water allocation strategies for Nairobi city with the current water sources, planned NCT I and proposed future water sources under climate variability using WEAP model. Sentinel 2 imagery in detecting changes in Thika reservoir area resulting from the introduction of NCT 1 flows is also discussed.

4.2.1 Mapping Reservoir Area Using Sentinel Imagery Data

Figure 4.9 shows the results of using Sentinel 2 imagery to map Thika reservoir area over the study period. Generally, the NDWI index was able to show changes in reservoir area once NCT 1 started operating in May 2022. The area was approximately 1.5 km^2 in April, 1.9 km^2 in May and 2.2 km^2 in June 2022. The results were validated using elevation- area-volume curves provided by AWWDA, as shown in Table 4.6. In May 2022, observed flows from NCT 1 were approximately 0.14 m^3/s however, by June 2022 the flows had increased to 3.52 m^3 /s. The planned NCT 1 inflow to Thika reservoir is approximately 1.5 m^3/s, from the results, in the month of May 2022, the actual flows were less than the planned. However, in June the flows increased to 3.52m^3/s. From the results it is possible to use Sentinel imagery to monitor contribution of NCT 1 flows to Thika reservoir from the changes in reservoir area. Thika reservoir water area was highest in the month of June which also had the highest recorded NCT 1 inflow. These results were in line with the water balance of the reservoir because with minimum rainfall, the month of June recorded high reservoir volume and elevation. Use of satellite data for surface water monitoring has been used successfully over the years. Bhaga et al., (2021) was able to detect and map variations in water bodies in Western Cape, South Africa during the dry and wet seasons of 2016, 2017 and 2018. Their results were able to show the influence of the 2017 drought period in the region that led to severe water shortages. However, the authors noted that since the area is highly mountainous, satellite imagery are sometimes affected by cloud cover. Peña-Luque et al., (2021) argue that the use of multiple dates satellite imagery improves the accuracy in detecting surface water bodies. Additionally, satellite imagery tends to underestimate the water area of reservoirs in areas with dense vegetation. This is because during the high filling rate periods some water may fill areas that are normally under vegetation during dry seasons making it difficult to be detected. Nevertheless, sentinel imagery provided satisfactory results in estimating reservoir levels in the Nile River basin and could be used to bridge the data gap especially in areas where the data is either scarce or unreliable (Kansara & Lakshmi, 2022).

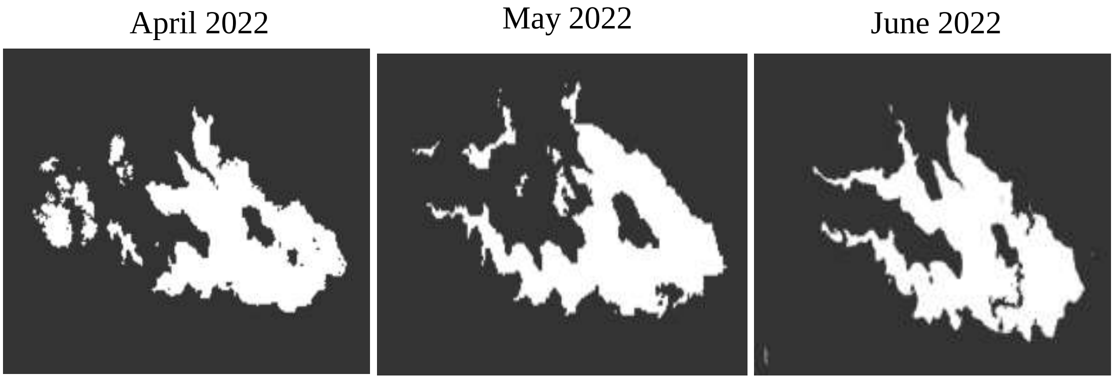


Figure 4.9: Thika Reservoir Spatial Variations during the Study Period

Table 4.6: Validation of Thika Reservoir Area Validation Using Sentinel Imagery

Date	Recorded (NCT 1) flow in m^3/s (source (AWWDA, 2022)	Recorded reservoir elevation (m) (source NWSC, 2022)	Reservoir vol in Mm (Source NWSC, 2022)	Corresponding area Km^2 (source (AWWDA, 2012)	Recorded rainfall in (mm) (Source NWSC, 2022)	Sentinel Area in Km^2	Agreement
08/04/2022	Operations not started	2029	41.70	1.5	0	1.58	100%
20/05/2022	0.14	2033	50.68	2.0	0	1.96	95%
30/05/2022	1.36	2034	52.62	2.1	0.2	Image not available	-
01/06/2022	3.52	2035	53.74	2.2	0	2.25	100%

These results have demonstrated as a proof of concept, the capability of Sentinel Images to detect and monitor reservoir water balance and the future inflows from IBWT when availability of the satellite images are enhanced.

4.2.2 Water Availability for Nairobi City with the Current and Planned Water Sources

Current Water Sources (B0) and Addition of NCT 1 (B1)

Figure 4.10 shows the unmet water demands and supply coverage under different climatic conditions in the B0 (current water sources) and B1 (B0+ NCT 1) scenarios. The results showed that unmet demands were highest under the very dry years in both B0 and B1 scenarios. In B0 scenario, the average supply coverage was less than 30% in very dry, dry and normal years while in the wet and very wet years it increased to 41 % and 57% respectively. With the introduction of NCT 1 (B1 scenario), the mean unmet demands reduced slightly under all the climatic conditions. The average supply coverage in the very dry and dry years was 31% and 39% respectively. In the normal years the average supply coverage increased to 47% while in the wet and very wet years the coverage further increased to 71% and 92% respectively.

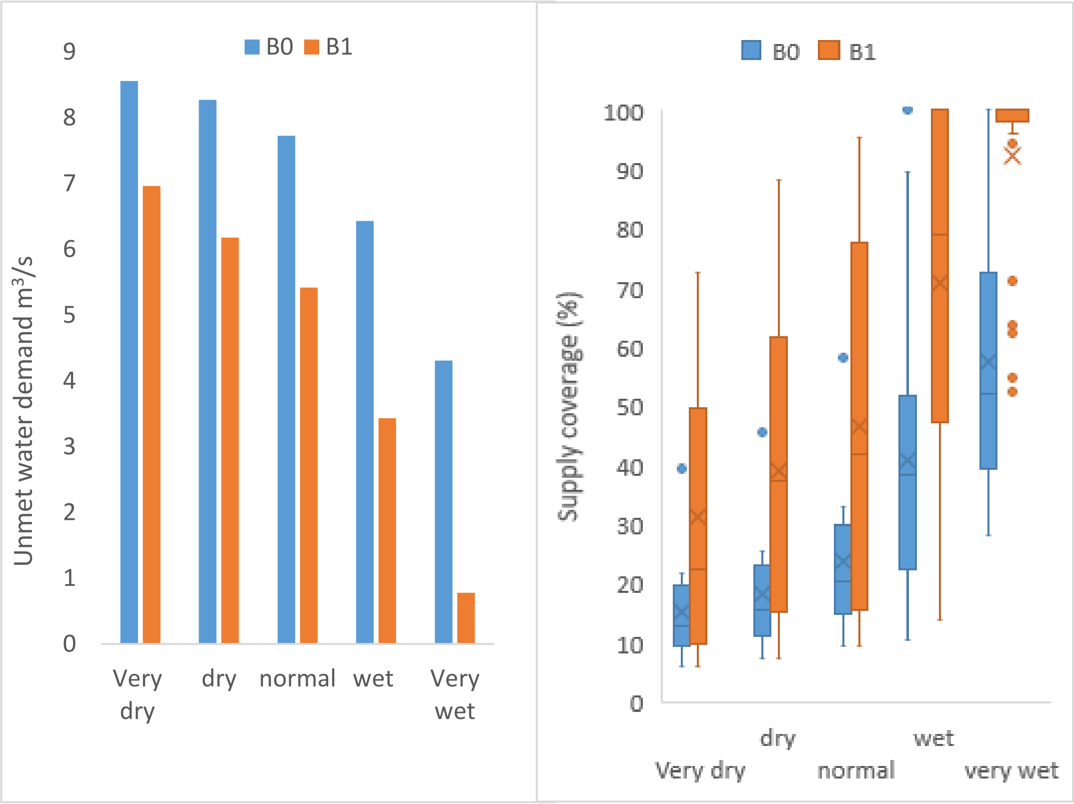


Figure 4.10: Unmet Water Demands and Supply Coverage under the B0 and B1 Scenarios

Demand Measures under the B1 Scenarios.

With the high unmet water demands in both scenarios under the very dry, dry and normal years, simulations were done using 10% (B2), 20% (B3) and 30% (B4) demand measures scenario. Results in Figure 4.11 showed that even with demand measures in place, NCT 1 will still not meet the desired supply coverage of over 70% in the very dry, dry, and normal years. More so in the very dry years the supply coverage will remain below 50% under the three demands measures.

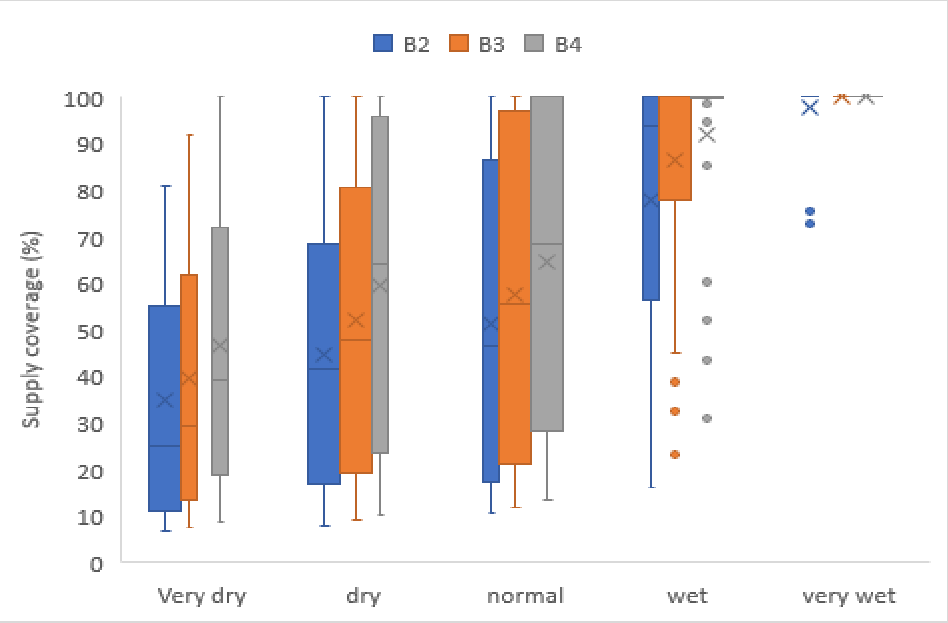


Figure 4.11: Water Supply Coverage under B2, B3 and B4 Demand Measures Scenarios

With the planned additional water sources

Figure 4.12 shows that under the B5 (NCT II constructed) and B6 (Maragua dam constructed) scenario, the average supply coverage in the very dry, dry and normal years will still be below the desired 70 %. It is only under the B6 scenario with 20% and 30% demand measures implemented that the supply coverage in the very dry, dry, and normal years will rise to over 70% (Figure 4.13).

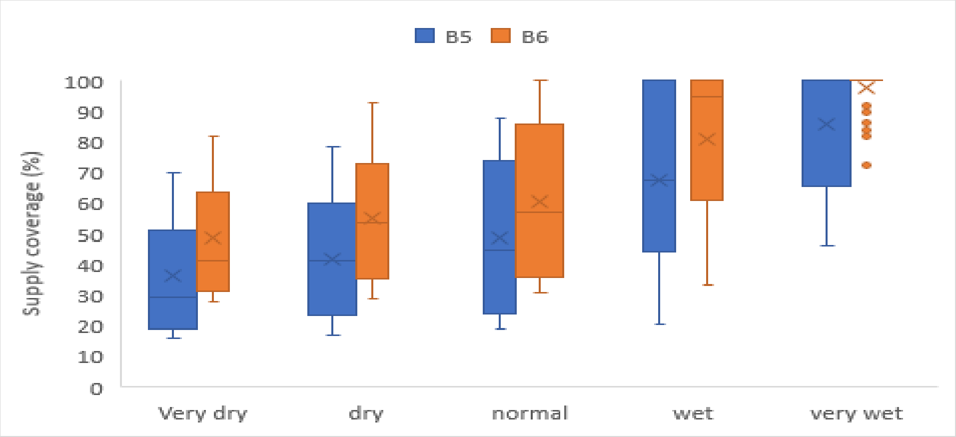


Figure 4.12: Water Supply Coverage under B5 and B6 Scenarios

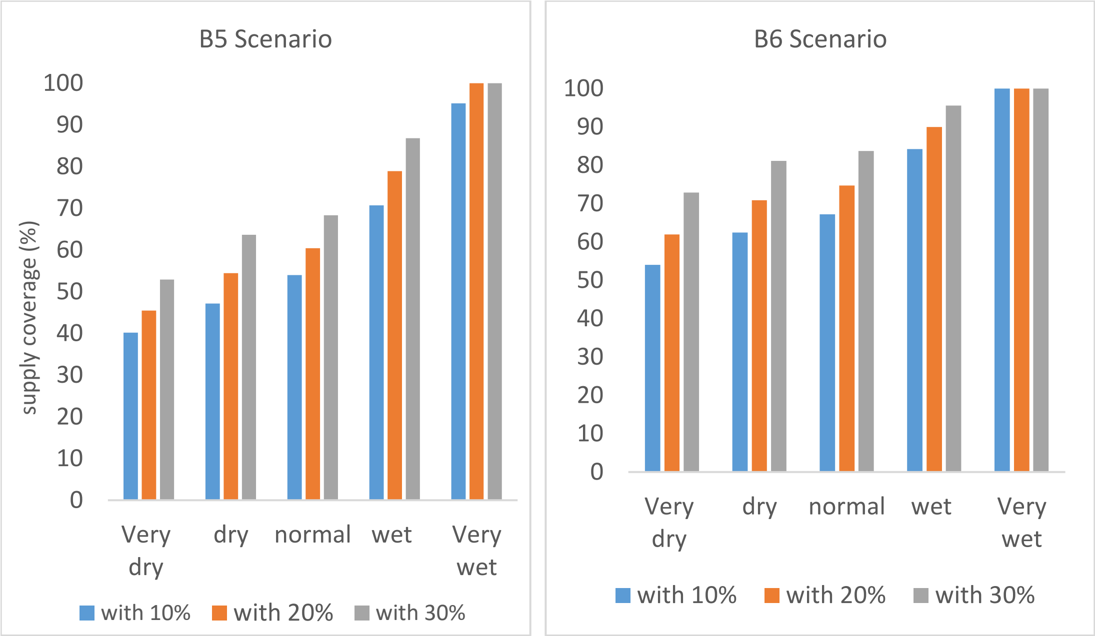


Figure 4.13: Supply Coverage under B5 and B6 Scenario with Demand Measures.

Nairobi residents rely heavily on inter-basin water transfers to meet their ever-rising water demand. The results showed that under very dry, dry and normal years the operations of NCT 1 will not meet the water demand and the city will continue to have severe water shortages. Even with the most optimistic demand measures, supply coverage with the contribution of NCT 1 will remain below the government's objective of achieving over 70% supply in the very dry, dry and normal years. The planned construction of NCT II and Maragua dam will reduce the water shortages significantly under all climatic conditions, but, only with 20% and 30% demand measures will the supply coverage increase to 70% in the very dry and dry years. Although, the planned new water resources will provide some hope in meeting the city's water needs, the challenge is on timely implementation of the projects and effective water demand management strategies. Often, governments lack the financial ability to develop infrastructure in line with the growing demand (Bischoff-Mattson et al., 2020; Grasham et al., 2019; Leichenko, 2011). Studies have shown that water demand increases further with introduction of new water sources. However, with the use of highly efficient water appliances for instance toilets, taps and showers, it is possible to reduce household water demand by up to 30% (Carragher et al., 2012; Lee et al., 2013; J. Zhuang & Sela, 2020).

Just like Nairobi, various cities in the world have continued to rely on surface storage to supply water to its residents. However, during periods of drought, surface storage solutions are likely to dry up to unprecedented levels causing major water crisis (Head, 2014; Nobre et al., 2016; Rodina, 2019). In Nairobi city, most of the residents have resorted to using groundwater to meet their water needs especially during dry periods. This has led to an increase in the number of private boreholes in the city, which has consequently lead to reduced groundwater levels raising long term sustainability issues (Nyakundi et al., 2022). However, studies have shown that with proper management and adequate regulation, sustainable groundwater use would supplement the current water sources thus enhancing urban water security (Oiro et al., 2020). Rainwater harvesting can also be used as an alternative water supply system in urban cities to meet up to 50% of the water demand. However, it is influenced by the size of the system, climatic patterns and water use (Steffen et al., 2013). Other non-conventional water sources like water re-use and harvesting storm water can also form part of the solutions to urban water shortages. In addition, they will reduce over-dependence of one source of water thus improving the resilience of the cities to climate variability(Ghosh, 2021; Nagendra et al., 2018; Sahin et al., 2017).

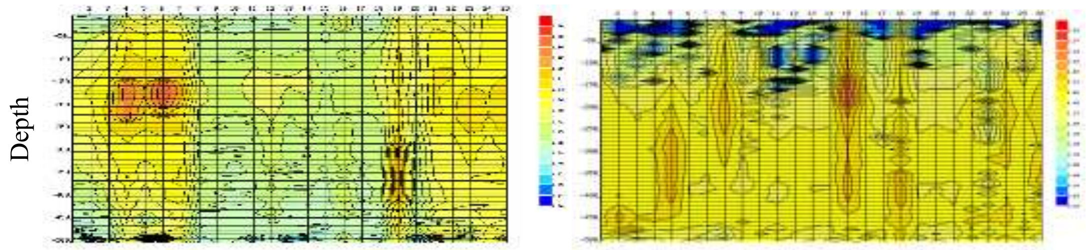
Thus, lessons learnt from San Paulo, Cape town, Chennai and Australia is that there is need to combine surface water reservoir or storage with other alternative sources especially during periods of failed or lower than expected rainfall amounts (Head, 2014; Nobre et al., 2016; Rodina, 2019). There is also consensus that regulations such as water pricing and incentives on water conservation greatly reduce water consumption. However, some authors note that the effect of pricing on water consumption is not significant while others show that although water demand is price inelastic in a way, price strategies could influence water consumption greatly (Hemati et al., 2016; Maggioni, 2015).

4.3 Barrier Effect from the NCT I Tunnel

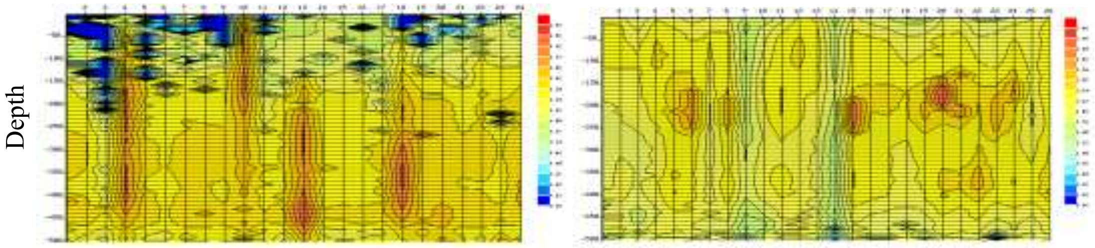
This section discusses the results of MODFLOW modelling and field measurements on changes in the hydraulic head of aquifers in the Upper Tana basin because of the construction of the NCT I project. Presented first are the results of characterization of the aquifer system using VES survey.

4.3.1 Vertical Electrical Sounding (VES) Results

Figure 4.14 shows the results of VES survey of the four profiles along the tunnel. A range of colours from blue to red was used to represent the potential differences in groundwater values. Blue marked weathered / loosely packed rocks with high groundwater flow while red /green showed compact rock with low groundwater flow. Resistivity was generally higher, 1 km downstream of the tunnel and 200m upstream of the tunnel. The results showed presence of shallow aquifers approximately 10-50 m deep with some perched aquifers at 1 km upstream of the tunnel and 200m downstream of the tunnel. Similarly, a study done by AWWA, on groundwater monitoring wells found shallow ground water depths with a maximum depth of 50m . The results showed that there is presence of shallow groundwater and springs, that the residents depend on for their water needs.



200m upstream of tunnel.   1km upstream of tunnel.



200m downstream of tunnel.   1km downstream of tunnel.

Figure 4.14: 2D VES Survey Profile Showing the Potential Difference of the Subsurface along NCT I

3D model of the profile lines showed that the upstream of the tunnel has high recharge zones with a lot of springs emerging (Figure 4.15)

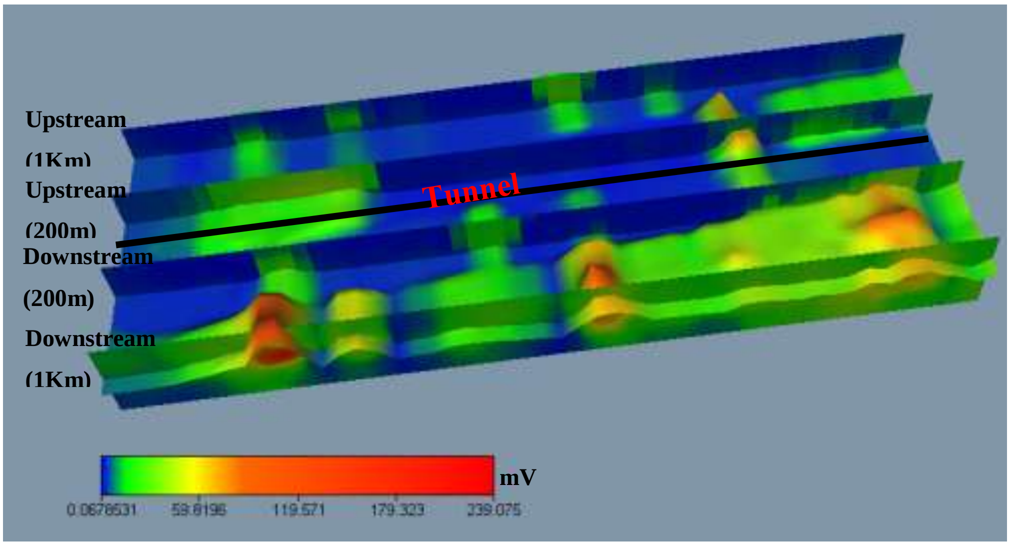


Figure 4.15: 3D VES Survey Profile Showing Potential Difference of the Subsurface along NCT I

Several studies have successfully used VES techniques to understand subsurface geological formation and groundwater potential zones like in the Karumeniya basin, India (Arunbose et al., 2021). In North-western Nigeria, VES was successfully used to investigate potential sites for groundwater explorations based on sub-surface characteristics (Kasidi & Victor, 2019) as well as aquifer parameters (de Almeida et al., 2021).

4.3.2 Effects of NCT I Tunnel on Groundwater Levels Using MODFLOW Modelling and Field Measurements

4.3.2.1 Barrier Effect from MODFLOW Modelling

The simulated and observed groundwater heads in the study area showed a good match with an R^2 of 0.99 (Figure 4.16).

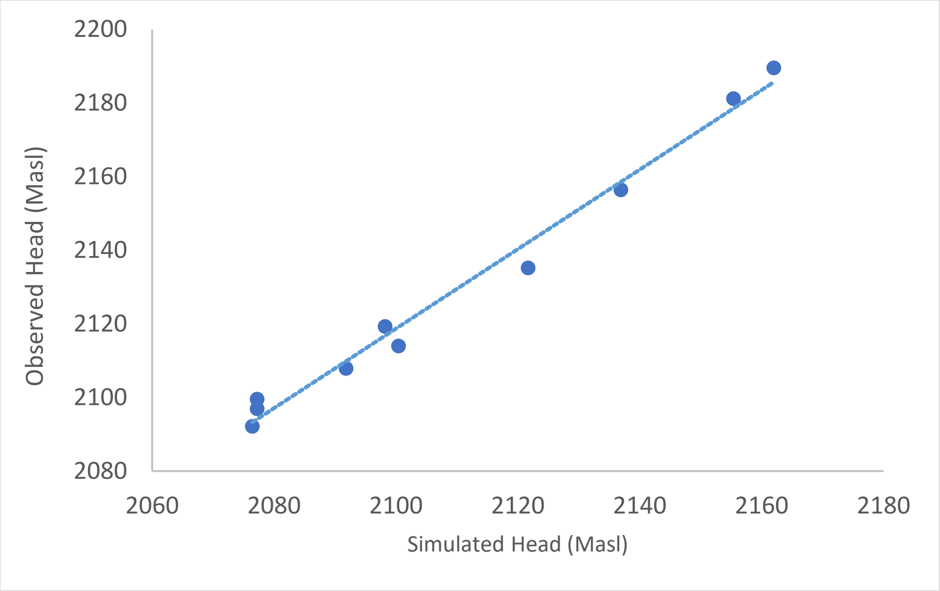


Figure 4.16: Simulated and Observed Heads Comparison

Model results showed that hydraulic heads declined when the tunnel was introduced, the biggest fall in the hydraulic heads (1%) was noted in BH 9 which is closest to the barrier at the downstream side. The average fall in the water table / hydraulic head surface after introduction of the tunnel was 4.5m. MW1 on the upstream side showed a rise in the water table of 0.2m when the tunnel was introduced (Figure 4.17)

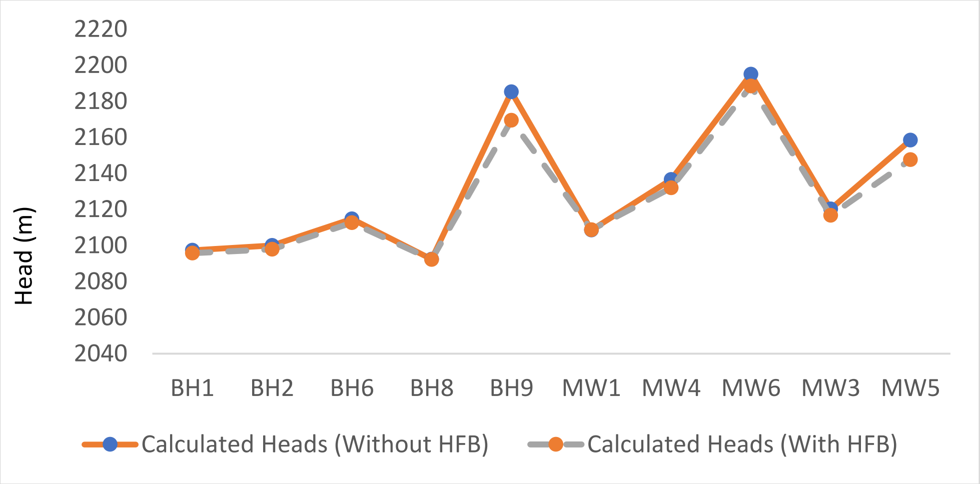


Figure 4.17: Comparison of Hydraulic Heads with and without the NCT I

Further, analysis was done using randomly selected boreholes (given the abbreviation (OBS)) in the study area (Figure 4.18). The results showed the biggest fall in the hydraulic head was in OBS 2, 4, 6 and 12 which are closest to the barrier at the downstream side. The average fall in the water table / hydraulic head after introduction of the tunnel was 3.6m. The boreholes on the upstream side OBS 1, 3, 5, 9 and 11 showed a rise in water table due to the tunnel with the average being 2.3m (Figure 4.19).

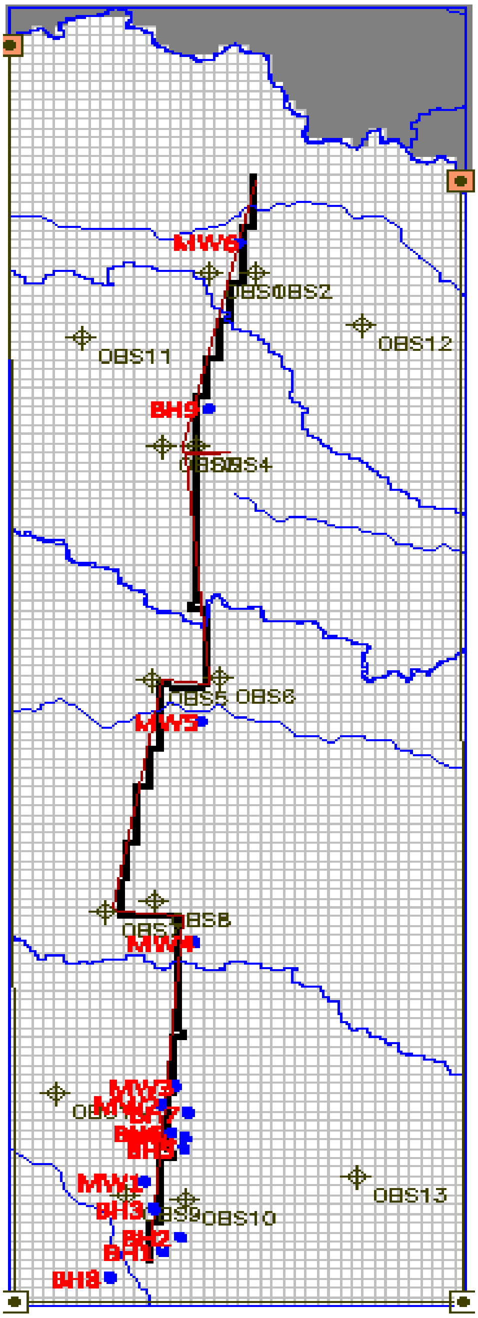


Figure 4.18: Randomly Selected Boreholes in NCT 1 Upper Tana Basin

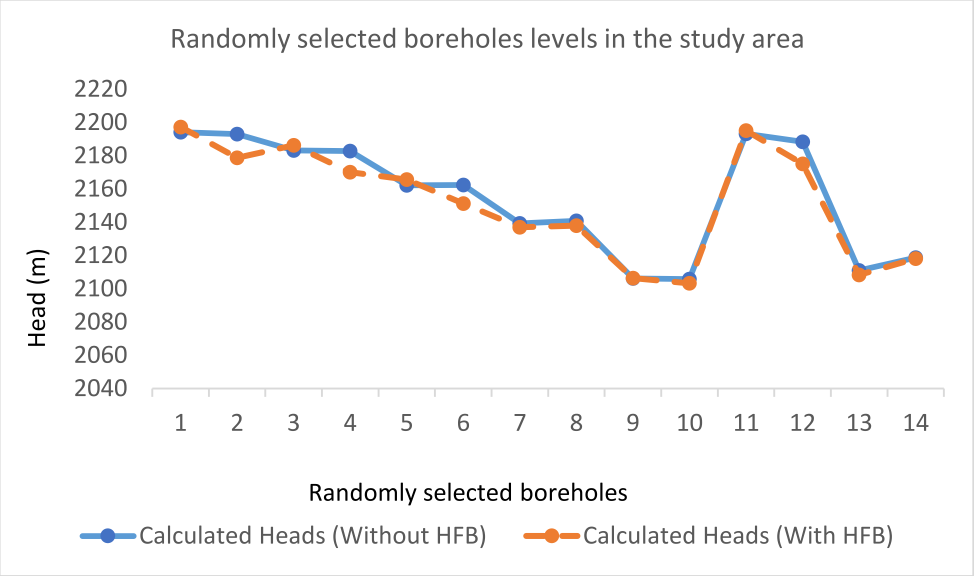


Figure 4.19: Comparison of Hydraulic Heads of the Randomly Selected Boreholes with and without the NCT I

4.3.2.2 Barrier Effect Using Field Measurements

Figure 4.20 showed that both BH3 and BH5 in the upstream side of the tunnel had a 0.9 m increase in hydraulic head while BH 6 showed a 4.8 m increase. BH 1 did not show any change. BH 7, BH 8 and BH 9 on the downstream of the tunnel showed a decrease in head of 1.9m, 0.6m and 0.7m respectively while BH 4 showed an increase in hydraulic head of 0.1 m. Results of field measurements showed inconsistent effects of the tunnel on borehole heads. Field measurements are subject to several inconsistencies because of several reasons for instances seasonal changes in recharge due to precipitation and human activities (Font-Capo et al., 2015).

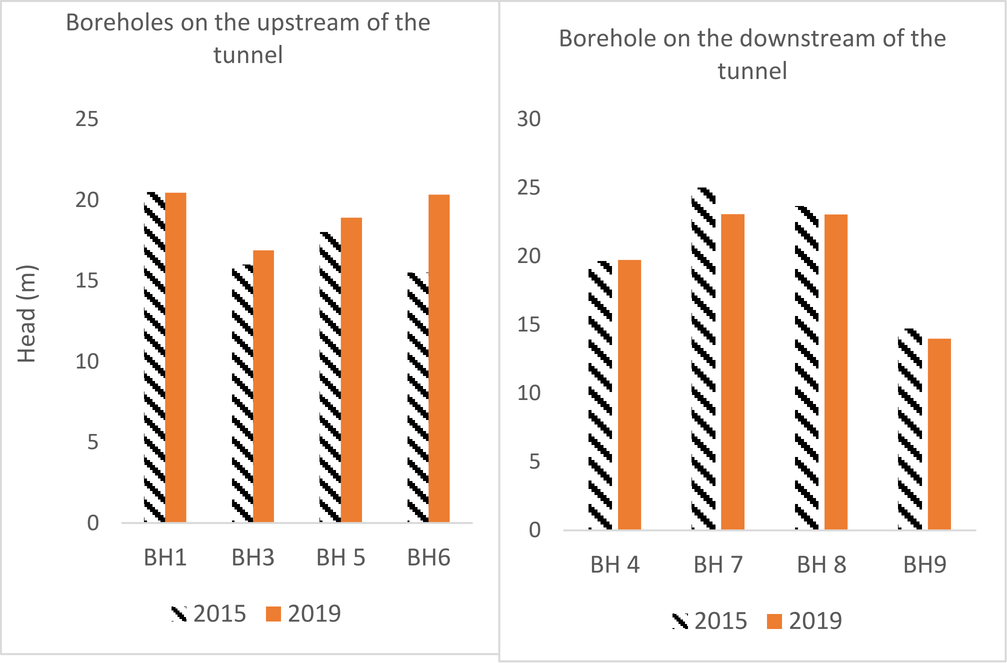


Figure 4.20: Changes in the Hydraulic Head from Field Measurements before and after IBWT Tunnel NCT 1

Barrier effects can be estimated through field measurements and numerical modelling. However, for aquifers with small hydraulic gradient, it is difficult to quantify the barrier effect because of errors caused by manual reading of the heads and natural causes. Nevertheless, field measurements can be used to validate numerical model results (Attard et al., 2017). In this study, field measurements of the boreholes were compared before tunnelling (2015) and after tunnelling (2019) for boreholes BH1-BH 9. Boreholes upstream of the tunnel showed a 10% increase in hydraulic head other than BH1 whose hydraulic head remained constant. A 2% decrease in hydraulic head in boreholes on the downstream side of the tunnel was observed apart from BH 4 which showed a slight increase in hydraulic head. The field measurements, however, do not consider climatic conditions for instance drought or intense rainfall and human activities that would have influenced the hydraulic levels in the study area (Font-Capo et al., 2015). Simulations were done using MODFLOW with an R^2 of 0.99 being obtained showing a good match with the observed head values. The results were consistent with the field observation indicating a general increase in the hydraulic head of up to 10% in the upstream of the tunnel while decreasing the hydraulic head in the downstream side by 2%. Studies have shown that an impermeable underground structure interferes with the flow of groundwater of an area (Pujades et al., 2012). Depending on aquifer and tunnel characteristics, the hydraulic head of an aquifer can be reduced by 40-60% which creates impacts on the people that depend on this aquifer (De Caro et al., 2020; Font-Capo et al., 2015; Tullia & Bellini, 2003)

4.4 Distribution of Benefits and Risks in NCT Phase I Inter-Basin Water Transfers to Nairobi City

This section describes the results of the stakeholder analysis carried out to investigate the distribution of risks and benefits in IBWTs (NCT 1 project). The study i) identified and categorized stakeholders with their roles and interests, ii) evaluated their inter-relationships and iii) investigated the distribution of risks and benefits amongst stakeholders in the NCT I project.

4.4.1 Stakeholder Identification and Their Roles in NCT I Project

The results identified seven categories of the twenty-seven stakeholders as having a role in the NCT I project (Figure 4.21 and Table 4.7). MoWI ranks highest in the hierarchy at the national level with the role of formulation of policy, sourcing of financing for water development and coordination of the other water service provision sub-sectors. As such, in the NCT I project, MoWI with the support from World Bank and AFD oversaw financing of the project under the Water and Sanitation Service Improvement Project Additional Financing (WaSSIP) investment loan. Water Sector Trust Fund (WSTF) under MoWI is mandated to provide funds for development and management of water services in the under-served areas. WSTF was not involved in the NCT I project although they funded the WRUAs for catchment conservation measures upstream of the NCT I abstraction points in the Aberdare Forest. The Kenya Water Act, 2016 outlines the role of the Water Resources Authority (WRA) as a regulator i.e., to allocate, protect, and conserve water resources. In the NCT I project, WRA oversaw the water allocation by issuing water abstraction permits for the Maragua, Gikigie and Irati rivers. Athi Water Works Development Agency (AWWDA) mandate is service provision through water infrastructure development. Thus, they were the implementing stakeholder in the NCT I project in charge of design and construction of the project. There were three water services providers (WSP) in the study area i.e., Kahuti Water & Sanitation Company (KAWASCO), Muranga South Water and Sanitation Company (MUSWASCO) and Muranga Water & Sanitation Company (MUWASCO). Although, WSP plays an extensive role in water provision, they were not actively involved in the project as majority of the community water supply projects promised to the residents were done through the community directly.

According to the Water Act 2016, Water Resources Users Associations (WRUAs), are involved in the management of water resources as well as representation of the consumers. There were two WRUAs in the study area i.e., Upper Maragua and Lower Maragua WRUAs formed in 2015. Involvement of the WRUAs and the community was limited, and they considered the project 'political' where most of the stakeholder meetings were attended and conducted by political leaders and government officials. The National Environment Management Authority (NEMA) as mandated by the Environmental Management and Coordination Act (EMCA,1999), oversaw the licensing of NCT I project to ensure that the environment will be protected. According to the Kenya Constitution 2010, water is a national resource and does not belong to any County. However, the County government does have the responsibility of sustainable development and management of the water resources for the benefit of present and future generations. Further, the Constitution states that the responsibility of water provision is to be shared between the County and National governments. Thus, Muranga County government's role was to ensure sustainability of the NCT I project in terms of sharing of benefits and eliminating / reducing environmental risks. Although reports show that, meetings were held between Muranga County government officials and AWWDA which resulted in a Consensus Agreement, the sitting administration (which came to office in August 2022) maintained that they had not been involved in the project at the time. Most of the other stakeholders had supportive and / or informative roles

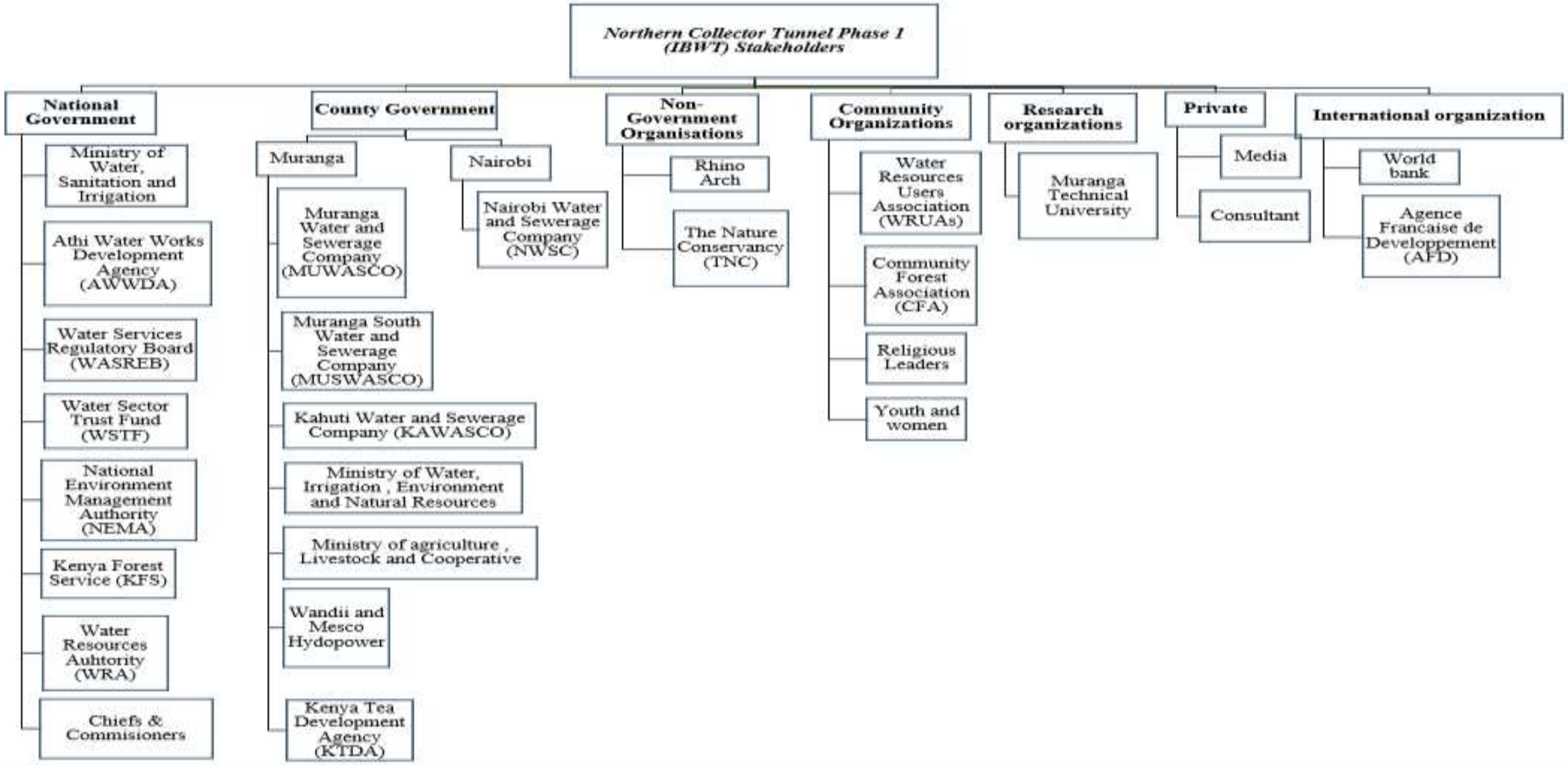


Figure 4.21: Stakeholder Identification and Categorization in the NCT 1 Project, Upper Tana Basin, Kenya

Table 4.7: Stakeholders' Role Based On Their Mandate **and Expertise**

Stakeholder	**Role/Mandate**
Ministry of water and irrigation (MoWI)	➢ Support the acceleration of water reforms. ➢ Mobilize resources for the sustainable development and management of water resources
Water Sector Trust Fund (WSTF)	➢ Provide grants to manage and develop water services in marginalised areas. ➢ Provide funds to WRUAs for catchment conservation activities.
Water Resources Authority (Upper Tana)	➢ Regulate and authorize the NCT I water transfer project. ➢
Water Services Regulatory Board (WASREB)	➢ To approve tariffs and license water services providers
Athi Water Works Development Agency (AWWDA)	➢ To develop NCT I project infrastructure together with the treatment plans
National Environment Management Authority (NEMA)	➢ Issuance of NEMA certificate and supervise the project on environmental issues through the Muranga office
Kenya Forest Services (KFS)	➢ Conservation of the Aberdare water towers through the Gatare Forest Station
Muranga County	➢ Represent Muranga residents on environmental and water resources concerns.
Muranga South Water and Sewerage Company (MUSWASCO)	➢ Provide water and sanitation services to Kandara, Kigumo and Muranga South Subcounty
Muranga Water and Sewerage Company (MUWASCO)	➢ Provide water and sanitation services to Muranga town and its environs
Kahuti Water and Sewerage Company (KAWASCO)	➢ Provide water and sanitation services to Kangema and Kahuro sub counties
Kengen (Wanjii and Mesco hydropower station)	➢ Hydropower generation using Mathioya and Maragua rivers
Kenya Tea Development Authority (KTDA)	➢ Small scale tea farmers company
Chiefs and Commissioners	➢ Support of the project through liaising with the community for any concerns
Nairobi Water and Sewerage Company (NWSC)	➢ Provide water and sanitation services to Nairobi County residents
Rhino Ark Foundation	➢ Provides funds/grants for Aberdare water towers conservation activities through collaboration with KFS
Water Resources Users Association (WRUAs)- Upper and Lower Maragua catchment	➢ To authorize abstraction of water from Maragua, Irati and Gikigie rivers for NCT I project ➢ Collaborate with WRA in illegal abstractions monitoring. ➢ Collaborate with WSTF for conservation of the catchment
Community Forest Association (CFA)	➢ Assist KFS in planting of trees .and scouting services

Stakeholder	Role/Mandate
International organization (World bank & Agence Francaise de Developpement (AFD)	➢ Provide credit facility for NCT I Project
Consultants & Contractors	➢ Design and construction supervision of the NCT I project components
Media	➢ Provide information on the project
The Nature Conservancy (TNC)- Upper Tana Nairobi Water Fund	➢ Support water and soil conservation measures

4.4.2 Characterization of Stakeholder Based on an Importance-Influence Matrix

The stakeholders were illustrated on a 2 x 2 importance-influence matrix (Figure 4.22) showing those who were likely to be affected by the project (importance) and those whose decisions affected the direction of the project but were not necessarily affected by it (influence). WRA, AWWDA and Muranga County were classified as the key players. AWWDA had the power and influence to make decisions in the NCT I project as it was the implementing agent for the project. Engineers from the agency were responsible for the design and construction of the engineering components. Muranga County was a key player of the donor basin because it was able to influence the design review of the project to abstract flood water and lobby for the development of off-shoot water supply projects for the benefit of the local communities. For the project to abstract water from the three rivers, it had to get water abstraction permits from WRA, thus WRA was a key player in the project. MoWI, NEMA, Media and International donors were classified as context setters since their decisions affected the direction of the project although, they were least affected by impacts of the decisions. WRUAs, WSPs, youth and women, chiefs, and consumers like KTDA and KENGEN were classified as ‘subjects’ because they were the stakeholders most likely to be affected by the project, but their power in decision-making was limited. Further, although they expressed interest in the NCT I project discourse, their engagement was limited at the planning and implementation stage of the project. One of the groups reiterated that the project was a national project and that they were not involved in the meeting held during the commencement of the project. KFS, CFA, Rhino Ark and TNC were classified as external stakeholders because they had little interest in the project and were also not affected by the project. However, they influenced aspects of the project through funding catchment conservation activities.

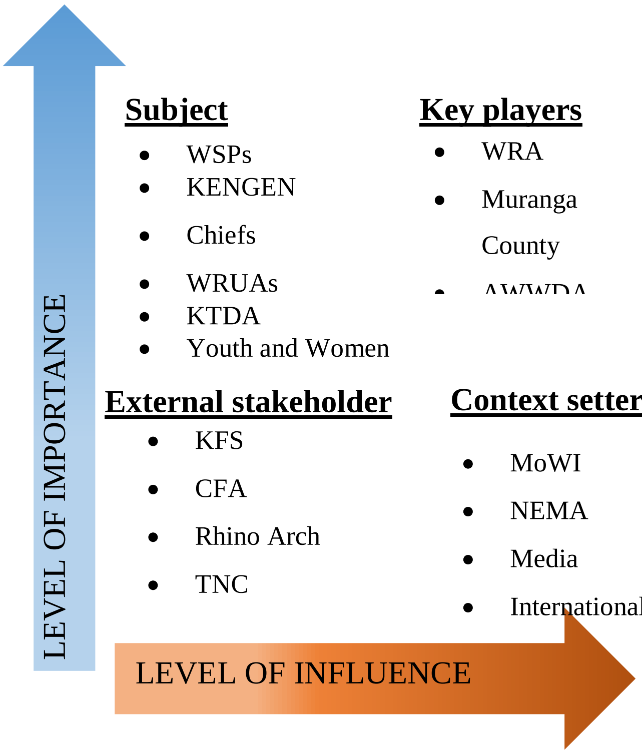


Figure 4.22: Stakeholders Position Based on Their Level of Importance and Influence in the Upper Tana NCT I Project, Kenya

4.4.3 Stakeholder Relationship in the NCT I Project Inter-Basin System

Table 4.8 shows the relationship between the various stakeholders in the NCT I project. Two strong inter-relationships emerged between the WRUAs and the WRA. The WRA collaborated with the WRUAs to regulate the water resources for instance in mapping illegal water abstractors and conservation of riparian areas along rivers. The WRUAs and WSTF had a strong relationship because of the funding from WSTF which was used for tree planting activities and pegging of riparian areas by the WRUAs. The relationship between AWWDA and Muranga County government was mixed with AWWDA expressing a strong collaboration with the County in the NCT I project. AWWDA referenced several meetings with the County which resulted in modification of the intake designs to cater for the local community water needs and community water projects. However, Muranga County government lamented on their role in the project terming it as limited as it was a national project through AWWDA.

It is worth noting, in the county there was a new administration that took office in August 2022 after the general election.

Another weak interrelationship in the project was between AWWDA and the WSPs where, AWWDA developed community water supply projects directly with minimum collaboration from WSPs. The community was made to believe that off-shoot water projects would be free thus they will not pay water bills. This created hostility towards the company (WSP) when collecting water revenue in form of water bills from the community. Part of the off-shoot projects were extensions of water distribution lines for the community which created conflicts between WSPs and the community because they did not have enough water for those lines. This was because the current water sources were not enough for the extended lines. The WSPs were concerned that AWWDA should have started by developing water sources before constructing distribution lines. The WRUAs and Muranga County had weak collaboration and the WRUAs had limited interactions with the county government. There was a strong inter- relationship between KFS and WRUAs when it came to catchment conservation issues and reporting of illegal encroachment. In addition, KFS and CFA collaborated in catchment protection and conservation. The CFA assisted in planting trees, providing scouting of forest and pruning of forest industrial plantations.

Table 4.8: Stakeholder Relation/Collaboration in the NCT I Project

Stakeholders	**AWWDA**	**Muranga County**	**WSP**	**KFS**	**WRA**	**NWSC**	**WSTF**	**WRUAs**	**CFA**
AWWDA		S	W		M	M		W	
Muranga County	W		W	M	M			W	
WSP	W	W			M			W	
KFS		S			S			S	S
WRA	S	S					W		
NWSC	S			M					
WSTF								S	
WRUAs		W		S	S		S		
CFA				S	S				

Where W= Weak, S= Strong, M= Medium

4.4.4 Perceived Risks and Benefits

4.4.4.1 Risks

The NCT I project was designed to abstract flood water such that the compensation flow is Q_{80} for Maragua and Gikigie rivers and Q_{68} for Irati river meaning only during high flows. However, there was consensus among stakeholders on the risks of **reduced flows** in the rivers or the viability of the project if they abstract flood waters. According to the WRUAs the last flood event was in 2020, thus flood events do not occur that often and therefore abstracting flood waters would not be viable. Although, AWWDA has given assurance that only flood flows will be abstracted, there was concern among stakeholders in Muranga County of their rivers drying up as they termed it uneconomical for a project of that magnitude to only operate a few times in a year. To ensure adequate water supply, the residents were promised off-shoot community water supply projects. The off-shoot water projects included Muranga community water project, Ichichi-Kiruri and Makomboki water project and extension of critical distribution lines. These projects as the Muranga county assembly committee on NCT I project noted, did not target areas that were adversely affected by water shortages in the county. In addition, several of the projects have not been completed and some have not been done thus residents still face severe water shortages. Further, some of the off-shoot community water projects became a source of **water conflicts** between WSPs and the community. This was observed in one of the projects where the community had been made to understand that the water will be free, thus, they resisted payment of any water bills to WSPs. For a community water project, only maintenance and permits are charged thus making the tariff of such a water project much cheaper that a WSP water supply system. In some projects, the distribution lines were done but there was not enough water to serve the residents who started faulting the WSPs.

Water demand in both the donor and recipient basins is projected to increase over time. Further, climate variability has led to prolonged drought which has been reducing water levels in the rivers thus continued diversion of the rivers may lead to **over-abstraction.** Therefore, there was consensus that Aberdare Forest needed to be conserved to ensure sustained flows in the rivers. However, the NCT I project, did not have a plan nor a budget for conservation activities in the forest. AWWDA acknowledged the importance of Aberdare’s Forest preservation and restoration but, noted that, it was not within their mandate but that of KFS.

Although, a water demand assessment was done in Muranga county before the allocation of water to NCT I project, the respondents expressed the risk of **future abstractions** for Muranga residents. In instances, where Muranga residents needed to abstract water in the future, the NCT I allocation will need to be taken into consideration during the water availability analysis. In addition, there were **concerns of drying of springs and wells** along the tunnel during the construction period. AWWDA constructed six monitoring wells (piezometric boreholes) in 2016 for monitoring changes in ground water flows. However, a full analysis has not been done and hence no information has been shared with the communities to date.

The stakeholders noted that there was poor **disclosure of information** as they were not involved in the project even though there were public participation meetings. In addition, most of the information was on websites yet the residents did not have access to internet services by then. Most Muranga stakeholders felt that public participation was stage managed and attended by the political class and that although information on the project was online, access to that information had restrictions and could not be downloaded by the public. Majority of the public meeting were done in the Upper basin areas whereas most of the people to be affected were in the lower part of the basin.

4.4.4.2 Benefits

Stakeholders agreed that the NCT 1 project would **increase water supply** to Nairobi residents as the project was projected to increase water supply to Nairobi by approximately 140,000 m^3/day, thus bridging the water deficit gap in the city. Further, there would be **employment** of locals during the construction phase of the project. Also, the spoil from the tunnel was used to **improve the weathered roads** for better access by the community. However, most of the stakeholders in the donor basin, did not see the benefits of the project (Figure 4.23) because even the **kick off community water projects** did not solve their water supply challenges. They argued that part of the money from the water revenue should be remitted back into the basin to carry out conservation activities. Muranga County government advocated for payment of a water fee to enable investments in water for domestic and agriculture use and other county activities. The WRUAs also advocated for some money to go towards conservation of rivers and the basin to ensure that rivers do not dry up.

According to a joint consensus agreement on the project, Muranga county was to form a bulk water utility company that would provide water services to companies in the county and beyond. In addition, the county was to advocate and fast track the enactment of the national resource benefit sharing bill. Guiding from a similar process in Karimenu Dam Kiambu County, Kenya, 15% of the water fees goes to operation and maintenance, 75% to loan repayment thus leaving only 10% for water abstraction permits and conservation activities (Figure 4.23). In addition, according to Muranga County the price of abstracting raw water was KES 0.5/m^3 (0.0047 USD) compared to an opportunity cost of KES 45/m^3 (0.43 USD) if the water was to be used for agricultural activities in the region (MCG, 2015). The regulation for raw water abstraction is a standard fee for all water abstractors, whether it’s for small scale agriculture or urban water supply and there are no special provisions for IBWTs on commercial purposes / urban water uses.

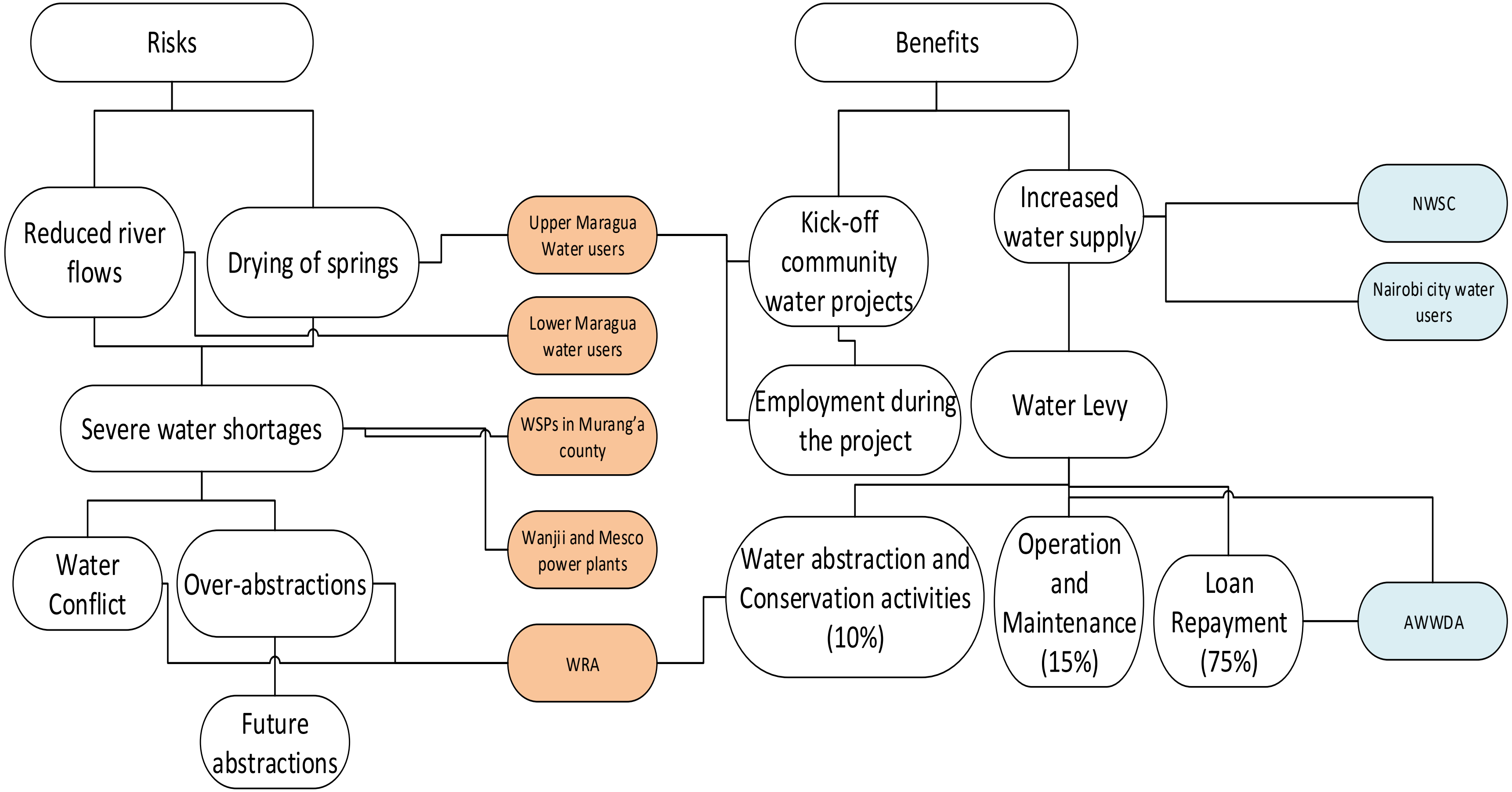


Figure 4.23: Distribution of Benefits and Risks among Stakeholder in the NCT I Project, Upper Tana Basin, Kenya.

The study identified different categories of stakeholders and their roles in the NCT I project. MoWI and AWWDA were shown to play an active role as they were considered the promoters of the project. WSPs and WRUAs had a high interest in the project, although, their involvement was limited. Similarly, although official documents show an agreement was signed between AWWDA and Muranga County government back in 2015, the current administration had a limited role in the project. Furthermore, most of the agreed incentives and interventions have not been implemented. Most of the stakeholders in Upper Tana basin (donor basin) had minimal role in the NCT I project and considered it a ‘national project’. Like in other countries, IBWT are greatly pushed by a coalition of engineers, politicians and financiers for the more economical and political strategic recipient region (Hernandez-Suarez et al., 2018; Rinaudo & Barraqué, 2015). As Fraj et al., (2019) notes water allocation in IBWT is largely determined by economic considerations and political will, the interest of the ecosystem and the less powerful communities are seldomly considered.

Public participation is a perquisite for big projects such as the NCT I in the Kenyan constitution, however, the mechanism of the process is not adequately provided for. Ballester & Mott Lacroix (2016) argues that an effective public participation depends on a legal framework that give clear guidelines on the process, the political good will and the social awareness (community initiatives for water issues in the region). In the NCT I project, although there was good political will, the process lacked clear guideline and the WRUAs were at infancy as they had just been formed in 2015.

Like many other IBWTs systems, Muranga county residents were concerned about the drying up of their rivers, over abstractions and future water needs. For instance, water allocation study in Hanjiang river basin, China showed that the donor basin was likely to be vulnerable to water shortages thus water supply and compensation mechanisms were necessary to cushion them from such severity (Tian, Liu, Guo, Pan, et al., 2019). According to AWWDA, the abstractions will not cause any harm to downstream users as they insisted that the compensation flow is sufficient. However, there were some doubts because flood flows occur only a few times in a year or none especially during dry years. Further, there is tendency by the national government agencies to over-abstract water during drought by using temporally structures to raise the water level beyond the design levels.

To assure Muranga County residents of sufficient water supply, they were promised off shoot community water projects which had not been implemented. However, these projects did not solve their water shortage challenges just like in many IBWTs (J. Gupta & van der Zaag, 2008) which may result in increased poverty in the community as there are linkages between water shortages and loss of income (Matete & Hassan, 2005). Although there was need to conserve the water towers to preserve and maintain the stream flows, the promoters of the project had no plans of funding conservation activities. Most of the conservation works was being done by CFA, WRUAs and KFS through funding by NGOs and WSTF.

The objective of NCT I project was to transfer water to Nairobi which is the capital city of the country which has more population and economic growth compared to Murang’a county. Thus, although, Nairobi city residents have direct benefits from the water transfer, they do not bear the total costs of the water resources regeneration. This is because some proportion of the water pricing (opportunity cost and externalities) ought to be paid to the donor basin (Figure 4.24).

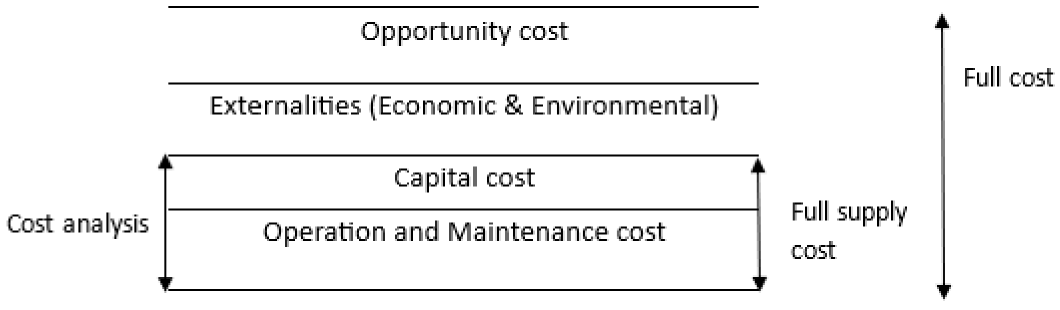


Figure 4.24: General Principles of the Cost of Water with the NCT I Project Cost Analysis

Source: (Rogers et al., 2002)

It follows thus that the recipient basin maybe paying only for the full supply cost and not the full cost of the project thus denying the donor basin the full value (sustainable) of the water resources. Furthermore, it has been noted that often promoters of IBWT system, will most likely overestimate the benefits and underestimate the costs of the water resources thus promoting unbalanced economic growth and unsustainable use (de Andrade et al., 2011). For economic sustainability, all the societal costs and benefits need to be explicitly made public and accounted for in a project. However, benefit-risks distribution is often complex as some costs cannot be easily monetarized for instance river flow reductions. One way is to shorten the scale of development such that solutions are localised to improve on the efficiency of projects (Savenije & Van der Zaag, 2008). Another way of solving these conflicts is by compensating the people who bear the risks for the present and future losses by creating a water transfer fund from the water levy (Yevjevich, 2001). For instance, in NCT I project, a water fund from the water diversion would be used for conservation activities of the Aberdare Forest and other externalities in Murang'a county, the donor basin. The water fund could be specific to the conservation needs of the catchment and should reflect the sustainable full value of the water diversion from the donor basin. Payment of ecosystem services is more elaborate in the tourism sector in Kenya, as in the case of Narok County, where the county gets approximately 70% of its revenue from the Maasai Mara National Reserve. The same concept can perhaps be used in the water sector. Because of the requirements needed in terms of legislation to approve IBWT, de Andrade et al.,(2011) notes that effective management of the project, right from its conceptualisation is key to enhancing institutional sustainability. That may include having an entity that includes all stakeholders in the project, proper communication channels that encourage airing of conflict and complains and resolving them in public scrutiny and clear communication of project benefits and how those at risk will be adequately compensated.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

The main objective of this study was to evaluate the hydrological and socio-economic implications of the water transfer scheme from Upper Tana River basin to the Athi river basin under growing water demand and climate change using the NCT I project as a case study.

5.1 Conclusion

5.1.1 Reliability of Stream Flow in Inter-Basin Water Transfer under Different Climatic Conditions Using Remote Sensing in the Upper Tana basin.

This research evaluated the variability and reliability of Maragua, Gikigie and Irati streams in the Upper Tana basin to meet the water requirements of Nairobi city under different climate conditions (NCT 1). All the streams showed an upward percentile and monthly flow trend, however, with significant seasonal variability. NCT I water transfers will not meet the demands in Nairobi city in the dry and normal years as the reliability was below 70% threshold. From the characterization of climatic conditions, periods of limited flow for the transfer system are likely to occur more often thus necessitating measures to enhance supply reliability. Maragua stream flow fluctuated more than Gikigie and Irati streams and since, the stream is proposed to contribute the highest amount of water in the transfer, catchment-based strategies like afforestation to mitigate this variability are necessary.

5.1.2 Optimal Urban Water Allocation Strategies Under Inter-Basin Water Transfer: Case of Nairobi city, Kenya.

WEAP analysis revealed that, although, NCT I reduced water shortages slightly, the increased flows from NCT I would not meet the city’s water demands in the very dry, dry, and normal years. While the government’s objective is to increase the supply coverage in Nairobi city to over 70%, this will only be achievable in the wet and very wet years. For the government to realize their urban water supply goal, sustainable water demand management measures need to be implemented in addition to the water resource developments to meet the increasing water demand.

5.1.3 Barrier Effect of Tunnelling on Groundwater Flow in Inter Basin Water Transfer: Case of Northern Collector Tunnel, Kenya.

VES survey results showed that upstream of the tunnel has fractured soil / rock potential for groundwater flow and recharge with maximum depths of 50m. MODFLOW and field measurements results implied that the tunnel influences the ground water levels along the route. Residents who are on the downstream side of the tunnel will experience reduced groundwater levels thus affecting their livelihoods through reduced water availability.

5.1.4 Distribution of Benefits and Risks in Inter-Basin Water Transfers: Upper Tana Basin to Nairobi City

Athi Water Works Development Agency (AWWDA) and the Ministry of Water and Irrigation (MoWI) were considered as the promoters of the project with the highest power and influence in the decision-making process. Although Water Services Providers (WSPs) and Water Resources Users Associations (WRUAs) had a high interest in the project, their participation was limited.

The risks of the project were reduced river flows, drying of springs and generally, the ability of Muranga County residents to access water in the present and future. Benefits from the project were perceived as water supply to Nairobi city residents, employment opportunities to the Muranga County residents during the construction of NCT I infrastructure and nominal water levy to the donor basin (Upper Tana) through WRA. Other than being a low annual permit fee, the water levy doesn’t take into consideration the opportunity and externalities (socio-economic / environmental costs) of the water transfers, thus it does not offer full / sustainable water value to the donor basin.

5.2 Recommendations from the Study

The outcome of this research has demonstrated the need for water practitioners and engineers to assess reliability of IBWTs at different climatic conditions using daily stream flow data for better insights into the technical viability of such projects. In addition, water management strategies where water is stored during the wet years for use in the dry and normal years will improve supply reliability.

The main objective of NCT I is to increase the city’s resilience, thus, water managers and policy makers in Nairobi County and national governments needs to consider alternative water sources other than surface water storage through IBWTs. Such may include decentralized water supply options like rainwater harvesting and wastewater reuse. In addition, with proper management and regulation groundwater could be an alternative water source to enhance urban water security.

The findings of this research further suggest that public participation must consider power dynamics and stakeholders’ interest in IBWTs to minimize conflict. In such, the risks and benefits need to be made explicit, properly accounted for, and balanced out by all actors to ensure sustainable value and use of the water resources in both recipient and donor basins.

5.3 Recommendations for Further Research

From the research findings, it is paramount for water managers in inter-basin water transfer systems that rely on flood waters, to come up with strategies that incorporate hydrological variability. Thus, stochastic approach modelling to stream flow is needed to account for stream flow uncertainty. In addition, research is required to investigate strategies for storing the diverted water during the wet periods for use during the dry and normal periods. Without storage, the objective of abstracting only flood water might not be achieved. This would mean studies into joint operation of reservoirs in IBWTs using evolutionary optimization algorithms to foster cooperated operation policies between the donor and recipient basins.

The study used IHA to show the changes in the stream flow due to IBWTs however the indicators are limited in quantifying the impacts of the changes in the habitat. Thus, more research is needed to evaluate how changes in stream flow will affect the ecosystem of the streams and downstream users.

IBWTs invoke benefits and risks that are borne differently among stakeholders; thus, it is paramount to quantify the economic value of the risks and benefits and come up with *a trade-off* mechanism between the basins. For instance, one way is to explore a water tariff policy specifically for IBWTs to ensure that the full value of the resource is realised.

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APPENDICES

Appendix I: Sample Questionnaire for the Semi Structured Interviews

Distribution of benefits and risks in inter-basin water transfers: insights from stakeholder analysis, a case of Upper Tana water transfer, Kenya

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The interaction of actors and their intervention on a water resource which is usually driven by their interest results in both benefits and costs distributed differently among a society. The distribution of costs and benefits can be analysed using actor analysis techniques. This study seeks to identify the actors, their roles, interests and interaction in the Northern collector tunnel (Phase1). We provide assurance that participation in this interview is solely voluntary and a participant can withdraw from the exercise at any time. The information collected will be confidential to be used only for the purpose of this research. Further your participation remains anonymous unless otherwise stated by you.

Contact person: Rosemary Nyingi

Email: nyingirosemary@gmail.com,

Semi-structured interview

1. What category of stakeholder are you and your organisation? international, national, non-governmental, local community, farmers, research institution or private organisation.

2. What is your mandate, key interest and/or stake in inter-basin water transfer in the Upper Tana basin? i) mandate ii) roles iii) interest or stake in water transfers.
3. Who are the beneficiaries of your activities?
4. Which other stakeholders is relevant to the Northern Collector tunnel (NCT phase 1) inter-basin water transfer in Kenya?
5. Which stakeholders do you think wields the most power (influence)/influential and who is most affected. (importance)?
6. Which other stakeholders (organisations or individuals) with the insight in inter-basin water transfers do you recommend we contact? (Snowball sampling) Please provide contact and address if any
7. Do you as a stakeholder or your organisation relate/collaborate or work with other stakeholders and/or stakeholder institutions in water transfers? Please, name them and map the level of collaboration (whether is strong, weak, or medium)
8. Would you say your collaboration with other actors is cooperative, complementary, conflicting. Please explain where possible and provide examples.
9. In what ways do you or your institution collaborate with stakeholders you mentioned above?
10. In your opinion, do you think the project will alleviate water shortages in Nairobi city? if no, what do you think should be done better?
11. In your opinion, what are some of the benefits from NCT Phase 1? And who enjoys the benefits mentioned.
12. What measures should be put in place to enhance the benefits?
13. In your opinion, what are some of the risks from NCT phase 1? Who bears the risks mentioned
14. What can be done to minimise the risks.

Thank you for making time to participate in this interview.

Appendix II: Pictures

	
Maragua River Intake	Gikigie River gauging station

	
Stakeholder focused group discussion at Maragua town	Gikigie River Intake

Appendix III: Publications Enamating from the Research

Nyingi, R. W., Mwangi, J. K., Karimi, P., & Kiptala, J. K. (2023). Reliability of stream flow in inter-basin water transfer under different climatic conditions using remote sensing in the Upper Tana basin. *Physics and Chemistry of the Earth, Parts A/B/C*, 103527. https://doi.org/https://doi.org/10.1016/j.pce.2023.103527

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