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COLLABORATIVE DECISION SUPPORT TOOLS FOR WATER RESOURCES MANAGEMENT - A SCIENTIFIC CASE STUDY OF NAIROBI RIVER CATCHMENT

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Declaration

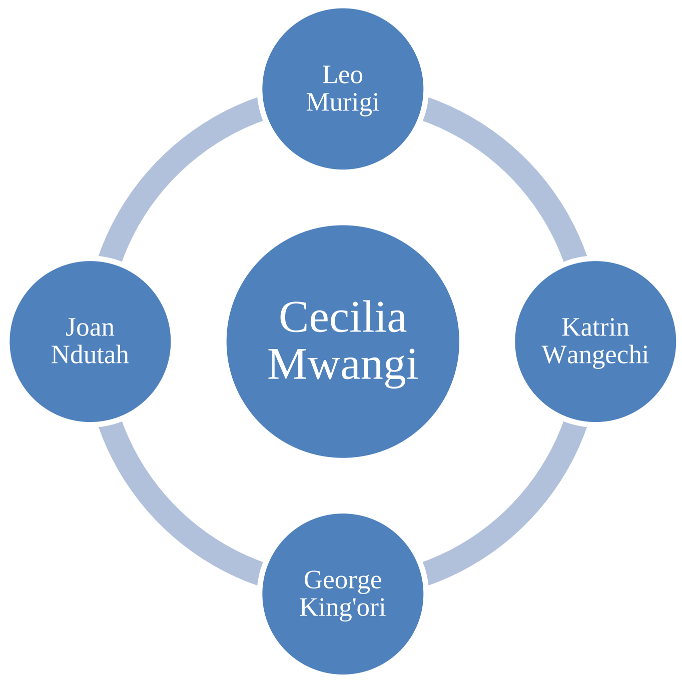
I hereby declare that the information in this report has been obtained in accordance to the stipulated rules and regulations governing doctoral studies at the Faculty of Civil Engineering, Geo-and Environmental Sciences in Karlsruhe Institute of Technology. All supplementary information that is not original to this work has been referenced accordingly.

MSc. Patrick Mwangi Murigi

Doctoral Candidate

Dedication

To



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Abstract

Water is a very essential resource, being one of the fundamental prerequisite for existence and sustenance of the biotic component of earth's natural ecosystem and also the primary input in almost every production. Satellite images of the earth shows a convincing evidence of an abundance of water on the planet. However, only a small percentage of the total water volume is available as freshwater suitable for human and many natural ecosystems. The relatively small volume of freshwater is further constrained by an uneven distribution over the globe. Over one-third of the world population live in countries whose renewable water resources endowment is below the global scarcity baseline (1000m^3/yr/capita), and over 70% of freshwater abstraction from rivers, lakes and groundwater is for subsistence crop production. (Entekhabi, et al., 1999).

Thus as countries develop and expand economically, socially and in technology, the demand for improved living standards precipitates development of increasing infrastructure in order to tap into and utilize water resources. Succinctly put, without a stable water supply economic activities are constrained and growth is stifled (MWI, 2009). Since fresh water resources are finite, increasing economic activities and growing population ultimately leave little room for water resources further development, without impacting on existing uses. Hence, water sources and water uses often become interrelated and water balancing and trade-offs between different sectors and uses play a key role in sustainable water resources management.

The disparities in water supply and water demand require understanding the underlying physical and temporal differences in the occurrence and magnitude of the water supply and subsequently use of simulation and/or optimization capabilities proffered by conventional water models to ensure equitable and sustainable exploitation of the resources (Ochola & Kerkides, 2003). To this end, the physical characteristics of water (especially phase changes and transportability in each of its phases) and a combination of natural processes, collectively recognized as the hydrologic cycle, provides the mechanism for the natural redistribution of water among the land, oceans and atmosphere that are significant in accounting for how the freshwater supply is sustained (Shelton, 2009).

This study seeks to exploit data pertinent to the strong coupling between climate and (land and agro-) hydrological processes as embraced in the hydrologic cycle, coupled with collaborated community level statistical and dynamic water demand data. Applying mass balance techniques within a model at catchment scale, the current status in water balance is established. Subsequently, using the model simulation capabilities and analysis of the data available to suit at least the minimum requirements for feasible results; and considering shared learning has shown potential to empower local people and strengthen their participation in adaptive collaborative management (Kamau & Kimberly, 2014); develop the methodology for substantive adoption of a preferred model to foster adaptive collaborative water resource management for catchment water balance in the case study area and typical catchments.

Zusammenfassung

Wasser ist eine unerlässliche Ressource, die eine der Grundvoraussetzungen für die Existenz und den Erhalt der biotischen Komponente des natürlichen Ökosystems der Erde; und auch die primäre Eingabe in fast jeder Produktion ist. Satellitenbilder der Erde zeigen ein überzeugender Beweis für den Reichtum an Wasser auf dem Planeten. Jedoch ist nur ein kleiner Prozentsatz der Gesamtwassermenge als Süßwasser für die Menschheit und viele natürliche Ökosysteme verfügbar. Darüber hinaus ist das relativ kleine Volumen aus Süßwasser ungleichmäßig auf der Welt verteilt. Mehr als ein Drittel der Weltbevölkerung lebt in Ländern, deren Verfügbarkeit an erneuerbaren Wasserressourcen unter dem globalen Knappheitsgrenzwert (1000m^3/Jahr/Kopf) liegt und die über 70% der Süßwasserentnahme aus Flüssen, Seen und Grundwasser für die Subsistenzwirtschaft verbrauchen (Entekhabi, et al., 1999).

Da die Ländern sich wirtschaftlich, sozial und technologisch entwickeln, führen die verbesserten Lebensstandards zu einer wachsenden Infrastruktur, um die Wasserressourcen zu erschließen und zu nutzen. Kurz gefasst, ohne eine stabile Wasserversorgung sind wirtschaftliche Aktivitäten begrenzt und das Wachstum gehemmt (MWI, 2009). Da die Süßwasserressourcen begrenzt sind, lassen zunehmende wirtschaftliche Entwicklung und steigende Bevölkerung letztendlich kaum Raum für die Weiterentwicklung der Wasserressourcennutzung ohne Auswirkungen auf vorhandenen Nutzungen. Daher hängen die Wasserressourcen und Wassernutzungen voneinander ab. Die Wasserbilanzierung sowie Kompromisse zwischen verschiedenen Sektoren und Nutzungen spielen eine Schlüsselrolle im Bereich der nachhaltigen Bewirtschaftung der Wasserressourcen.

Die Ungleichheiten zwischen Wasserdargebot und Wasserbedarf erfordern das Verständnis der zugrunde liegenden physikalischen und zeitlichen Unterschiede in Häufigkeit und Menge des Wasserdargebots; und in der Folge die Anwendung konventioneller Wasserbewirtschaftungsmodelle um eine gleichverteilte und nachhaltige Nutzung der Ressourcen zu gewährleisten (Ochola & Kerkides, 2003). Diesbezüglich stellen die physikalischen Eigenschaften des Wassers (insbesondere die Phasenwechsel und Transportfähigkeit in jeder Phase) und die Kombination von natürlichen Prozessen, die zusammen als der Wasserkreislauf bezeichnet werden, den Mechanismus für die natürliche Wasserumverteilung zwischen Land, Ozean und Atmosphäre dar, der maßgebend für den Erhalt der Süßwasserversorgung ist (Shelton, 2009).

Diese Studie zielt darauf ab, geeignete Daten zur Kopplung von Klima und hydrologischen sowie agrohydrologischen Prozessen, wie im Wasserkreislauf gegeben, zu nutzen, verbunden mit statistischen und dynamischen Wasserbedarfsdaten die auf kommunaler Ebene erarbeitet wurden. Es wird ein Massenbilanzverfahren innerhalb eines Modells angewandt, das auf Einzugsgebietsebene erstellt wurde, um den aktuellen Status der Wasserbilanz festzustellen. Anschließend wird aufgezeigt, dass die Modellanwendung und Datenanalyse den Mindestanforderungen für plausible Ergebnisse entspricht. Eine Methodik wurde entwickelt, die Fachleute befähigt in Kooperation mit den Stakeholdern ein angepasstes Wasserbilanzmodell zu erstellen und anzuwenden.

Table of Contents

Chapter 1. **Introduction**

1.1 **Water Scarcity**

It is acknowledged that sustainable development in ecological, economic and social terms can only be achieved if sufficient water is available (Simonovic, 2009). Accordingly, numerous arguments have been put forward on the need of a constant review of water resources management paradigm to meet the emerging challenges. In particular, the increasing awareness of the impacts of climate change has led to the insight that water management must become more flexible in order to deal with increasing uncertainties emanating from the shifting demographics, socio-economic and environmental boundary conditions. Water problems and water management options are as much a product of the social, economic and institutional context as they are of the technical and bio-physical factors governing local hydrological conditions. Many water related challenges have to do with socio-economic distribution and access, especially in developing countries (Mogaka, et al., 2006). Since water is a primary input in most economic activities, equitable distribution of supplies under dynamic economic conditions is often more of a challenge than absolute limitations on the available resource.

The interconnected nature of water uses, together with the finite resource capacity that limits supply increase at a reasonable economic and environmental costs has led to the emergence of concepts such as Integrated Water Resources Management (IWRM) and Adaptive Water Resources Management (AWRM). AWRM has been advocated as a timely extension of IWRM, to cope with increasing water resources challenges. Adaptive management is a systematic process for improving management policies and practices by learning from the outcomes of implemented management strategies i.e. “learning to manage by managing to learn” (Lannerstad & Molden, 2009). It can be seen as an attempt to transform technocratic, top-down and sectoral water management into a more democratic, polycentric, cross-sectoral and synchronized approach. This helps in addressing the dynamic and highly uncertain conditions that characterize complex water systems. AWRM takes into account environmental, technical, economic, institutional and cultural characteristics of a region in its pursuits to achieve regional water balance. However, the development and implementation of adaptive approaches have been slow due to the inertia inherent in effecting structural changes on the prevailing water management regimes.

Water scarcity, whether absolute or induced, is not the only fundamental challenge; water quality and pollution are also major issues contributing to the emerging water crisis. Less publicized are challenges inherent in the limited nature of scientific information and technical knowledge especially in the third world. In many situations, basic hydrological and other data are unavailable or unreliable due to poor collection methods and/or absence of well-coordinated databases to avail the data when require for objective analysis. Moreover, projections of future drivers, such as climate change, are rather uncertain, which means the reliance on conventional methods of water management based on the statistical analysis of historical data series, is not sufficient. For instance, it is uncertain how much pollution humans will be adding to the atmosphere in the future. Innovations that stop or limit the amount of greenhouses gases that are produced, laws and rules that change the amount of pollutants that are released, and how the growing human population lives in the future are all somewhat uncertain. For such considerations therefore, analysis of systems behaviour must proceed iteratively with an emphasis on uncertainties rather than on the known. In light of this prevailing situation, a model's efficacy in simulating uncertainties is of key interest even in this study, but their effect on relevant parameters will be simulated through pragmatic scenarios.

To start with, the selected case study area typifies the challenges expected in a representative catchment within a water scarce region in a developing country. The catchment depicts the typical uncertainties encountered in water systems analysis, with urban settlements, uncontrolled agricultural activities and the effects of their related environmental degradation, inequitable distribution of the water resources due to fragile economic situation and the looming water related conflicts.

1.2 **Problem Statement**

Akin to many developing countries, Kenya faces complex water crisis arising not only from resources' scarcity, but also from extreme imbalance arising due to spatial and temporal variations in precipitation. Even in areas where favourable precipitation occurs, issues like inadequate natural and artificial storage to buffer against escalating climate shocks and shared trans-boundary water resources (e.g. Nile basin) that impact on regional socio-economic security abounds. Climate variability and its closely related catchment degradation have severe impacts on water retention and ground water recharge, which exacerbate the situation considering the low investment in basic water infrastructure. The efforts to level the imbalances by transporting water are also mired by serious technical, social, ethical and economical limitations. These notwithstanding, rapid growth in water demand for multi-purpose/multi-sectoral uses persist; being steered by a growing population and its claims for improved standards of living.

Situated at the tropics, the climate has especially in recent times been typified by increasingly erratic seasonal and annual rainfall variations with an overall annual natural endowment of renewable fresh water estimated at 20.7km^3/year, where groundwater share at about 2.1km^3/year, is approx. a tenth of surface water (Mogaka, et al., 2006). However, these previously trusted figures have been disapproved lately with more research in ground water showing high endowment especially in arid and semi-arid regions. The most recent estimates have renewable ground water storage at 56km^3/year (see Figure 2). Further research to establish recharge reliability, key recharge zones and the ground hydrodynamics is underway. This development redefines the country status from among critically water scarce to water stressed according to the global standards.

All the same, the renewable fresh water resources have been on decline with reduction in yield from natural ecosystem, which as previously stated, has been exacerbated by cyclical events of floods and droughts, leading to collapse of infrastructural and increased siltation in rivers and reservoirs. Moreover, population growth of approximately of 3% p.a. from 10.9 million in 1969 to 38 million in 2009, current estimates at 43 million, with projected growth to 60 million by the year 2030 is another demand driving force (Murigi, et al., 2012).

1.2.1 **National Water Master Plan 2030**

Due to the increasingly uncertain water resources situation in the country, as a result of global climate change and increasing socio-economic development demand with population growth; also with the fact that previous annual renewable water resources estimates availed by the NWMP 1992 were continuously being disputed by recent research; it was agreed that the time for a new water master plan was long overdue. However the objectives of NWMP 2030, inaugurated in the year 2010, were expanded to accommodate country's new development blue print as envisaged in state development agenda dubbed 'Vision 2030' (MSP, 2012).

The hitherto theoretical supply had duly scaled from 1853m^3/cap, to 647m^3/cap and 535m^3/cap in 1969, 1992 and 2009 estimates respectively (see Figure 1). It was projected that without proper planning and mitigation the theoretical renewable fresh water supply would slip to a paltry 235m^3/yr/cap by year 2020 (compared to 345m^3/yr/cap assuming a static resources status. Globally, for supplies less than 1000m^3/cap, a country is categorized as water scarce. Hence, Kenya had been ranked among the chronically water scarce countries with the situation further aggravated by the growing decline of the renewable water resources (FAO, 2005).

Based on estimates obtained in this study, the country's renewable fresh water resources currently stands at 76.7 km^3/yr and the projected average water demand in the country's was 14% by 2010, which will steadily rise to 81% by 2030 and accounting for temporal hydrodynamics remain at 81% by 2050. Severe water scarcity will be found in Athi River Basin (case study area) where actual water demand will be 4.6 km^3/yr; i.e. 276% of the available water resources at 1.6 km^3/yr. This will be followed by Tana River Basin at 8.2 km^3/yr; i.e. 105% of the available water resources at 7.8 km^3/yr. Both Lake Victoria North and South Basins will remains safe with annual water demand of 0.228 km^3/yr and 0.385 km^3/yr respectively in 2010 to 1.34 km^3/yr and 3.0 km^3/yr by 2030 to 1.57 km^3/yr and 3.25 km^3/yr by 2050 respectively (MEWNR, 2013).

In target year 2030, water demand will have increased substantially in all catchment areas, and water balance is expected to be tight in all areas except in Lake Victoria basin. As for the year 2050 the ratio between water resources available and demand is almost the same as that for 2030 due to increase in both water resources due to climate change and demand. These findings clearly vindicate the ongoing efforts to ensure areas with water deficits have water resources development optimized fully in order to meet future water demand challenges. In addition, demand management strategies such as water pricing, water efficient appliances, water reuse, recycling of water, allocation of water to the most effective and optimal use etc. should be introduced to control future water demand. This will especially control irrigation water demand that requires up to 80% of the available water.

Other the other hand, demand for higher living standards for the growing population precipitates an increase in housing, food stuffs, industrial goods, recreation facilities, clean environment, energy and other infrastructures, all with substantial implication on water demand. The increased water demand subsequently poses serious impacts on the entire river basins ecosystem stability and resilience. Thus, the social-economic effect of water deficit is a drag on economic growth with serious environmental and health impact (MWI, 2009).

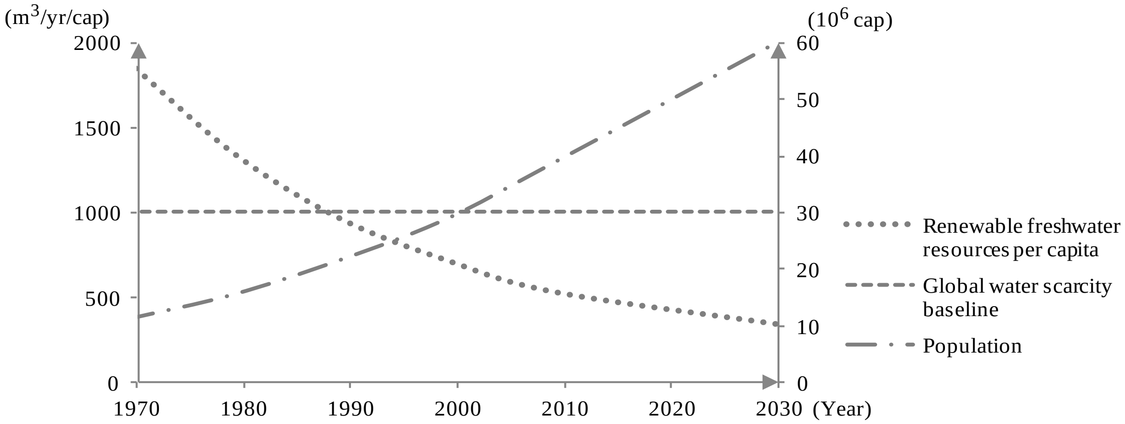

Figure 1: Water resources per capita, population and water scarcity baseline curves for static renewable freshwater resources scenario (MWI, 2009)

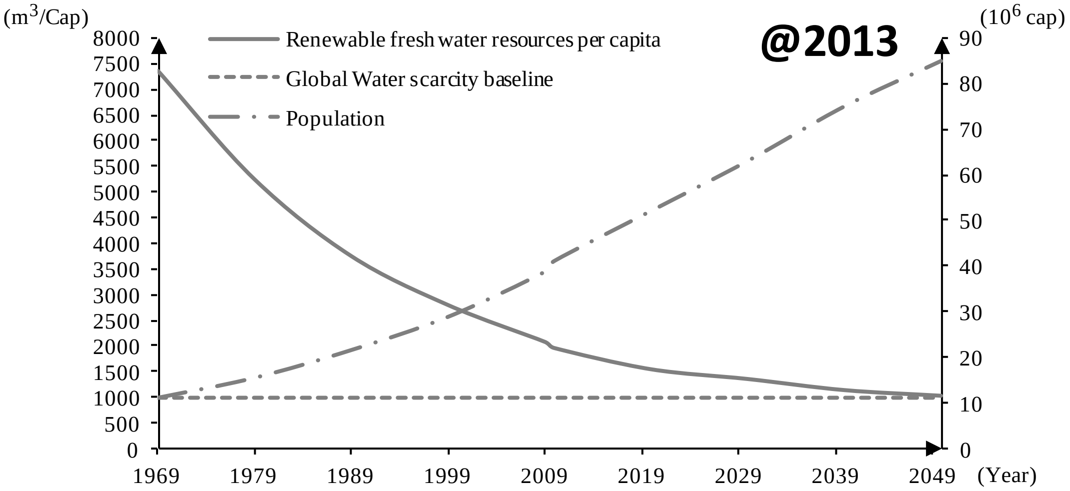

Figure 2: Renewable water resources per capita, population and global water scarcity baseline for static water resources scenario (MEWNR, 2013)

For a viable solution to guarantee optimal water resources usage and sustainability three key initiatives have been identified, i.e. catchment protection, water infrastructure and decision support tools backed up by a well-coordinated water resources database to facilitate progressive studies and iterative systems' development. The hitherto alienation of the public and other stakeholders in policies formulation and decision-making in prioritising infrastructure development and resources allocation, has fostered the misapprehension of water as an infinite resource. Consequently, the societal actors persists in lobbying for tariffs that are out of sync with the economic cost of water and usage habits that breed misuse and laxity leading to high non-revenue water (NRW) in the distribution systems, currently estimated at 50%. Moreover, inefficient revenue collection with average estimate at 65% of the total billed is rampant (MWI, 2010). Subsequently, this has incapacitated the management and sustainability in conservation of water resources and progressive expansion of water infrastructure. NWMP 2030 has been envisaged to provide structure towards an equitable access to water and sanitation; development of total irrigation potential; securing clean and sustainable environment and energy production by exploiting total viable hydraulic potential head in rivers and streams (MSP, 2012).

1.2.2 **Local Water Sector Maladies and Opportunities**

The sector has partially been dependent on loans and grants from industrialized countries, whose financing has often been attached to consultancy conditions, to check on funds appropriation and foster tested technologies and policy tools mostly developed and honed within temperate basin districts. However, the efficacy of most choice tools for application in tropical catchment regimes is hampered mostly by technical skills shortfall, hydroclimatic differences, incompetence in operation and maintenance of water works and equipment and above all their socio-economic and cultural implications, which have been underestimated (Falkenmark, et al., 1987). Failure to appreciate and accommodate the local culture and capacity has led to incapacitation of any meaningful adaptation of feasible decision support tools, leading often to polarisation of water and related infrastructure development and catchment conservation efforts as politics fill the void (see Figure 3).

Water resources allocation and management involves a complex decision making process which require technical support and involvement of all stakeholders in the decision making at all levels. Well-coordinated hydro-climatic, land use, land cover, socio-economic and hydro-geological surveys' database supported by real time resources monitoring through data collection, compilation and analysis, have been key to a sustainable management of water resources (Mogaka, et al., 2006). These have been especially crucial in the decision process, where timely construction of water infrastructure and adoption of demand management policies have helped mitigate effects of climate change and manage increasing demand in the developed countries (Simonovic, 2009).

The adoption and collaborative adaptation of DSS tools would aid water managers and stakeholders to better understand water resources potential in a given basin; hence, facilitate consensus on the best management practices as to proffer water balance through equitable and sustainable water resources allocations, catchment protection and conservation (Ochola & Kerkides, 2003). DSS tools are multifaceted to serve the key interests in the water sector i.e. overall resources supply and demand analysis and simulation of the same within a model to assess the temporal impacts of various variables (e.g. population growth, land use, climate change etc.) (Sieber, 2011). The ultimate results are both comprehensive and simple to understand and therefore allow stakeholders' effective participation in the decision making process to avoid contentions and polarisation during policies implementation.

Figure 3: Collaborative Ondiri swamp conservation initiative

1.2.3 Fundamental Assumptions

It is assumed at the onset of this study is that ample spatial and temporal hydroclimatic, hydro-geological, demographic, land use, and water infrastructure databases are maintained at the relevant water management authority. This is, however, only possible where appropriate monitoring devices have been installed in strategic locations (to proffer representative data) within the basin to collect samples for processing and storage in databases for release to various experts on demand. Normal surveys should regularly be conducted whereas monitoring surveys should be conducted occasionally with separate equipment to calibrate on-site devices and ensure accuracy in the long-term. All the same, due to the subjective focus of this study targeting the developing countries, where socio-economic and technical constraints continue to obstruct objective development of well-coordinated databases, the operations boundary conditions for a feasible tool for water management must be versatile enough to accommodate prevailing data limitations.

Consequently, the efficacy of any tool would not only be pegged on its ability to proscribe water resources management solutions, but also its estimated capital demand and level of expertise beside related capacity building need for managers, planners, and stakeholders to actively participate in the decision process.

1.3 Research Questions

The study endeavours to proffer an adaptive collaborative water resources management in the country by addressing the following questions:

- Are there technical decision making apparatus currently in use in the water sector in Kenya that espouse the IWRM paradigm in not only adopting a holistic approach in water resources management, but also proffering universal stakeholders' participation in decision making for interventions that are appropriate, targeted and sustainable?
- How critical are the prevalent constraints, i.e. data availability and accuracy, socioeconomic, technical, infrastructural and environmental within the industry as to influence the choice, adaptability and functionality of a potential/desirable DSS tool?
- What are the main variables influencing and best illustrate the dynamic effects on water balance within the catchment in simulation of current and pre-determined future scenarios?
- Evaluating various DSS tools currently in use in the water sectors, which tool or set of tools have the greatest efficacy to be adapted and yield a customised methodology that is versatile yet comprehensive enough for application within typical catchments?

1.4 Research Objectives

The study is a concerted effort to develop a methodology for adapting a feasible decision support tool capable of integrating the modern state of art in science and technology to foster holistic water resources management through sustainable development, equitable allocation, use and conservation. The criteria is critical analysis of the underlying concepts and fundamental operational constraints like technical and infrastructure requirements, flexibility and especially their ability to substantially function within data requirement constraints typical of developing countries while addressing the prevailing gaps in water resources management.

The idea is to unambiguously illustrate a catchment and all the related water appurtenances and demand sites therein, through schematics (or GIS pre-processed raster and shape files); proffer a powerful tool for data collection; storage; processing; and dissemination of results using maps, graphs or tables; so as to foster an expert-stakeholders roundtable decision making. Hence real participation by all members within the catchment and especially the hitherto marginalised groups is enhanced, to elicit their input in design and development of watershed management instruments. On the other hand, catchment managers get impetus to make optimal trade-offs and sustainable allocations between competing water uses. Ultimate choices would therefore be based on informed democratic policies, available resources, social-economic implications and consideration of the environmental impacts.

The study therefore seeks to recommend functional DSS tool for adoption within developing countries to help water planners, managers and stakeholders appreciate and foster long-term oriented water management strategies. This will help maintain the natural ecosystem balance by availing facts to argue the case for base flows in river and groundwater regimes. Potentially, the adopted tool will be used to simulate future scenarios as to foster informed decision making by water planners in developing various intervention and mitigation measures for an efficient and sustainable water resources management within their jurisdiction.

It is envisaged to culminate with preparation of a basic methodology for adapting a universally feasible DSS tool, which is comprehensive enough to allow holistic assessment of management policies and regulations on properties that are specific to individual water catchment. The propensity of a DSS tool to be ingrained within the integrated water resources management regime already in effect in most countries is a key factor. It should certainly proffer sound decision making through real time evaluation of infrastructural needs and the necessity, timing and quantity of trans-basin water resources transfers. Moreover, cost implications for capacity building and other encumbrances e.g. software licences, have great impact on universal adoption and enforceability in developing economies and should therefore be realistic.

1.5 **Research Approach**

The first step is to identify the fundamental problems that plague water sector in Kenya, especially emanating from resource scarcity and related weak management techniques. In this phase, the prevailing challenges are clearly illustrated providing not only the background, but also the underpinning rational and motivation behind this study. The prevailing and potential challenges and the respective perceived solutions and/or prospects are hereby outlined in a manner that constitutes the basis, i.e. the objective, of the study to steer the pursuit for the envisaged solution.

The fundamental goal is to substantially address the challenges of water scarcity within the constrained socio-economic realities of developing countries, with a functional management tool; that would, in spite of the prevailing data insufficiency, engender a holistic, participatory approach in water allocation for social equity, economic efficiency and sustainability. A variety of tools referred to as ‘decision support systems (DSS)’, have been hailed to facilitate decision making in WRM as to balance interests of water planners, societal actors and other stakeholders. While the water planner’s goal is to improve the management efficiency, sustainability of the resources and growth of the infrastructure, the goals, interests and concerns of other stakeholders are varied, conflicting, competing, unascertainable and therefore complex to analyse and quantify.

The multi-criteria analysis (MCA) is therefore adopted within DSS tools for iterative simulations and establishment of how varied management policies would affect various system elements; and therefore proffer the best prospective option. In the second phase of this study, the tools whose core or part functionality is comprehensive water resource potential and demand appraisal for water balancing and related simulation and/or optimization are identified and discussed in detail.

Accordingly, in the third phase, different groups likely to be affected by water management policies i.e. stakeholders and their goals, interest and concerns in the water sectors are identified and their dynamic character considered as variables for scenario simulations. These serve concurrently as an outline of the underlying driving forces of pressure on the water resources. In the effort to gain a better understanding of basin issues and in recognition of weaknesses in technical infrastructure, much effort has been devoted to data collection and analysis in order to avail multiplicity of options to bridge the gaps posed by insufficient data.

The fourth phase encompass identification of a base year or the status quo period, which is the basis of future scenarios simulation using tools considered feasible for further evaluation. Feasibility of various DSS is hereby evaluated on the basis of substantial capacity to model surface and ground water flows, and integrate external water supplies as to establish spatial and temporal catchment water resource potential. Subsequently, using various model's graphical user interface and/or ArcGIS pre-processing, the case study area is demarcated and all available water appurtenances and demand data attributes incorporated; with especially the demand attributes being cumulatively built from the smallest logical zone that would constitute a node for mass balance calculations.

For socio-economic administration, the country Kenya is divided into 47 semi-autonomous counties which are further subdivided to yield a total of 159 districts, 596 divisions, 2606 locations and 7151 sub-locations respectively. Counties form the pillars for both socio-economic and resources allocation, administration and development, with a sub-locations being the lowest administration level, which is the foundation for statistical data for both water resources supplies and demand. In this study, the locations, which are basically constituted of two or more sub-locations, are used as the nodes for the purpose of mass balance calculations involving both water quantity and quality. In some instances, several small locations are lumped up together and allotted one node to simplify the model schema. Figure 4, here below shows a section of the model schema for the case study area with the sub-locations demarcation being highlighted, and the main rivers that form the basis for surface water resource evaluation also highlighted. Moreover, the red dots within the schema represent various demand sites while the green and the red lines represents withdrawals from sources by various demand sites and their subsequent return flows respectively.

Comprehensive data collection facilitated construction of a mini-database in the interest of the study, which heralded a technical evaluation of the prevailing physical, infrastructural and environmental constraints within which the DSS tools envisaged for application will have to conform or be flexible to accommodate. Since 90% or thereabout, of the water demand in the case study area is met through water import from adjacent basin, this implies that a feasible DSS tool would have to support trans-basin transfers. A dynamic, interdisciplinary and multi-sectoral approach has been assumed in modelling both conventional (river, lakes, groundwater etc.) and non-conventional (reuse, recycle etc.) water resource supplies and demands.

The approach adopted in this study to choose, validate, test and recommend a methodology for adoption of a feasible DSS tool involves analysis of the potential tools according to the following objective criteria:

- **Comprehensive yet user-friendly interface:** capacity to proffer clear illustration of watersheds, related water appurtenances, demand site and key operation variables (e.g. flow requirements) through schematics, raster and shape files; process data and disseminate information using maps, graphs and tables that support universal stakeholders' perception as to elicit reaction/contribution in opinions.

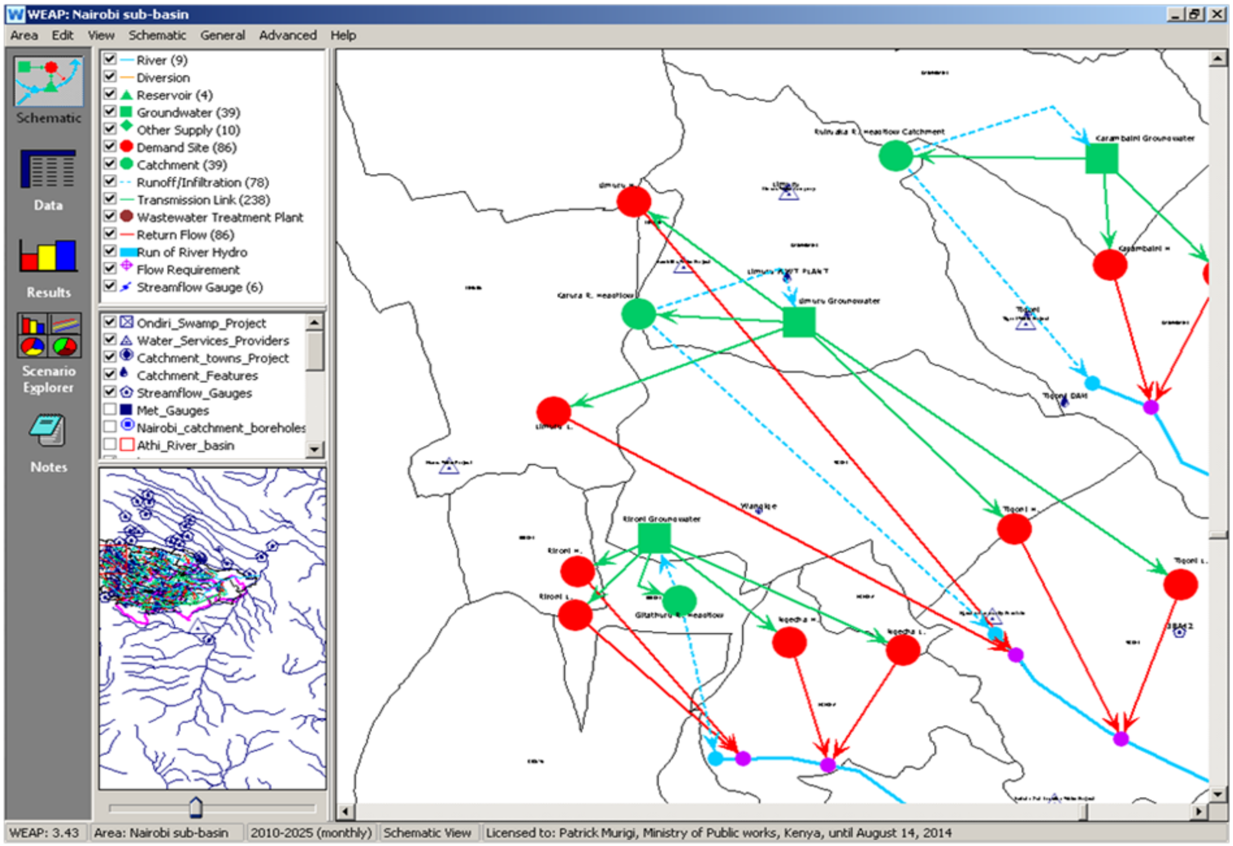

Figure 4: Schematic of sub-locations within the case study area represent the lowest level at which data is aggregated/disaggregated to, for the fixed and variable parameters.

- **Accommodate trans-boundary water transfers:** hence provide a platform for trans-basin dialogue and cooperation in developing and managing shared resources; inform water planners and managers of potential conflict areas to aid in preparing various interventions and conflict mitigation measures.
- **Adaptability:** the model ought to be applicable not only within the case study area but should also substantially perform in typical but diverse catchment regimes with reasonable modification.
- **Proffer an expert-stakeholders round-table experience:** Use of simple real time and scenarios simulations to foster universal perception of the real issues and various stakeholders roles within the catchment; hence, enhance engagement of hitherto marginalised group as to present:-
    - Facts on water quantity and quality with demand management measures to supplement the conventional supply oriented measures to ensure optimal benefit from catchment water allocations;
    - case for vital base flow regimes for healthy natural ecosystem and;
    - case for Down-stream water users;

This is in appreciation of the fact that WRM has shifted from being sectoral and supply oriented to a multi-sectoral activity that requires incorporation of demand management policies and effective collaboration and coordination among relevant stakeholders at all levels. Consequently facilitation of information flow promotes awareness of sector problems and needs; thus fostering exchange of ideas and experiences that leads to prospective solutions fronts for proactive and collaborative action. Demand management policies are meant to prompt behavioural trends among water providers and users that encourage efficiency and sustainable exploitation of the resources.

1.6 Structure of the Thesis

The report commences with an elaborate introduction featuring a highlight of various challenges that beset the case study area, which are especially typical of water sector in developing countries. The prevailing WRM issues specific to the case study area are expounded in a systematic approach geared toward arousing legitimate research questions and thus precipitate the rationale that has been used to set the study objective, in pursuit of legitimate solution to the problems.

The second chapter delves on among others the physical, socio-economic and infrastructural character of the study area. The objective is to introduce the geographical area and illustrate in detail the potential in resources within the area of study. The third chapter present an incursion of modelling into the modern decision making process as propagated by IWRM. The fourth chapter presents literature review where alternative methods are highlighted and the adopted system and the preference rationality in relation to this research undertaking also extensively expounded. The supporting literature related to the various decision support systems available in the water industry is reviewed, especially delving in detail on the fundamental usage, performance, versatility, and limitations in applications within diverse catchments.

Chapter five delves into the methodology, which in essence is an elaborate systematic flow of events and measures adopted to accomplish the set objectives as laid out at the onset of the study. It depicts the step by step layout of the undertakings and key focus at every stage, as well as the envisaged outcome of initiatives pursued. The actual results obtained from every undertaking within the methodology section are presented in detail within chapter 6, while chapter 7 outlines a typical methodology for effective adoption and application of a universally adaptive collaborative decision support tool within the developing economies. Chapter 8 delves into detailed deductions as per the perceived results and implications presented in the chapter 6. This entails subjective, thorough interpretations and intricate discussions with emphasis on both successes achieved and challenges encountered in the process; which subsequently precipitate recommendations on feasible alternative approach and/or system modifications that might yield improved performance. Last, but not least, chapter 9 presents a detailed conclusion which in essence corresponds to the ultimate deductions made from the entire process, winding up with the hypothetical way forward.

Chapter 2. Case Study Area

2.1 Physiology and Topography

Kenya is located on the east coast of Africa, with the equator running almost straight along the middle of the country, between approximately latitudes 5°20'N and 4°40'S and longitudes 33°50'E and 41°45'E; bordering Somalia at the East, Ethiopia and South Sudan at the North, Uganda at the West, Tanzania at the South and the Indian Ocean at the South-East as shown in the location map (appendix Figure 64).

Kenya claims a total area of 582,646 km^2, inclusive of 11,230 km^2 in open water surface area, as her territory. The major part of the inland water surface area is accounted for by the 6% portion of Lake Victoria (3,755 km^2), which is shared with Uganda and Tanzania, and Lake Turkana (6,405 km^2), the largest desert lake in the world, which has a vital catchment on the Ethiopian side of the border. Approximately 490,000 km^2 of the land area (more than 80%), is classified as arid and semi-arid land (ASAL), which is characterised by low quality, loose sandy soil; dry climate extremes and subsequent dismal surface water resources endowment exhibited by poor acacia vegetation. The hardship conditions notwithstanding, the area supports almost 30% of the country's human population and 70% of the livestock production presently. The remaining area of about 81,000 km^2 is classified as profitable arable lands, where rain-fed agriculture is practised and accordingly sustains over 70% of the total human population while generating substantial portion of the country's GDP (MEWNR, 2013).

Kenya is characterised by tremendous topographical diversity, ranging from low marine mangrove forests at the coast; to the eastern highlands ridges and glaciated mountain at the central; to a true desert landscape on the North-West part of the country around Lake Turkana. The elevation varies greatly from sea level at the Indian Ocean to 5,199 m (asl) at the Batian Peak of Mount Kenya, the second highest mountain in the Africa continent. The East and western highlands are the uplifted faults and the low lying land between them is the Great Rift Valley that extends from Tanzania at the South across the country to the North extending into the neighbouring Ethiopia. Most of the inland lakes in the country, save for Lake Victoria, are found at the floor of the Rift Valley. In general, the country has six natural geographic regions i.e. coastal belt and plain; the Coastal hinterland (Duruma-Wajir low belt; Foreland plateau; the highlands (East and West); Nyanza low plateau and the Northern plain lands (see appendix Figure 75).

2.1.1 Geology

Four major geological series, Precambrian, Palaeozoic, Mesozoic and Cenozoic represent the complex geologic formation of Kenya. The Precambrian series, the lower portion of the geologic formation, is represented by volcanic rocks as well as igneous and metamorphic rocks. They are distributed is South-western and central part of Kenya (appendix Figure 74). The Palaeozoic series is characterised by the sedimentary rocks (a monotonous series of grits, sandstones, shale and traces of coal) known as Karoo Series which is distributed in the South-eastern part. The Mesozoic series is well developed in the North-east and the South-east and represented by sedimentary rocks (shale, siltstones, grits and sandstones). The Cenozoic series, distributed in central and eastern part, is probably the best developed and most important in terms of surface coverage and is represented by sedimentary (alluvial and colluvial deposits) and volcanic rocks (basalt, pyroclastics and trachyte) of Tertiary and Quaternary deposition (MEWNR, 2013).

2.1.2 **Lithology**

The coastal belt and plains are characterised by alluvial debris around river deltas and estuaries, while coral reefs and coral sands are found on other banks and smooth sweeping beaches respectively. The coastal hinterland also features alluvial section in the floodplain along major rivers, which have huge development potential for irrigation. The underlying geological foundation in the highlands feature complex basement rock systems, which include granites, gneisses, schist, granulites and quartzite, all of which are metamorphic in character and date back to the pre-Cambrian period. However, outcrops of the basement rocks are not widespread because they have largely been covered by tertiary to recent volcanic material in areas varying in altitude from 1,500-2,300m. The soils especially on the eastern and South-eastern slope of Aberdares, where the head waters of Tana and Athi Rivers are to be found (see Figure 74), are well-drained, deeply weathered and fertile having been formed from parent rock material which consists chiefly of Tertiary to Recent trachytic basalts and phonolites. Other regions features varied advanced form of volcanic rocks weathered through erosion and sedimentation or transformed by metamorphism.

2.2 Hydroclimatic Conditions - Climate

The climate in Kenya is primarily controlled by the Northward dry continental air mass (N/E trade winds) and Southward movement of moist, tropical wind (S/E trade winds) converging at the Inter Tropical Convergence Zone (ITCZ); also known as the equatorial trough. Frequency and intensity of rainfall is influenced by large water bodies like Lakes and ocean, with typical convectional rainfall occurring around them; and is also influenced by complex topography of the Great Rift Valley, and high mountains such as Mt. Kenya and Mt. Elgon. Consequently, a relatively wet and narrow tropical belt lies along the coastal shores of the Indian Ocean; with extensive tracts of semi-arid and arid lands behind the coastline. The land then rises steeply to a highland plateau at the central and western region with the Great Rift Valley running in between.

There are generally two seasons (bimodal) of rainfall experienced in most parts of the country, which corresponds with the Northward and Southward migration of the ITCZ. The first season termed as the “long rains” in the East African region occurs from March to May, while the second season termed as the “short rains” is observed from October to December. However, some stations in the western and central parts of the Rift Valley experience a trimodal rainfall pattern, with a third rainfall season during the month of June to September.

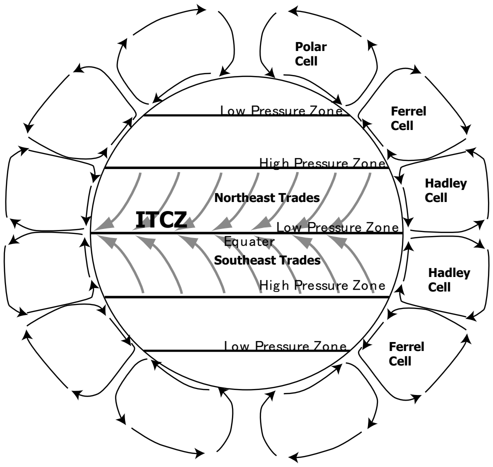

Figure 5: Global pressure belts that influence convergence of North-bound and South-bound Trade winds at the ITCZ (MEWNR, 2013)

This is associated with the incursion of the Congo air mass (MEWNR, 2013).

Other factors affecting rainfall pattern in Kenya are: the position and strength of subtropical high pressure systems in the Southwest Indian Ocean (Mascarene High), Southeast Atlantic Ocean (St. Helena High), North Atlantic Ocean (Azores/Saharan High), and the Arabian High to the northeast; position and intensity of the tropical cyclones (TCs); El Niño/Southern Oscillation (ENSO); Latitude which affect the timing of rainfall minima and maxima; Inter-seasonal annual waves: the quasi-biennial oscillations (QBO).

The moisture availability zones are classified from I to VII: (I) >80 Humid, (II) 65-80 Sub-humid, (III) 50-65 Semi-humid, (IV) 40-50 Semi-humid to Semi-arid, (V) 25-40 Semi-arid, (VI) 15-25 Arid, and (VII) <15 Very arid (MEWNR, 2013).

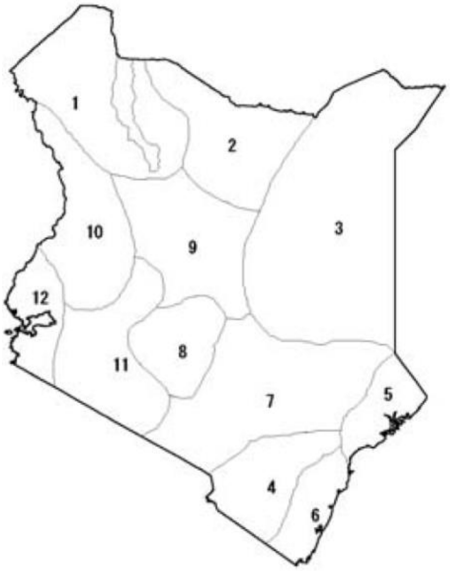

Figure 6: Climatic Zones (source KMD)

2.2.1 **Rainfall**

Humid zones receive between 1000 - 2000 mm of annual rainfall that facilitate semi-intensive and intensive production of subsistence food, cash crops as well as livestock and support about 50% of country's population; Semi-humid zones receive 700 - 1000 mm of rainfall annually, which supports cattle and small stock rearing, and production of drought-tolerant crops; while ASALs receive 200 - 700 mm of rainfall annually and, as show in fig 5 above and collaborated by Table 1 below and (appendix Figure 65), cover over 80% of the country's land area. The average annual rainfall over the country is approximately 680 mm (MEWNR, 2013).

Table 1: Rainfall seasons (KMD)

Season	**Abbreviation**	**Characteristics**
December – February	DJF	Dry season
March – May	MAM	Rain season, called as Long Rain
June – August	JJA	Dry season
September – November	SON	Rain season, called as Short Rain

2.2.2 **Temperature**

Temperature in Kenya ranges from a minimum of below the freezing point on the permanently snow-capped Mt. Kenya to a maximum of over 40 °C in the North and North-East arid and semi-arid zones. Temperature in the coastal town of Mombasa (17 m ASL) ranges between 22-33 ^{o}C; while at the capital city Nairobi (1,661 m ASL) it ranges between 11 - 28 ^{o}C (MEWNR, 2013).

2.2.3 **Sunshine Hour**

Since Kenya is situated at the Equator, there are equal day and night times, but due to cloud cover, the mean monthly sunshine hours are approximately 7 - 8 hours. Lodwar at the North-West has the longest mean monthly sunshine hour with 10.3 hours in September. On the other hand, the shortest mean monthly sunshine hour has been recorded in Dagoretti station in Nairobi with 3.0 hours in July (MEWNR, 2013).

Table 2: Climatic zones of Kenya as classified by Kenya Meteorological Department (KMD)

Area	Climatic Zone	Representative Station
(1) North Western	Arid (VI) to Very Arid (VII)	Lodwar
(2) Northern	Arid (VI) to Very Arid (VII)	Marsabit, Moyale
(3) North Eastern	Arid (VI) to Very Arid (VII)	Mandera, Wajir, Garissa
(4) Southern Lowlands	Semi-arid (V) to Arid (VI)	Voi
(5) Northern Coast Strip	Semi-humid (III) to Semi-arid (V)	Lamu
(6) Southern Coast Strip	Semi-humid (III) to Semi-arid (V)	Mombasa, Mtwapa, Malindi, Msabaha
(7) South Eastern Lowlands	Semi-arid (V) to Arid (VI)	Machakos, Makindu
(8) Central highlands including Nairobi	Humid (I) to Semi-humid (III)	Nairobi, Nyeri, Meru, Embu
(9) Highlands North	Sub-humid (II) to Arid (VI)	Isiolo
(10) Highlands West of the Rift Valley	Humid (I) to Semi-humid (III)	Kericho, Eldoret, Kitale, Kakamega
(11) Central Rift Valley	Semi-humid (III) to Semi-arid (IV)	Narok, Nakuru, Nyahururu, Laikipia Air Base
(12) Lake Victoria Basin	Humid (I) to Sub-humid (II)	Kisii, Kisumu

2.2.4 Evaporation and Relative Humidity

The mean annual evaporation depth varies from 1,215 mm at Kimakia forest station to 3,945 mm at Lokori in South Turkana. The estimation of evaporation rates from water surface is important for water resources development, especially in arid and semi-arid land (ASAL) regions. The potential evapotranspiration evaluated using Harmon’s equation and FAO Penman-Monteith method (MEWNR, 2013).

The highest annual mean maximum relative humidity has been recorded at Mombasa Met. Station at approximately 90% and the minimum relative humidity recorded there was 82%. On the other hand, the lowest annual mean maximum relative humidity has been recorded at the Lodwar Met. Station at approximately 60% and the mean minimum relative humidity there was 34%. The annual mean maximum relative humidity recorded within Nairobi and environs is approximately 80% and the mean minimum relative humidity recorded is 50%.

2.2.5 Vegetation and Landscape

Vegetation cover of any place reflects the sum total of environmental conditions and is therefore regarded as a fairly reliable indicator of ecological potential. In general the climate and soils largely govern the occurrence and distribution of natural vegetation. Kenya's has three main classes of vegetation i.e. forest, woodland and grassland, semi-desert communities (bushed grassland and barren land) and mountain summit. The forest and mountain communities occur from 1975 to 3040 m (ASL) and include bamboos (Arundinalia alpina), camphor, olives, podo and cedar, while extensive mangrove forests occur along tidal wave zones at the coast.

The rest of the country is dominated by grassland communities including savannah vegetation and high grass bush land and acacia that are dominant in central between 910-1850m (ASL). The grassland vegetation are perfect habitat for the small to medium wildlife animals while birds and the larger species prefer the woodland and forest environment. The high concentration of carbonates in the lake waters of Rift Valley host the blue-green algae and diatoms which in turn give the lake water nutrients on which flamingos flourish.

2.3 Hydrology

2.3.1 Rivers and Drainage Basins

The central highlands especially Mt. Kenya region (199,558 ha) and the Aberdares ridges (103,315 ha); the western highlands and specifically the Mau forest complex (400,000 ha), Cherangani hills (128,000 ha)) and Mt. Elgon (73,089 ha) at the western border with Uganda, constitute the five main water towers in the country (appendix Figure 66). All the permanent rivers in the country emanate from these areas. Two major rivers from central highlands i.e. Tana River, the longest river in Kenya at 1000km, with source in both slopes of Mt Kenya and Aberdares, and Athi River from the slopes of Aberdares ridges, flow towards east through vast ASAL and drain into the Indian ocean. The Mau forest complex on the Western highlands is the most endowed water tower in the country with 16 rivers which are tributaries to 8 major rivers that replenish Lake Victoria emanating here.

The L. Victoria basins covers approximately 8% of the country's total land area but holds over 54% of the total annual renewable fresh water resources, the Mau catchment also serve Rift Valley basin; an internal drainage basin that host almost all natural inland lakes in the country and cover 22.5% of land area, but is endowed with only 3.4% share of country's water resources. The other three main basins, their sizes and water resources share, are as outline in Table 3 below, while Figure 7 also below, shows the delineation of the five basins as designated by National Water Resources Management Strategy (NWRMS). Other than rivers and Lakes, springs also play a major role as sources of portable water, the major ones include the Mzima, Njoro Kubwa, Nolturesh, and Kikuyu springs. Regrettably, there is no viable data regarding springs, their discharge rates and/or potential. The skewed distribution of water resources in country contribute to the overall limited natural renewable water resources estimated at 76.7 BCM/year; which consists of 20.7 BCM/year of surface water and 56.0[1]BCM/year of groundwater recharge. Subsequently, the annual renewable water resources, considering the country's population of 38.53 million as per 2009 census, is estimated at 1990 m^3 per capita. This figure is a great leap from the meagre 535 m^3 per capita that has always been fronted previously that consistently understated

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[1] Research on Kenya groundwater potential is still in progress

groundwater potential, ranking Kenya among chronically water scarce countries. All the same, assuming that the sustainable groundwater yield is 10% of the recharge, then the annual available water resources would be 26.2 BCM and accordingly, the annual per capita available water resources would be a meagre 681 m^3, which implies that effective WRM is vital if robust economic growth is to be achieved.

Table 3: Drainage Basin as demarcated by NWRMS (MEWNR, 2013)

Basin	% of Total land area	Renewable Surface WR (MCM/yr)	Renewable Ground WR (MCM/yr)	Catchment Total WR (2009) (MCM/yr)	Catchment Total WR (2030) (MCM/yr)
Lake Victoria	8	9,399	15,820	25,219	26,428
Athi River	11.5	1,198	3,330	4,528	4,634
Tana River	21.7	5,858	8,790	14,648	15,991
Rift Valley	22.5	2,457	14,020	16,477	16,965
Ewaso Nyiro	36.3	1,725	14,010	15,735	16,446
Total Renewable WR		**20,637**	**55,970**	**76,607**	**80,464**

2.4 Athi River Catchment

Athi River Catchment Area (ACA) occupies the South-eastern part of Kenya. ACA is 65,935 km^2, delineated to accommodate 37,750 km^2 (or 57% of ACA) catchment of Athi River, which at 390Km is the second longest River in Kenya and the main river within ACA. Others are, the two transnational sub-basin of River Namanga and Lake Amboseli (3,155 km^2); River Lumi, which has source at the outskirt of Mt. Kilimanjaro in Tanzania and feed border Lake Jipe (2,804 km^2). River Rare, also known upstream as R. Rare/Voi (7,625 km^2), R. Mwachi (3,874 km^2), R. Pemba (4,760 km^2), and R. Ramisi (3,234 km^2), all flow independently into the Indian Ocean. The South-most River in Kenya is Umba which crosses from Tanzania just before it empty into the ocean, and its mouth mark the most eastern border point between the two countries (Appendix, Figure 70).

Upstream Athi River is a conglomeration of several perennial tributaries, which include Stony Athi River and River Mbagathi with their numerous tributaries from around the slopes of Ngong hills at the South-west of Nairobi city. River Nairobi which is the focus area of this study has its source at Ondiri swamp also at the South-west of Nairobi, and is joined by R. Ruiru at the North-eastern boundary of Nairobi County before it drains into Athi River. Further in the North-eastward course, there are confluences with R. Ndarugu and then Athi River turn sharply to the South-east and is joined along the course by R. Thwake and then R. Tsavo, before it turn eastward and drain into the ocean at the North of Malindi town (Appendix, Figure 70).

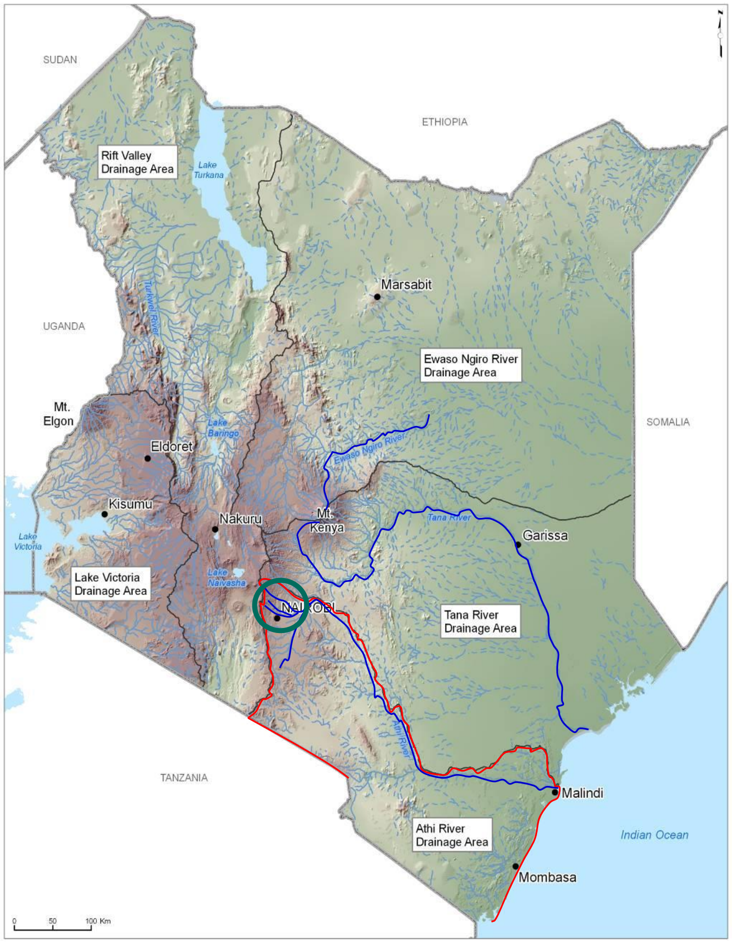

Figure 7: Delineation of the five main drainage basins in the country with emphasis on the case study area 'circled' (source: MoWD and JICA 1992)

Major cities/towns in the catchment are: Nairobi (the capital city), Mombasa (the second largest city), Kiambu, Kikuyu, Limuru, Ruiru, Juja, Thika, Athi River, Kajiado, Machakos, Makueni, Kibwezi, Makindu, Loitoktok, Kilifi, Taita Taveta and Malindi. The catchment hosts approximately 10 million people, or more than 25% of the country total population; and also vital economic (agricultural, industrial and commerce) hubs in capital and port cities, among other key urban and rural economic zones. The respective counties population as per 2009 census includes Kiambu (1.62M), Nairobi (3.14M), Machakos (1.1M), Kajiado (0.69M), Makueni (0.88M), Taita Taveta (0.28M), Kwale (0.65M) and Mombasa (0.94M), and Kilifi (1.11M).

Moreover, vital wildlife ecosystems that include Nairobi, Ol Donyo Sabuk, Amboseli, Chyulu Hills, Tsavo East and Tsavo West and Arabuko Sokoke National Parks and numerous forest and game reserves are under stringent protection within the catchment. Consequently, management of water to spur and sustain economic growth and cater for the ecological needs is pertinent in the catchment.

This was one of the major factors that influenced the study choice of this catchment. Nairobi River catchment was established as a representative unit of the entire catchment in that it play host almost all the complex water demand and supply scenarios prevalent within the entire basin and typical to most third world countries.

2.4.1 **Water Resources Situation in ACA**

From the recent study, the available water resources consisting of the surface water runoff and sustainable yield of groundwater were estimated in ACA for the years 2010 and 2030 as in the table below.

Table 4: Annual Available Water Resources for ACA (source: WRMA)

Year	**Surface Water (MCM/yr)**	**Groundwater (MCM/yr)**	**Total**
2010	1,198	333	1,531
2030	1,334	330	1,664
Percentage of 2010 values	111%	99%	109%

The sustainable yield of ground water was derived as 10% of the estimated total recharge in the catchment area excluding river courses and riparian areas with a width of 1km. The annual water demands for 2010 and 2030 are summarised below.

Table 5: Water Demands by Subsector for ACA (Source: WRMA)

Year	**Water Demands (MCM/yr)**						
	Domestic	**Industrial**	**Irrigation**	**Livestock**	**Wildlife**	**Fisheries**	**Total**
2010	519	93	498	25	3	7	1,145
2030	941	153	3,418[2]	59	3	12	4,586

Table 6: Available Water Resources and Water Demands ACA (Source: WRMA)

The ratio of 75% of water demand to water resources, which is called a water stress ratio, shows a very tight balance between water resources and demands compared with the ratio of 40% regarded to indicate severe water

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[2] Assuming that total annual recharge could be impounded progressively

2010		2030	
Water Resources (MCM/yr)	**Water Demands (MCM/yr)**	**Water Resources (MCM/yr)**	**Water Demands (MCM/yr)**
1,531	1,145	1,664	4,586
Percentage of Resources	75%	Percentage of Resources	276%

stress. The existing water transfer facilities from the Tana River Catchment (TCA) to Nairobi with the capacity of 210 MCM/year have an important role in alleviating the stress. The water demands for 2030 are expected to increase for about 276% against the related estimates of available water resources. This implies that the available water resources and demands should maintain a balance by maximum utilisation of water resources (MEWNR, 2013). It also implies that mitigation measures have to be put in place to avert extreme water stress in the catchment by construction of buffer storage within the catchment. This will ensure that the 90% annual recharge to groundwater that is considered vital for maintenance of base flow in rivers for human exploitation and ecological sustenance throughout the year is not interfered with. Therefore the demand for irrigation had to be modified (see table below) in order to rationalise it with the limited available water resources.

Table 7: Modified Water Demand Projections for 2030 for ACA (Source: WARMA)

Source	**Water Demands (MCM/yr)**						
	Domestic	**Industrial**	**Irrigation**	**Livestock**	**Wildlife**	**Fisheries**	**Total**
Surface Water	819	77	882	59	3	12	1852
Groundwater	122	76	59	0	0	0	233
Total	941	153	917	59	3	12	**2,085**

Around 54% of the population in the catchment area are supplied with water through pipes by registered WSPs. As for Nairobi and satellite towns, according to the Performance Report of Kenya's Water Services, No. 4, 2011 and the data from WSBs, 11 registered urban WSPs and seven registered rural WSPs manage the water supply systems to cover 2.96 million of the service population with 572,895 m^3/day (i.e. 95% of water supply capacity). The NRW ratio in the area is relatively lower than the other areas. Out of the 11 urban WSPs, only two WSPs have records of more than 50% of NRW (MEWNR, 2013).

2.5 Nairobi River Catchment

The Nairobi River is one of the main tributaries of the Athi River at the upstream. It originates at Ondiri swamp within Kikuyu District of Kiambu County in Central Kenya, to the South West of Nairobi city. It has a complex network of tributaries from the foot of Ngong hills and slope of Aberdares ridges, all flowing eastwards. They include Motoine –Ngong, Kirichwa, Mathare, Kamiti, Gitathuru, Karura, Rui Ruaka and Ruiru Rivers. Nairobi River flows through Nairobi city centre before emptying Mathare River which flows at the Northern outskirt of the city, then converging with Ngong River that flows from the South-west of Nairobi, before picking the other tributaries as it tends towards North-East of the county where it pours into Athi River. The Nairobi River and its tributaries drain a catchment area of approximately 1145 km^2 (Appendix Figure 69).

2.5.1 **Topography**

The topography of ACA varies from the highland on the Aberdare Range at around 2,600 m above mean sea level (amsl) to the coastal area at the sea level. ACA is divided into three zones i.e. the upper zone at 2,600-1,500 m amsl, middle zone at 1,500-500 m amsl and coastal zone at 500-0 m amsl. Nairobi River catchment is exclusively in the upper zone with the Nairobi city lying at 1500 – 1900m amsl. The city is generally flat but rises steeply to the South-west towards Ngong Hills and to the North-west towards Kiambu in Central Kenya as you approach the slopes of Aberdares; the source of several tributaries of Nairobi River.

2.5.2 **Soil and Drainage**

The geology of the area mainly exhibit a succession of lavas and Pyroclastics of the Cenozoic age and overlying the foundation of folded Precambrian schist's and gneisses of the Mozambique belt. The crystalline rocks are rarely exposed but occasionally fragments are found as agglomerates derived from former Ngong volcano. The soils of the Nairobi area are products of weathering of mainly volcanic rocks producing red soils that reach more than 50 feet (15m) in thickness (Saggerson, 1991).

The catchment drainage follows the regional slope of the volcanic rocks towards the east. The lava plains east of the line Ruiru-Nairobi-Ngong are underlain by a succession of lava flows alternating with lakebeds, streams deposits, tuffs and volcanic ash. These plains, comprising mainly the Athi plains and the northern section of the Kapiti plain, extend westwards, rising from 1493 m at the Athi River to 1829 m in the faulted region near Ngong. The lava plains are crisscrossed with steep-walled gullies and canyon-like gorges, such as those along the Mbagathi valley. Further east this valley widens slightly where soft material is being actively eroded (Saggerson, 1991). Water draining eastward from the hill area accumulates on the low-lying ground between Parklands at the north and Nairobi South estate, forming a perched water table above the Nairobi phonolite. The Kerichwa Valley Tuffs lying to the east of the highway function like a sponge and the contact between them and the underlying impermeable phonolite thus forms a perfect aquifer, so much so that a number of channels containing water occur beneath Nairobi (UNEP, 2007).

2.5.3 **Climate**

As demonstrated earlier, the larger portion of ACA lies under ASAL; hence making the catchment have a low average mean annual rainfall of around 810 mm. In the year 2010, the renewable water resources for the entire basin, which is defined by precipitation minus evapotranspiration was estimated at 4.5 BCM/year (Table 3) and thus per capita renewable water resources estimate was 450 m^3pa. But the climate in upper zone where the Nairobi catchment lies ranges from humid with average annual rainfall at 1000 - 1500mm to semi-humid at the middle with average annual rainfall of 600 - 800mm ; while the lower extreme exhibits semi-arid conditions with average annual rainfall ranging between 400-600mm. The mean daily temperature ranges from 9 to 26ºC. July is the coldest and driest month while January is the hottest (CBS, 2003). The mean monthly relative humidity ranges between 39% to 75% in Nairobi County and 43% to 80% in Kiambu County. The mean daily sunshine varies between 3.4 to 9.5 hours (CBS, 2003).

2.6 Sedimentation

Deforestation especially on steep slopes, poor cultivation methods, cultivation on riparian zones, urbanization and degradation of wetlands and floodplains contribute to increased frequency and intensity of flash floods after storms. The extreme flow dynamics aggravates the loss of valuable soil cover and degradation of aquatic environment through erosion and deposition at regions where flow is impeded. Higher sediment loads in rivers and streams exacerbate siltation behind dams, causing loss of useful storage for the modern multipurpose reservoirs and lakes while also causing loss of vital depth in navigation and irrigation channels. Similarly, sediments deposit at downstream floodplains, coastal deltas and estuaries; also cause gradual transformation in river morphology.

Consequently, siltation reduces the economic life of reservoirs and hydraulic capacity of water conveyance structures; disrupts water supply operations; render navigation utilities like jetties redundant; and affects natural aquatic ecosystem functioning. The catchment area of the Upper Tana and Athi River basins, particularly the Aberdares, have undergone intensive environmental degradation as a result of agriculture and settlements encroachment into forests and related deforestation; hence reducing natural flow retention capacity that help attenuate flood intensity. Every year, the Tana River and the Athi (also known as Sabaki at downstream) River deposit several million tons of sediment. Consequently, management of sediment loads in rivers and canals constitutes one of the key factors for the formulation of water resources development.

2.7 Governance and Socio-Economics

2.7.1 **New Governance Opportunities and Challenges**

Kenya is governed under a unitary democratic system, whose operation until March 2013 was centralised with Nairobi being the seat of government and state. The new constitution promulgated on August 2010, which became fully operational on March 2013, devolved the government into 47 semi-autonomous counties headed by elected governors. The counties are further administratively divided into 159 districts, 596 divisions, 2606 locations and 7151 sub-locations respectively. Thus a sub-location headed by a sub-chief is the lowest administrative division from which statistical data on population, demography, land etc. are consolidated.

Devolution of governance is expected to enhance equity in distribution of national resources and balanced development throughout the country. But as expected, some counties like Nairobi, which have hitherto enjoyed greater share of national resources will suffer the blunt of the necessity and competition from development in adjacent counties. Currently, Nairobi draws huge quantities of water from Murang'a and Nyandarua counties and with growing population and industrial demand, development of more sources are underway (Appendix Figure 68). This is an indisputable source of future potential conflicts, since for the benefits of devolution to be actualised, the new counties are expected to develop their urban and rural districts, provide services and proffer higher living standards to the residents. Availability and sustainability of adequate supply of clean water at favourable economic cost is pertinent to any tangible social-economic development; hence future growth for counties that share water resources will depend on both the demand management policies and collaboration in developing future supply infrastructure and policies and rehabilitation and conservation of catchment areas.

2.7.2 **Population and Demography**

Since 1948, a population census has been conducted in the every 10 yrs and recently demographic indicators have been incorporated to accommodate increased interest in data for planning and development.

Table 8: Selected Demographic Indicators for consecutive Kenya population census (KNBS)

Indicator	**1969**	**1979**	**1989**	**1999**	**2009**
Population(millions)	10.9	15.3	21.4	28.7	38.6
Density(pers./km^2)	19.0	27.0	37.0	49.0	66
Percent urban	9.9	15.1	18.1	19.4	32.3
Percent rural	90.1	84.9	81.9	80.6	67.7
Growth rate	3.3	3.8	3.4	2.9	2.8
Infant mortality(/1000 births)	119	88	66	77.3	
Life expectancy at birth	50	54	60	56.6	60
% People with disability: Male	-	-	-	-	3.4
% People with disability: Female	-	-	-	-	3.5
% Households with a computer	-	-	-	-	3.6

Indicator		1969	1979	1989	1999	2009
% Household with safe water	Urban	-	-	-	-	89
	Rural	-	-	-	-	43
	Total	-	-	-	-	56
% Household with improved sanitation	Urban	-	-	-	-	67
	Rural	-	-	-	-	42
	Total	-	-	-	-	57

In the 2010 the population in the ACA was estimated at 9.79 million, with the urban population at 6.51M, and the rural population at 3.28M. The population in Nairobi and surrounding urban centres accounting for 64% and 30% being accounted for by Mombasa and surrounding areas (MEWNR, 2013).

Table 9: Selected Population Projected for ACA (Source: WRMA)

(Unit: million persons)

Year	Urban Population (Million)	Rural Population (Million)	Total (Million)
2010	6.51	3.28	9.79
2030	17.73	2.81	20.54

2.7.3 **Socio-Economic - Water Supply and Sanitation**

The population of the Nairobi River Catchment is estimated to be approximately 4.5 million, of which approximately two-thirds live in the major urban areas, namely Nairobi, Kiambu, Kikuyu and Limuru. It is estimated that activities within the catchment, many of which are highly dependent on water, generate between 40 and 50 percent of the gross domestic product (GDP) of Kenya. Economic ventures are diverse and include manufacturing, processing and assembling industries, trade and commerce, cash crop and subsistence agriculture, and tourism. There are wide variations in economic development throughout the catchment and large inequities in domestic and productive water use between the affluent and poor society habitats. A large proportion of the population lives in low-income settlements, including informal settlements.

At present, over 90% of the water is from surface resources drawn from the adjacent Tana River basin and more supply have been planned to import more water (appendix Figure 68 and Figure 71). This reliance on external sources of water has over time inculcated a lethargic approach to local catchment conservation leading to the current situation; where heavily polluted main rivers of Nairobi catchment i.e. Nairobi, Mathare, Kamiti and

Ngong, whose riparian areas have been overexploited by informal peri-urban settlements, need extensive rehabilitation before any abstraction can be conceived.

A case in point is the Nairobi Dam, which was commissioned in 1953 along Ngong River as a special reservoir to provide potable and emergency water supply for the Nairobi City. Its water surface area is 356,179m^2 with a total holding capacity of 98,422 m^3 when completely full. However, unchecked heavy pollution especially from solid waste emanating from neighbouring Kibera informal settlement has completely choked the dam with organic nutrients causing eutrophication and emergence of invasive plant species; mainly water hyacinth and parrots feather, that are now the face of the water body since 1998 (See Figure 8&9 below).

Unabated pollution, sedimentation and flooding during rainy seasons is typical of all the rivers flowing within Nairobi County due to urban development and pollutants loading from non-point sources like fertilisers and chemicals from upstream agricultural activities and point loading from direct disposal of waste water and industrial chemicals; especially from informal settlement and industries respectively. Thus Nairobi and her environ depends mainly on imported water from Kikuyu springs (5500 m^3/day) and Ruiru dam (21,912 m^3/day) both in Kiambu County; Sasumua dam (71,232 m^3/day) in Nyandarua County; and Thika dam (504,408 m^3/day) in Murang'a County. It is estimated that about 42% of households in Nairobi have household piped water supply, while in informal settlements most people obtain water from vendors (UNEP, 2007).

There is increasing exploitation of groundwater to bridge the supply deficiency within the city and immediate environ, a situation that is further exacerbated by water loss especially due illegal connections and leakage in old pipes and also due to vandalism especially within informal settlements where the line pass through and yet households are not connected. To attend to the underpinning social conflict, water supply companies lately introduced water kiosks to serve water vendors and the unconnected households along the pipeline. In entire Nairobi Catchment, the annual utilizable quantity of groundwater is estimated to be approximately 250 Mm^3, of which between 75 to 100 Mm^3 are currently abstracted (MEWNR, 2013).

Figure 8: Aerial view of Nairobi dam (UNEP, 2007)

Figure 9: Water Hyacinth; the face of Nairobi dam (WARMA 2012)

Nairobi has two major sewage treatment plants: Dandora with a daily treatment capacity of 80,000 m^3, and Kariobangi with a daily treatment capacity of 32,000 m^3. Dandora is a lagoon-based plant, while Kariobangi is a conventional plant based on biological aerated filters (ECFA, 2008). Together, the two plants discharge about 90,000 m^3 per day of partially treated effluent to the Nairobi River system, about 7 km downstream and north-east of the city centre (UNEP, 2007). The estimates of sewerage system coverage differ widely: about 10% of the population according to UN-Habitat (UN-Habitat, 2003b), and about 48% of the population according to the government estimates (ROK, 2002). The system currently serves only some of the wealthy/middle-income residential and commercial districts, but informal settlements are not served yet in some areas the trunk sewer run close or through them. Septic and conservancy tanks are the main solution for upmarket districts that are not served, while improve pit latrine and open pit latrine serve most informal settlements.

The gross deficient in water supply and wastewater drainage infrastructural leads to sanitation crisis typical of most urban settlements in developing countries; where significant proportion of the population have no access to hygienic sanitary facilities and subsequently large proportion of wastewater is discharged without adequate treatment to the environment; with major impacts on quality of human life, terrestrial and aquatic environment (Hutton, et al., 2007).

Chapter 3. Adaptive and Collaborative WRM

3.1 Paradigm Shift in Water Sector

Integrated water resources management (IWRM) approach has been universally accepted and adopted within the water sector in Kenya and the Water Act 2002 was enacted in the year 2003, to institutionalise relevant provisions; especially for promoting and facilitating a coordinated development and management of water, land and related resources to maximize the resultant economic and social welfare in an equitable manner; without compromising the sustainability of vital ecosystems (Agarwal, et al., 2000).

IWRM initiative besides the water efficiency plan (WEP) encompasses the spirit of the Kenya national policy on water resources management and development (MWI, 2009). The policy, together with the water act, provides the necessary strategy and legislative as well as a framework for the sustainable management and efficient utilization of the water resources. The national water resources management strategy recognizes IWRM and WEP as national priorities, with obligations to ensure capacity building, collective stakeholders' participation and to decentralize management to the lowest appropriate level. This has been necessitated by appreciation that, when authoritative natural resource management agendas ignore the knowledge and perspectives of local people, they often do not achieve their objectives. Shared learning, on the other hand, shows potential to empower local people and strengthen their participation in adaptive collaborative management (Kamau & Kimberly, 2014).

This is also in resonance with the spirit driving the prevailing local political and socio-economic governance devolution, to ensure equitable distribution of resources nationwide for balanced growth; and which also inculcate bottom-top/top-bottom flow of information between managers and users at grass root level (see Figure 10) to promote sustainable allocation of scarce resources. This management approach presents a stronger position to effectively link, horizontally and vertically, learning by experience and experiment with policies and regulations and local co-management (Kamau & Kimberly, 2014).

This is a welcome shift in paradigm from water resources management regime where technology advancement has been synonymous with better supply infrastructure development without local engagement at any level, to a holistic collaborative approach which seeks opportunities beyond fostering infrastructural development. The new regime endeavours, through participatory approach to provide better environment, socio-economic, health, and liveability outcomes in all aspects of water supply, disposal and management. The approach is fundamental to creating vibrant communities which meet their social and economic needs while being in harmony with the local environment. Moreover, "Water for All" policy advocates that water is a vital social and economic good that needs careful management and a participatory approach to help develop, use, manage, conserve and protect it (OECD, 2009).

To advance appreciation of water in its economic context, water tariffs on use should be commensurate with the resource reality and investment involved in developing it. On the other hand, permits on abstraction should be pegged on the opportunity cost to ensure trade-off between alternative uses and make allocations in a manner that optimal benefits accrues from available resources.

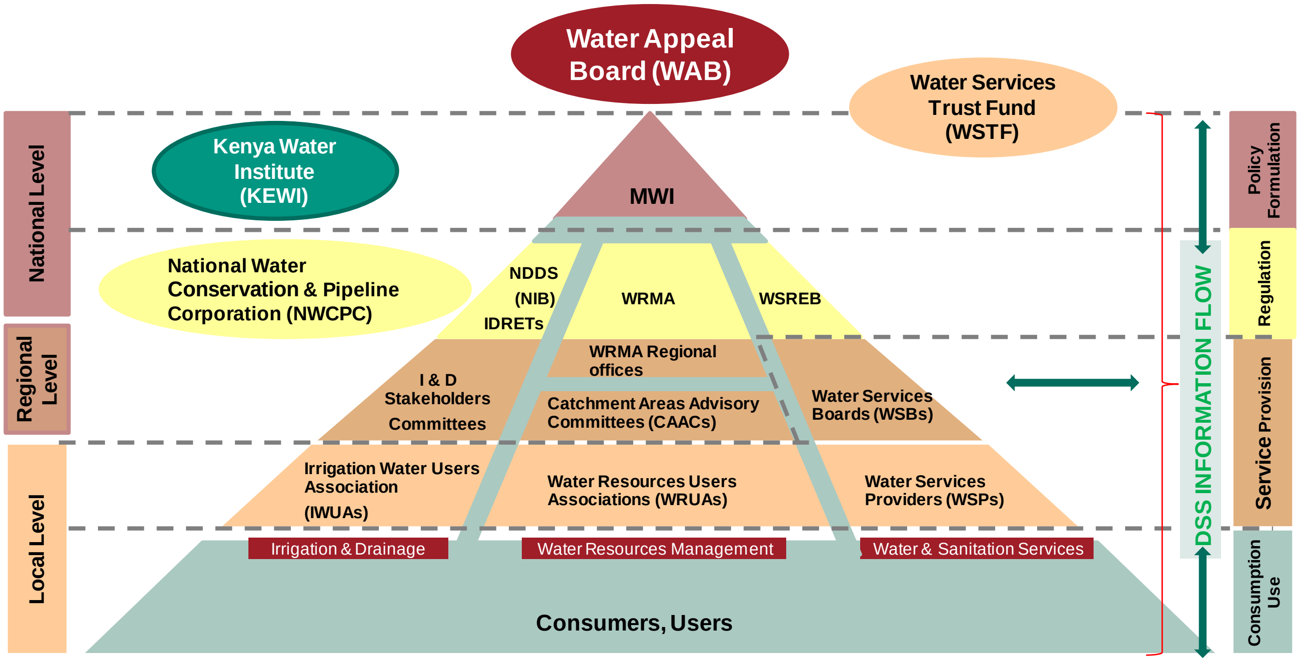


Figure 10: National structure for participatory water resources management (WRMA -reviewed)

To cushion the underprivileged members of the society, who would be alienated if the economic cost of water were to be demanded across the board, Water Services Trust Fund (WSTF) has been set up with an annual fund vote to ensure development and maintenance of water supply and sanitation infrastructure in low income settlements and provision of water and sanitation services at subsidised rates to ensure hygienic living condition for all. Water institutes are mandated with capacity building in the sector, both to promote innovations and to ensure information flow (horizontally) and (vertically) at various levels of management as shown in Figure 10. To ensure any conflicts arising from sectoral engagements (among various stakeholders or between managers and aggrieved users) are solved amicably, Water Appeal Board (WAB) was set up with mandate to arbitrate on all disputes ensuing from water allocation, abstraction and subsequent disposal.

The above illustrated national structure for participatory management provides an auspicious platform for engagement of all stakeholders within the water sector, and for inter-sectoral collaborations. Which will ensure comprehensive information is gathered especially on issues pertinent to individual users' community and entity; as to facilitate decision making during trade-offs on alternative allocation of water resources. It also proffers information dissemination to aid communication of decisions and sector policies, and to get feed backs for iterative improvement of management regime. By integrating the availed socio-economic and statistical data with hydroclimatic data availed through relevant time series measurements, this structure offers a perfect environment for integral operation of various decision support tools.

The prospect of providing water in and efficient and sustainable manner to boost economic growth is envisaged in ‘Kenya vision 2030’ and the study on National Water Master Plan 2030 has been engineered to develop and roadmap on how the direly needed (equitable and sustainable) economic growth could be achieved without compromising sustainability of vital ecosystem as proffered in IWRM. Accordingly, Water Resource Management Authority (WARMA) and National Environmental Management Authority (NEMA) have been set up with mandates to coordinate the national water resources management strategy and to ensure prior to development of any infrastructure its environmental impacts are assessed and efforts put in place to mitigate any adverse effects respectively. Catchment management strategies and environment management strategies, though spearheaded by two independent authorities, are by and large extracts of the one broad strategy which in entirety endeavour to ensure sustainable provision of water to critical sectors of the economy, e.g. irrigation to boost food security, while maintaining the environmental integrity (MWI, 2008).

3.2 System Analysis for Decision Making

The investigation of complex environmental systems that are affected by human action is considered a major scientific feat. The challenge is how to overcome the gap between natural and social sciences and master modelling on different scales through integration of knowledge from natural and social sciences. The principal feature of modelling is the facilitation of system representation and evaluation; hence aiding speedy investigation of various policies, regulations, controls and feedbacks, and in particular, on adaptive cycles that describe real and/or sustainable system behaviour. System’s behaviour is modelled from a decision theoretic perspective differentiating between goal setting, strategy formulation, strategy selection and action, (Scholz & Binder, 2004). Through interpretation and evaluation of model outputs, managers are able to make deductions that facilitate decision making for planning, development, operation and management.

Water resources management and hydrologic modelling studies are intrinsically related to the spatial processes of the hydrologic cycle (Figure 11) i.e. the movement and exchange of water among various components of the environment.

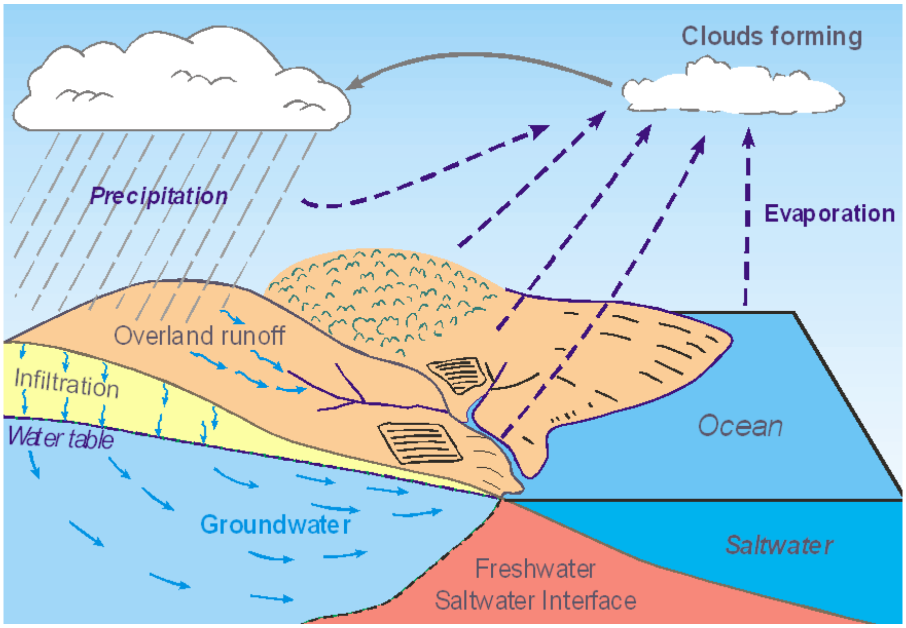


Figure 11: Schematic of the hydrologic cycle

3.3 Modelling as a Decision Making Tool

Developments in computer technology have revolutionized the study of hydrologic systems. A variety of computer-based hydrologic/water quality models have been developed for applications in hydrologic modelling and water resources management applications. Lumped hydrologic models simulate a spatially averaged hydrologic system, while distributed models involve a more accurate representation of the hydrologic system by considering the spatial variability of model parameters and inputs (Chow, et al., 1988). Distributed parameter hydrologic models generally subdivide the watershed into smaller sub-basins and require data on model inputs such as soil and land use for each of those sub-basins. Though this results in a better illustration of the natural hydrologic system, data assembly and input files development for such models require enormous effort and time especially when simulating large river basins.

Advances made in GIS technology led to the development of interfaces between hydrologic models and GIS with the later availing digital spatial data necessary for water resources studies. In the past, these interfaces have aided the assembly of the required spatial data, enabling water resources professionals to study large watershed systems with significant savings in time and cost. As a result, they facilitate analysis of the impact of different watershed management scenarios on water yield and quality. Some of the modelling tools have subsequently been incorporated in GIS environment as extension e.g. MIKE BASIN. However, with the need to be more flexible and avoid environment limitations, many (e.g. WEAP) have preferred individual platform while retaining interface with other applications to allow importation and sharing of data from GIS, excel etc.

Today, there is wide agreement that the decision process cannot be reduced to choice (Langley *et al.*, 1995), and the role of information and the building of possible alternatives are widely regarded as critical. Decision making

(DM) is the process of that facilitate selection from several alternative products or ideas, and taking action or implementing the ultimate choice in order to achieve an objective. Any empirical, analytical or numeric procedure that facilitates decision makers in water resources planning, operations and management is referred to as a 'tool' for water resources systems management (Simonovic, 2009). The stages involved in DM are, problem structuring i.e. to identify and define or describe the situation at hand; identification and generation of alternatives that can address the problematic situation; information gathering – collection of relevant input data; selection – choosing the best option among those considered through either optimization, constrained optimization, pre-selection, satisficing or randomization strategies; action – adopt a course of action and implement it.

Decision Support System (DSS) on the other hand are software based systems that support collection, analysis and simulation of data to facilitate an informed decision making process involving all stakeholders. In the context of this study, DSS is exclusively used in reference to various computer applications that both manages and analyse water resources data through various water management policy scenarios and present results in a form that aids various stakeholders make planning, development and management decisions more effectively. The performance of a decision support tool is thus dependent on the quality of the data input by the user; therefore more emphasis should be placed on the first three steps of DM process. The main factor responsible for involving computers in the decision making process is the treatment of information as the sixth economic resource i.e. besides people, machine, money, materials and management (Simonovic, 2009).

Decision making for sustainable management of natural resources has always been a very complex process. Moreover, population growth, climate variability, regulatory requirements and the demand for longer spatial and temporal scale planning to factor the needs of future generations are factors that increase the complexity of water resources problems. It's for this reason that DSS tools have been adopted, within which a decision making process is facilitated starting with problems understanding through exploring spatial and time series databases encompassing social-economic, environmental and resource factors to best structure the problem as to model and aggregate decision preferences. The exercise is intended to manage decisional problems as to proffer a management regime that is optimal, equitable and sustainable. This management paradigm, which has also been adopted in countries hitherto considered to be richly endowed in water resources, has been precipitated by the fact that internationalisation of markets has immensely altered the scale of economic activities and, as a result, impacted on the intensity of water use in many sectors (Giupponi, et al., 2004).

Decision Support Systems are integrated in the water management strategy to provide a dynamic and effective supply and demand analysis and water allocation to competing uses. The main goal is to guarantee optimal and sustainable exploitation of water resources to meet the social-economic needs of the populace, while allowing for ecological base flows, which are affected when normal demand allocation mechanisms prevail. There is especially a necessity for a management regime that is robust enough to cope with the impacts of climate change that has challenged the traditional hypothesis that past hydrological experience provides a good guide to future conditions.

Climate change continues to influence the Earth's surface temperature, as well as the amount, timing and intensity of precipitation, including storms and droughts. It is expected to exacerbate pressure, directly or indirectly, on all aquatic ecosystems, with catchment degradation leading to escalation in runoffs, flash floods, reduced infiltration, erosion and siltation. Therefore there is a dire need for mitigation and adaptation options designed to ensure water supply during drought conditions that require not only integrated supply-side strategies (e.g. expanding supply infrastructure) but also the demand-side measures (e.g. introducing scaled water tariffs, water reuse and water recycle). Water resources management clearly impacts on many other policy areas, e.g., energy, health, food security and nature conservation which require the decision makers to adopt a multi-sectoral, multi-disciplinary and multi-criteria approach.

The complexity of the problem requires taking into account qualitative approaches based on broad-based perceptions and quantitative approaches based on measurements. The quantitative approaches can be particularly useful for decision making, but a well-balanced decision-making process requires taking into account three fundamental cores of influence (Figure 12): Rational, subjective and ethical ones. The ultimate choice is by and large subject to how it balances satisfaction accrued from the three:

- **Rationality**: capacity to proffer economy and optimality is vital i.e. decision process should facilitate evaluation of alternative water use trade-offs, to optimize the benefit accruing from the resource and investment;
- **Subjectivity**: in that the judgements is based on decision maker's perception on system performance within the prevailing constraints; hence providing ground for stakeholders' consensus; and finally
- **Ethics**: decision process should take into account the prevailing social-economic and technical capacity without substantially compromising performance and also allowing reasonable sacrifices for ecological demand.

Previous models in decision making using operations research have relied more on rational influence ignoring the decision maker's freedom of choice and ethical interests. However, it has been shown that, if well adapted, multi-criteria decision approach can provide well-balanced solutions between rationality, subjectivity and ethical conscience of mankind (Brans, 2002).

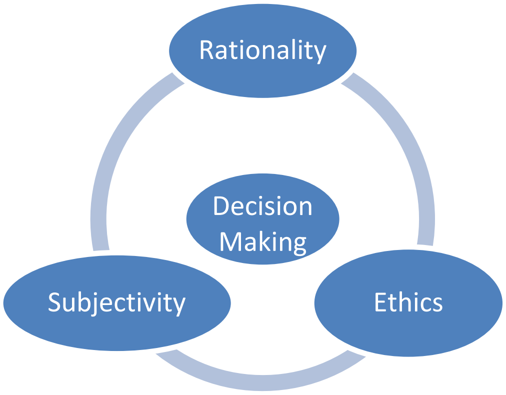


Figure 12: Decision making cores of influence (Brans, 2002)

3.3.1 **Multi-Criteria Analysis**

This approach emphasizes on the role of subjective core in the decision process; where the decision maker is no longer subjected to the drastic rationality of the optimal solution, but has the freedom to consider several optimality points of views and ascertain solution optimising all of them. Many methods have been proposed which mainly differ in the kind of additional information they need, the methodology they use, their user-friendliness, the sensitivity tools they offer, and the mathematical properties they verify. Ethics should also influence decisions because of the necessity to respect the social and the natural environment. It allows evaluation of policies that can cause social ills (i.e. social conflict, unemployment etc.) environmental ills (waste, pollution etc.) and consideration of future generations where sustainability plays a vital role.

The basis of this methodology is the multi-criteria decision analysis whose principal objective is to reduce multiple option performances into a single value to facilitate the ranking process. This helps decision makers learn about the problem situation, about their own and others values and judgements, and through organisation, synthesis an appropriate presentation of information to guide them in identifying, often through extensive discussion, a preferred course of action" (Belton & Stewart, 2002). Whereas using Multi-criteria approach in water resources management will help provides an objective analysis in the effort to obtain the right answer when we have to decide between different sets of policy options; it will not relieve decision makers the responsibility of making difficult judgements. All the same, the approach endeavours to make the subjective judgements explicit and the process by which they are taken into account transparent, which is very important when a large number of actors are involved in the decision process (Belton & Stewart, 2002).

3.3.2 **Modelling Catchments as Water Administrative Units**

Catchments, or river basins and sub-basins, have become the point of reference for developing a long list of activities required in water resources management, such as the establishment of monitoring systems, the application of hydrologic models, and the design of River Basin Management Plans (RBMP) (Giupponi, et al., 2004). Each river basin encompasses complex and interactive relationships that include both physical elements and human societies whose activities are an integral part of the areas system dynamics. The large amounts of information required for integrated spatial analysis and evaluation of impacts resulting from possible options and public participation put high expectations on ‘sound’ and ‘transparent’ decisional processes that can guarantee spatially balanced sustainable resources development and conservation (Giupponi, et al., 2004). The spatial dimension in all field of environmental planning is increasing becoming vital with demand for harmonised geo-referenced information to aid an integral environmental management strategy. The need for a sound scientific knowledge and economic assessment, reliable and up-to-date environmental data and information to support the formulation, implementation and evaluation of environmental policy is emphasised. The development in the field of geographic information (GI) and geographic information technology (GIT) has allowed more geographical differentiated policies targeting policies for local conditions (Mysiak, et al., 2002).

3.3.3 **Good Modelling Practice in Information Synthesis**

There are great benefits in the use of modelling as an approach to understanding and supporting decisions on environmental systems. However, for a model to be of value, good practice in its construction, testing and application is as essential, as is awareness of the purpose, capability and limitations of the modelling approach.

Without this, there is a risk of the model user misinterpreting or misusing model outputs, and drawing invalid conclusions (Jakeman, et al., 2006). Good modelling practice will result in better understanding of the development and application of models; this benefits not only the modelling community but also model users who employ the models for improving knowledge of the system or decision making. Poor modelling practice reduces the credibility of the model and can lead to the model capabilities being overrated, potentially causing poor decisions to be made based on models, or where model transparency and testing has not been completed, users mistrusting models and their outputs (Refsgaard & Henriksen, 2004). Consequently, guidelines for good modelling practice that create standards to help ensure the development and application of credible and purposeful models are essential. The key components for good practice include: clear definition of model purpose and the assumptions underlying it; thorough evaluation of the model and its results; transparent reporting of the whole modelling process, including its formulation, parameterisation, implementation and evaluation (Crout, et al., 2008).

Chapter 4. **Decision Support Systems**

4.1 Introduction

As previously stated water resources management in Kenya as in most developing countries is fret with lack of necessary institutional infrastructure, obsolete techniques (see Figure 13), poor quality or totally unavailable data, highly variable spatial and temporal distribution leading to water use conflicts between competing stakeholders and enterprises. These challenges calls for a systems that support informed choices to alleviate these drawbacks. Grounded on efficient data acquisition, storage, processing and output management systems, decision support systems (DSS) software would facilitate the achievement of this goal. Decision support systems (DSS), if integrated with appropriate geographical information systems (GIS), can enhance water resources management by enabling spatial investigations (Ochola & Kerkides, 2003).

Figure 13: Flow measurement techniques using current meter at the Nairobi River (WRMA 2012)

The computer-based modelling systems enable processing of large amounts of data to information required for better analysis and evaluation of water resources parameters and their environmental, physical and socio-economic impacts to facilitate informed decision making. The approach is intended to support watershed management strategies by guiding stakeholders in developing and evaluating water resources management alternatives for a catchment. It take various stakeholders through series of perceptible steps and present them with information in a logical manner so that they can understand real problems and issues arising from varied and conflicting uses and demands for the finite water resources; hence proffer a catchment-based decision support framework for sustainable water use.

Some DSS makes it possible to use spatially integrated water appurtenances and demand structures in form of schema interfaced with GIS to facilitate uploading of a wide range of water resources, land use and diverse statistical data relevant to the actual study objectives, hence facilitating holistic water resources assessments.

The use of the single platform, through integration of DSS and GIS functionalities, for assessments of different themes permits simultaneous examination of diverse water resources attribute data (e.g. demand, supply, stream flows, quality etc.), thus enabling the interpretation of a wide range of interrelated geographical information for the catchment area. This is complemented by other DSS functionalities like forecasting ability via simulation of expected future scenarios to provide powerful tool for planning, design and development of various water appurtenances and policies to mitigate foreseeable conflicts and adverse conditions. Data pre-processing in GIS environment promotes seamless linkage of all modules for data acquisition and production of a variety of thematic maps e.g. terrain, geology, soils, population, demography, water resources types, farm unit holdings, land cover as well as water use and land use practices (Ochola & Kerkides, 2003).

More importantly, visualization capacity within DSS is expected to proffer improved dissemination of water related policies and decisions to both the scientific community and the local community, hence facilitating closed-loop information flows. The feedback from users and model evaluators within the scientific community in turn help in iterative development of the model to yield progressively better results and more reliable and user-acceptable systems.

4.2 MULti-sectoral INtegrated and Operational Decision Support System – (MULINO DSS)

This is a real-time operational tool based on hydrological modelling, multi-sectoral indicators and a spatial-temporal multi-criteria evaluation designed to proffer decision support for catchment-based management especially in coping with real problems and issues arising from varied and conflicting uses and demands for water resources. Through integration of social-economic and environmental modelling techniques with geographic information system (GIS) capabilities and multi-criteria decision aids, mDSS is an operational tool for solving decision problems. The design, testing and evaluation of MULINO-DSS was funded by European Union in effort to foster a truly integrated approach in the management of water resources within river basins, in line with the EU water framework directives (WFD). The MULINO methodology and the mDSS software are designed to assist in decision making for water resource management when a choice has to be made between diverse management options (Giupponi, et al., 2004).

The mDSS software is one of the tools for the implementation of the NetSyMoD methodological framework for Social Network Analysis, Creative System Modelling and Decision support approach. In particular, mDSS was originally developed in the context of availing an application for sustainable use of water resources at the catchment scale. The NetSyMoD methodology and software tool are designed to support decision /policy makers in all instances in which there are choices to be made between alternative options in the field of environmental management and with the involvement of multiple actors. The methodology facilitates the integration of environmental, social and economic concerns and the involvement of interested parties in the formulation of strategies and decisions.

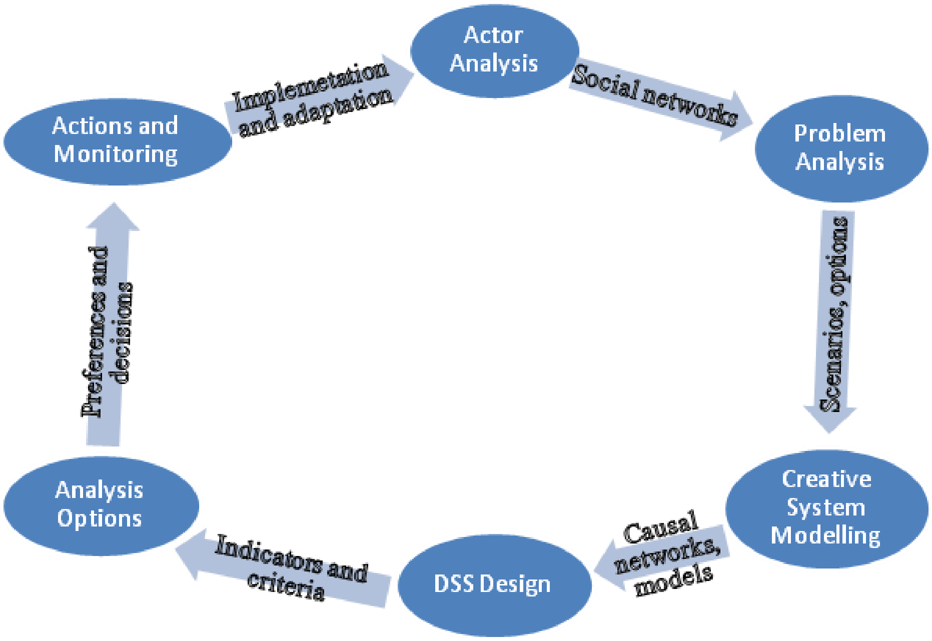


Figure 14: Flowchart of the NetSyMoD approach to participatory modelling and decision making (Giupponi, et al., 2010)

The mDSS software is a generic decision support system specifically designed and developed to manage the two steps of DSS design and the analysis of options as to assist decision makers in the management of environmental problems. It can help users to:

- Explore possible decision options, also within the contexts of alternative scenarios,
- Better understand the systems and discuss with affected societal actors (disciplinary experts, policy/decision makers and other interested stakeholders) the problem at hand,
- Facilitate public participation,
- Extend intra- and inter-watershed collaborations amongst different stakeholder groups
- Smoothen the conflicts related to alternative courses of action,

4.2.1 **Methodology**

MULINO can provide competent authorities with an operational approach to support the "integration of disciplines, analyses and expertise", by combining hydrology, ecology, chemistry, economics, and sociology to assess pressures and impacts on water resources. The specific application context for the methodology and the mDSS software is defined in terms of a decision which will affect the use of water resources. Such a decision might be related to ordinary water management activities or be connected to unusual events. Such work is needed to design the programmes of measures (PMs) and to develop the River Basin Management Plan (RBMP) for a river basin or specific plans for constituent sub-basins. The MULINO methodology approaches the choice among a finite set of options through Multi-Attribute Analysis (MAA) methods, used to identify the "best" option. mDSS guides the user through three decision phases: "Intelligence phase" i.e. where the problem is structured and various alternative options identified; “Design phase”- i.e. where analysis and evaluation matrices are developed, and finally “Choice phase”- i.e. where decision criteria are set and sensitivity analysis conducted to compare the robustness of choices made by exploring variations in the weights of decisional criteria, which facilitates stakeholders make a final choice that is then implemented (Simon, 1977).

The mDSS tool is one of the components of the MULINO methodology, which starts with the formalisation of a problem which triggers a decisional process in which various actors are involved, with their contributions co-ordinated by the water management administration responsible for decision implementation. The mDSS can be used throughout to document the selection of criteria and the preferences of the various parties and to identify the “best” option, given the set of choices that have been made to set up the decision problem. In a typical application, the main steps are:

- The identification of the area where water resources are to be managed: either the entire basin, or a sub-basin within the catchment area.
- Illustrate the socio-economic and environmental characteristics according to the DPSIR conceptual framework (Driving forces, Pressures, State, Impact and Response; EEA, 1999).
- Conceptualize causal relationships and dynamic interactions within the catchment through construction of DPS “chains”, to identify the main cause-effect relationships between human activities and the state (or change of state) of water resources.

This first phase is termed “Conceptual Phase”. The decision-maker structures the problem in collaboration with stakeholders, through a questionnaire targeted to the decisional problem in question. The MULINO methodology introduces a local network analysis to be completed through a series of interviews with selected stakeholders, and the application of modelling tools to analyse the dynamic aspects of the water cycle. The socio-economic and environmental information is stored in catalogues, and organised according to the DPSIR approach in formats that allow the user to deal with spatial and temporal data series. The user is then ready to enter the “Design Phase” where he describes the alternative options, selects the decisional criteria taking into account the results of the local network analysis, and the results of data coming from surveys, census, monitoring and modelling are stored in the Analysis Matrix (AM). The AM is a tabular representation of decision outcomes measured in natural units (such as kg/yr, m^3, ppm etc.), which are commonly not directly comparable; it is structured with options in the columns and decisional criteria in the rows.

The evaluation, normalisation and weighting of the multidimensional data stored in the AM takes the decision maker to the “Choice Phase” in which the Evaluation Matrix (EM) is built and one or more decision rules are applied to identify the “best” option. Local network questionnaires are designed to support public participation by collecting structured information about stakeholders’ preferences that relate to the decision problem. These preferences can be combined in the mDSS’s group decision making routine. Through sensitivity analyses and a simplified “sustainability assessment” the mDSS software allows the user to analyse the variables that influence the selection of the "best" option, and explore their relevance. During each of the three mDSS phases ("Conceptual Phase", "Design Phase" and "Choice Phase"), the decision process and the final outcomes are described using charts, graphs and matrices which illustrate how the decision-maker arrives at the "best" option.

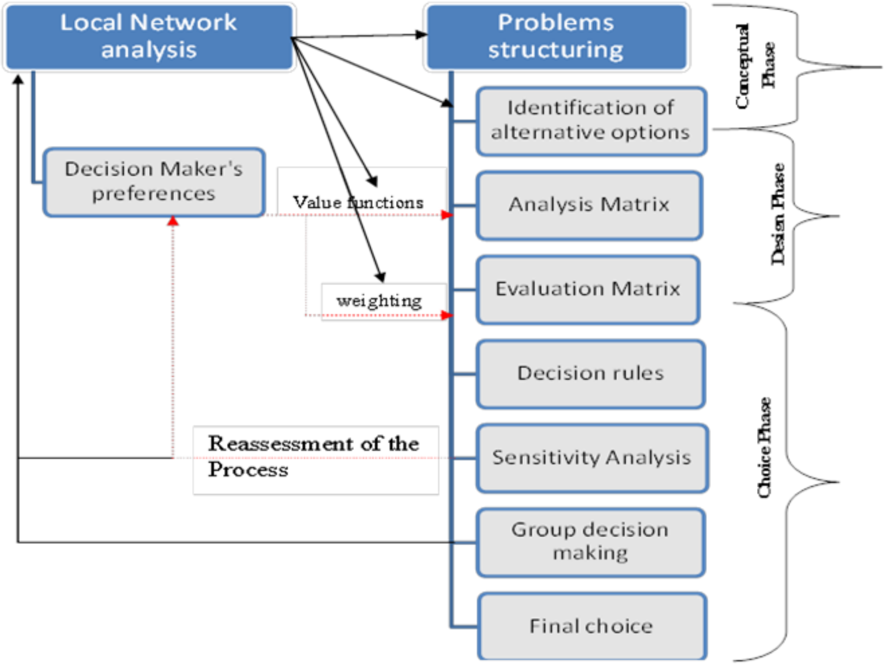
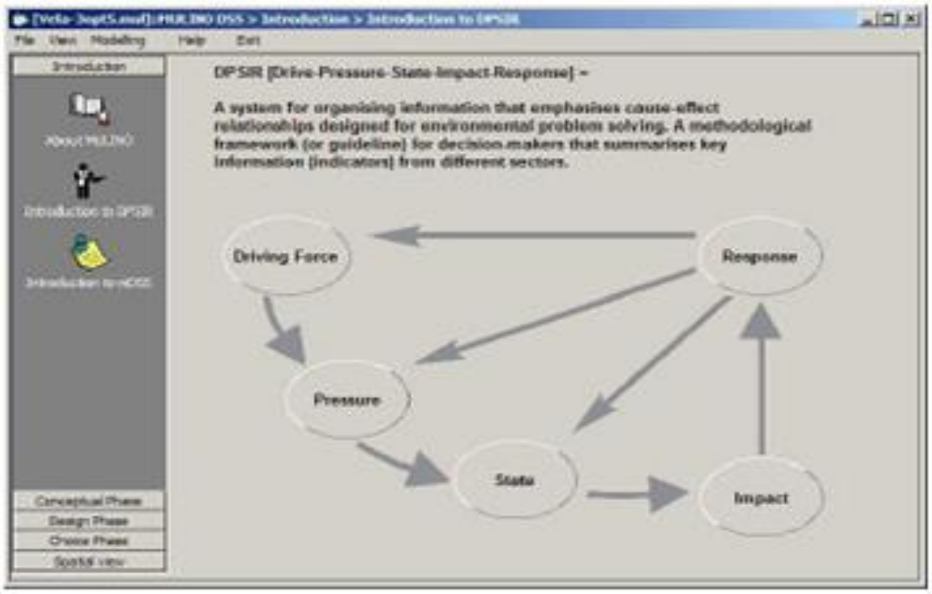


Figure 15: The main components and steps in typical mDSS (Giupponi, et al., 2010)

4.2.2 **DPSIR Conceptual Framework**

In the mDSS interface the ***DPSIR*** framework is presented as a system for organising information that emphasises cause-effect relationships designed for environmental problem solving. It is a methodological framework (or guideline) for decision makers that summarises key information (indicators) from different sectors. ***Driving forces*** are underlying **processes** and causes of pressures on the environment (e.g. fertiliser use in agriculture; urban waste water). ***Pressure*** indicators are the **variables** which directly cause the environmental problems (e.g. total quantity of nitrogen in chemical or biological fertilisers applied per unit of agricultural land). ***State*** indicators represent the current condition (or change) of the environment (e.g. average concentration of nitrogen in surface or ground waters). ***Impacts*** represent the ultimate effect of changes of State indicators, or the damage caused by the DPS chains of causes and effects (e.g. eutrophication of surface water or water becoming unsuitable for drinking). ***Responses*** are the efforts to solve the problems identified by Impact indicators: a set of alternative options among which the decision maker chooses the preferred one (e.g. alternative plans for ecologically sound production systems, or alternative designs for a water treatment plant).



DPSIR [Drive-Pressure-State-Impact-Response] –

A system for organising information that emphasises cause-effect relationships designed for environmental problem solving. A methodological framework (or guideline) for decision makers that summarises key information (indicators) from different sectors.

Figure 16: DPSIR structure (Giupponi, et al., 2010)

The DPSIR conceptual framework is implemented along with Integrated Assessment Modelling and Multi-Criteria Analysis Methods. The mDSS software has been designed to facilitate the "integration of stakeholders and the civil society in decision making", by promoting transparency and communication about decisional processes. The MULINO methodology has been developed through several subsequent prototypes in which the essential features of the software and human interface has been built up iteratively with end user involvement. In this study mDSS, which encompass simplified meta-models that surmounts the intense computing time of comprehensive hydrological models, has been utilised making the DSS more interactive. Meta-models provide the results immediately and various models settings may be explored, giving the decision maker more explorative power (Giupponi, et al., 2004).

The use of mDSS in a water planning context can support the following:

- Long-term vision for the River Basin: Through the mDSS scenario functionality, MULINO supports the development of "a vision of what the basin will be in the future" and through the use of the sustainability chart, "help[s] to determine what measures have to be taken in the perspective of a sustainable development".
- Knowledge and information management and the need of building capacity. mDSS allows the decision-maker to store socio-economic and environmental information in the DPSIR conceptual framework. The user identifies the main cause-effect relationships between human activities and the state of water resources within the catchment. Many data formats are compatible with mDSS, and can be used in the "Conceptual" phase of mDSS tool, facilitating greater access to the information supporting the decisional process. A participatory multi-level approach supports capacity building and "the raising of

public awareness", an "informal transfer of know how (e.g. through the exchange of experience between river basin managers)", and "formal training both internal and external"

- Integration at the operational level. Different bodies can be involved at different scales, and at different steps of the planning process. Since "the scale is a very relevant aspect for a good integration" the MULINO methodology has been developed and tested at both local and regional scales. MULINO's flexibility allows the user to adopt the same approach at different scales and stages of decisional processes. A common methodological approach can help to establish "better overall coordination at the river basin level" and to achieve "more integration at the operational level, especially: [...] among bodies involved directly with water management".
- The appropriate toolbox. The mDSS tool could be a useful component of a toolbox that helps the decision-maker to "to make right priorities concerning the program of measures" and to define and evaluate "numerous alternatives that represent various possible compromises among conflicting groups, values, and management objectives" in a detailed manner (Giupponi, et al., 2004).

The MULINO approach facilitates an integrated and transparent organisation of information, favouring public participation and the implementation of experts' knowledge and judgements. Planning is intended as "a systematic, integrative and iterative process" which "culminates when all the relevant information has been considered and a course of action has been selected" (Giupponi, et al., 2010). In the "Conceptual" phase of mDSS it is possible to structure the decisional problem with input from stakeholders through the local network analysis. A questionnaire is designed to collect structured information from stakeholders, which make their preferences explicit. In the subsequent phases the participation of the stakeholders can be structured using simplified Group Decision Making (GDM) functionalities that allow the different actors' preferences to be considered in the evaluation of options (Mysiak, et al., 2002). Water managers can adopt the MULINO methodology "to increase the legitimacy and transparency for water management", by facilitating an open dialogue between members of the public, interest groups and authorities, and "to facilitate the interaction and discussion among managers and stakeholders providing tools for conflicts resolution." The problem of developing "a balance between environmental functioning and users with conflicting aims" is approached through the functionalities for GDM.

The result is a general approach and a software tool, which support decision-makers in conducting a ”flexible, dynamic, cyclic and prospective planning process" in order to implement the water policies and strategies in "a socially acceptable manner", in different contexts. The uncertainties that challenge the planning process can be managed with original features such as MULINO's sensitivity analysis (Giupponi, et al., 2004). It is used for analysing the robustness of choices made by exploring variations in the weights of decisional criteria. Decision matrix is a (M x N) matrix in which the element x_{ij} indicates the performance of the option a_i evaluated in the terms of the decision criterion c_j. While the "raw" performances expressed in different non comparable units and scales are represented in the so called analysis matrix, the relative performance (u_{ij}) is constituted by the preference mapping using a value/utility function and expressed in the same scale as the evaluation matrix.

4.2.3 **Multi-Criteria Decision Analysis**

As demonstrated in Figure 17 below, the decision process starts with problem structuring during which the problem to be solved is explored and available information is collected. The possible options – responses in terms of the DPSIR framework – are defined and criteria aiming at evaluation of their performance are identified. In the next step the options' performance in terms of the criteria scores is modelled. As a result a matrix – called analysis matrix – is constructed. The analysis matrix contains the raw options' performance with different criteria scales, which have to be standardised to comparable scales before being aggregated.

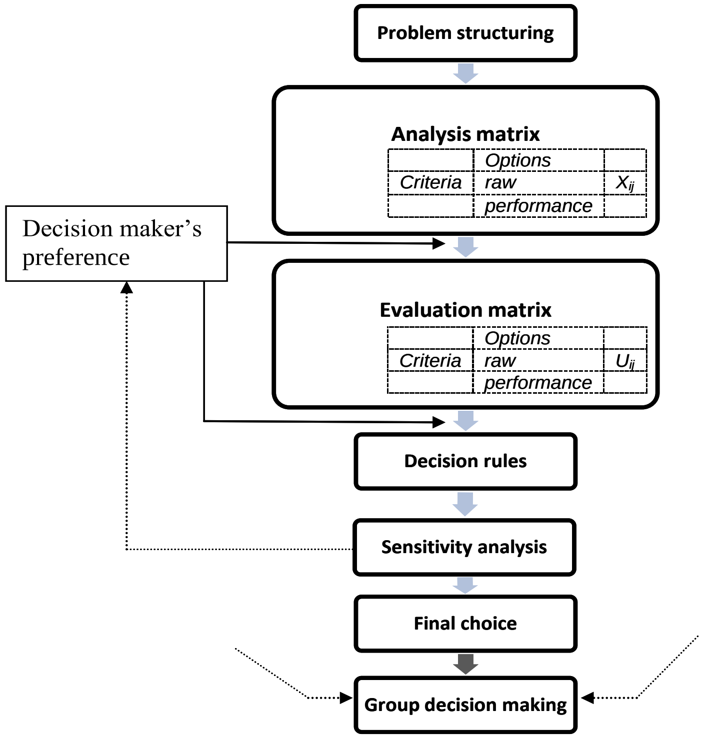


Figure 17: The basic steps of MCA that is implemented in mDSS (Giupponi, et al., 2004)

Since the main aim of a multi-criteria decision analysis is to reduce option of each performance into a single value to facilitate the ranking process, the heart piece of any MCA decision rule is an aggregation procedure (Mysiak, 2010). The large quantity of known decision rules differ in the way the multiple options performances are aggregated into a single value. There is no single method that is universally suitable for any kind of decision problem, the decision maker has to choose the method which best corresponds with his purpose. Finally, a sensitivity analysis examines how robust the final choice is to even a small change in the preferences expressed by the decision maker. In a situation where there are several decision makers involved in the decision process, the individual choices are to be compared and an option is to be chosen, which represents the group compromise decision (Mysiak, 2010).

The Analysis Matrix

The analysis matrix (M x N: i.e. M options and N criteria) is to be built from the environmental indicators identified in the conceptual phase. The cells of the matrix relate to the option-criterion pairs and contain the outcomes or consequences for a set of options and a set of evaluation criteria (Mysiak, 2004).

In spatial decision-making, the options are a collection of points, lines, and areal objects with associated attributes. The decision outcomes, as in Figure 18b-c, may have spatial extensions. For example, in the case of two-dimension a spatial extended decision outcomes (Figure 18c), a cell of the decision matrix corresponds to a map, which contains the spatially distributed consequences of an option with regards to a criterion. Different to the case of non-dimensional (value- or point-like outcomes, Figure 18a) consequences, an additional aggregation must be done (Mysiak, 2010).

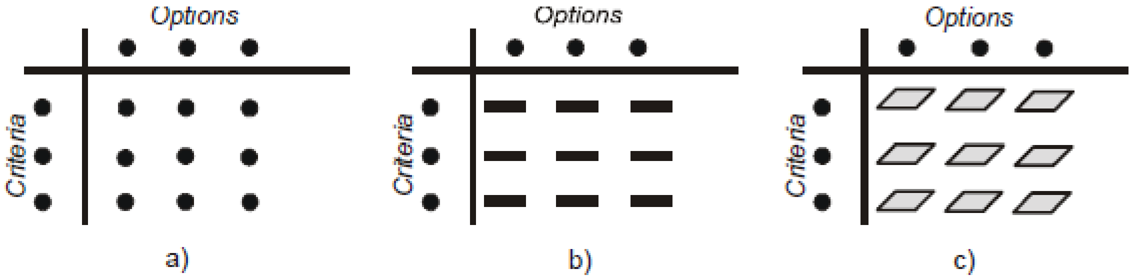


Figure 18: Different dimensions of decision outcomes: spatial dimensions 0(a); 1 (b) and 2 (c) (Mysiak, 2010)

Standardising the Analysis Matrix

During the standardisation the criterion values expressed in different measurement units are transformed into a common scale, which allows their comparison. The mDSS utilises a linear scale transformation method - the *score range* method. The method doesn't maintain the relative order of magnitude, but scales the raw options' scores precisely in the interval [0,1] (formulas below) (Mysiak, 2010).

$X'_{ij} = \left[X_{ij} - X_j^{min}\right] / \left[X_j^{max} - X_j^{min}\right]$ For a criterion to be maximized

$X'_{ij} = \left[X_j^{max} - X_{ij}\right] / \left[X_j^{max} - X_j^{min}\right]$ For a criterion to be minimized

A value X_{ij} corresponds to the option (i) and the criterion (j). The notations X_j^{min} and X_j^{max} means the lowest and the largest score of the jth criterion.

With the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) the option which is closer to ideal positive solution and further from the negative ideal solution is considered as being best. Both ideal solutions are described by the extreme criteria performances. Since these solutions are not real and describe only ideal states (which cannot be achieved), the distance of the real options from both of them is combined to make the final choice. The TOPSIS decision rule uses vector normalisation (formula below). This method has a particular property of producing vectors (the rows of the decision matrix) with the same Euclidean length (equal 1) (Mysiak, 2004).

$$X'_{ij} = X_{ij} \Big/ \sqrt{\sum_{i=1}^{m} \left(X_{ij}\right)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . . Eqn.$$

Modelling Value Function

The value function is another way of transforming the raw criteria scores into a common scale. However, it allows the preferences of the decision maker to be considered during the transformation. Decision theory provides a theoretical framework for representing the decision maker's preferences about the options' performance. In order to make them more "computational", the preferences are mapped by the value/utility[3] function (u). Value function (u) is thus a mathematical representation of human judgements. It translates the performances of the options into value scores, which represent the degree to which a decision objective is matched. A value/utility function maps the preference about two options a and b. i.e. (Mysiak, 2010):

$u(a) > u(b) \Leftrightarrow a > b$ *where a and b* are options; a > b means a is preferred to b

$u(a) < u(b) \Leftrightarrow a < b$ *u()* …value function; a < b means b is preferred to a

$u(a) = u(b) \Leftrightarrow a \sim b$ ~ …is indifferent; a ~ b means no options is more preferred

There are several methods for the estimation of the value functions. The mDSS utilises the direct rating method by which the decision maker immediately assigns a value to each criterion score. The shape of the value function may be selected from the implemented set of value functions and only their parameters must be specified. See Figure 19 below some of the widely used types of value function (Mysiak, 2010).

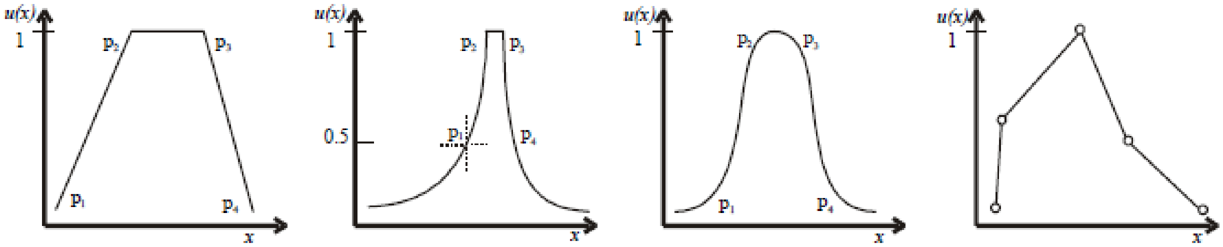


Figure 19: Some kinds of value function: (a) linear; (b) j-shaped; (c) Sigmoidal: (d) user defined (Mysiak, 2010).

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[3] The term value function is used in the context of decision under certainty. The utility function refers to the situation under risk consideration, i.e. when the outcomes are associated with a probability

Modelling Criteria Weights

The criterion weights usually provide the information about the relative importance of the considered criteria to the decision maker. There are many techniques commonly used for assessing the criterion weights such as ranking and rating methods, pair wise comparison and trade-off methods. Ranking methods use the rank order on the considered criteria. As the rank order describes the importance of the criteria, the information describing them (rank number r_i) is used for generating numerical weights (Mysiak, 2010).

$$w_i = (n - r_i + 1)^p \Big/ \sum_{k=1}^{n} (n - r_i + 1)^p \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..Eqn.$$

Where n.....number of criteria

r_i.....rank number of criterion i

p.....parameter describing the weights distribution; p = 0 results to equal weights. As p increases, the weights distribution steepens.

$$TRADEOFF = 1 - \sqrt{\left(n \sum \left(W_{orderi} - {}^{1}\!/_{n}\right)^2\right)/(n-1)} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots Eqn.$$

Where: n .... number of criteria

i .... criterion rank order

W_{order_i} ......order weight of i-th criterion

The parameter *p* may be estimated by a decision maker through interactive scrolling (as in Table 10) or with the help of trade-off formula above using the weight of the most important criterion as an input from the decision maker.

Table 10: The behaviour of the generated numerical weights depending on the parameter p of the rank component method (Mysiak, 2010)

		Parameter p					
	Rank	0	0.5	1	....	....	10
Most important criterion	1	0.2	0.26	0.33	---	---	0.89
	2	0.2	0.23	0.26	---	---	0.09
	3	0.2	0.2	0.2	---	---	0
	4	0.2	0.16	0.13	---	---	0
Less important criterion	5	0.2	0.11	0.06	---	---	0
Sum		1	1	1	1	1	1

Pairwise comparison method was developed by SAATY (1980, quoted by MALCZEWSKI 1999) in the context of his decision rule called Analytic Hierarchy Process. The method involves pairwise comparisons to create a ratio matrix. Through the normalisation of the pairwise comparison matrix the weights are determined. The method uses an underling scale with values, from 1 to 9 for example, to describe the relative preferences for two criteria. Results of pairwise comparision is a reciprocal quadratic matrix (as in Table 11) (Mysiak, 2010).

Table 11: Pairwise comparison matrix between 4 criteria (C1-C4) (Mysiak, 2010)

1	Equal importance		**C_1**	**C_2**	**C_3**	**C_4**
3	Moderate importance	**C_1**	1	4	7	5
5	Strong importance	**C_2**	1/4	1	1/3	9
7	Very strong importance	**C_3**	1/7	3	1	5
9	Extreme importance	**C_4**	1/5	1/9	1/5	1

Using the pairwise comparison matrix $A \in IR^{n \times n}$ the weights w_j may be determined as follows:

1. Estimate the maximum eigenvalue λ_{max} of the comparison matrix, which fulfil formula below

   $$\det(A - 1 \times I) = 0 \qquad \text{i.e. } |A - \lambda I| = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn.$$

   Where

   A = $[a_{ij}]$ is a square matrix,

   1 is a scalar quantity i.e. a number; it is multiplied by the unit matrix I since only a matrix can be subtracted from another matrix

2. Determine the solution $\widetilde{w}$ as in following formula

   $$(A - 1 \times I) \times \widetilde{w} = 0 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn.$$

   $$\widetilde{w}_i \geq 0$$

3. Normalise the $\widetilde{w}$ by formula below

   $$w_j = \widetilde{w} \Big/ \sum_{i=1}^{n} \widetilde{w}_j \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn.$$

After the weights have been determined, the consistency of pairwise comparison must be evaluated. For consistency, if the decision maker says a criterion ***x*** is equally important to another criterion ***y*** (so the comparison matrix will contain value of $a_{xy} = 1 = a_{yx}$), and the criterion ***y*** is absolutely more important as an criterion ***w*** ($a_{yw} = 9$; $a_{wy} = 1/9$); then the criterion ***x*** should also be absolutely more important than the criterion ***w*** ($a_{xw} = 9$; $a_{wx} =$

1/9). Unfortunately, the decision maker is often not able to express consistent preferences in the case of multiple criteria. Saaty's method measures the inconsistency of the pairwise comparison matrix and sets a consistency threshold which should not be exceeded. In ideal cases the comparison matrix (A) is fully consistent, the rank (A) = 1 and l = n (n = number of criteria). In this case, the following equation is valid:

$A \times x = n \times x$ (where x is the *eigenvector* of A)

First the consistency index (CI) is calculated and the consistence ratio (CR) is then calculated as the ratio of consistency index and random consistency index (RI). The RI is the random index representing the consistency of a randomly generated pairwise comparison matrix; its value depends on the number criteria being compared.

$$CI = \frac{[\lambda_{max} - n]}{n-1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Eqn.$$

$$CR(A) = \frac{CI(A)}{RI(n)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Eqn.$$

If CR (A) ≤ 0.1, the pairwise comparison matrix is considered to be consistent enough. In the case CR (A) ≥ 0.1, the comparison matrix should be improved (Mysiak, 2010).

Decision Rules

Decision rules aggregate partial preferences describing individual criteria in a global preference and then rank the options. The decision rules chosen for implementation in the *m*DSS include

(i) Simple additive weighting (SAW):- Most popular method due to its simplicity. It assumes additive aggregation of decision outcomes, which is controlled by weights expressing the importance of criteria.

$$\Phi_{SAW}(a_i) = \sum_{j=1}^{n} w_j \text{ x } u_{ij} \qquad w_j \ldots\ criterion\ weights\ \ldots\ldots\ldots\ldots. Eqn.$$

Table 12: Example using SAW to establish the preferred options along three criteria (Mysiak, 2004).

	w_i	a_1	a_2
c1	0.4	0.2	0.8
c2	0.4	0.5	0.11
c3	0.2	0.9	0.25

The SAW aggregation is performed as following:

$\Phi SAW(a_1) = 0.2 * w_1 + 0.5 * w_2 + 0.9 * w_3 = 0.2 * 0.4 + 0.5 * 0.4 + 0.9 * 0.2 = 0.46$

$\Phi SAW(a_2) = 0.8 * w_1 + 0.11 * w_2 + 0.25 * w_3 = 0.8 * 0.4 + 0.11 * 0.4 + 0.25 * 0.2 = 0.414$

Since $\Phi(a_1) = 0.46 > 0.414 = \Phi(a_2)$, the option (a_1) is preferred - $a_1 \succ a_2$

(ii) Order weighting average (OWA):- has potential to control the trade-off level between criteria and to consider the risk behaviour of the decision makers. The criteria are weighted (order weights applied) on the basis of their rank order rather than their inherent qualities (Mysiak, 2004). By so doing the weights – called order weights - are applied to the criteria according to the rank order across their scores. For a given option, the order weight ow_1 is assigned to the criterion with the lowest score, order weight ow_2 to the criterion with next higher-ranked scores, and so on.

$$\Phi_{OWA}(a_i) = \sum_{k=1}^{n} ow_k \; x \; b_k \quad where\ b_k\ denotes\ the\ k\text{th lowest score of the options i}\left(u_{ij}\right)$$

Table 13: Using OWA to established preferred option (Mysiak, 2004).

<table>
<tr><td colspan="3">Considering two options and three criteria as in the table below</td></tr>
<tr><td></td><td>a_1</td><td>a_2</td></tr>
<tr><td>c_1</td><td>0.2</td><td>0.8</td></tr>
<tr><td>c_2</td><td>0.5</td><td>0.11</td></tr>
<tr><td>c_3</td><td>0.9</td><td>0.25</td></tr>
<tr><td colspan="3">Order weights [$ow_1 = 0.5$; $ow_2 = 0.2$; $ow_3 = 0.3$] will be assigned to the criteria as follows</td></tr>
<tr><td></td><td>a_1</td><td>a_2</td></tr>
<tr><td>c_1</td><td>Ow_1</td><td>Ow_3</td></tr>
<tr><td>c_2</td><td>Ow_2</td><td>Ow_1</td></tr>
<tr><td>c_3</td><td>Ow_3</td><td>Ow_2</td></tr>
<tr><td colspan="3">The OWA aggregation is performed as following:
$\Phi(a_1) = 0.2 * ow_1 + 0.5 * ow_2 + 0.9 * ow_3 = 0.2 * 0.5 + 0.5 * 0.2 + 0.9 * 0.3 = 1.4$
$\Phi(a_2) = 0.11 * ow_1 + 0.25 * ow_2 + 0.8 * ow_3 = 0.11 * 0.5 + 0.25 * 0.2 + 0.8 * 0.3 = 0.345$
Since $\Phi(a_1) = 1.4 > 0.345 = \Phi(a_2)$, the option ($a_1$) is preferred - $a_1 \succ a_2$</td></tr>
</table>

Trade-off means that a very low score in one criterion may not be compensated with a very high score in another one. OWA may be characterized as a control allowing an aggregation between the MAXIMAX (decision rule in which the decision maker selects the option with the maximal scores in the best criterion), MAXIMIN (rule, by which the option with the best scores in the worst criterion is selected), both of which do not allow any trade-off as the decision is made according only to one criterion, and SAW (allowing full trade-off) extremes. In the case of 3 criteria the set of order weights [1, 0, 0] assigns the extreme importance to the lowest criterion score and corresponds to the MAXIMIN rule. The order weights [0, 0, 1] in contrast assign the extreme importance to the largest criterion score and correspond to the MAXIMAX rule. Equally distributed order weights [0.33; 0.33; 0.33] apply some importance to each rank and don't change the options ranking obtained from the SAW rule (Mysiak, 2010).

The ANDness, ORness and TRADE-OFF characteristics of any particular distribution of the order weights may be calculated using the formulas (Mysiak, 2010).

$$ANDness = \left(\frac{1}{(n-1)}\right)\sum_{i=1}^{n}\left((n-i)\mathrm{W}_{\mathrm{orderi}}\right)$$

$$ORness = 1 - ANDness$$

$$TRADEOFF = 1 - \sqrt{\left(\frac{n\sum\left(W_{orderi} - {}^{1}\!/_{n}\right)^{2}}{(n-1)}\right)}$$

Where: n ...... number of criteria

i........ criterion rank order

$\mathrm{W}_{\mathrm{order\_i}}$ ......order weight of i-th criterion

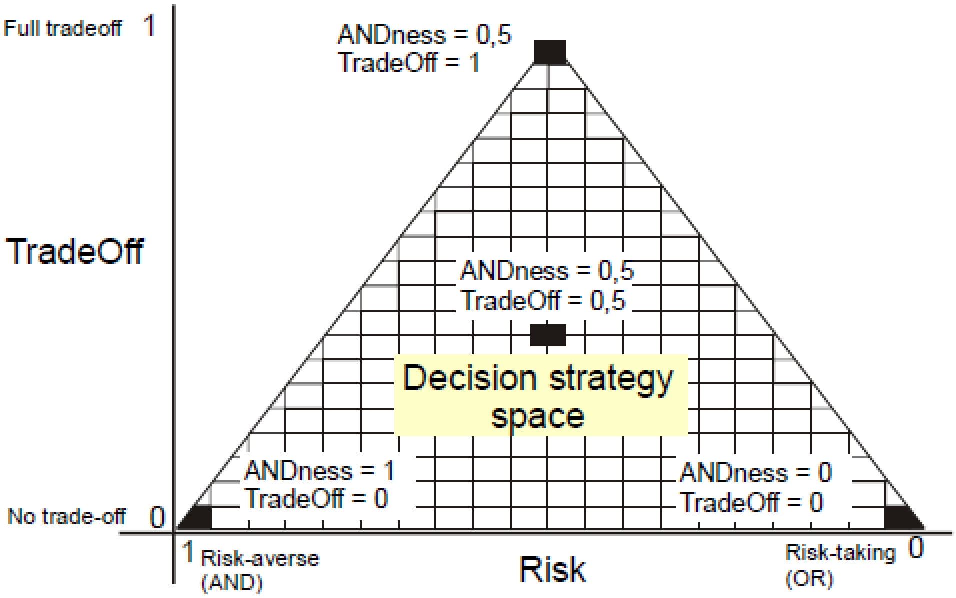


Figure 20: Decision behaviour according to the selected order weight distribution (Mysiak, 2010)

(iii) Ideal point methods (TOPSIS):- order a set of options on the basis of their separation from the ideal solutions. The ideal solution represents a hypothetical option that is not achievable, but is the most desirable level of each criterion across the options under consideration. The option that is closest to the ideal positive solution and furthest from the negative ideal solution is the best one.

$$S_{i+} = \left[\sum_{j=1}^{n} w_j^p \left(u_{ij} - u_{+j}\right)^p\right]^{1/p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Eqn.$$

S_{i+} ....separation of the *ith* option from the ideal point

W_j-------weight assigned to the criterion j

U_{+j} ....ideal value for the jth criterion

p...........power parameter ranking from 1 to ∞; for p=1, the rectangular distance is calculated and for p=2 the Euclidian distance is obtained.

$$S_{i-} = \left[\sum_{j=1}^{n} w_j^p \left(u_{ij} - u_{-j}\right)^p\right]^{1/p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Eqn.$$

S_{i-} ....separation of the ith option from the negative ideal point

U_{-j} ....negative ideal value for the jth criterion

The distance from the ideal and negative ideal point is calculated as follows (Mysiak, 2010):

$$S_{i+} = \left[\sum_{j=1}^{n} \left(u_{ij} - u_{+j}\right)^2\right]^{0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Eqn.$$

$$S_{i-} = \left[\sum_{j=1}^{n} \left(u_{ij} - u_{-j}\right)^2\right]^{0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. Eqn.$$

The relative closeness to the ideal solution (C_{i+}), which will be used for the ranking of options, is calculated as (Mysiak, 2010):

$$C_{i+} = \frac{S_{i-}}{S_{i+} + S_{i-}}$$

Table 14: Calculating closeness to ideal solution two options and three criteria (Mysiak, 2010).

Considering two options and three criteria with already weighted performances

	a_1	a_2	Ideal positive solution	Ideal negative solution
c_1	0.08	0.32	0.32	0.08
c_2	0.2	0.044	0.2	0.044
c_3	0.18	0.05	0.18	0.05

The distance from the positive and negative ideal solutions as well as the final aggregation according to the formula above is performed as following:

	a_1	a_2
S_{i+}	0.24	0.20
S_{i-}	0.20	0.24
C_{i+}	0.46	0.54

For example $S_{i+}(a_1) = ((0.08-0.32)^2 + (0.2 – 0.2)^2 + (0.18 – 0.18)^2)^0.5 = 0.24$

$C_{i+}(a_1) = 0.20/(0.20 + 0.24) = 0.46$

Since $C_{1+} = 0.46 < 0.54 = C_{2+}$, the option ($a_2$) is preferred - $a_1 \prec a_2$

Sensitivity Analysis

This is a crucial task in multi-criteria decision making that establishes how robust (or weak) the final decision is. It investigates the impact of the potential changes and errors on the results of a model by capturing the uncertainties related to decision outcomes and/or preferential judgements (i.e. value functions and weights). Sometimes the sensitivity analysis is distinguished from a robustness analysis: while the sensitivity analysis is assumed as the analysis of the effects of changing data and model parameters in a constrained vicinity to a base solution, the robustness analysis is considered as a systematic analysis of a large set of variations which are plausible in the decision problem context.

The SA methods are useful within (Mysiak, 2010):

- Decision making for identifying critical value/criterion, testing robustness and riskiness of decision;
- Communication for increasing credibility and confidence; and
- Modelling process for better understanding of input-output relationship and for understanding the model needs and restrictions. The mDSS utilises two approaches for SA:

i) **Most critical criterion**: identifying the criterion for which the smallest change of current weight may alter the existing ranking of options and whether that minimal change is within/outside confidence range; and

ii) **Tornado diagram**: graphically comparing the chosen option with any other one and showing ranges within which the parameters may vary.

Group Decision Making(GDM) - Aggregation of Group Members' Preferences

GDM involves two or more decision makers in a joint decision whereas each of them has his own perception of the decision problem and the decision consequences. According to (Choi, et al., 1994) group decision problems are social problems rather than mathematical ones with only few methodologies to verify their fairness, i.e. the way in which the individual preferences are aggregated. Various attempts have been undertaken to extend MCA techniques to be able to deal with interpersonal conflicts. The different preferences of decision group members create a new "dimension" of a decision problem, which, in order to obtain a common decision model, has to be aggregated in a similar way as the preferences for multiple criteria are dealt with in MCA.

"Behaviour aggregation", preferred by mDSS in GDM situation, is the name for the process by which the group members are able to compromise their expectations and agree on a common system of objectives and preferences. After a communicative phase, the decision makers assume a unified problem structure and common value/utility functions. If this process fails – i.e. the behaviour of any group member is uncooperative – formal aggregation procedures (voting rules) may be used to select a compromise solution. In this case each decision maker may solve the given decision problem on his own. The individually chosen solutions are then presented and compared to each other through voting. A large decision group may take advantage of this procedure, but in a small group there is a risk, that one group member (dictator) systematically affects the decision process and thus "dictate" a solution.

Compromising the final solution

Sometimes a group in DM is unable to reach a compromise to find a common value function for all criteria. The Borda technique assigns ranks to options based on the rationale that the higher the position of an option on the voter's list, the higher the rank assigned. The voting position of an option is determined by adding the ranks for each option from every voter using the Borda vote aggregation function. The best option is one that receives the highest score calculated such that all options are assigned a score starting with 0 for the least favourable solution, 1 for the second worst, 2 for the third worst, and so on. All scores are weighted by the number of voters, resulting in the Borda score for each option. This process takes care of the variance in decision makers' ranking of various options and promotes a consensus option.

The best option in an individual ranking obtains (n-1) value, where n is number of criteria, and the worse option in a given ranking is marked with 0. The number of options that the decision maker k ranks at most as good as

a_j (number of options which are less ranked as a_j) are $r(a_j \mid A, \succsim_k)$. To determine consensus ranking, the total Borda mark is calculated according to formula: $r(a_j \mid \mathrm{A}, \succsim_\mathrm{k}) = \#a_i \in A \mid a_j \succsim a_i$. The individual marks are summarised for each option and the best (consensus) option is the one highest total Borda mark.

An option a_j is preferred to another option a_i ($a_j \succsim a_i$) in the final group ranking only if:

$$\sum_{k=1}^{m} r(a_j \mid \mathrm{A}, \succsim_\mathrm{k}) \geq \sum_{k=1}^{m} r(a_i \mid \mathrm{A}, \succsim_\mathrm{k})$$

Consistency test of reciprocal matrix of pairwise comparison

In ideal cases the comparison matrix (***A***) is fully consistent, the rank (***A***) = 1 and eigenvalue (λ) = ***n*** (***n*** = number of criteria). In this case, the following equation is valid: ***A ´ x*** = ***n ´ x*** (where ***x*** is the eigenvector of ***A***). The eigenvector of matrix ***A*** is an estimate of the relative weights of the criteria being compared. In the inconsistent' cases (which are more common) the comparison matrix ***A*** may be considered as a perturbation of the previous consistent case. When the entries a_{ij} changes only slightly, then the eigenvalues change in a similar fashion. Moreover, the maximum eigenvalue (lmax) is slightly greater to n while the remaining (possible) eigenvalues are close to zero. Thus in order to find weights, we are looking for the eigenvector which corresponds to the maximum eigenvalue (lmax).

The consistency index (CI) is calculated as following:

$$CI = \frac{\lambda_{max} - n}{n-1}$$

Then, the consistence ratio (CR) is calculated as the ratio of consistency index and random consistency index (RI). The RI is the random index representing the consistency of a randomly generated pairwise comparison matrix. It is derived as an average random consistency index calculated from a sample of 500 of randomly generated matrices based on the AHP scale.

$$CR\ (A) = \frac{CI(\mathrm{A})}{\mathrm{RI}(\mathrm{n})}$$

If CR (A) ≤ 0.1, the pairwise comparison matrix is considered to be consistent enough. In the case CR (A) ≥ 0.1, the comparison matrix should be improved. The value of RI depends on the number of criteria being compared.

4.3 Water Evaluation and Planning System (WEAP)

Formulation of policies for sustainable allocation and use of scarce water resources, allowing adequate base flows in both surface and groundwater sources for environmental requirements, is an issue of increasing concern. So much so in the developing countries where population growth and increasing agitations for improved standards of living, coupled with impacts of climate change that force disadvantaged societies to over-exploit natural resources, continue to pose grave challenges to the environment. The conventional supply-oriented approaches in tackling water-related issues have been found to be lacking, due to the fact that these resource are finite. Over the last decades, an integrated approach to water development has emerged which places water supply projects in the context of demand, as well as water quality management and ecosystem preservation (Sieber, 2011).

WEAP was created in 1988, as a flexible, integrated, and transparent planning tool for evaluating the sustainability of current water demand and supply patterns and exploring alternative long-range scenarios. It was primarily developed by Stockholm Environment Institute through the support of, among others, the US Army Corps of Engineers. It provides a comprehensive, flexible and user-friendly framework for policy analysis that attempts to assist rather than substitute for the skilled planner. It is distinguished by its integrated approach in simulating water systems and by its policy orientation that places the demand side of the equation i.e. water use patterns, equipment efficiencies, reuse, prices, hydropower energy demand, and allocation on an equal footing with the supply side i.e. stream-flow, groundwater, reservoirs and water transfers. WEAP can thus be referred to as a laboratory for examining full range of alternative water development and management options, taking account multiple and competing uses of water systems [Sieber J., et al., 2011].

4.3.1 WEAP Approach

Operating on the basic principle of a water balance, WEAP is applicable to municipal and agricultural systems, single catchments or complex trans-boundary river systems. Moreover, WEAP is asserted to capably address a wide range of issues, e.g., sectoral demand analyses, water conservation, water rights and allocation priorities, groundwater and stream flow simulations, reservoir operations, hydropower generation, pollution tracking, ecosystem requirements, vulnerability assessments, and project benefit-cost analyses (Sieber, 2011). It places evaluation of specific water problems in a comprehensive framework; integration is over several dimensions: between demand and supply, between water quantity and quality, and between economic development objectives and environmental constraints (Sieber & Purkey, 2011).

WEAP has several integrated functions i.e. it functions like a database by providing a system for maintaining water demand and supply information; as a forecasting tool through simulation of water supply and demand, flows in various regimes, storage, pollution generation, waste water treatment and discharge; and finally it functions as a policy analysis tool through evaluation of a full range of water development and management options, taking into account the multiple and competing uses of water systems.

The analyst using WEAP represents the system in terms of it’s:

- various supply sources (e.g., rivers, springs, groundwater, reservoirs, external sources and desalination plants);
- withdrawal, transmission and wastewater treatment facilities;
- ecosystem requirements, water demands and pollution generation.

The data structure and level of detail may be easily customized to meet the requirements of a particular analysis, and to reflect the limits imposed by restricted data. WEAP applications generally include several steps: The first step is study definition where the model time frame is set up; the spatial boundary for the catchment being modelled is then demarcated in the schematic view of the model, the system components are then input by use of representative schema available in the schematic bar of the schematic view or through imported GIS shape files and/or raster, which also help in configuration of the problem. Current account year serve as the base year for the model and all system information is input into the current account. It can be viewed as a calibration step in the development of an application, as it provide a snapshot of actual water demand, pollution loads, resources and supplies for the system. Key assumptions may be built into the current accounts to represent policies, costs and factors that affect demand, pollution, supply and hydrology.

Scenarios build on the current accounts allow one to explore the impact of alternative sets of assumptions and/or policies on future water availability and use. Finally, the scenarios are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables. WEAP can interact with MODFLOW, MODPATH, QUAL2K and PEST, all of which are installed with WEAP and serve to boost specific modelling capacities; hence enhancing WEAP overall performance with respect to the modeller objective. WEAP can also communicate with Microsoft Excel and Microsoft Word, but they are not essential (Sieber & Purkey, 2011).

4.3.2 **Scenario Analysis**

The foundation of scenario analysis is anchored in the setting up of a current account that represents the status quo of water resources in a given area or the water system under study. Then based on a variety of economic, demographic, hydrological, and technological trends, a "reference" or "business-as-usual" scenario projection is established, referred to as a ‘Reference Scenario’ (Sieber, 2011). Subsequently, one or more policy scenarios with alternative assumptions about future developments can be developed. Scenarios are self-consistent plot of how a future system might evolve over time in a particular socio-economic setting and under a particular set of policy and technology conditions. Simulation of scenarios can address a broad range of "what if" questions, that are relevant in ascertaining the impact of various patterns of demographic, hydrological, socio-economical, infrastructural and environmental changes and/or policies adoption within a basin.

Scenarios in WEAP encompass any factor that can change over time, including those factors that may change because of particular policy interventions, and those that reflect different socio-economic assumptions. These scenarios may be viewed simultaneously in the results for easy comparison of their effects on the water system. They also help explore a wide range of demand and supply options for balancing environment and development. Sensitivity analyses may also be done by varying uncertain factors through their range of plausible values and comparing the results. The comparison of these alternative scenarios proves to be a useful guide to development policy for water systems from local to regional scales [Sieber J., et al., 2011].

4.3.3 **Demand-Supply and Environmental Management**

WEAP is very versatile in that it allows extensive disaggregation of demand and supply in water systems to the extent that it is possible to conceptualize development objectives by placing end-use goods and services at the foundation of water analysis. For instance, water demand in agriculture sector can be disaggregated to demand by different crops, irrigation areas and irrigation technique etc. On the other hand supply can be from one or several sources with the option of using treated or untreated water from other demand site with admissible impact on water quality. This allows scenarios to be created to evaluate the impacts of improved technology as well as targeted inducements on the system at various levels e.g. through economic policies like tiered water tariffs with increasing demand quantities, water reuse etc. Moreover, priorities for allocating water for particular demands or from particular sources may be specified by the user (Sieber, 2011).

These scenario analyses allows the modeller to conceptualise the effects of various demand and supply regime on the environment and especially providing a summary of the pollution pressure different water uses impose on the aquatic system. Pollution is tracked from generation through treatment plants and outflow into surface and underground bodies of water.

4.3.4 **WEAP Versatility**

An “area” in WEAP is defined as a self-contained set of data and assumptions with its geographical extent typically being a river basin. However, study area boundaries could be more flexible than the confines of the hydrologic boundaries so as to account for the adjacent demand areas served from within the system, or possibilities of importing or exporting water from or to sites outside the study area. An intuitive graphical interface provides a simple yet powerful means for constructing, viewing and modifying the system and its data (SEI, 2012). The adaptability of the application to whatever time series (daily, weekly, monthly or annual time steps) data is available to describe a water resources system is an big relieve to analysts in developing countries where lack/inadequacy of data incapacitate most DSS systems. This flexibility means that it can be applied across a range of spatial and temporal scales. Further still, it can be used to analyse a small community scale system, an entire catchment as well as complex trans-boundary river systems. The expandable and adaptable data structures of WEAP accommodate the evolving needs of water analysts as better information becomes available and planning issues change. In addition, WEAP allows users to develop their own set of variables and equations to further refine and/or adapt the analysis to local constraints and conditions (Sieber & Purkey, 2011).

4.3.5 **WEAP Application in Urban Management**

Historically, WEAP has been used primarily to assess the reliability of water deliveries and the sustainability of surface water and groundwater supplies under future development scenarios. This type of application of WEAP has focused on the water supply implications of proposed management and/or infrastructural changes, but has overlooked the impacts of these changes on the management of storm water and wastewater. Recent advancement of the model, however, has allowed for the holistic, comprehensive consideration of each of these facets of managing local water resources. The updated model can now be used to address questions surrounding the integration of storm water, waste water, and water supply (SEI, 2012). These include:

- How will water supply and wastewater treatment facilities be affected by the retention and/or diversion of storm waters?
- How will improvements in water collection systems affect water supply and wastewater treatment?
- How will modifications of combined sewer overflow systems affect wastewater treatment?
- How can reclaimed wastewater be used to augment water supply?

The enhanced WEAP model includes updated features that allow the user to model:

1. The “Infiltration and inflow” from groundwater to sewage collection systems - These inflows can stress rivers and streams by removing clean water from watersheds and place additional burden on wastewater treatment by taking up valuable plant capacity and limiting future sewer connections;
2. “Infiltration Basins & Retention Ponds” as supply management practices - These can be used to offset the impacts of urbanization, where water demands increase while increasing development negatively impact water supplies as more rainfall runs off rather than recharging local aquifers due to expanding impervious surfaces. They can also serve to attenuate non-point source pollution;
3. “Tiered Water Pricing” policies as a means of promoting demand management; and
4. “Combined Sewer Overflows (CSOs)” that pose potential risks to public health and aquatic life, because they discharge chemicals and disease-causing pathogens directly into waterways.

Moreover, WEAP ability to display user-defined performance measures as results allows for the output of site-specific performance measures and criteria, which are commonly guided by the objectives of individual studies and systems configuration and local conditions (Sieber & Purkey, 2011).

4.3.6 **System Structure**

WEAP consist of five main views namely; schematic, data, results, scenario explorer and notes. The schematic view is the starting point for all WEAP activities and its drag and drop graphical interface allows creation and editing of system physical features for spatial illustration and visualization. GIS layers can also be uploaded directly either as vectors or raster.

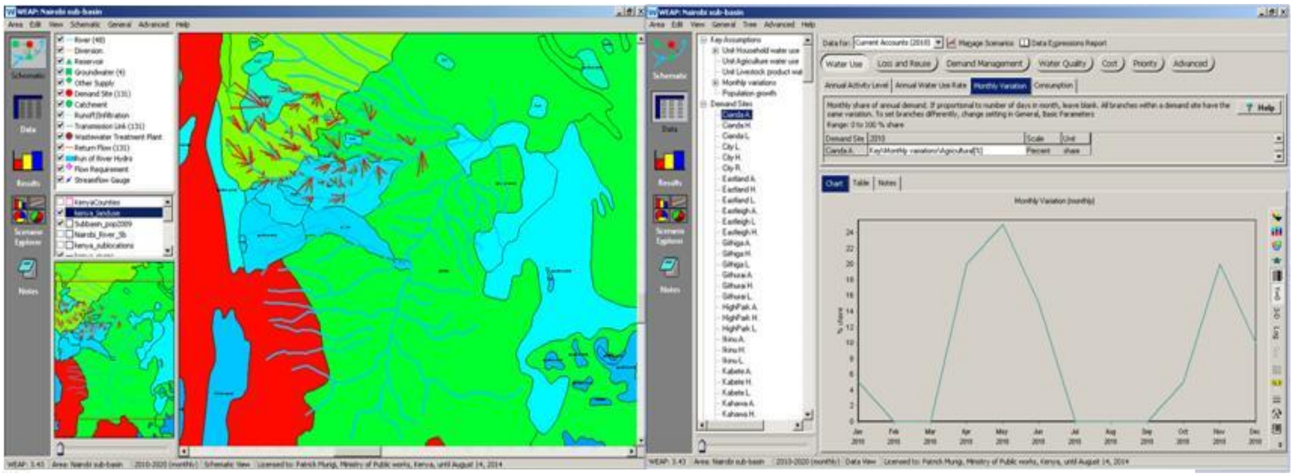


Figure 21: Schematic and data views - source: Nairobi River catchment model

The data view allows creation of variables and relationships, entering assumptions and projections using mathematical expressions and dynamically linking WEAP to other applications. The Results view allows detailed and flexible display of all model outputs, in charts, maps and tables, and on the Schematic. The scenario explorer helps in highlighting key data and results in the system for quick viewing. And finally, the note view provides a place to document systems' data and assumptions.

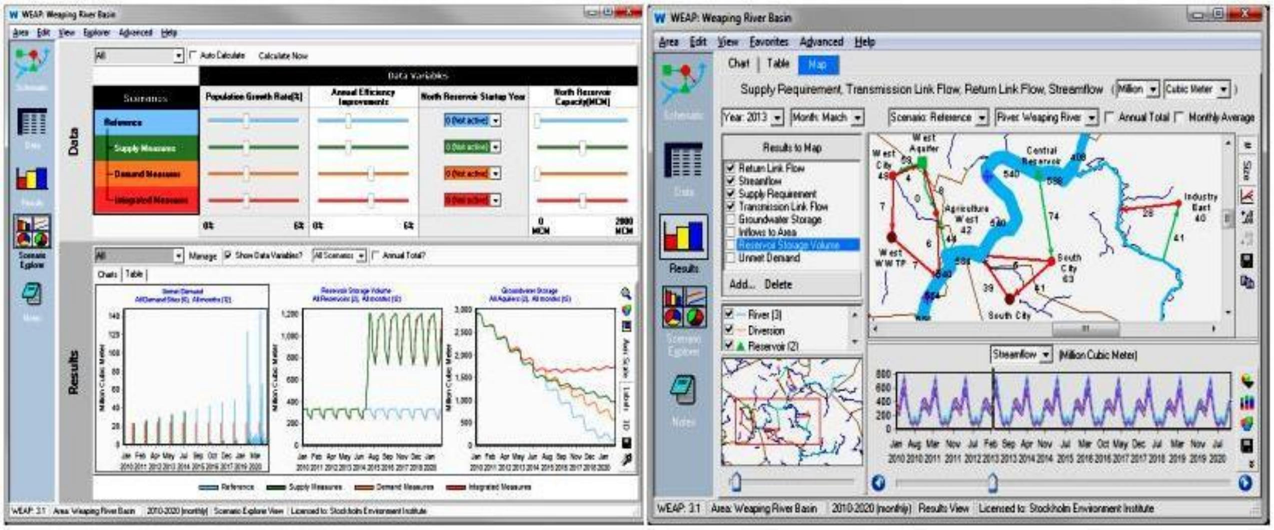


Figure 22: Results view - source: Sieber J., et al., 2011

Hierarchical data presentation

Data in WEAP is organised in a hierarchical outline that facilitate overview and editing of the main data structures during analysis. It comprises of (Sieber, 2011):

- **‘Key assumptions section’** under which one creates and organizes independent variables used to guide analysis calculations. Driver variables are not directly calculated in WEAP, but they are useful as intermediate variables that can be referenced in modelling calculations. It is very useful to create variables here for all major modelling assumptions, especially those that will vary from scenario to scenario;
- **‘Demand Sites section’** on the other hand allows demand disaggregation with end-use based approach for modelling the requirements for water consumption in a catchment and any other water needs from areas depending directly on water from the catchment area being modelled.
- **‘Hydrology section’,** is where the future inflows for each supply source are projected using either the ‘Water Year Method’ (discussed later) or the linking the model with other applications like Excel which contain the time series data to be imported through in-build ‘ReadfromFile Method’;
- **‘Supply and Resources section’** on the other hand uses the monthly supply requirement established from demand and hydrology definitions of the system to determine the amounts, availability and allocation of supplies, simulates monthly river flows, including surface/groundwater interactions and in-stream flow requirements, hydropower generation, and tracks reservoir and groundwater storage. The subsections here include: Transmission links; Rivers and diversions; Groundwater; Local reservoir (not on a river); other supplies (supplies not modelled e.g. inter-basin transfers or desalination) and Return flows. For comprehensive integrated catchment modelling with WEAP the useful data for this section include: Streamflow gage records and their locations; estimates of streamflow for ungaged locations; reservoir storage levels, volume-elevation relationship, net monthly evaporation rates, operating rules, recreation, hydropower, navigation, water supply and other conservation purposes; Groundwater recharge rates, gains from losses to rivers; In-stream flow requirements for recreation, water quality, aquatic and wildlife, navigation, other conservation purposes and downstream obligations; Transmission link capacities and losses; wastewater and effluent routing; costs of delivered water.
- **‘Environment section’** tracks pollution from generation to treatment to its outflow and accumulation in surface and underground bodies of water; and
- **‘Other Assumptions section’** where user-defined intermediate variables are created.

4.3.7 Scenarios

Reference scenario

Assuming a conventional situation where demands increases steadily over time, while the supply infrastructure remains static i.e. no improvements are made that might increase availability of supply. As demands increase and groundwater sources are depleted, there are increasing shortfalls in meeting demand and in stream flow requirements. Pollution generation and loads follow demand trend, increasing over time. Identification of arising problems guides creation of scenarios to alleviate them. The following three scenarios implement measures designed to reduce demand or increase available supply (Sieber, 2011).

Demand Measures

The Demand Measures Scenario slows the increasing rate of the demands by decreasing water use rates in the future. Supply coverage is thus improved because the supply requirement is decreased, although still it may still be less than full coverage. This scenario also slows, but does not halt, the depletion rate of the groundwater. There is, however, a costs increase due to demand efficiency measures (Sieber, 2011).

Supply Measures

The supply measures allow the storage of surplus surface water in reservoirs or in artificial groundwater recharge zone, to be made available to augment lower available supplies in the dry seasons. Supply coverage is thus improved year round due to the increased supply available, although it may still be less than full coverage. This scenario slows the depletion of groundwater and allows all flow requirements to be met. Construction of a new reservoir and/or ground water artificial recharge could lead to costs increase (Sieber, 2011).

Integrated Measures

The integrated measures scenario combines measures from demand measures and supply measures scenarios. This scenario decreases demand and provides excellent supply coverage leading to increase in groundwater storage and fulfilment of all flow requirements. Costs increase is however unavoidable due to the demand efficiency measures and construction of new reservoir etc.

4.3.8 Functions

WEAP allow users to enter data and construct models (specify the values of variables) using mathematical expressions. WEAP supports a comprehensive set of functions that can be included in expressions to create models. Functions are divided into three groups i.e. Modelling functions which are the major functions used in data modelling; mathematical functions for standard mathematical functions, similar in syntax to the ones used in Microsoft Excel and the logical functions, which can be used to create complex conditional modelling expressions (Sieber, 2011).

4.3.9 Calculation Algorithms

WEAP calculates a water and pollution mass balance for every node and link in the system on a monthly time step. Water is dispatched to meet in-stream, consumptive and hydropower requirements, subject to demand priorities, supply preferences, mass balance and other constraints. Point loads of pollution into receiving bodies of water are computed, and in-stream water quality concentrations are calculated. WEAP operates on a monthly time step, from the first month of the current accounts year through the last month of the last scenario year. Each month is independent of the previous month, except for reservoir and aquifer storage, and catchment soil moisture levels (soil moisture method only) (Sieber, 2011). Thus, all of the water entering the system in a month (e.g., head-flow, groundwater recharge, or runoff into reaches) is either stored in an aquifer, reservoir or catchment, or leaves the system by the end of the month (e.g., outflow from end of river, demand site consumption, reservoir or river reach evaporation, transmission and return flow link losses).

Because the time scale is relatively long (monthly), all flows are assumed to occur instantaneously; thus, a demand site can withdraw water from the river, consume some, return the rest to a wastewater treatment plant that treats it and returns it to the river. This return flow is available for use in the same month by downstream demands. If a MODFLOW model is linked, WEAP results (groundwater pumping and recharge, and river stage) will be loaded into the MODFLOW input files, MODFLOW will be run for one time step, and MODFLOW results (cell heads, and flows between surface and groundwater) will be read into WEAP (Sieber, 2011).

Annual Demand and Monthly Supply Requirement Calculations

Annual demand: A demand site's (*DS*) demand for water is calculated as the sum of the demands for all the demand site's bottom-level branches (*Br*). A bottom-level branch is one that has no branches below it.

$$\mathbf{AnnualDemand_{DS} = \sum_{Br} (TotalActivityLevel_{Br}\, x WaterUseRate_{Br})}$$

The total activity level for a bottom-level branch is the product of the activity levels in all branches from the bottom branch back up to the demand site branch (where Br is the bottom-level branch, Br' is the parent of Br, Br'' is the grandparent of Br, etc.) (Sieber, 2011).

$$\mathbf{TotalActivityLevel_{Br} = ActivityLevel_{Br}\ x\ ActivityLevel_{Br'}\ x\ ActivityLevel_{Br''}\ x...}$$

Both the activity level for a branch and the water use rate for a bottom-level branch are entered as data.

Monthly Demand - The monthly demand represents the amount of water needed each month by the demand site for its use. The demand for a month (*m*) equals that month's fraction (specified as data under Demand\ Monthly Variation) of the adjusted annual demand (Sieber, 2011).

$$\mathbf{MonthlyDemand_{DS,\,m} = MonthlyVariationFraction_{DS,\,m}\ x\ Adj'dAnnualDemand_{DS}}$$

Monthly Supply Requirement - supply requirement is the actual amount needed from the supply sources. The supply requirement takes the demand and adjusts it to account for internal reuse, demand side management strategies for reducing demand, and internal losses. These three adjustment fractions are entered as data--see Demand\Loss and Reuse and Demand\Demand Side Management (Sieber, 2011).

MonthlySupplyRequirementDS, m = (MonthlyDemandDS, m x (1 - ReuseRateDS) x (1 - DSMSavingsDS)) / (1 - LossRateDS)

4.3.10 Evapotranspiration, Runoff, Infiltration and Irrigation

There is a choice among four methods to simulate catchment processes such as evapotranspiration, runoff, infiltration and irrigation demands. These methods include: the rainfall runoff and irrigation demands only versions of the FAO crop requirements approach; the soil moisture method, and the MABIA method. The choice of any method is subjective and should depend on the level of complexity desired for representing the catchment processes and data availability (Sieber, 2011).

Irrigation Demands Only Method

It uses crop coefficients to calculate the potential evapotranspiration in the catchment, then determines any irrigation demand that may be required to fulfil that portion of the evapotranspiration requirement that rainfall cannot meet. It does not simulate runoff or infiltration processes, or track changes in soil moisture (Sieber, 2011).

Rainfall Runoff Method

It determines evapotranspiration for irrigated and rain fed crops using crop coefficients, the same as in the Irrigation Demands method. The remainder of rainfall not consumed by evapotranspiration is simulated as runoff to a river, or can be proportioned among runoff to a river and flow to groundwater via catchment links (Sieber, 2011).

Rainfall Runoff Method (Soil Moisture Method)

The Soil Moisture method is the most complex of the four methods, representing the catchment with two soil layers, as well as the potential for snow accumulation. In the upper soil layer, it simulates evapotranspiration considering rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow, and changes in soil moisture. This method allows for the characterization of land use and/or soil type impacts to these processes. Base flow routing to the river and soil moisture changes are simulated in the lower soil layer. Correspondingly, the soil moisture method requires more extensive soil and climate parameterization to simulate these processes (Sieber, 2011).

Note that the deeper percolation within the catchment can also be transmitted directly to a groundwater node by creating a Runoff/Infiltration Flow Link from the catchment to the groundwater node. The method essentially becomes a one-layer soil moisture scheme if this is link is made (Sieber, 2011).

MABIA Method (Dual Kc, Daily)

This is a daily simulation of transpiration, evaporation, irrigation requirements and scheduling, crop growth and yields, and includes modules for estimating reference evapotranspiration and soil water capacity. It was derived from the MABIA suite of software tools, developed at the Institut National Agronomique de Tunisie by Dr. Ali Sahli et al. MABIA Method uses the „dual‟ K_c method, whereby the K_c value is divided into a „basal‟ crop coefficient, K_{cb}, and a separate component, K_e, representing evaporation from the soil surface. The basal crop coefficient represents actual ET conditions when the soil surface is dry but sufficient root zone moisture is present to support full transpiration (Sieber, 2011).

FAO Crop Requirements Methods (Rainfall Runoff & Irrigation Demands Only)

Crop requirements are calculated assuming a demand site with simplified hydrological and agro-hydrological processes such as precipitation, evapotranspiration, and crop growth emphasizing irrigated and rainfall agriculture. Non-agricultural land classes can be included as well. The following equations were used to implement this approach where subscripts LC is land cover, HU is hydro-unit, I is irrigated, and NI is non-irrigated (Sieber, 2011):

$$\mathbf{PrecipAvailableForET_{LC} = Precip_{HU} * Area_{LC} * PrecipEffective_{LC}}$$

$$\mathbf{ETpotential_{LC} = ETreference_{HU} * Kc_{LC} * Area_{LC}}$$

$$\mathbf{PrecipShortfall_{LC,\,I} = Max\ (0,\ ETpotential_{LC,\,I} - PrecipAvailableForET_{LC,\,I})}$$

$$\mathbf{SupplyRequirement_{LC,\,I} = (1\ /\ IrrFrac_{LC,\,I}) * PrecipShortfall_{LC,\,I})}$$

$$\mathbf{SupplyRequirement_{HU} = \sum\nolimits_{LC,\,I} SupplyRequirement_{LC,\,I}}$$

The above four equations are used to determine the additional amount of water (above the available precipitation) needed to supply the evapotranspiration demand of the land cover (and total hydro unit) while taking into account irrigation efficiencies. Based on the system of priorities, the following quantities can be calculated:

$$\mathbf{Supply_{HU} = Calculated\ by\ WEAP\ allocation\ algorithm}$$

$$\mathbf{Supply_{LC,\,I} = Supply_{HU} * (SupplyRequirement_{LC,\,I} / SupplyRequirement_{HU})}$$

$$\mathbf{ETActual_{LC,\,NI} = Min\ (ETpotential_{LC,\,NI},\ PrecipAvailableForET_{LC,\,NI})}$$

$$\mathbf{ETActual_{LC,I} = Min\ (ETpotential_{LC,I},\ PrecipAvailableForET_{LC,I}) + IrrFrac_{LC,I} * Supply_{LC,I}}$$

$$\mathbf{(Evaporative\ fraction)\ EF_{LC} = ETActual_{LC} / ETpotential_{LC}}$$

As a result, the actual yield can be calculated with the following equation:

$$\mathbf{ActualYield_{LC} = PotentialYield_{LC} * Max\ (0,\ (1 - YieldResponseFactor_{LC} * (1 - EF_{LC})))}$$

In the Irrigation Demands Only method, runoff is not calculated. In the Rainfall Runoff method, runoff to both groundwater and surface water can be calculated with the following equations:

Runoff$_{LC}$ = Max (0, PrecipAvailableForET$_{LC}$ - ETpotential$_{LC}$) + (Precip$_{LC}$ * (1 - PrecipEffective$_{LC}$)) + (1 - IrrFrac$_{LC,I}$) * Supply$_{LC,I}$

RunoffToGW$_{HU}$ = $\sum_{LC}$ (Runoff$_{LC}$ * RunoffToGWFraction$_{LC}$)

RunoffToSurfaceWater$_{HU}$ = $\sum_{LC}$ (Runoff$_{LC}$ * (1 - RunoffToGWFraction$_{LC}$))

Soil Moisture Method

This one dimensional, 2-compartment (or "bucket") soil moisture accounting scheme is based on empirical functions that describe evapotranspiration, surface runoff, sub-surface runoff (i.e., interflow), and deep percolation for a watershed unit. This method allows for the characterization of land use and/or soil type impacts to these processes. The deep percolation within the watershed unit can be transmitted to a surface water body as base flow or directly to groundwater storage if the appropriate link is made between the watershed unit node and a groundwater node.

A watershed unit can be divided into N fractional areas representing different land uses/soil types, and a water balance is computed for each fractional area, j of N. Climate is assumed uniform over each sub-catchment, and the water balance is given as,

$$Rd_j \frac{dz_{1.j}}{dt} = P_e(t) - PET(t)k_{e.j}(t)\frac{5z_{1.j} - 2z_{1.j}^2}{3} - P_e(t)Z_{1.j}^{RRF_j} - f_j k_{z.j} z_{1.j}^2 - \left(1 - f_j\right)k_{z.j} z_{1.j}^2 \ldots\ldots\ldots Eqn.(i)$$

Where $z_{1,j}$ = [1,0] is the relative storage given as a fraction of the total effective storage of the root zone, Rd_j (mm) for land cover fraction, j. The effective precipitation, P_e, includes snowmelt from accumulated snowpack in the sub-catchment, where m_c is the melt coefficient given as,

$$m_c = \begin{Bmatrix} 0 & & T_j < T_S \\ 1 & if & T_j > T_1 \\ \frac{T_j - T_S}{T_1 - T_S} & & T_s \leq T_j \leq T_1 \end{Bmatrix} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn.\ (ii)$$

Where $T_i$is the observed temperature for month i, and $T_1$and T_S are the melting and freezing temperature thresholds. Snow accumulation, Ac_i, is a function of m_c and the observed monthly total precipitation, P_i, by the following relation,

$$\boldsymbol{Ac_i = Ac_{i-1} + (1 - m_c)P_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots Eqn.\ (iii)}$$

With the melt rate,m_r, defined as,

$$m_r = Ac_i m_c \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots Eqn.\ (iv)$$

The effective precipitation, P_e, is then computed as

$$P_e = P_i m_c + m_r \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots Eqn.\ (v)$$

In Eqn.(i), PET is the Penman-Monteith reference crop potential evapotranspiration, where $k_{c,j}$ is the crop/plant coefficient for each fractional land cover. The third term represents surface runoff, where RRF_j is the Runoff Resistance Factor of the land cover. Higher values of RRF_j lead to less surface runoff. The fourth and fifth terms are the interflow and deep percolation terms, respectively, where the parameter $k_{s.j}$ is an estimate of the root zone saturated conductivity (mm/time) and f_j is a partitioning coefficient related to soil, land cover type, and topography that fractionally partitions water both horizontally and vertically (Sieber, 2011). Thus total surface and interflow runoff, RT, from each sub-catchment at time t is,

$$RT(t) = \sum_{j=1}^{N} A_j\left(P_e(t) Z_{1.j}^{RRF_j} + f_j k_{s.j} Z_{1.j}^{2}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots..Eqn.(vi)$$

For applications where no return flow link is created from a catchment to a groundwater node, baseflow emanating from the second bucket will be computed as:

$$S_{max}\frac{dz_2}{dt} = \left(\sum_{j=1}^{N}\left(1 - f_j\right) k_{s.j} Z_{1.j}^{2}\right) - k_{s.2} Z_2^{2} \dots\dots\dots\dots\dots\dots\dots..Eqn.(vii)$$

where the inflow to this storage, S_{max} is the deep percolation from the upper storage given in Eqn. 1, and K_{s2} is the saturated conductivity of the lower storage (mm/time), which is given as a single value for the catchment and therefore does not include a subscript, j. Equations 1 and 7 are solved using a predictor-corrector algorithm.

When an alluvial aquifer is introduced into the model and a runoff/infiltration link is established between the watershed unit and the groundwater node, the second storage term in Eqn. 7 is ignored, and recharge R (volume/time) to the aquifer is

$$R = \sum_{j=1}^{n} A_j(1 - f_j) k_{s.j} Z_{1.j}^{2} \dots\dots\dots\dots\dots\dots\dots\dots..\dots\dots\dots\dots\dots\dots.Eqn.(vii)$$

Where A is the watershed unit's contributing area. The stylized aquifer characterizes the height of the water table relative to the stream, where individual river segments can either gain or lose water to the aquifer.

Runoff Flows from Irrigation

Irrigation runoff can be included in total runoff emanating from a catchment. WEAP calculates this irrigation runoff by first assuming no irrigation exists and calculating flows accordingly. WEAP then performs the calculations incorporating irrigation, assuming all requested irrigation is supplied. Knowing how much more runoff would flow due solely to irrigation; WEAP calculates an "average" irrigation runoff fraction (that goes to a river and/or groundwater). This fraction is then applied to the quantity of irrigation that was actually supplied, and essentially becomes the runoff fraction. Note: this irrigation runoff fraction is specified as data by the user when simulating a catchment with the Rainfall Runoff method (Sieber & Purkey, 2011).

Reference Evapotranspiration (ETref)

Reference crop evapotranspiration or reference evapotranspiration, denoted as ET_o or ET_{ref}, is the estimation of the evapotranspiration from the "reference surface." The reference surface is a hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23. The reference surface closely resembles an extensive surface of green, well-watered grass of uniform height, actively growing and completely shading the ground. The fixed surface resistance of 70 s/m implies a moderately dry soil surface resulting from about a weekly irrigation frequency (Sieber, 2011).

There are two options for ETref i.e. to input ETref provided directly from climate stations data, or ETref calculated using the Penman-Monteith equation. The latter approach requires data on minimum and maximum daily temperature; relative humidity; solar radiation; wind speed; latitude and altitude of the climate measurement station. If humidity data is not available, and estimate can be obtained by assuming that the dew point temperature is the same as the daily minimum temperature. For solar radiation, depending on the availability of data, different equations are used with following data requirements, in decreasing order of preference i.e. direct solar radiation data, hours of sunshine per day, cloudiness fraction, or estimate using the Hargreaves formula based on minimum and maximum daily temperature and an adjustment coefficient (K_{rs}).

Depending on the setting in General: Basic Parameters, the values for climate data can either be entered once for each catchment and will apply to all the land use branches within that catchment, or they will be entered separately for each branch within each catchment. This second option might be necessary if there is a large variation in the elevation among different land uses within a catchment. Alternatively, the catchment could be divided into several different catchment nodes according to elevation, so that the climate within each catchment did not vary by land use.

The calculation methods implemented in the MABIA Method are those of the FAO Penman-Monteith equation (Allen, et al., 1998) written as follows:

$$ET_O = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T_{mean} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

Where

ET_O = reference evapotranspiration [mm/day]

R_n = net radiation at the crop surface [MJ/m^2/day]

G = soil heat flux density [MJ/m^2/day] which can be neglected (G=0)

T_{mean} = mean air temperature [°C]

u_2 = wind speed measured at 2 m height [m/s]

Δ = slope vapour pressure curve [kPa/°C]

γ = psychrometric constant [kPa/°C]

e_s = saturation vapour pressure [kPa]

e_a = actual vapour pressure [kPa]

$(e_s - e_a)$ = saturation vapour pressure deficit [kPa]

Chapter 5. **Research Methodology**

This section provide a chronology of processes and tasks undertaken within the study and serves as a technical guide into the relevant data collection methods, data processing and analysis and information management system adopted pursuant to the study objective. Literature review and subsequent setting up of various DSS prototype models facilitated the formulation of the models' requirements, which greatly enhanced data collection exercise. A systematic approach facilitated the assessment of various decision support tools available in the water industry as to establish their efficacy in proffering the envisaged decision making attributes as outlined in chapter 4 at the onset of the study. The current state of art and technology in water resources management in the country, and especially in the case study area, was established and outlined to demonstrate the sectoral achievements, the limitations and gaps that this study sought to address.

A feasible adaptive and collaborative DSS tools for prospective adoption by catchment management authority was evaluated subject to the three fundamental cores of decision making as outline by (Brans, 2002) i.e.:

- **Rationality**: capacity to cost-effectively proffer economical and optimal catchment water resources development and allocation by facilitating a dynamic evaluation of alternative spatial water uses and related trade-offs, to optimize the benefit accruing from investment in resource development;
- **Subjectivity**: judgements are based on decision maker's informed insight on system performance within the prevailing constraints; hence providing ground for collaboration in assembling relevant and comprehensive data and consensus building between managers and stakeholders' within a catchment; and finally
- **Ethics**: management decision making that take into account the prevailing social-economic and technical capacity without substantially compromising system performance while also allowing reasonable sacrifices for ecological demand.

The chapter outlines the strategy used for case study area identification and arrangement of conditions for the collection and analysis of data to help evaluate various scenarios that are imperative towards realisation of the set objective. For instance, the extent, detail and flexibility of data application by a DSS tools constitute a key constraint that play a great role in determining its efficacy, and thus its prospects of being a tools of choice for the case study area. This is owing to the fact that availability of detailed and coordinated water resources database is currently a major impediment to establishment of a historical trend, for a pragmatic projection into future prospects. The prospective tool or tools are then evaluated on the basis of other operational constraints i.e. social-economic, technical and environmental implications. The most viable tool is then chosen, set up, calibrated and evaluated within various operating scenarios to further demonstrate its efficacy.

5.1 Review of the State of Art in Technology within the Water Sector in Kenya

A comprehensive review of the state of the art and technology of the WRM regime in the country with a special focus on how decisions on catchment water allocations for water balance, trade-offs between various prospective uses and users, mitigation of conflicts related to water use, land use or waste water disposal. To this end special attention has been accorded to establishing availability and substantive use of technical tools (models), and to answer the questions on 'what, where, why, when, how, who, and which' in relation to water resources quantities availed by various sources on one side and the corresponding uses by respective abstractors on the other. The variables in this respect include:

- The nature of the decision support tool/s adopted and their functionality,
- User's objective,
- Level of stakeholders' participation and their capacity to be proactive,
- Availability and adequacy of relevant data,
- Technical, institutional and socio-political good will to facilitate implementation of system output and advancement through dynamic policies and strategies application to assist WR managers in decision making process.

Moreover, the methodological background upon which the structure of the tool/s, in application in the case study area, has been designed is ascertained and the key features that aid integrated analytical modelling and decision making are outlined. This was to help identify any existing limitations to a holistic, participatory decision making process as espoused by IWRM and especially to identify the gaps and/or needs in technology and their respective cost-effective solutions.

5.1.1 Existing Decision Making Process in WRM

Currently, most projects in the water sector are planned and financed by some government department or public utility companies mandated with municipal water supply, sewerage systems, irrigation, flood mitigation, hydropower generation dams etc. Due to diverse public interests, many such projects become controversial political issues and are debated at length, albeit with socio-political undertones, by stakeholders whose understanding of the fundamental technical aspects or other impacts of the projects is limited. Since, majority stakeholders' opinions, especially local communities' proactive participation at conceptualisation and reconnaissance stages of the projects are ignored and/or overlooked, many potentially noble projects and initiatives subsequently suffer negative publicity and are ultimately nipped in the bud.

It has therefore become imperative to introduce a mechanism for positively and proactively engaging stakeholders at every stage of project and sector operations to ensure consistency and security in investment returns. Accordingly, it is a clear responsibility of engineers, in collaboration with experts from all relevant disciplines, to carefully analyse the facts and present a sound case in the simple terms as the basis for discussions and consensus building for the benefit of the public (Linsley & Franzini, 1979). Subsequently, it is imperative for engineers in collaboration with experts from related disciplines and water managers to exploit modern technology especially in computer applications to complement their skills in arriving at authentic judgement in water development and management.

To this end, it was necessary to first establish the technical tools in application within the case study area; and also to ascertain what, why and how data is availed and input into the system and the how the output is applied to aid WRM decision making process. For the prevailing DSS tool/s in operation within the case study area, it was also imperative to expound on their strength and limitations and subsequent gaps in informing decision process as to capture the relevance of the study and use the same parameters in evaluating prospective tools.

5.1.2 **Basin/Sub-Basin Performance**

A review of the status quo in water resources management and performance was meant to establish how the current regime achieve equity and sustainability requirements in water allocation , adopted supply and demand management policies and reform measures espoused to address present and forecasted conflict of interest in resources demand and use within the context of current and projected resource potential. A set of questionnaire questions were prepared and distributed to the various water service providers and community self-help groups to help establish the issues underlying the sector at community level and opinions of various operative on what could be done to improve the services and mitigate water conflicts. A few water managers were also interviewed, while a seminar on water resources database management organised for catchment managers provided a better overview of the status quo in technical infrastructure and competence.

5.2 Choice of the Case Study Area

The main objective being identification of a feasible adaptive and collaborative decision support tool/s for the case study area and therewith formulation of a methodology for achieving water balance at catchment scale and especially within catchments with typical challenging social-economic, technical and cultural water resources management constraint prevalent in developing countries. Consequently, each of the five (5) prospective basins in the country i.e. Lake Victoria, River Tana, River Ewaso Nyiro, Athi River basin and Rift Valley inland basin (appendix Figure 67) was favourably considered. This approach was adopted while keeping open the option of narrowing down the spatial extent to a representative sub-catchment, which presented reasonable data and logistics challenges surmountable within the temporal confines of the envisaged study targets.

5.3 Data Collection and Analysis

To understand the status quo in technique, infrastructure and the unmet needs consequential to the prevailing gaps in WRM, interviews were conducted at institutional and community level, targeting water services providers, users and other stakeholders to gather their perspective. Local prevailing policies and approaches, especially the insight on how they manage inadequacies on essential data and in some instance total unavailability of crucial data, that is fundamentally imperative to dynamic systems analysis, policies interpretations, policies and strategies implementation and evaluation for consistent exercise of their mandate, were important in establishing the effectiveness of decision making process within the current system.

Among the data and information compiled in this section were comprehensive hydroclimatic, population, social-economic statistics, land cover, land and water uses, water infrastructure and environmental data, with key emphasis on the quantity and quality of the same. These are the key parameters that influence and overall impacts on efforts to achieve sustainable WRM solutions at basin level. The main focus on one hand is on geography, climate, topography, land use/cover, surface and ground water hydrology, lithology and hydro-geological processes and water infrastructure which impact the basin water resources supply; and on the other hand there is population and its demography, social-economic activities and other ecological demand i.e. environmental flow requirements (base flow) that determine the basin's overall water resources demand. Demography is significant since different groups of people will have not only varying needs in water quantity and quality, but also some divergent views as to what makes a community or watershed sustainable.

As already established in the literature review of the various models outlined in this study, the baseline raw information required as input in various water balance oriented decision support models includes:

- Meteorological/ climatically data i.e.
    - Recorded precipitation data
    - Maximum and minimum Temperature
    - Maximum and minimum Relative humidity
    - Solar radiation/Sunshine hours/ cloudiness fraction
    - Wind speed
    - Evaporation; Reference crop evapotranspiration (ET_O or ET_{ref})
- Hydrological data i.e.
    - Stream flow gauged records and geographical location, altitude
    - Estimates of stream flow for ungaged locations calculated using gage records, drainage area or other parameters
    - Ground water estimated recharge rates; interflow/ groundwater and surface water interface; gains from and losses to rivers
    - Reservoir and water pans storage levels and their operation regimes, volume-elevation relationships, net monthly evaporation rates, operating rules for fish and wildlife, recreation, hydropower, navigation, water supply and other conservation purposes
    - Water abstraction and water use regimes; transmission links' location, capacities and losses
    - Water transfer from and into the catchment from other catchments.
    - Waste water treatment plants operation and effluent routing; return flow links' location, capacities and losses

    - Return flow from irrigated lands etc.
    - Operating conditions of drainage facilities in the catchment area - feedback/ suggestions from operators
- Spatial-temporal schematic features i.e.
    - Geographical location –latitude, longitude and altitude
    - Lithology
    - Geology
    - Topography
    - Land cover/land use practices e.g. forest; urban settlement; grasslands etc.
    - Population i.e. including population growth and socio-economic welfare (demography)
    - Economic activities (commercial; industrial; agriculture/irrigation; energy production etc.)
    - Environmental requirements i.e. in-stream flow requirements for recreation, water quality, aquatic ecosystem conservation and wildlife, navigation, other conservation purposes, and any downstream obligations etc.
- Institutional management policies and strategies
    - Demand management policies: water tariff policies (costs of delivered water); water recycle and reuse policies;
    - Supply management policies: storage expansion; ground water recharge initiative; reservoir storage control policies;
    - Intra- and inter-catchment conflict management: policies implementation and feedback mechanism.

5.4 Description of the Case Study Area - Physical and Social-Economic Parameters

A detailed description of the case study area in more specific reference than projected by the outline in Chapter 2 (sec. 2.4) is meant to introduce the area and especially illustrate the features of relevance to the study through a comprehensive discussion of the physical, social-economic, technical, infrastructural, and environment conditions. Hence proffer the stakeholders' perspective of the variety of social-economic and environmental claims to the available water resources and the prevailing structural, operation and management challenges. It delves on the physical description and schematic representation of features, landscape, land use, water infrastructure, demography and other socio-economic parameters which have an impact on the basin water resources supply and demand patterns. Moreover, the section highlights the prevailing local management adopted policies, strategies and general sector reforms that promote or seek to introduce transformation from the status quo.

5.5 Review of DSS Tools and Choice of the most Feasible Tool

Review of the available DSS tools currently in application in water industry delved on their critical input data requirement and simplicity albeit with appreciable performance, user-friendliness, output effectiveness, versatility and adaptability within local cultural setting. Others include the level of capital investment required for universal adoption and operation in the local water sector; the technical capacity and ease of acquiring the skills required to run the tool and for capacity building among the stakeholders in promotion of an all-inclusive participatory decision making process. The evaluated performance of various tool in these aspects helped determine their efficacy for successful adaptation as collaborative tool for water resources management in typical catchment area; i.e. in due cognizance of input data requirement, technical and social-economic boundary conditions. In this stage availability of significant data to enable competent setting up, calibration, test and validation of the potential model and the flexibility of the said model to accommodate data scarcity without substantially compromising the quality of results played a big role in determining the choice.

To this end three DSS tool stood out namely: Water Evaluation and Planning System (WEAP); MULti-sectoral INtegrated and Operational decision support system (MULINO DSS); and MIKE BASIN. However, in the later course of the study MIKE BASIN was replaced by MIKE HYDRO BASIN, a more advanced tool, which attended to a variety of established limitations attributed to the earlier version. In effect, introduction of the new module rendered MIKE BASIN inferior and subsequent evaluation on its efficacy as an adaptive collaborative tool for catchment water balancing was considered untenable and evidently inadmissible to the objective of this study. A variety of latitudes used as yard sticks in evaluation and comparison of various decision support tools are presented in Table 15 below.

Table 15: Objective review of various decision support tools in operation within the water sector.

Attributes	***WEAP21***	***MULINO-DSS (mDSS)***	***MIKE Basin***	***MIKE Hydro Basin***
Main focus i. *Optimization* (O) ii. *Simulation* (S)				
Functionality *i. Water R. planning* *ii. Water balancing* *iii. Hydrodynamic*				

Attributes	***WEAP21***	***MULINO-DSS (mDSS)***	***MIKE Basin***	***MIKE Hydro Basin***
iv. *Combined –DSF^*				
Type *i. Hydrological model* *ii. Hydraulic model* *iii. Operation model^* iv. *Combined –DSF^*				
Input				
Output *i. Database capability* *ii. Forecasting* *iii. Policy analysis* *iv. Qualitative* v. *Quantitative*				
Complexity				
Limitations *i. Installation cost* *ii. Operation and Maintenance demands* *iii. Technical demand* iv.				
Remarks				

The method adopted in the determination of the most feasible tool for the case study area was based on the fundamentals espoused by (Giupponi, et al., 2004) in the evaluation of mDSS as a modelling tool for water management at catchment scale. The choice and implementation of modelling tools is based upon common criteria of adopting, if possible, those approaches most widely used in particular by the targeted end users and deriving from, or compatible with, standardised methodologies at both local and international scale. Therefore the already existing and tested modules or pieces of software could also be implemented in a modular framework so as to be adapted to the local contexts of application. Improved versions of these modules would then be tested first independently with available reference data sets referring to past land use and ecological water resources use dynamics. The modules would then be built into an integrated tool and a prototype applied to operational simulations, evaluated and probably further modified based on the analysis of the prototype (Giupponi, et al., 2004). However development of modules and/or modification of existing modules and integrated models were beyond the scope of this study and effort was restricted in establishing a methodology and proposing any modification pertinent to successful adoption of an already functional and tested model feasible for typical local settings.

5.6 Setting up the Preferred DSS Model, Calibration and Testing

To set up the most feasible model, sufficient data or methods to close the gaps for the missing data are crucial. The programme was downloaded from the developers website and since the free evaluation module available online was not sufficient for the detailed research, a scholars licence for complete access to the tool was organised. The complexity of water allocation models and the fact that they are required to simulate human behaviour (i.e., to reflect changes in demand) in addition to physical processes means that model calibration and validation is extremely difficult and has often been neglected in the past (McCartney & Arranz, 2007).

Calibration involved changes to model parameters to better simulate the historic scenario. These included changing assumptions about the pattern of historic demand, altering demand priorities, modifying the operating rules of the reservoirs and including environmental flow requirements, to improve the fit between simulated and observed flows (McCartney & Arranz, 2007).

5.7 Running various Projected and Presumed Scenarios

The following scenarios were investigated starting with the reference scenario which assume the demand continue growing at the current rate while the supply remain static i.e. natural flow scenario without anthropogenic influences like supply management (e.g. expansion of storage). Higher population growth; projected management policy impact scenario e.g. land management, supply management (e.g. expansion of reservoirs) and Demand management (e.g. water reuse). When examining the effect of change of water management policy within a catchment, the assumption is that the policy has had enough time to be implemented and take effect.

5.8 Formulation of a Methodology for an Adaptive Collaborative DSS Tool

Development of a methodology to facilitate effective data collection that encompass means and mode of data collection, data processing that entails making fundamental assumptions to bridge the gaps availed by data inadequacy; information flow and dissemination, to database management; and subsequently setting-up a functional DSS model for water balancing within typical catchments.

Chapter 6. Results and Interpretation

This section presents a chronology of outcome of various courses and approaches adopted and outlined in the methodology of this study, starting with the decision support models and integrated policies and strategies already in effect within the case study area. Especially expounding on the questions as to what, why, when, where and how the data pertinent to IWRM is availed and input into the adopted system and the how the output data is applied to aid decision making process. The prevailing limitations, gaps and needs in technology, both from individuals and institutions perspective as derived from the interviews and questionnaires distributed to a sample catchment operators and from study analysis are also identified and their implications outlined.

6.1 State of Art and Technology in Decision Making in the Case Study Area

Since the Water Act 2002 (Leg., Ass., 2003)was enacted in the year 2003, institutions envisioned in the Act have already been put in place. However, economic, technical and logistic challenges continue to hinder proactive collaboration, integration and information flow between the public entities; hence curtailing optimal performance of their individual and collective mandates. For instance, in accordance with the Water Act, WRMA is mandated with gathering and maintaining information on water resources and from time to time publishing forecasts, projections and information on water resources; in addition to liaising with other relevant institutions, legislative and enforcement entities for the better regulation and management of water resources.

To achieve these mandates meteorological data time series is as crucial as stream flow time series and monitored ground water time series. Whereas collection and storage of hydrological data are effectively within WRMA realms, collection and storage of meteorological data would duplicate the mandate of Kenya Meteorological Department (KMD). However, due to lack of institutional inter-linkage mechanism to ensure complementary usage, sharing and collaboration in technical, infrastructural and financial resources, each entity is prompted to procure services rendered by the other public institution, which is a fallacy as they are mainly funded by public coffers and responsibility to yield return for public investment should be a collective goal.

The financial encumbrance in obtaining data pertinent to institutions' operations is also a great set back not only on the spirit of integration espoused in IWRM, the main paradigm behind the formation of these entities, but also on the dynamic evaluations of water balance within a catchment, forecasts, projections and ultimate conservation initiatives for water resources. Moreover, it yields a fundamental gap established at the onset of this study, which is the absence of a consistent and well-coordinated database for hydroclimatic, lithological, agro-hydrological and ecological data pertinent to objective study of water balance within a catchment.

6.1.1 **Existing Decision Making Process in WRM**

To promote adaptive collaborative management between various catchment water resources users associations (WRUAs), responsible for facilitating equitable and sustainable resources allocation within a given catchment, WRMA has in recent past procured and tested implementation of a decision support system (MIKE BASIN). However, after the successful rolling out of the system at national and regional levels of the authority, technical and economic challenges curtailed further cascading of the tool usage to community level (WRUAs) as initially intended. The ensuing inconsistent usage and the setbacks of inadequate finances for requisite capacity building and maintenance of licenses ultimately all but nipped the initiative in the bud.

The main challenges towards maintenance of MIKE BASIN tool was first and foremost the encumbrance arising from duplicate licenses required for effective rolling out and maintenance of the system; i.e. MIKE BASIN is an extension within ArcGIS platform which require the users of the later to obtain a licence from the tool developers to activate the extension. The licence, that further require periodic authorisation renewal, is availed in form of a Dongle, which is essentially a program laden flash disk to be connected to a computer or server to activate the extension for the computers already installed with an active ArcGIS application. Though the need abide and initiative was a proactive response to the fundamental demands of catchment scale water resources management, the financial burden of acquiring and maintaining ArcGIS and MIKE BASIN licences was beyond the financial capacity of entities below the regional level, and even at regional level lack of technical competence in usage of the tool curtailed its effective usage.

As a response to this challenge and also due to the fact that hosting the tool within ArcGIS exposed the tool to other platform related limitations like memory allocation, which in effect limited the complexity of potential analysis, has prompted the developer to release MIKE HYDRO BASIN as from December 2013. The new version attends to most of the shortcoming of MIKE BASIN, and to start within, it does not require ArcGIS platform and can effectively handle more complex analysis. Within one license requirement out of the way, the new tool is effectively more economical to maintain; however due to the late introduction within the course of the study it was not possible to carry out a detailed review of the new version to establish an informed opinion.

6.1.2 **Basin/Sub-Basin Performance**

Due to the challenges with data collection, management and decision support systems as expounded above, the prevailing decision making process for water resources management in the Kenya is neither based on dynamic analysis and evaluation of the spatial-temporal resources and related demand to promote water balance, nor is it effectively collaborative in integrating stakeholder’s views and interests. All the same, the financial, technical and institutional framework impediments notwithstanding, the water sector reforms in the country have been progressive and are consistently bringing about fundamental changes in the way water is used and shared among the different users. To ascertain the spatial and temporal situation in water resources, thematic studies and census on distinct and general parameters are usually commissioned and continue to substantially inform and facilitate decision making and policy formulation within the water sector. The ultimate objective is to ensure a balance between efficiency in water use, as per national Water Efficiency Plan (WEP) that encompasses the spirit of the Kenya national policy on water resources management and development (MWI, 2009), and equity in all water allocations and resources sustainability (Leg., Ass., 2003)

6.1.3 **Water Allocation Policy - WRMA**

Currently the Guidelines for Water Allocation (First Edition, 2010) prepared by WRMA are effective in conformity to the stipulated requirements of Water Act 2002 Section 8 (1) (a) with regard to water allocation and prioritisation, as follows:

a) The allocation of water from a water body should take into consideration four demands on the water, namely:
   i. the portion of the water resource required to meet ecological demands, which forms part of the reserve;
   ii. the portion required to meet basic human needs, which forms the other part of the reserve;
   iii. the portion of water for which commitments have been made in international treaties and inter basin water transfers; and
   iv. the portion of water that can be allocated to individual uses by means of a permit

The individual uses mentioned in the item (iv) above include domestic (rural and urban), agriculture (irrigation), livestock, energy, industrial, tourism, recreation, wildlife, and aquaculture. All users of water resources other than the reserve, international obligations and inter-basin transfers are authorised according to the criteria of equitable allocations (MEWNR, 2013).

b) The reserve commands the highest priority in terms of water allocation.
c) The domestic water has a higher priority than other uses as stipulated in the Water Act 2002 Section 32 (2), (Sub-section 2.3.1).
d) With respect to all the other types of demands, the Water Act 2002 is silent with respect to priority, although various considerations must be made (Section 32 (1)) in regard to:
   i. existing lawful uses in line with efficiency and public benefit;
   ii. commitments or priorities stated in the Catchment Management Strategies;
   iii. potential impacts on other water users and the water resources;
   iv. the class and resource quality objectives;
   v. existing and future investments by the applicant;
   vi. strategic importance of the water use application;
   vii. quality of the water resource which may be required for the reserve; and

viii. probable duration of the water use activity

According to the Water Resources Management Rules 2007 Section 2, the basic human needs mean the quantity of water required for drinking, food preparation, washing of clothes, bathing, and basic sanitation, which are assumed to be equal to 25 l/p/d. However, for the sake of this study, the basic human need for the lowest water consumers, urban poor, has been considered to be equal to 50l/p/d. The fundamental goal of water allocation and prioritisation policy is to develop high productivity and carrying capacity of the catchment whilst achieving acceptable environmental quality and protection of the land and water resources (Saifuka & Ongsomwang, 2003).

6.2 Choice of the Case Study Area

Since DSS tool are designed to assist the decision maker and not to substitute decision maker's skills and experience, the importance of data availability and quality for input into the system cannot be overstated (Sieber, 2011). Accordingly, with the anticipated data related constraints especially in the absence of a well-coordinated hydroclimatic database, it was from the onset determined that for the purpose of this study, data availability would constitute the critical variable by which a representative case study area would be ratified from among various potential catchments.

Consequently, Athi River basin was adopted as the study area, but due to typical bias in data collection and storage within the catchment, the Upper Athi sub-basin (Nairobi River catchment) was settled upon and delineated (see Figure 23 below and appendix Figure 69). The imbalance in field measurements and record keeping was attributed to inadequate financing that hinders installation of adequate stream flow and meteorological measuring gauges; inadequate infrastructure and means for sites accessibility and lethargy, both leading to irregular calibration and reading of measuring gauges in remote areas. Moreover rampant vandalism of the already insufficient devices frustrates progressive enhancement of infrastructure. Consequently, there is an apparent practice of favouring measuring sites within close proximity to urban areas and rural settlements where accessibility for regular calibrations and record taking for largely manual devices are easily enforceable, and security against theft and vandalism can be guaranteed.

This is the main reason why the upper Athi catchment, which encompasses Nairobi city and its environ, had a more reliable database with more expansive data time series than any other sub-basin within ACA. It was therefore determined that for purposes of this study, Nairobi River catchment proffered a representative case study area with significant and relatively sufficient hydroclimatic, agro-hydrological and related multifarious data that would suffice for the pilot model. With the case study area already settled upon, data collection exercise commenced from 2nd May 2013 the exercise lasted for six months until 29th October 2013.

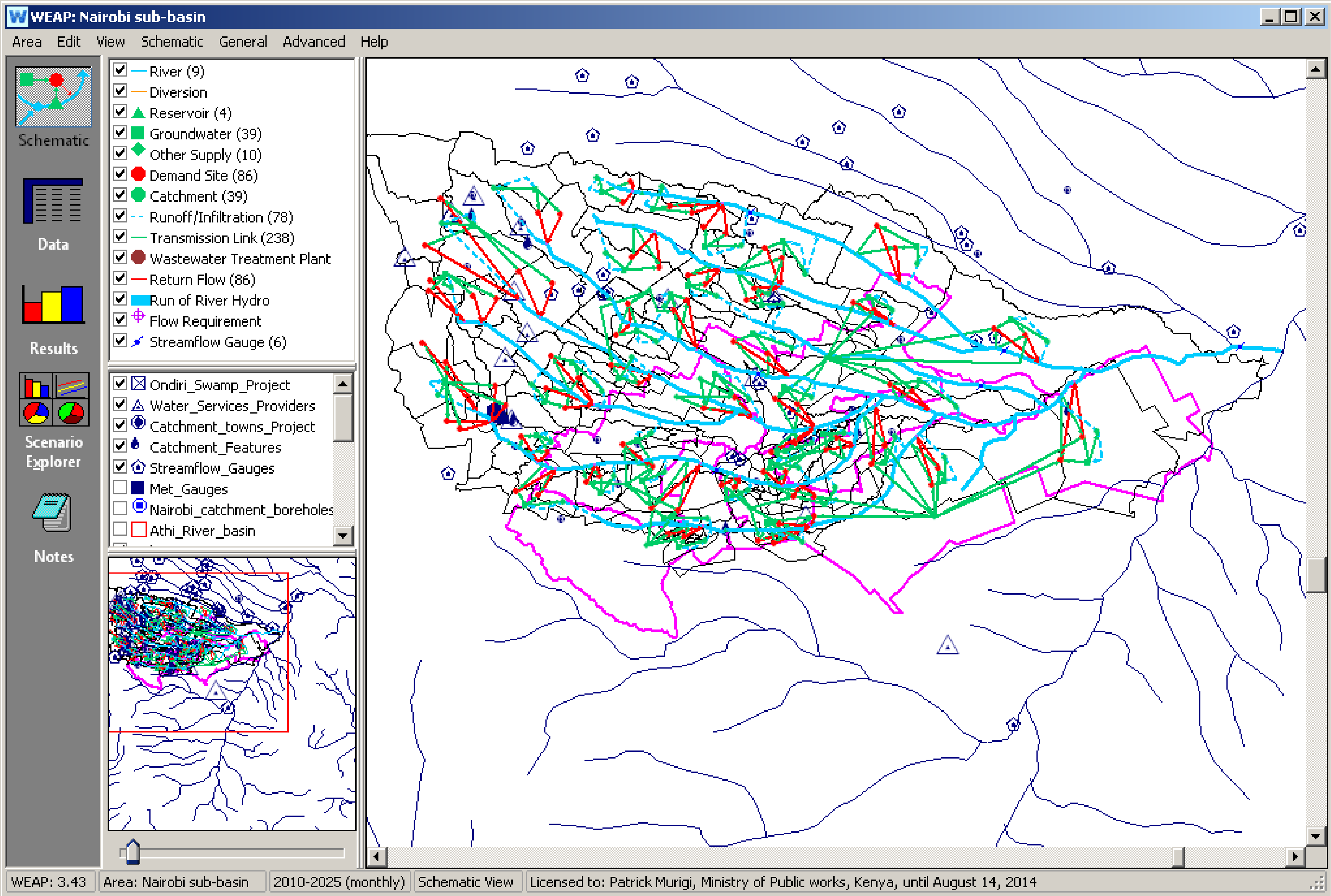


Figure 23: Deliniation of the Nairobi River Catchment showin the Main river and its triburaties

6.3 Data Collection and Analysis

In accordance with universal norm that water flowing in streams, rivers, and groundwater is not necessarily available for use by any person or group desiring it (Linsley & Franzini, 1979), WRMA in Kenya is mandated with spatial-temporal, catchment-based control of water resources development, allocation, use, conservation and management. Accordingly, they receive applications for water abstraction by prospective users and after studying viability of requested water allocations, issues permits or decline effectively. To achieve this objective, they are the main custodian of terrestrial hydrological data, data on protected terrestrial-based land and aquatic ecosystems, pollution trend data and any other resource that is vital for a holistic water resources management.

Consequently, the bulk of the data, information and material relied upon to actuate this study has been obtained and assembled with facilitation by Water Resources Management Authority. A relatively comprehensive set of climatic data for a 20 years' time series was also obtained from Kenya Meteorological Department headquarter offices in Nairobi at a subsidised fee. To ensure the data was representative of the entire case study area, time series from six (6 No.) fairly distributed meteorological stations within the case study area were sought. The time series data obtained from KMD database include:

i) Monthly mean precipitation
ii) Monthly mean maximum and minimum temperatures
iii) Monthly mean maximum and minimum relative humidity
iv) Monthly mean evaporation (pan evaporation)
v) Monthly mean sunshine hours
vi) Monthly mean wind speed

In most of the considered meteorological Stations, the data on precipitation and relative humidity for the twenty years was rather complete but for all the other climatic parameters, the data obtained had substantial gaps and therefore required pre-processing to take care of the gaps before exploiting it. The availability of temperature data was checked using daily mean temperature which was calculated by averaging the daily maximum and minimum temperatures. The monthly results were compared to obtain a common trend for the area and estimates to represent the missing data were constructed accordingly. Temperature time series were available for the 20 years at most of the stations, albeit with significant gaps.

As demonstrated in this study, the data available and accessible from WRMA was not adequate for a holistic evaluation of water balance within the catchment, implying that collaboration with other related ministries, departments and/or organisations is imperative to ensure not only accessibility to crucial data and information, but also to provide a united pro-active interactions between experts within these entities on one side and water service providers, community operators and representatives at community level for integrated water resources management. Some information was accessed from other sources privy to previous studies and surveys commissioned by WRMA and other operators and stakeholders within the water sector i.e. water services providers, National Environment Management Authority (NEMA).

6.3.1 **Institutional Structure for Integrated Collaborative Decision Making Process in WRM**

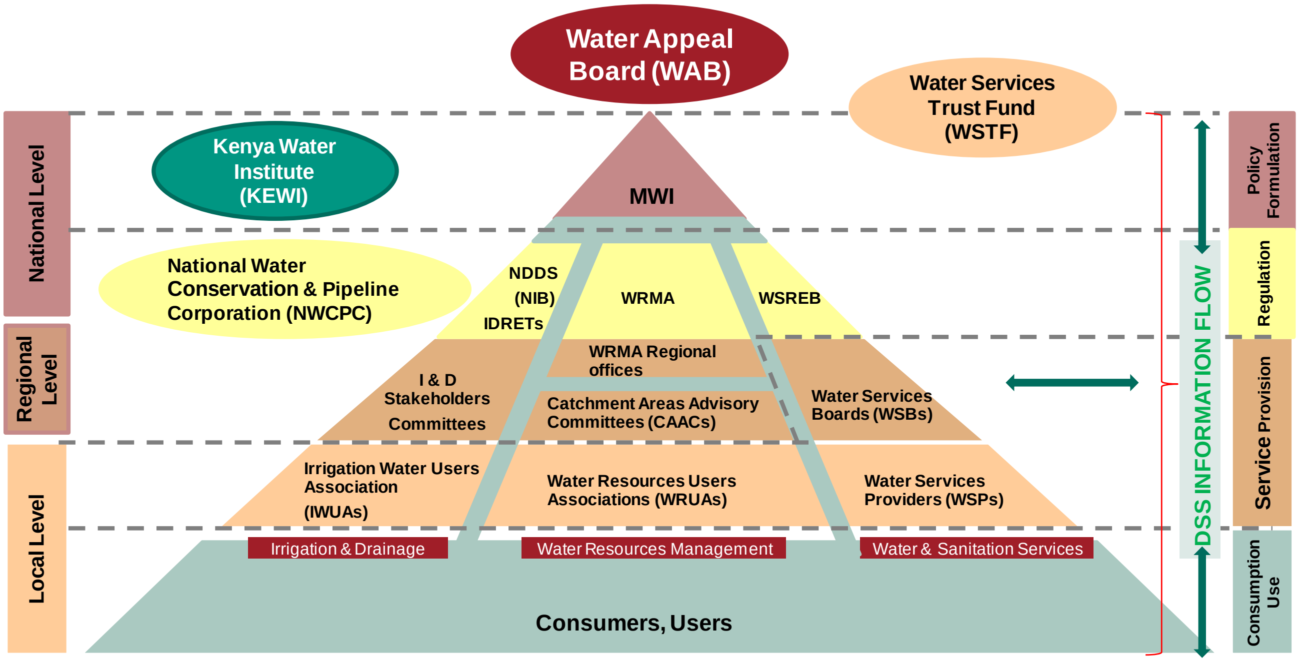


Figure 24: National structure for participatory water resources management (WRMA -modified)

6.4 Description of the Case Study Area - Physical and Social-Economic Parameters

A detailed description of the case study area in more specific reference than projected by the outline in Chapter 2 (sec. 2.4) is meant to introduce the area and especially illustrate the features of relevance to the study through a comprehensive discussion of the physical, social-economic, technical, infrastructural, and environment conditions. Hence proffer the stakeholders' perspective of the variety of social-economic and environmental claims to the available water resources and the prevailing structural, operation and management challenges.

It delves on the physical description and schematic representation of features, landscape, land use, water infrastructure, demography and other socio-economic parameters which have an impact on the basin water resources supply and demand patterns. Moreover, the section highlights the prevailing local management adopted policies, strategies and general sector reforms that promote or seek to introduce transformation from the status quo.

6.5 Review of DSS Tools and Choice of the Most Feasible Tool

Initially three DSS tools were considered i.e.: Water Evaluation and Planning System (WEAP); MULti-sectoral INtegrated and Operational decision support system (MULINO DSS); and MIKE BASIN. Since once a model is developed it can be operated from other Graphical User Interfaces (GUIs) or within a DSS, MIKE BASIN has been ideally an extension in 'ArcGIS version10'utilising the Geographical Information System Graphical User Interface (GIS-GUI). In this respect, it was rolled out in the case study area in an initiative geared towards providing both data management capacity and decision support in one package. But due to technical, economic and institutional challenges, it could not be cascaded beyond regional level. The demand for multiple licences and the capacity building required to amass a team with ample technical savvy to run and maintain both the model and its graphical user interface (GUI -platform) were too overwhelming for WRMA, a new institutions that is yet to get sound financial footing. This especially affected sub-regional level where data is collected and coordinated but where technical capacity financial and technical capacity was already strained. The pursuit to have the data routed to regional centres for processing and analysis also suffered from both institutional capacity and model incapacity to analyse complex networks due to constraining capacity proffered by GIS platform. Hence, by and large the initiative was nipped in the bud.

Perhaps working on the feedback from this and other experiences elsewhere and/or in consistent with their system development initiative, DHI has since developed their own GUI framework (MIKE Zero), from where currently all their water resources model are operating. MIKE Basin has since also been replaced by a more advanced MIKE HYDRO BASIN, launched in December 2013 which not only attended to stated limitations attributed to the earlier version; but has wider scope of applications that rival WEAP (discussed earlier). This development by and large implied that MIKE Basin would gradually become outdated and its further evaluation for possible adoption was henceforth inadmissible with respect to the objective of this study.

From the literature review of the various physical, conceptual, operational and integrated management model systems that could provide catchment scale modelling for decision support in planning, development, allocation and management of water resources as discussed in the previous section, the Table 16 below was developed. The table present an overview of the models, both from the developer's perspective and from this study field research data, interviews and evaluation. They are therefore largely subjective to this study and experiences.

Table 16: Summary review of various decision support tools in operation within the water sector.

Attributes	*WEAP21*	*MULINO-DSS (mDSS)*	*MIKE Basin*	*MIKE HYDRO Basin **
Main focus v. *Optimization* (O) vi. *Simulation* (S)	 ☑ ☑	 ☑ ☑	 ☑ ☑	 ☑ ☑
Functionality i. *Water R. planning* ii. *Water balancing* iii. *Hydrodynamic* iv. *Combined –DSF^*	i. ii. iv.	i. ii iv.	i. ii. iv.	i. ii iv.
Type i. *Hydrological model* ii. *Hydraulic model* iii. *Operation model^* iv. *Combined –DSF^*	i. iii. iv.	i iii. iv.	i. iii. iv.	i. iii. iv.
Input	*	*	*	*
Output i. *Database capability* ii. *Forecasting* iii. *Policy analysis* iv. *Qualitative* v. *Quantitative*	i. ii. iii. iv. v.	iii. iv. v.	i. ii. iii. iv. v.	i. ii. iii. iv. v.
Complexity	User-friendly	Expert based	Expert based	Not applicable
Limitations	Complex systems analysis	Capacity building	ArcGIS GUI Platform etc.	Not applicable

^ DSF – Decision support framework i.e. inter-linkage of various models for a holistic decision making process;

^ Operation model are also called water resources planning model;

* - generally hydro-climatic and ecological data; MHB license requirements hindered comprehensive review

From this subjective theoretical overview, both WEAP and MIKE HYDRO Basin opined feasible whereas practical model setting-up and comprehensive analysis could determine the most feasible IWRM compliant adaptive collaborative DSS model for possible adoption within the prevailing financial, technical and data adequacy related constraints typical of developing countries water resources management regimes.

6.6 Setting up the Preferred DSS Model, Calibration and Testing

Whereas all four systems discussed in the previous section are outstanding and unique in their approaches and ability to offers legitimate catchment scale decision making environment, WEAP system's was found to exhibit a rather outstanding capability to proffer an all-inclusive decision making environment that is very versatile without undermining results authenticity, elaborate but simple and broadly comprehensible and also user friendly. It was, for the purpose of this study, adjudged to be a feasible adaptive and collaborative tool that could potentially be adopted by catchment-based community water resources users associations (WRUAs) to help improve prevailing dialogue on water allocation, streamflow requirement and downstream releases to avert conflicts between catchment upstream and downstream users, as well as guide cost-benefit discourse on the most optimal use of the scarce water resources.

The following sections therefore concentrate on catchment modelling with WEAP; starting with data analysis, setting up and calibration of the model and ultimately modelling and using the experience to derive a requisite methodology for its adaptive and collaborative utilisation within the developing countries IWRM regimes.

6.6.1 Catchment Water Supply Assessment

High population growth and increasing rural-urban migration to the city and numerous satellite towns within the surrounding environ, mostly driven by social-economic reasons and industrialisation, have made the water use and disposal infrastructure to increase at a higher rate than local authorities could commensurately expand waste water treatment infrastructure. Direct disposal of household and industrial wastewater into rivers leads to extreme level of pollution within the catchment; and subsequent dead water conditions in the mid- and downstream of most rivers within the Nairobi catchment which is untenable for any beneficial use. High levels of fluoride in groundwater within some zones of the Nairobi Aquifer system also pose a great challenge on catchment potable water supply (MEWNR, 2013). Thus the bulk of the water used in the city and satellite towns in the environ is imported from the adjacent Tana Catchment Area (TCA) and Ruiru river catchment within the Athi Catchment Area (ACA) as demonstrated in Table 17 below.

With respect to the ground water, initial storage at the beginning of the study has been overlooked, and only the annual renewable share of ground water resources has been accounted to constitute water available for exploitation within the catchment. To calculate the renewable ground water resources, it has been assumed than 10% of the precipitation within the catchment is used to recharge ground water. To effect surface runoff to ground water interface within WEAP environment, considering the model adopts monthly time steps, further assumption has been adopted to the extent that groundwater portion not abstracted by demand nodes is directed to the stream for each monthly time step and therefore is available for abstraction by downstream users instantaneously like other water resources. In light of this assumption, the recharge of ground water via transmission and return flow leak of at demand sites has also been overlooked and therefore the entire return flows from demand nodes are routed to the streams. These assumptions were made to account for the base flows for ecological sustenance within the ground water regime, with the flow at the beginning being considered to represent the base flow that is neither exceeded nor reduced during the entire simulation period. The available ground water was calculated for each location as a factor of coverage area, multiplication factor (10%) and monthly mean precipitation (see Figure 25 below).

Table 17: Daily water transfer to Nairobi River Catchment (source: NWSC 2013)

Source	**Catchment area**	**Reservoir Capacity 2010 (Mm^3)**	**Rated supply capacity 2013 (m^3/day)**
Ruiru dam	ACA	2.98	21,912
Sasumua dam	TCA	15.59	71,232
Thika Dam	TCA	70.08	504,408
Total		**88.65**	**597,552**

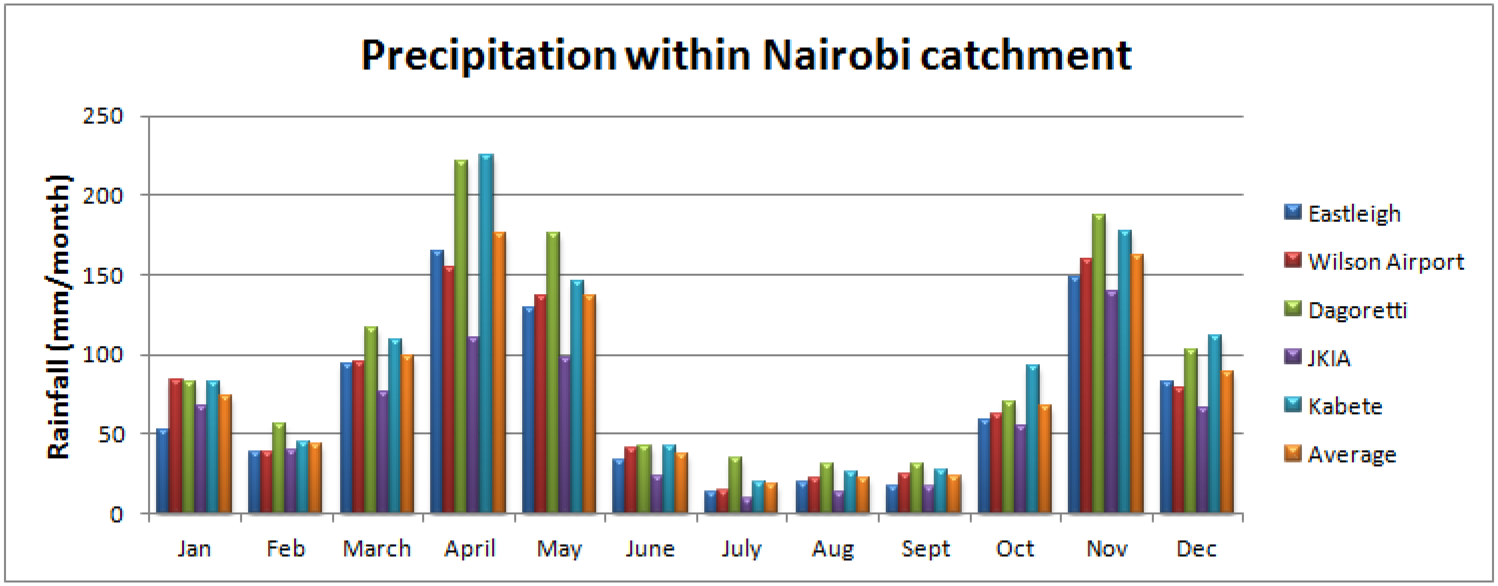


Figure 25: Monthly mean precipitation as recorded from five meteorological stations (source: KMD)

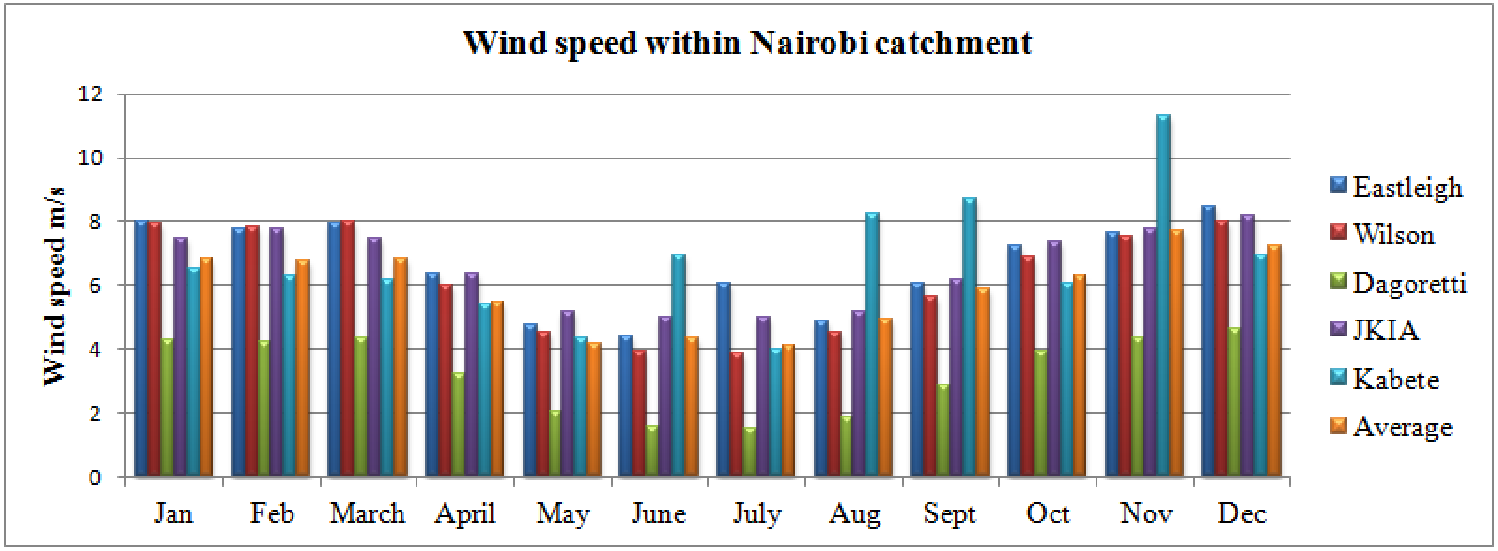


Figure 26: Monthly mean wind conditions as recorded from five meteorological stations (source: KMD)

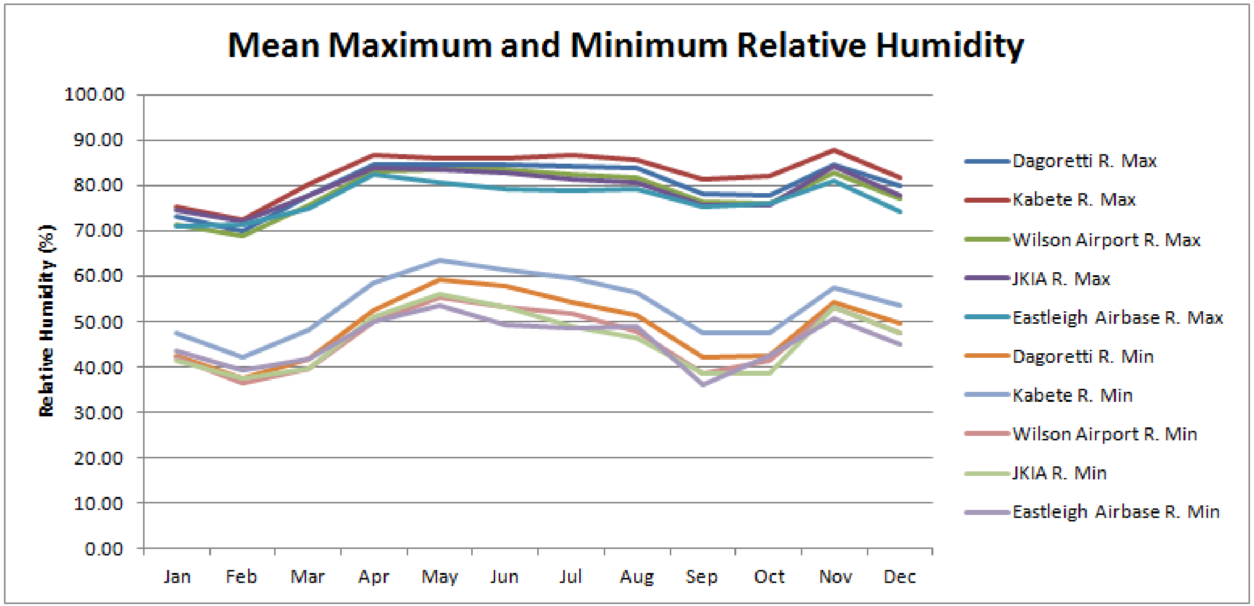


Figure 27: Mean maximum and minimum relative humidity recorded from five meteorological stations (source: KMD)

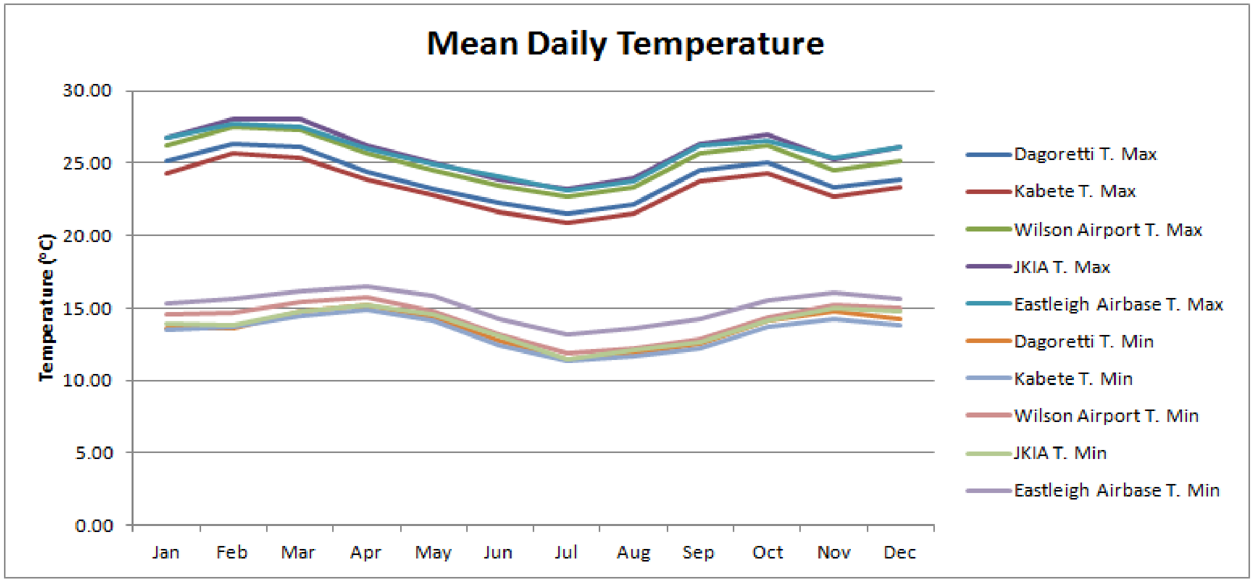


Figure 28: Mean daily temperature recorded from five meteorological stations (source: KMD)

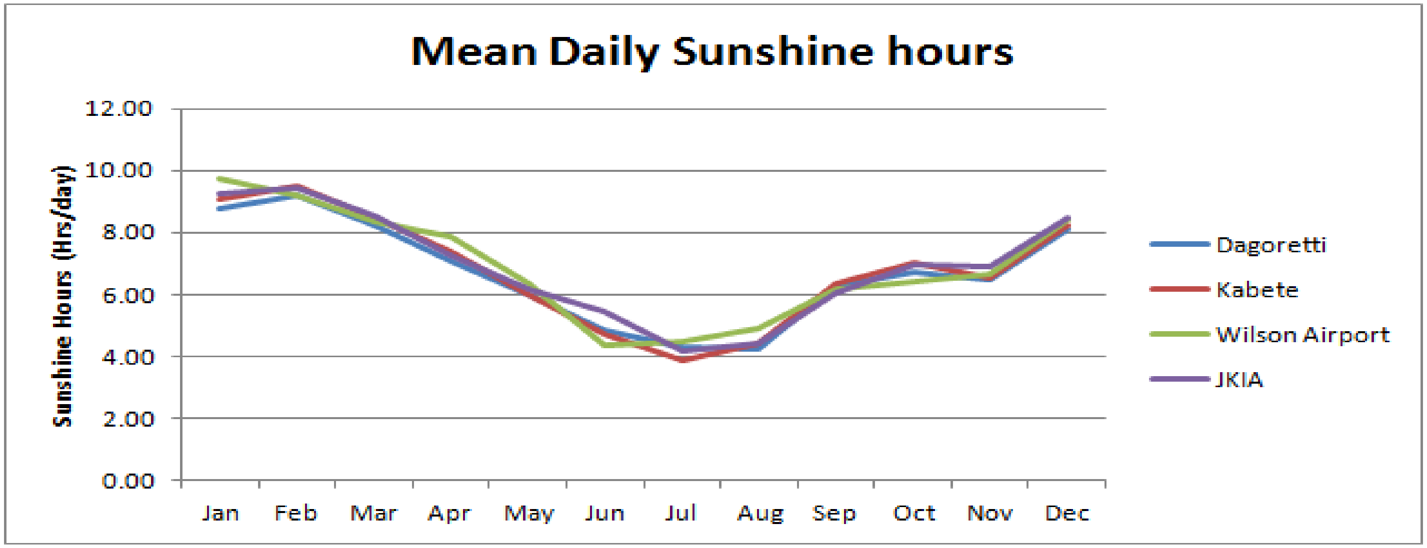


Figure 29: Mean daily sunshine hours as recorded from four meteorological stations (source: KMD)

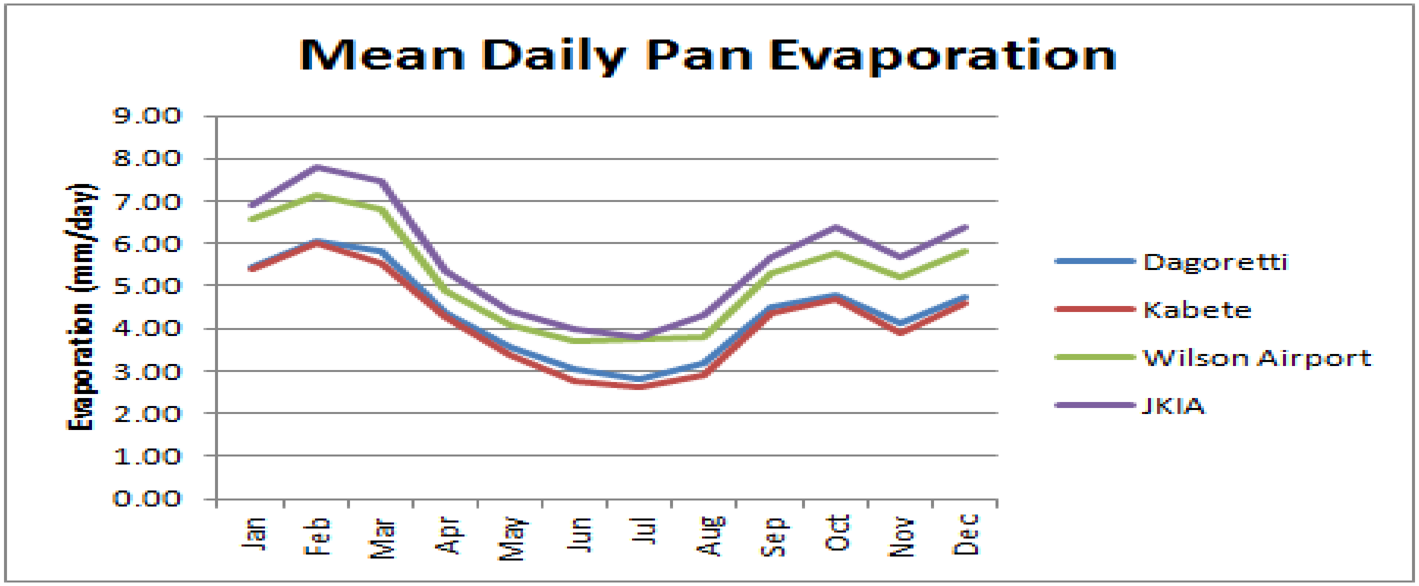


Figure 30: Mean daily pan evapotranspiration as recorded from five meteorological stations (source: KMD)

6.6.2 **Catchment Water Demand Assessment**

The assumption adopted in this study is to consider an ideal situation where rainfed agriculture and irrigated agriculture overlap seamlessly; i.e. when precipitation is not enough to meet the catchment evapotranspiration needs, the arising irrigation needs is met by water abstracted from catchment stream flows and renewable groundwater. To meet the total or partial catchment evapotranspiration needs. There is therefore presumption of cropping throughout the year with the only limiting factor being availability of water to meet crops evapotranspiration needs. The effects of variability in the water availability pattern, which is highly related to precipitation pattern, on crop yield throughout the year were however not evaluated as the subject falls outside the scope of this study.

To establish the catchment water demand, a variety of demand sites were considered i.e.

i. **Household demand:** this entail the water abstracted from water bodies for drinking, hygiene, sanitation and a variety of other household uses. The amount demanded depends mainly on social and economic class of households, with the poor settlements demanding water for basic uses only. In this study household demand has been disaggregated into three groups according to socio-economic status i.e.: High income settlement (HIS) with average water consumption of 200 litres per capita per day; Middle income settlement (MIS) with average water consumption of 90 litres per capita per day; and Low income settlement (LIS) with average water consumption of 50 litres per capita per day. These values varies significantly from the one represented in Table 18 below, mainly because this case study encompass both urban and rural areas and whereas high class housing are only available in posh urban environment, middle class housing are available across the board and the typical average daily demand across the board was adopted.. Low class housings were on the other hand allocated more water in line with improving standards of hygiene demand pursuant to increased welfare rights awareness.

Table 18: Design Unit Water Consumption of Urban Water Supply in Kenya

Category	**Design Unit Water Consumption (water loss unaccounted)**
High class housing	200 L/p/d
Middle class housing	120 L/p/d
Low class housing :Individual connection :Non-individual connection	60 L/p/d 20 L/p/d

Source: MWI Design Manual, based on data of the 2009 Census backed by field interviews

ii. **Agriculture:** in most developing countries agriculture has generally been rainfed, but with the increasingly erratic climate many countries are currently expanding area under irrigation to boost food security. Irrigation is the major consumer of water worldwide with 70% of water abstraction being used extensively for cash crops and horticultural productions; for subsistence crop production in low income countries; and also at increasing rate for renewable energy production in both developed and emerging economies (Allen, et al., 1998). In the current study, the amount of water used in agricultural enterprises is a factor of land cover in hectares, reference evapotranspiration for the catchment as calculated using FAO Penman-Monteith formula and crop coefficient for the vegetation to obtain the demand in terms of potential evapotranspiration. Potential evapotranspiration represent the maximum amount of water drawn by a particular crop for optimal productivity in absence of limiting factors; while actual evapotranspiration obtained through model simulation considers demand and supply requirements and priorities constraint, is thus the amount of water actually transpired from catchment vegetation and evaporated from various catchment surfaces.

iii. **Stocks/assets (in production unit):** For simplification purposes, in this study all the other catchment demand have been aggregated and a formula adopted to help in calculating individual components demand for assessing their individual contribution and for future scenario simulation if necessary. The average typical daily water consumption of 115 litres per unit per day for a daily cow has been adopted as the basis for aggregation and the demand of other livestock and production of other goods and services within the case study area. Subsequently, to aggregate water consumption for each location, the population of every other species is multiplied by the ratio of its unit average typical daily water consumption to the unit average typical daily cow consumption. The typical ratios for diverse livestock available in the case study area are as shown in Table 19 below.

Table 20 below shows the classification of various locations within the case study area alongside their respective population; general rank in social-economic status; livestock in equivalent production units; and surface coverage in hectares. Where production unit is equivalent to a typical daily cow, whose average typical daily water consumption hereby set at 115 litres per day, is used as the basis for water consumption analysis for both livestock and all other goods and services production enterprises but agriculture. It is important to note that though livestock require water of similar quality to that required by humans, for some of the other enterprises for goods and services production like recreation, considerably lower water quality and (treated, semi-treated or even untreated water depending on the source) return flows from other demand sites may suffice. However, the focus of this study is on the mass balance between water supply vis-à-vis water demand within the catchment and the fundamental assumption is that the available water is fully treated and/or reticulated between various demand nodes to effectively cover respective quantities required until it exit the catchment either through evapotranspiration or surface and ground water flow past the last node at the lowermost catchment extreme. To the extent that water quality, though very key to effective demand coverage due to stringent municipal water supply standards is assumed, the comparison and/or aggregation of various demands is tenable. Water quality is defined by the presence or absence of minerals substances and materials that influence its taste, smell, turbidity and electrical conductivity. Water quality analysis is very crucial in realistic water allocation planning and assessments at catchment scale; but for logistical purposes as stated, it lies beyond the scope of this study. The assessment of the diverse catchment demands, other than the prioritised ecological and household demands, is utilised in the determination of the quantity of water used to produce different products and services; as well as to help plan and allocate water to the most optimal use of catchment scarce water supplies between varied agricultural, livestock, industrial, recreational and commercial enterprises.

Moreover, with the emergence of virtual water concept, the comparative water demand approach could be applied within each catchment in evaluating equity and sustainability in water allocations in an increasingly broader perspective. Virtual application is a global water-use concept developed to place all goods and services production industries within various countries on an equal basis when describing their use of water as part of global trading and environmental accounting systems. Virtual water content has been devised as a tool to estimate the amount of water used to produce different products and services, and to help plan the best use of scarce water supplies (Hoekstra & Chapagain, 2007). Virtual water content has been defined as the difference between the total water volume used from domestic water resources in the national economy and the volume of virtual water exported to other countries in domestically produced products. The virtual water content of primary crops is calculated on the basis of crop water requirements and yield. The virtual water content of live animals is calculated on the virtual water content of their feed and the volumes of drinking and service waters consumed during their lifetime. The final water content in the finished product is significantly less than the water used to produce the product, hence the concept of virtual water content. This concept has been used to compare water use by various industries and enterprises as well as to investigate, using economic models, the potential of such industries and enterprises to pay for the extracted water, on the basis of full cost recovery for the water used (Schlink, et al., 2010).

Table 19: Ratio of various livestock units daily water demand to that of a typical daily cow demand

Livestock	**Equivalent daily cow**	**Livestock**	**Equivalent daily cow**	**Livestock**	**Equivalent daily cow**
Dairy cow	1	Turkeys	0.004	KTBH bee hive	0.002
Indigenous Zebu	0.5	Geese	0.004	Langstroth hive	0.003
Exotic beef cow	0.7	Local goat	0.052	Log hive	0.002
Indigenous	0.002	Dairy goat	0.09	Camel	0.5
Layers	0.002	Hair sheep	0.052	Rabbits	0.003
Broilers	0.003	Wool sheep	0.09	Donkeys	0.174
Ducks	0.003	Pig	0.174	Horses	0.5

Adopted from research reports by (Ward & McKague, 2007) and (Stewart & Rout, 2007)

Since water is a finite economic resource, the comparison of various economic water use pursuits; for instance cash crop and horticultural production under irrigation, livestock production under irrigation will help establish the most profitable enterprise. In the dairy sector of Kenya, it has been found that irrigating fodder for dairying improves farmers' net incomes and compares favourably irrigation for vegetable production (Hoekstra & Chapagain, 2007).

Table 20: Catchment water demand activity levels

Item	Location	Population	Rank	Livestock in Equivalent (Production units)	Area in ha
1	CIANDA	15119	MIS	6541	3669
2	CITY	143425	HIS	678	1098
3	EASTLANDS	316136	MIS	1454	1658
4	EASTLEIGH	174389	MIS	988	743
5	GITHIGA	22936	MIS	11334	1492
6	GITHURAI	133926	MIS	2400	985
7	HIPARK	64837	HIS	4735	4633
8	IKINU	23668	MIS	6221	2235
9	KABETE	41460	MIS	2049	1580
10	KAHAWA-Githurai	56437	MIS	2006	1508
11	KAKODA	279323	MIS	500	1073
12	KAMITI	6657	MIS	6873	3855
13	KANJI	225402	MIS	876	1453
14	KARAMBAINI	28348	MIS	4418	5789
15	KASARANI	100472	MIS	4051	3046
16	KIAMBAA	48674	MIS	3676	2062
17	KIAMBAA S/A	27239	MIS	5883	3300
18	KIBERA	224660	LIS	1097	632
19	KIHARA	49067	MIS	2305	1293
20	KIKUYU	29418	MIS	4882	3765

Item	Location	Population	Rank	Livestock in Equivalent (Production units)	Area in ha
21	KIKUYU TOWNSHIP	16302	MIS	1835	1415
22	KILIKENA	111854	MIS	5048	3245
23	KINOO	100072	MIS	3462	2505
24	KITIKILE	58444	HIS	3101	3034
25	LIMURU	42878	MIS	3027	3966
26	MAHU	193416	MIS	392	295
27	MIHANGO	22936	MIS	900	1492
28	MUGUGA	45901	MIS	3005	2317
29	MUKURU	123944	LIS	1083	986
30	MUWA	49027	MIS	2071	999
31	NDUMBERI	21958	MIS	1460	819
32	NGECHA	12473	MIS	792	1038
33	NYATHUNA	28771	MIS	2311	1782
34	RIABAI	25909	MIS	1637	918
35	RIKAKA	293319	MIS	2801	1586
36	RIRONI	9535	MIS	588	771
37	ROYRAKA	199852	MIS	4514	3394
38	RUAI	35961	LIS	6059	10047
39	RUAKA	23663	MIS	1316	738
40	RUIRU	41596	MIS	550	864
41	TIGONI	11511	MIS	3161	4142
42	TINGANGA	13070	MIS	1605	900
43	VIWANDANI	71390	MIS	679	1126
44	WAGUTHU	22395	MIS	2409	1351

iv. Computing water consumption by agricultural and natural vegetation

The respective estimates of reference evapotranspiration (ETo), that represent the effect of climate on crop water requirements, for various catchment zones were calculated using FAO Penman-Monteith formula adopted from (Allen, et al., 1998) as demonstrated in Table 22 here below; utilising climatic data provided by KMD (see Figure 25 to Figure 30 here above). For the purpose of simplifying the calculations in the pilot study, evapotranspiration demand for the entire catchment was aggregated and subsequently a crop coefficient (Kc) for an idealized average crop covering the entire catchment was adopted to assess catchment potential evapotranspiration (ETp). With respect to the case study area, the calculated ETp is on the higher extreme, since the case study area is densely populated and within the settlements and built-up areas evaporation is the major component of evapotranspiration, which does not affect water in the deep root zone. Previous studies have reported an estimated evaporation to transpiration ratio of 0.43 (Novák & Havrila, 2005), with the latter being the key process of biomass production and earth temperature stabilization; and the major component of evapotranspiration in humid and sub-humid terrestrial environments. Moreover, by aggregating vegetation both perennial and seasonal crops are lumped up together, which makes it difficult to effect the respective monthly demand variations.

The average crop coefficient (Kc) listed in Table 21 here below have been drawn from the guideline for computing crop water requirements published by FAO in Paper No. 56. Kc represents the crop's (canopy and aerodynamic resistance) effect on evapotranspiration relative to a reference crop; it serves as an aggregation of the physical and physiological differences between crops (Allen, et al., 1998). Only the crops comprising the natural vegetation and diverse cultivated crops within the case study area have been listed here, alongside their respective crop coefficient values for sub humid conditions at wind conditions (see Figure 26 above) typical to the case study catchment. As previously expounded, an aggregated average Kc was adopted in this study and used in WEAP model to calculate catchment potential evapotranspiration and shortfall in potential evapo-transpiration (ETp and ETsf – Figure 43 and Figure 42 below). The ETp represents a scenario where enough moisture is available for total evapotranspiration with crop coefficient being the only limiting factor, while ETa could be equal or less than ETp with the available moisture being one of the limiting factors.

The sum of evapotranspiration demand, ecological demand, households demand and the aggregated demand by diverse 'stocks' within the catchment help establish the prevailing water demand, which on multiplication with factors representing water savings and losses help obtain the catchment water supply requirement. The initial or base year, termed as current account, present the basis for policies and management scenario simulations in water planning, development, allocation and catchment water balancing. Precipitation within the catchment; head flows into the catchment from upstream; ground water resources and trans-boundary water transfers (see appendix Figure 71and Figure 72) constitute the main catchment water supply.

Table 21: Average crop coefficients for the common crops grown in the basin Adopted from FAO-33; Source: (Allen, et al., 1998)

Crop	total growing period for the Average Kc	Average Kc
Beans	0.88	0.84
Cabbage	0.75	
Maize	0.88	
Onions	0.85	
Peas	0.88	
Pepper	0.75	
Potatoes	0.82	
Tomatoes	0.82	
Rose flowers	0.70	
Cassava	0.70	
Arrow roots	0.85	
Sorghum	0.90	
Green grams	0.90	
Spinach	0.90	
Carrot	0.85	
Cabbages	0.90	
Kales	0.90	
Tea	0.90	
Coffee	0.90	
Banana	0.90	

The figures listed in the table above represent Basal crop coefficients, Kc, for non-stressed, well-managed crops in subhumid climates (RHmin ≈45%, u2 ≈ 2 m/s) for use with the FAO Penman-Monteith Reference Evapotranspiration (ETo).

Table 22: Calculating Reference Evapotranspiration using Penman Monteith equation

$$ET_O = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T_{mean} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

Where

ET_O = reference evapotranspiration [mm/day]

R_n = net radiation at the crop surface [MJ/m^2/day]

G = soil heat flux density [MJ/m^2/day] which can be neglected (G=0)

T_{mean} = mean air temperature [°C]

u_2 = wind speed measured at 2 m height [m/s]

Δ = slope vapour pressure curve [kPa/°C]

γ = psychrometric constant [kPa/°C]

e_s = saturation vapour pressure [kPa]

e_a = actual vapour pressure [kPa]

$(e_s - e_a)$ = saturation vapour pressure deficit [kPa]

Each of the variables is calculated independently and the figure input in the main equation for each set of meteorological data.

Net radiation

The net radiation, R_n, is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net long wave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl}$$

Net solar or net shortwave radiation

The net shortwave radiation resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = (1 - \Delta)\,R_s$$

Where

R_{ns} = net shortwave radiation [MJ/m^2/day],

Δ = albedo or canopy reflection coefficient for the reference crop [dimensionless] (a fixed value of 0.23 is used),

R_s = solar radiation [MJ/m^2/day].

Table 22: Calculating Reference Evapotranspiration using Penman Monteith equation

Net long wave radiation

The net long wave radiation, R_{nl}, is given by:

$$\boldsymbol{R_{nl} = \sigma\left[\frac{T_{max},K^4 + T_{min,}K^4}{2}\right](0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}} - 0.35\right)}$$

Where

R_{nl} = net long wave radiation [MJ/m^2/day],□
σ = Stefan-Boltzmann constant [4.903 10^-9 MJ/K^4/m^2/day],
T_{max} = K maximum absolute temperature during the 24-hour period [K = °C + 273.16],
T_{min} = K minimum absolute temperature during the 24-hour period [K = °C + 273.16],

e_a = actual vapour pressure [kPa],
$\frac{R_s}{R_{so}}$ = relative shortwave radiation (limited to <= 1.0)
R_s = solar radiation [MJ/m^2/day],
R_{so} = clear-sky radiation [MJ/m^2/day]

Solar radiation R_s : was calculated with the Angstrom formula, which relates solar radiation to extra-terrestrial radiation and relative sunshine duration:

$$\boldsymbol{R_s = \left(a_s + b_s\frac{n}{N}\right)R_a}$$

Where

R_s = solar or shortwave radiation [MJ/m^2/day],
n = actual duration of sunshine [hour],
N = maximum possible duration of sunshine or daylight hours [hour],
n/N = relative sunshine duration [fraction],
R_a = extra-terrestrial radiation [MJ/m^2/day],

a_s = regression constant, expressing the fraction of extra-terrestrial radiation reaching the earth on overcast days (n = 0),
$a_s + b_s$ = fraction of extra-terrestrial radiation reaching the earth on clear days (n = N).

The default values for a_s and b_s are 0.25 and 0.50.

Table 22: Calculating Reference Evapotranspiration using Penman Monteith equation

Clear-sky solar radiation

The calculation of the clear-sky radiation,R_{so}, when n = N, is required for computing net long wave radiation.

$$\boldsymbol{R_{so} = \left(0.75 + 2 * 10^{-5} z\right) R_a}$$

Where

R_{so} = clear-sky solar radiation [MJ/m^2/day],
z = station elevation above sea level [m],
R_a = extra-terrestrial radiation [MJ/m^2/day].

Extra-terrestrial radiation R_a: for each day of the year and for different latitudes was estimated from the solar constant, the solar declination and the time of the year by:

$$\boldsymbol{R_a = \frac{24(60)}{\pi} G_{SC} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)]}$$

Where

R_a = extra-terrestrial radiation [MJ/m^2/day],
G_{SC} = solar constant = 0.0820 MJ/m^2/min,
d_r = inverse relative distance Earth-Sun,

ω_s = sunset hour angle [rad],
φ = latitude [rad],
δ = solar declination [rad].

The latitude, φ, expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere. The conversion from decimal degrees to radians is given by: $\boldsymbol{\varphi = \frac{\pi}{180} * Lat_{degree}}$

The inverse relative distance Earth-Sun, d_r, and the solar declination, δ, are given by:

$$\boldsymbol{d_r = 1 + 0.33 \cos\left(\frac{2\pi J}{365}\right)}$$

$$\boldsymbol{\delta = 0.409\, sin\left(\frac{2\pi J}{365} - 1.39\right)}$$

Where

J = number of the day in the year between 1 (1 January) and 365 or 366 (31 December).

The sunset hour angle, ω_s, is given by:

$$\boldsymbol{\omega_s = arccos\,(-tan(\varphi)\, tan(\delta)\,)}$$

Table 22: Calculating Reference Evapotranspiration using Penman Monteith equation

Daylight hours N, are given by: $\boldsymbol{N = 24 * \omega_s/\pi}$	
Psychrometric constant The psychrometric constant, γ, is given by: $\boldsymbol{\gamma = \frac{c_p P}{\varepsilon\lambda} = 0.665 * 10^{-3} P}$	Where γ = psychrometric constant [kPa/°C], P = atmospheric pressure [kPa], λ = latent heat of vaporization = 2.45 [MJ/kg], C_p = specific heat at constant pressure = $1.013*10^{-3}$ [MJ/kg/°C],□ ε = ratio molecular weight of water vapour/dry air = 0.622.
The value of the latent heat varies as a function of temperature. However, because λ varies only slightly over normal temperature ranges, a single value of 2.45 MJ/kg is used. (This value corresponds to an air temperature of about 20°C.)	
Atmospheric pressure P: is the pressure exerted by the weight of the earth's atmosphere: $\boldsymbol{P = 101.3\left(\frac{(293 - 0065z)}{293}\right)^{5.26}}$	Where P = atmospheric pressure [kPa], z = elevation above sea level [m]
Mean saturation vapour pressure: is the mean of the saturation vapour pressures at maximum and minimum air temperatures for the day: $\boldsymbol{e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2}}$	where $\boldsymbol{e_s}$ = saturation vapour pressure [kPa], $\boldsymbol{e^o(T_{max})}$ = saturation vapour pressure at the mean daily maximum air temperature [kPa], $\boldsymbol{e^o(T_{min})}$ = saturation vapour pressure at the mean daily minimum air temperature [kPa].

Table 22: Calculating Reference Evapotranspiration using Penman Monteith equation

Saturation vapour pressure

The saturation vapour pressure, $\boldsymbol{e^o}$, is a function of air temperature:

e^o (T) = 0.6108 exp ((17.27 T) / (T+237.3))

where

e^o (T) = saturation vapour pressure at the air temperature T [kPa],

T = air temperature [°C].

Actual vapour pressure

The actual vapour pressure $\boldsymbol{e_a}$ was calculated from the relative humidity.

Using $\mathrm{RH_{max}}$ and $\mathrm{RH_{min}}$:

$$\boldsymbol{e_a = \frac{e^o(T_{min})\frac{RH_{max}}{100} + e^o(T_{max})\frac{RH_{max}}{100}}{2}}$$

Slope vapour pressure curve: is the slope of the relationship between saturation vapour pressure and temperature, Δ. The slope of the curve at a given temperature is given by:

$$\boldsymbol{\Delta = \frac{4098\left[0.6108e^{\left(\frac{17.27T_{mean}}{T_{mean}+237.3}\right)}\right]}{(T_{mean}+237.3)^2}}$$

where

$\boldsymbol{\Delta}$ = slope of saturation vapour pressure curve at air temperature T [kPa/°C],

$\boldsymbol{T_{mean}}$ = mean air temperature [°C].

Table 23: Calculation of Psychrometric constant for the various meteorological data set

Altitude (z) (m)	atmospheric pressure (P) [kPa],	$\lambda =$ latent heat of vaporization [MJ/kg]	cp = specific heat at constant pressure [MJ/kg/°C],	ε = ratio molecular weight of water vapour/dry air.	Psychrometric Constant (γ) (kPa/^{0}C)	
1624	83.5199	2.45	0.001013	0.622	0.055519	**Dagoretti**
1637	83.38855	2.45	0.001013	0.622	0.055432	**Eastleigh**
1676	82.99551	2.45	0.001013	0.622	0.055171	**Wilson**
1798	81.77567	2.45	0.001013	0.622	0.05436	**JKIA**
1941	80.36439	2.45	0.001013	0.622	0.053422	**Kabete**

The value of the latent heat varies as a function of temperature. However, because λ varies only slightly over normal temperature ranges, a single value of 2.45 MJ/kg is used. (This value corresponds to an air temperature of about 20°C.)

Table 24: Calculation of mean temperature for various catchment meteorological data sets

DAGORETTI				**Kabete**			**Eastleigh**					**Wilson**				**JKIA**		
(T_{max}) Max. daily Temp. (^{0}C)	**(T_{min}) Min. daily Temp. (^{0}C)**	**(T_{mean}) Mean Temp. (^{0}C)**	**Month**	**(T_{max}) Max. daily Temp. (^{0}C)**	**(T_{min}) Min. daily Temp. (^{0}C)**	**(T_{mean}) Mean Temp. (^{0}C)**		**(T_{max}) Max. daily Temp. (^{0}C)**	**(T_{min}) Min. daily Temp. (^{0}C)**	**(T_{mean}) Mean Temp. (^{0}C)**		**(T_{max}) Max. daily Temp. (^{0}C)**	**(T_{min}) Min. daily Temp. (^{0}C)**	**(T_{mean}) Mean Temp. (^{0}C)**		**(T_{max}) Max. daily Temp. (^{0}C)**	**(T_{min}) Min. daily Temp. (^{0}C)**	**(T_{mean}) Mean Temp. (^{0}C)**
25.115	13.580	19.348	**Jan**	24.337	13.476	18.907		26.700	15.329	21.014		26.200	14.600	20.400		26.763	13.888	20.325
26.347	13.553	19.950	**Feb**	25.705	13.681	19.693		27.686	15.643	21.664		27.456	14.706	21.081		27.988	13.838	20.913
26.085	14.810	20.448	**Mar**	25.405	14.490	19.948		27.529	16.186	21.857		27.320	15.437	21.378		27.994	14.725	21.359
24.437	15.200	19.818	**Apr**	23.832	14.855	19.343		25.986	16.500	21.243		25.700	15.728	20.714		26.253	15.233	20.743
23.258	14.394	18.826	**May**	22.772	14.132	18.452		24.975	15.825	20.400		24.455	14.747	19.601		25.067	14.550	19.808
22.211	12.711	17.461	**Jun**	21.582	12.467	17.025		24.025	14.213	19.119		23.470	13.147	18.309		23.840	13.047	18.443
21.500	11.461	16.481	**July**	20.905	11.300	16.103		23.067	13.138	18.102		22.676	11.853	17.265		23.187	11.487	17.337
22.174	11.889	17.031	**Aug**	21.510	11.695	16.603		23.800	13.588	18.694		23.322	12.247	17.785		23.971	12.071	18.021
24.484	12.533	18.509	**Sept**	23.765	12.150	17.958		26.175	14.233	20.204		25.660	12.863	19.262		26.343	12.585	19.464
24.995	14.083	19.539	**Oct**	24.265	13.665	18.965		26.543	15.486	21.014		26.163	14.367	20.265		26.986	14.169	20.577
23.322	14.771	19.046	**Nov**	22.725	14.255	18.490		25.314	16.014	20.664		24.489	15.171	19.830		25.277	15.031	20.154
23.878	14.253	19.065	**Dec**	23.300	13.795	18.548		26.071	15.629	20.850		25.105	14.982	20.044		26.073	14.736	20.405

Table 25: Calculation of inverse distance Earth-Sun $d_r$and the solar declination δ for the catchment

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
inverse relative distance (Earth - d_r Sun)	1.032	1.024	1.01	0.992	0.977	0.968	0.968	0.976	0.991	1.008	1.023	1.032
Solar declination - δ (rad)	-0.37	-0.236	-0.0474	-0.1658	-0.3288	-0.406	-0.38	-0.239	-0.0369	-0.1626	-0.335	-0.407

Table 26: Calculation of Saturation vapour pressure (e_s) and actual vapour pressure (e_a) for Dagoretti

Tmax (°C)	Tmin (°C)	$e^0(T_{max})$ (kPa)	e^0(Tmin) (kPa)	(e_s) (kPa)		RHmax	RHmin	(e_a) (kPa)
25.1150	13.5800	3.1895	1.5556	2.3725		73.2857	42.6190	1.2497
26.3474	13.5526	3.4311	1.5528	2.4919		70.0500	37.3500	1.1846
26.0850	14.8100	3.3784	1.6846	2.5315		77.6190	41.6667	1.3576
24.4368	15.2000	3.0631	1.7274	2.3952		84.5500	52.3000	1.5313
23.2579	14.3944	2.8536	1.6400	2.2468		84.6316	59.2105	1.5388
22.2105	12.7111	2.6780	1.4697	2.0739		84.5263	57.8947	1.3964
21.5000	11.4611	2.5644	1.3535	1.9590		84.3158	54.2105	1.2657
22.1737	11.8889	2.6721	1.3923	2.0322		83.7368	51.2105	1.2671
24.4842	12.5333	3.0717	1.4527	2.2622		78.1053	42.2105	1.2156
24.9947	14.0833	3.1668	1.6073	2.3870		77.7368	42.4737	1.2972
23.3222	14.7706	2.8647	1.6803	2.2725		84.5556	54.3889	1.4894
23.8778	14.2529	2.9621	1.6250	2.2936		79.9444	49.4444	1.3819

Table 27: Calculation of slope of saturation vapour pressure for various catchment meteorological station data sets

Month		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dagoretti	**(Δ) - (kPa/^{0}C)**	0.1397	0.1443	0.1483	0.1433	0.1358	0.1260	0.1193	0.1230	0.1334	0.1412	0.1374	0.1376
Kabete	**(Δ) - (kPa/^{0}C)**	0.1364	0.1424	0.1443	0.1397	0.1330	0.1230	0.1168	0.1201	0.1295	0.1368	0.1333	0.1337
Eastleigh	**(Δ) - (kPa/^{0}C)**	0.1529	0.1583	0.1599	0.1548	0.1479	0.1380	0.1305	0.1348	0.1463	0.1529	0.1500	0.1515
Wilson	**(Δ) - (kPa/^{0}C)**	0.1479	0.1534	0.1559	0.1504	0.1416	0.1320	0.1246	0.1282	0.1391	0.1468	0.1434	0.1451
JKIA	**(Δ) - (kPa/^{0}C)**	0.1473	0.1520	0.1557	0.1507	0.1432	0.1330	0.1251	0.1299	0.1406	0.1493	0.1459	0.1479

Table 28: Calculation of net Radiation Rn

Dagoretti Met. Station																					
Solar constant - Gsc (MJ/m^2/min)	inverse relative distance (Earth - dr Sun)	Sunset hour angle - Ws (rad)	Lat.-f (rad)	Solar dec. - δ (rad)	regr. constant (as)	(bs)	Fraction of extra. radiation on clear day (n=N) (as+bs)	actual duration of sunshine (n) (hour)	Max. Possible duration of sunshine (N) (hour)	Altitude (z) (m)	Extrater. radiation (Ra) (MJ/m^2/day)	σ - Stefan Bolzmann constant (MJ/K^4/m^2/day)	Max absolute temp. (Tmax,K) [K = °C + 273.16]	Main absolute temp. (Tmin,K) [K = °C + 273.16]	(ea) Actual vapour pressure (kPa)	Clear sky solar radiation (Rso) (MJ/m^2/day)	(Δ) - albedo or crop canopy coef.	Rs - solar radiation (MJ/m^2/day)	incoming net shortwave radiation - (Rns) (MJ/m^2/day)	outgoing net long wave radiation (Rnl) (MJ/m^2/day)	net radiation - Rn (MJ/m^2/day)
0.082	1.032	1	-0.0227	-0.37	0.25	0.5	0.75	8.78125	12	1624	30.74199	4.903E-09	298.275	286.74	1.24967	24.05499	0.23	18.93354	14.578828	4.704131	9.874697
0.082	1.024	1	-0.0227	-0.236	0.25	0.5	0.75	9.173333	12	1624	31.68526	4.903E-09	299.507	286.7126	1.18462	24.79308	0.23	20.03212	15.424735	5.044187	10.38055
0.082	1.01	1	-0.0227	-0.047	0.25	0.5	0.75	8.211765	12	1624	31.94056	4.903E-09	299.245	287.97	1.35761	24.99285	0.23	18.91382	14.563642	4.338072	10.22557
0.082	0.992	1	-0.0227	-0.166	0.25	0.5	0.75	7.05	12	1624	31.07607	4.903E-09	297.597	288.36	1.53126	24.31641	0.23	16.89761	13.011163	3.548192	9.462972
0.082	0.977	1	-0.0227	-0.329	0.25	0.5	0.75	5.988235	12	1624	29.50688	4.903E-09	296.418	287.5544	1.53878	23.08854	0.23	14.73898	11.349011	3.038	8.311011
0.082	0.968	1	-0.0227	-0.406	0.25	0.5	0.75	4.826667	12	1624	28.44631	4.903E-09	295.371	285.8711	1.39637	22.25867	0.23	12.83245	9.8809838	2.61917	7.261813
0.082	0.968	1	-0.0227	-0.38	0.25	0.5	0.75	4.284615	12	1624	28.73112	4.903E-09	294.66	284.6211	1.2657	22.48153	0.23	12.31202	9.4802579	2.456119	7.024139
0.082	0.976	1	-0.0227	-0.239	0.25	0.5	0.75	4.230769	12	1624	30.18066	4.903E-09	295.334	285.0489	1.26713	23.61576	0.23	12.86547	9.9064156	2.449253	7.457162
0.082	0.991	1	-0.0227	-0.037	0.25	0.5	0.75	6.3125	12	1624	31.34469	4.903E-09	297.644	285.6933	1.2156	24.52659	0.23	16.08048	12.381969	3.533744	8.848225
0.082	1.008	1	-0.0227	-0.163	0.25	0.5	0.75	6.717647	12	1624	31.59125	4.903E-09	298.155	287.2433	1.29725	24.71952	0.23	16.74027	12.890005	3.673611	9.216394
0.082	1.023	1	-0.0227	-0.335	0.25	0.5	0.75	6.45	12	1624	30.83594	4.903E-09	296.482	287.9306	1.48943	24.12851	0.23	15.99614	12.31703	3.299258	9.017773
0.082	1.032	1	-0.0227	-0.407	0.25	0.5	0.75	8.126667	12	1624	30.31497	4.903E-09	297.038	287.4129	1.38186	23.72086	0.23	17.84373	13.73967	4.18116	9.55851

Table 29: Reference evapotranspiration in mm/month for various zones

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dagoretti	155.407	155.244	161.358	118.906	95.463	79.096	79.744	89.974	122.558	144.412	118.579	139.037
Kabete	163.890	166.080	164.265	123.857	104.700	104.451	92.081	122.322	156.354	151.296	136.330	144.231
JKIA	195.870	197.641	205.901	151.105	128.479	117.452	122.361	134.289	171.427	196.288	149.248	180.398
Eastleigh	200.315	195.140	206.699	153.801	131.335	121.053	132.977	129.477	175.073	186.549	156.899	191.409
Wilson	198.661	200.537	208.567	149.019	122.627	108.358	107.328	123.952	162.912	182.366	145.668	174.712

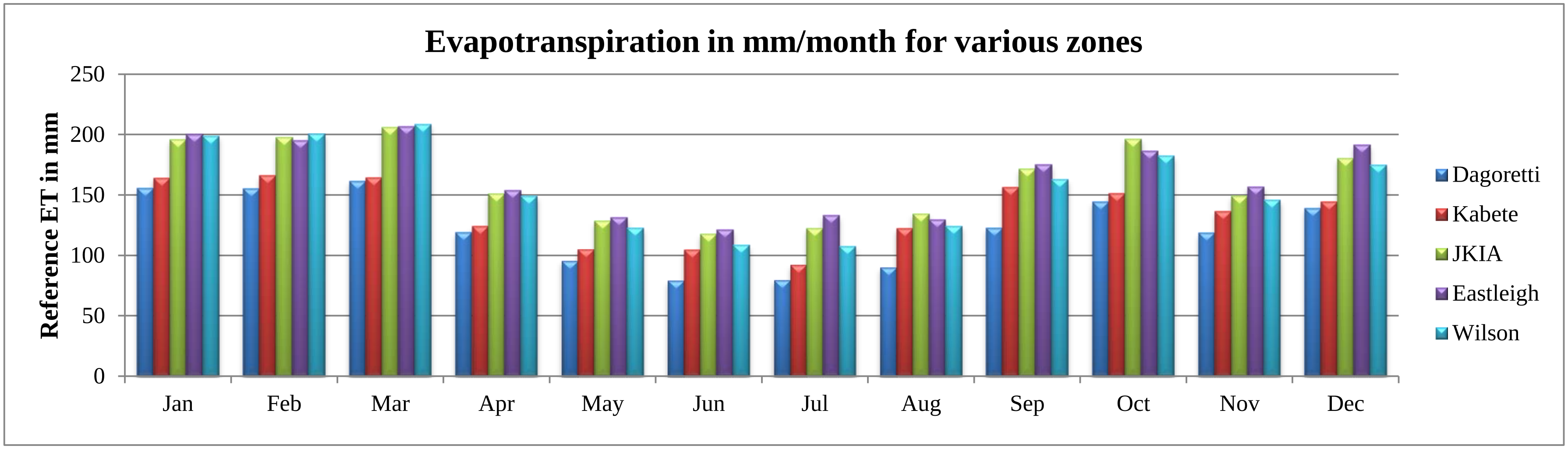


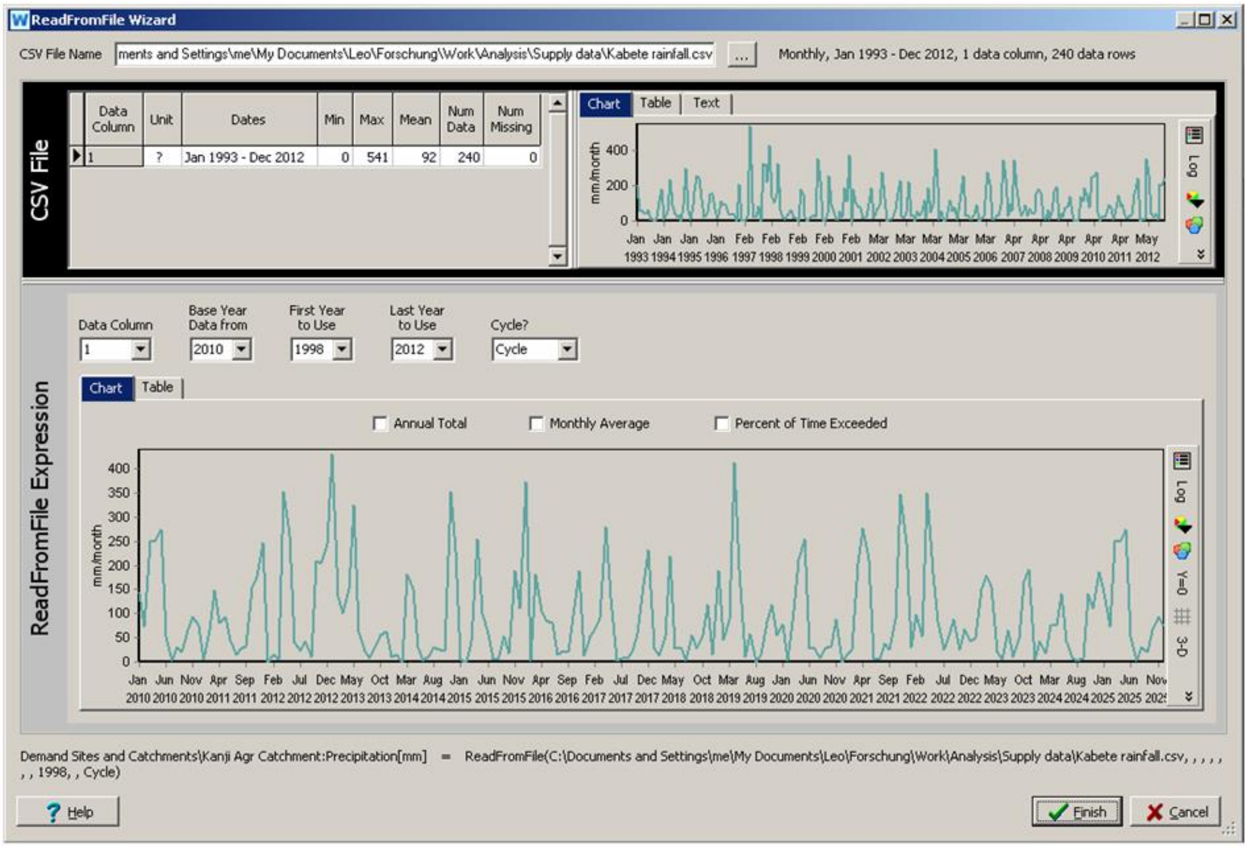
Figure 31: Calculated reference evapotranspiration (mm/month) for five catchment zones

Table 30: Calculation Reference Evapotranspiration for Dagoretti meteorological station data sets

Dagoretti Met. Station																	
Month	**Constant**	**(Δ) - slope vapour Pressure (kPa/^{0}C)**	**(R_n) Net radiation (MJ/m^2/day)**	**Soil heat flux density (G) (MJ/m^2/day)**	**Psychrometric Constant (γ) (kPa/^{0}C)**	**Constant**	**(T_{mean}) Mean temperature (^{0}C)**	**Constant**	**(u_2) Wind speed (m/s)**	**(e_s) Saturation vapour pressure (kPa)**	**(e_a) Actual vapour pressure (kPa)**	**constant**	**constant**	**(Et_o) Reference Evapotranspiration (mm/day)**	**Days**	**(Et_o) Reference Evapotranspiration (mm/month)**
1	0.408	0.139703788	9.874696957	0	0.055519164	900	19.3475	273	4.27419	2.372546722	1.249674713	1	0.34	5.013123764	31	155.4068367
2	0.408	0.144348898	10.38054772	0	0.055519164	900	19.95	273	4.1986	2.491933425	1.184616937	1	0.34	5.544417685	28	155.2436952
3	0.408	0.148282367	10.22557078	0	0.055519164	900	20.4475	273	4.35081	2.531482191	1.357610686	1	0.34	5.205094534	31	161.3579306
4	0.408	0.143323463	9.462971654	0	0.055519164	900	19.8184211	273	3.23305	2.395242951	1.531259967	1	0.34	3.963544786	30	118.9063436
5	0.408	0.135787203	8.311011451	0	0.055519164	900	18.8261696	273	2.03939	2.246773618	1.538777457	1	0.34	3.079441003	31	95.46267108
6	0.408	0.125967805	7.261813377	0	0.055519164	900	17.4608187	273	1.57644	2.073874696	1.396366559	1	0.34	2.636534422	30	79.09603267
7	0.408	0.119295186	7.024139396	0	0.055519164	900	16.4805556	273	1.51613	1.958957857	1.26569813	1	0.34	2.572374714	31	79.74361613
8	0.408	0.123006047	7.457162434	0	0.055519164	900	17.0312865	273	1.86834	2.03218565	1.267128304	1	0.34	2.902371331	31	89.97351125
9	0.408	0.133448554	8.84822548	0	0.055519164	900	18.5087719	273	2.8375	2.262202418	1.215601317	1	0.34	4.085263164	30	122.5578949
10	0.408	0.141166549	9.216394411	0	0.055519164	900	19.5390351	273	3.92466	2.387027572	1.297245702	1	0.34	4.658444914	31	144.4117923
11	0.408	0.137430263	9.017772692	0	0.055519164	900	19.0464052	273	4.32949	2.272490523	1.48943081	1	0.34	3.952633197	30	118.5789959
12	0.408	0.137572454	9.55851029	0	0.055519164	900	19.0653595	273	4.6205	2.293565988	1.381858752	1	0.34	4.485050037	31	139.0365511
														Annual Total		**1459.775871**

6.6.3 **Setting- up WEAP Model and Fundamental Assumptions**

As discussed previously WEAP consist of five main views with the schematic view, and importantly so, being the starting point for all WEAP activities. It is here where the catchment of interest is spatially represented by aid of its drag and drop graphical interface that allows creation and editing of system physical features for spatial illustration and visualization. Very crucial to this study was WEAP interface with GIS layers, that allowed catchment features of interest and important data gathered throughout the study to be processed in Microsoft office tools and exported to database files that were then geo-referenced using ArcGIS and finally uploaded to the schematic, with seamless rapport, directly either as vectors or raster (see Figure 23 in previous section).



CSV File Name: ments and Settings\me\My Documents\Leo\Forschung\Work\Analysis\Supply data\Kabete rainfall.csv

Monthly, Jan 1993 - Dec 2012, 1 data column, 240 data rows

Data Column	Unit	Dates	Min	Max	Mean	Num Data	Num Missing
1	?	Jan 1993 - Dec 2012	0	541	92	240	0

Data Column: 1
Base Year Data from: 2010
First Year to Use: 1998
Last Year to Use: 2012
Cycle?: Cycle

☐ Annual Total ☐ Monthly Average ☐ Percent of Time Exceeded

Demand Sites and Catchments\Kanji Agr Catchment:Precipitation[mm] = ReadFromFile(C:\Documents and Settings\me\My Documents\Leo\Forschung\Work\Analysis\Supply data\Kabete rainfall.csv, , , , , , 1998, , Cycle)

Figure 32: Using Historical data time series

WEAP also allows the modeller to flexibly utilise historical dataset by specifying the historical year to use; after specifying the first year of use, WEAP will loop through the historical sequence up to the number of years specified in the model time horizon. The model time frame for this study was set at 15 years and in the general parameters menu, the year 2010 was set as the current account year and the last year of scenarios set accordingly at 2025. This was precipitated by the fact that the data time series obtained for some key parameters spanned 20years and this was especially for climatic data procured from the meteorological department, which spanned from1993-2012. By specifying 2010 as the base year and 1998 as the first year of use, it was possible to utilize precipitation data for the last fifteen years that was adjudged to be more consistent (see Figure 32 above).

Important to note, if needed, different time intervals would have been chosen to simulate the system over various historical time periods but that was beyond the scope of this study.

To accurately capture and represent both the inflows and outflows, the entire Nairobi River catchment was subdivided into various sub-catchments hereby represented as head flow catchments for the river and its tributaries; agricultural catchments; and a few residential and commercial catchments. The head flow sub-catchments are for all intent and purposes treated like agricultural catchments with the only difference being that their runoff inflow into respective streams are treated as rivers' head flow (see Figure 33 below).

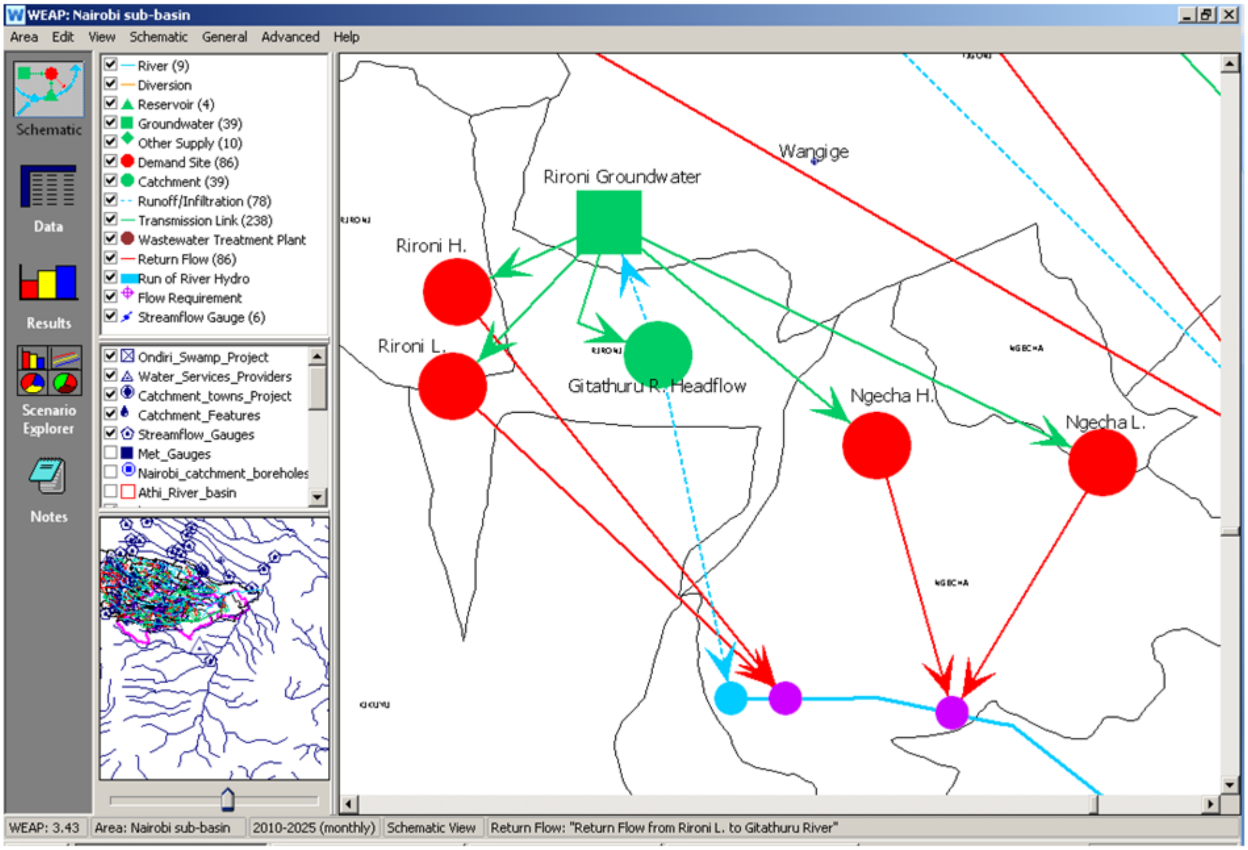


Figure 33: Schematic representation of the headflow to Gitathuru River, catchment recharge of groundwater, water transmission to various demand sites and return flow routing

The rainfall-runoff method was adopted in this study, drawn from FAO irrigation and drainage paper 56 (Allen, et al., 1998), which computes runoff as the difference between precipitation and plant's evapotran-spiration. It is therefore the simplest of the methods that can be used in WEAP for computing mass balance within a catchment. As demonstrated in the schematic figure above, a portion of precipitation is assigned to go directly to runoff to maintain base flow in rivers and is therefore not available for evapotranspiration, while the remaining portion termed as 'effective precipitation', assumed to be 88% in this study, is available for crop potential evapotranspiration. To help account for ground water recharge and surface water and ground water interaction, a portion of precipitation is also assigned to go directly to recharge the aquifer and is only available for crop evapotranspiration if irrigation is provided for whereby a transmission link is provided in the schematic to connect ground water source to the catchment, as in the case for all sub-catchments in this study.

In modelling with WEAP, transmission link and return flow links are used to respectively connect demand sites with supply sources and to rout return flow from demand sites either to and/or the river and groundwater aquifers directly or through water treatment plants. On the other hand, demand and supply priorities settings are used to determine the respective allocation of scarce water resources with the demand node with lower priority drawing water only after nodes with superior priorities are satisfied and supply sources with lower priorities supplying water to top-up demand sites needs after the superior priorities sources are exhausted. To account for the water lost from the system via embodiment in products, treatment processes, evaporation, or else unaccounted for water, consumption losses for each demand sites are entered in the model.

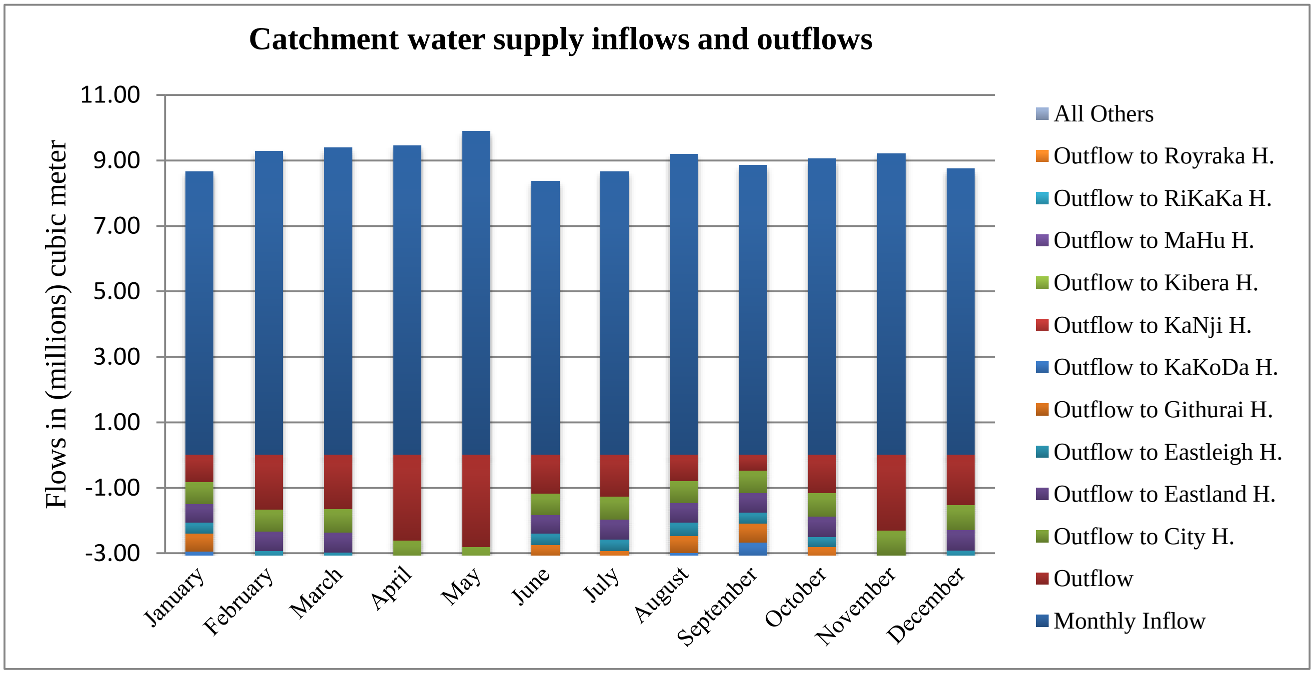


Figure 34: Balance between the catchment demand sites water supply inflows and outflows

This system creates a closed loop that account for entire water resources flow from supply sources, demands sites, treatment plants, reservoirs, stream flow and ground water regimes through simple mass balance as illustrated in Figure 34 above. From the illustration, January, August and September are the driest months in the catchment; causing over-abstraction of base flow by demand sites that severely reduce flow available for ecological needs and downstream users. An apparent limitation to the preciseness of flow accumulation for the individual streams within the catchment, which may also affect simulated water allocations, is that individual head flows and intermediate sub-catchments in this study were delineated with due consideration of both hydrologic units and existing administrative zones, in reconciliation with other existing data statistics. Though the approach has little effect on the overall catchment mass balance assessments, more flow from the catchment could be allocated to one stream than actual catchment topography allows; hence complicating model calibration with WEAP which is pegged on comparison between observed stream gauge flow and simulated flow at a node in the immediate upstream reach. Another challenge was to decide the source of supply for various demand sites within the catchment, which has potential to allocate water to less deserving demand sites whereas superior priority demand site assigned to lower potential sources go unmet.

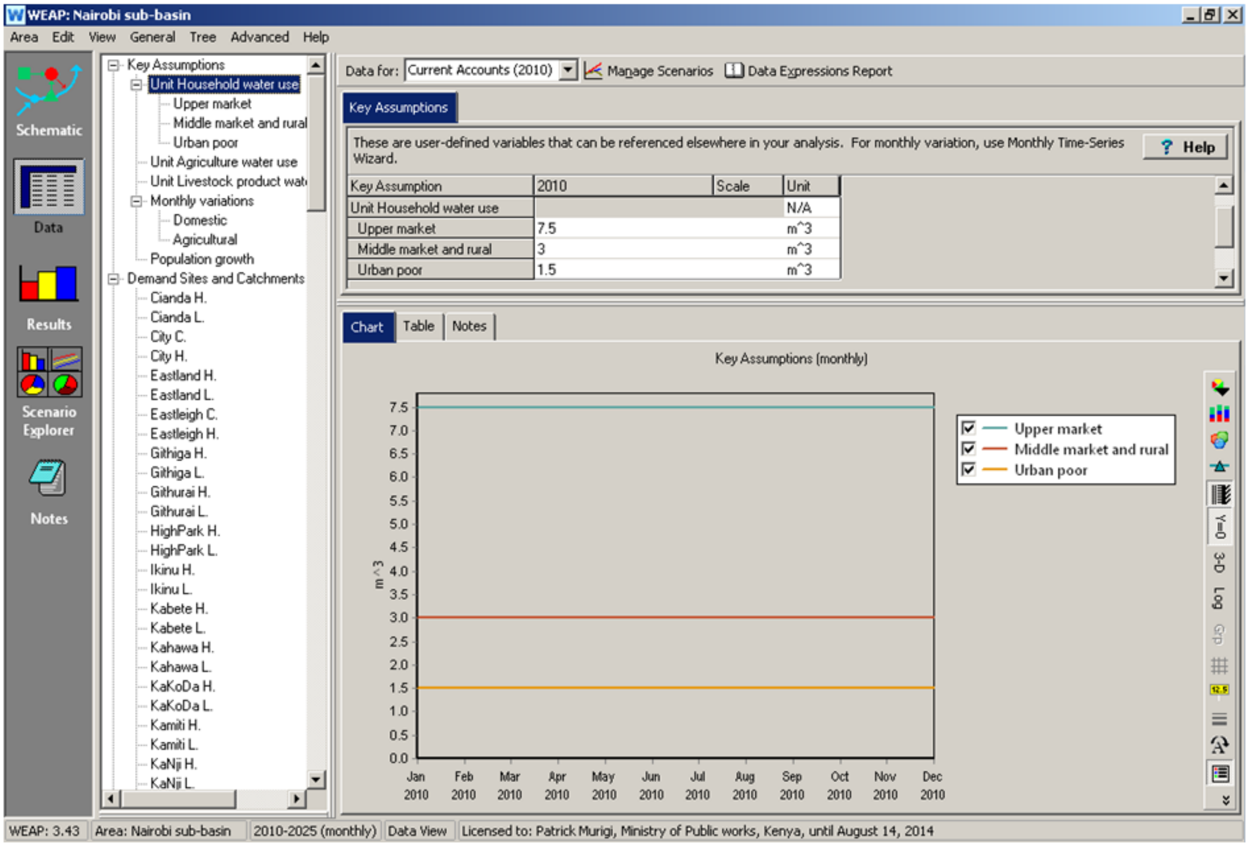
These limitations however could be ameliorated, for the first instance, through processing of catchment delineation and flow accumulation layers in GIS and importing the same through WEAP schematic view for a more precise structuring of the sub-catchments. The other challenge could also be surmounted through either simulation of various stream flows conditions while continuously restructuring the assignment of demand sites to connect more sites to supply sources with higher flow. The challenge of imbalance in supply allocation will however be workable in simulation of scenarios where catchment demand are supplied from reservoirs; since it's more pragmatic to ensure municipal supplies are prioritised in allocation of resources available, regardless of demand site location. Downstream releases can also be set through sluices to ensure flow requirements is met for base flow for ecological demand.

The runoffs from the delineated agricultural, commercial and residential sub-catchments were solely named to distinguish diverse catchment land use as to integrate their dynamic influence on water resources storage, use and disposal. A commercial catchment was considered to be densely populated and with expansive transport network and other trade enabling infrastructure; all leading to increased impermeable surface relative to other catchment areas. The impermeable surfaces impede infiltration of water to lower soil zones and have potential to yield depletion of exploited aquifers due to failure in vital ground water recharge processes. Moreover, the impermeable surface caused by increasing urbanization and also by poor land use and management techniques often yield hard pans in sub-soil zone in estates and agricultural catchments (Kathuli, et al., 2008). This often leads to low infiltration, decreased water retention and catastrophic flash floods during storms. The lower interflows and base flows that continue to recharge effluent river systems long after rainfall event elicits metamorphosis of perennial streams to intermittent streams. The lower piezometric head in groundwater flow regime turn gaining streams to losing streams as water infiltrates to recharge local aquifers leading to dry stream beds downstream (Goodrich, 2008).

To model crop water consumption, an average crop coefficient (0.84) calculated as expounded in the previous section was used to represent crop effect in agricultural catchment potential evapotranspiration calculations, while a reduced figure of 0.6 was used for the commercial catchment to represent the reduced potential evapotranspiration due to evaporation being the major component as a result of increased built-up area and impermeable surfaces. This was adjudged to be a plausible account of the catchment system corresponding to rainfall-runoff method used to model water balance in this study, as it will yield a typical increase in runoff component experienced in urban environment. To arrive at the latter figure, it was estimated that 50% of the land surface in commercial catchment is impervious and that estimated evaporation to transpiration ratio is 0.43 and transpiration to evapotranspiration ratio is 0.757 (Novák & Havrila, 2005). The consequences of this scenario are increasingly being mitigated in many urban environments through supply management policies and practices to offset especially the adverse impacts posed by increased impermeable surfaces. The adopted measures include the construction of infiltration basins and retention ponds to reserve run offs from impervious areas (Sieber, 2011), providing artificial recharge through wells and/or surface spreading and construction of water pans and roof traps(gutters) for water harvesting. And also through drainage management practices like using permeable wearing courses for feeder roads and unlined road side drains; all meant to intensify infiltration and recharge urban aquifers.

In this study 10% of total precipitation within the catchment was assumed to infiltrate and recharge the aquifer, and the otherwise renewable resources was the only amount available for demand allocation, as the initial ground water storage at the first year of scenario was considered to be the base flow for land and ecological stability and sustainability within the catchment. Since WEAP adopts monthly time steps, this portion was calculated for every month and was considered to be available for catchment demand within the same month, with storage taking place only during the months when precipitation exceeded potential evapotranspiration and both the surface runoff portion and water importation from adjacent river basin exceeded other catchment demands. Each sub-catchment groundwater potential was considered separately, with the respective surface area being the main variable as uniform precipitation potential was adopted for the entire catchment. This is because lower precipitation occurred in the lower most extreme of the catchment where waste water treatment plants were also situated and therefore recharge of ground water in the area is potentially higher than in other areas due to infiltration from retention ponds and unlined drains; more so in the reference scenario where no changes in management practice for the catchment is considered.

Various sub-catchments household demands were disaggregated into three classes in accordance to social and economic class of households (see Figure 35 below), with the poor settlements demand being allocated water for basic uses only. This is in line with the IWRM paradigm that considers water as both a social and economic good to ensure both the optimal recovery of investment for its development and also to ensure that those who cannot afford the economic water tariff, are provided with basic supplies at subsided prices. Basic supply, as explained earlier is determined by water managers and generally harmonised with the reasonable water allocation to accord the less fortunate a hygienic living conditions. The rural household demand was classified under the middle class category considering, in addition to explanation given in previous section, the fact that with lower transport costs water tariffs are relatively low and therefore domestic water is affordably utilised to maintain other household demands like vegetable gardens, and non-livestock domestic animals. Their demand therefore ranks comparatively at par with middle class household in urban settlements.



These are user-defined variables that can be referenced elsewhere in your analysis. For monthly variation, use Monthly Time-Series Wizard.

Key Assumption	2010	Scale	Unit
Unit Household water use			N/A
Upper market	7.5		m^3
Middle market and rural	3		m^3
Urban poor	1.5		m^3

Figure 35: Disaggregation of household water demand to reflect socio-economic status influence

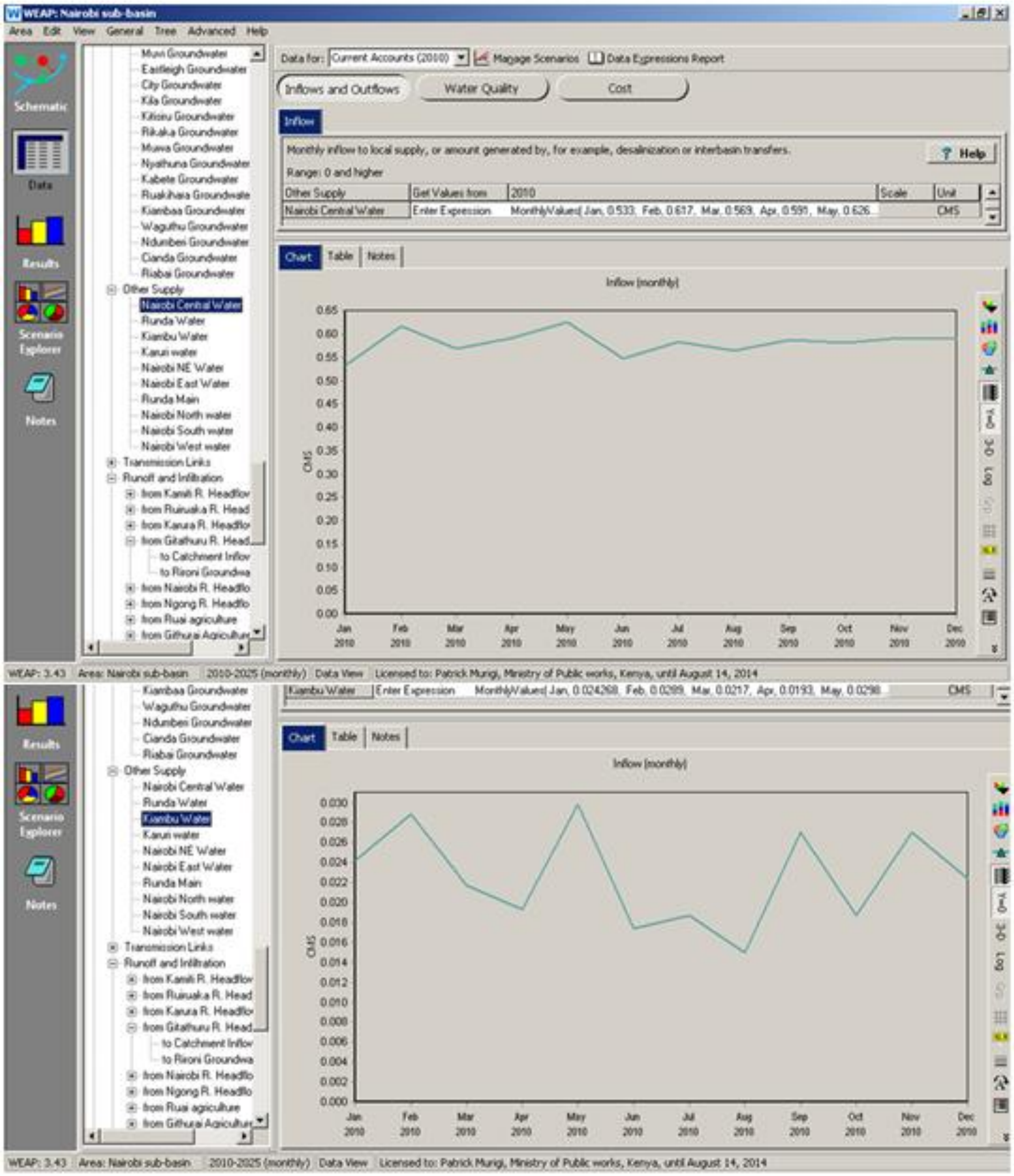
As previously explained, the ‘livestock class’ herein quantified in production units, was used for evaluation and aggregation of all the other catchment demands but household and agriculture. A ratio evaluated by comparing daily demand of every livestock breed, commercial product or service to the typical average daily demand for a typical daily cow was used to aggregate water consumption thereby facilitating quantification of multifarious demands in all sub-catchments to ascertain their estimated water consumption in comparable rate. The average daily water consumption of 115 litres per day for a typical daily cow was adopted and used as a bench mark for gauging and aggregating water consumption by other livestock breeds and production of other goods and services within the case study area. Correspondingly, to aggregate water consumption for each sub-catchment, total population of every breed of livestock was multiplied by the ratio of its unit average typical daily water consumption to the given unit average typical daily cow consumption; and similarly the total estimate of products produced and services delivered were multiplied with the respective ratio of the estimated water consumption in daily production of individual products or batch of products for the small products (and likewise for services delivery), to same prescribed consumption by a typical daily cow. The resultant was an aggregated figure than represented the daily level of activity for each sub-catchment by ‘Stocks’ in terms of a production units (Table 19 and Table 20).

This approach has some limitations in that from the model interpretation, in absence of background information and calculations, it would be difficult to ascertain the individual impact of production of a breed of livestock, production of a particular good or service on catchment water resources demand. But WEAP also operates like a database for water resources data and information, which can be uploaded in the versatile schematic view as part of attributes in GIS vector and raster files. It also proffers the benefit of a simplified analysis of impacts posed by commercial activities' demand for water resources within a catchment. Thus, through the economic analysis of the benefits accrued from respective productions via simulation with cost-benefit analysis module integrated in WEAP, the most beneficial use of scarce water resources that also foster total recovery of water infrastructure development and management costs can be ascertained. Since water is a finite economic and social resource, simulations of various economic and social water applications; for instance cultivating horticultural products under irrigation on one hand, and using the same resources in production of livestock fodder on the other hand, will help establish the more profitable enterprise. In the dairy sector of Kenya, it has been found that irrigating fodder for dairy farming improves farmers' net incomes and compares favourably irrigation for vegetable production (Hoekstra & Chapagain, 2007).

All the requisite demand sites and other the system components were then input by use of representative schema available in the schematic bar of the schematic view and the processed data uploaded either by right clicking demand sites or opening the data view directly to edit various parameters and variables accordingly. As discussed in the literature review, the current account is the base year for the model and it bears all the system information input. It provide a snapshot of actual water demand, resources and supplies and pollution loads for the system and is thus appreciated as the calibration step in the model development. It is the basis for building various scenarios through input of assumptions to represent prevailing policies, costs and factors that affect system demand, pollution, supply and hydrology. Simulations of the various scenarios allow one to explore the impact of alternative sets of assumptions and/or policies on future water availability and use. Not considered in this study, but also proffered by WEAP are scenarios evaluation with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables (Sieber & Purkey, 2011).

Due to the current high levels of pollution in the stream within the Nairobi catchment, land challenges as a result of dense population and also small streams that would complicate efforts to maintain reliable flow to reservoirs all year round, the bulk of municipal water exploited in Nairobi city and her environ is imported resource from the adjacent Tana Catchment Area (TCA). This was represented in the schematic by relevant Nairobi water distribution zones and distribution points within neighbouring satellite towns (identified with their geographical location), where the bulk water is delivered by gravity from the source and distributed to regional household and commercial demand sites. Unlike other sources of supply, the imported water quantities depend entirely on the reliability of the source, capacity and efficiency of transport infrastructure, and the existing policy on water distribution that normally allot higher priority to some zones over the others as illustrated by Figure 36 below.

Supply to key national institutions, estates and economic zones is prioritised while supply to satellite towns and regions that have alternative service providers is rationalised according to imminent fluctuations of supply.



Monthly inflow to local supply, or amount generated by, for example, desalinization or interbasin transfers.

Range: 0 and higher

Other Supply	Get Values from	2010	Scale	Unit
Nairobi Central Water	Enter Expression	MonthlyValues(Jan, 0.533, Feb, 0.617, Mar, 0.569, Apr, 0.591, May, 0.626		CMS

WEAP: 3.43 Area: Nairobi sub-basin 2010-2025 (monthly) Data View Licensed to: Patrick Murigi, Ministry of Public works, Kenya, until August 14, 2014

Kiambu Water	Enter Expression	MonthlyValues(Jan, 0.024268, Feb, 0.0289, Mar, 0.0217, Apr, 0.0193, May, 0.0298		CMS

WEAP: 3.43 Area: Nairobi sub-basin 2010-2025 (monthly) Data View Licensed to: Patrick Murigi, Ministry of Public works, Kenya, until August 14, 2014

Figure 36: Illustration of the mean monthly priorities allocations of the imported water

The time series data on other supply for the Nairobi catchment area was obtained from the Nairobi Water and Sewerage Company (NWSC), a public-private partnership company appointed by Athi water services board to provide water services to Nairobi city resident. To facilitate their operations efficiency, the company is mandated with the management of the reservoirs, water supply treatment plants and the distribution infrastructure from the sources to the demand sites. Water supplied to the satellite towns and water kiosks in areas adjacent to the water sources and trunk distribution infrastructure is part of company's cooperate responsibility to harmonise its core interest with legitimate interests by other water resources stakeholders.

Due to the high cost involved in treatment and distribution of imported water resources, the resources is allocated exclusively to household and key institutions as a priority and to the key economic zones; but is not allocated to irrigation demand. Even so, currently only estimated 50% of Nairobi residence have water connections and of the 50% only 40% of them have regular water in their pipes (N.C.W.&S.C., 2011). The skewed water allocation reality has been appreciated in the model by allocating the water to household demand at first priority and second priority to commercial demand sites and no allocation to agricultural catchment demand nodes.

WEAP data structure and level of details, as exploited in aggregation of livestock water demand in this study, may be easily customized to meet the requirements of a particular analysis, and also to reflect the limits imposed by restricted data (Sieber, 2011). The simplified approach used in setting up the model is fashioned towards ensuring universal comprehensibility at the lowest devolved water resources management and societal level; every interested catchment stakeholder should be able to understand the interaction between multifarious catchment water demand enterprises and their supply sources; and how their individual consumption of the resource impact on other legitimate needs for the same resources. This would facilitate proactive participation in decision making and subsequent support in implementation of collective resolution for catchment scale supply, demand or integrated water resources management measures. The simplicity should not however undermine the foundation of scenario analysis, which is anchored in setting up of a current account that represents the status quo of water resources in a given area or the water system under study.

Very crucial to adaptive and collaborative resource management approach is the setting up of the spatial boundary for the catchment being modelled, which is then delineated in the schematic view of the model allowing the system components to be uploaded by use of representative schema available in the schematic bar of the schematic view and imported GIS shape files and/or raster. The spatial appeal of the model offer appreciable capacity to not only aid in configuration of the problem (Sieber, 2011), but also in facilitating proactive stakeholders' dialogue and collaborations as every party can forthrightly, or with minimum capacity building, identify with the area and comprehend the model, the problem and/or the issues at hand.

6.6.4 **Model Calibration, Validation and Testing**

In this study, calibration, test and validation of the models was done using the stream flow records obtain from the stream gauge BA29 and B10 (see appendix Table 37), which had significant recorded historical data time series. However, there was some valid reservation on the quality of the recorded data, since the methods used to obtain stream flow record, i.e. using analysis of channel cross-sectional depth and corresponding flow readings with current meter (velocity-area method), were considered error-prone, inconsistent and largely unreliable, safe for estimates purposes; especially due to rampant river sedimentation challenges and practical inadmissibility usually during high flows and floods. However, since the study was about evaluation of the model capability to facilitate decision making process within the available data regime with anticipation of progressive system advancement (see appendix Figure 73), the available recorded estimates were considered admissible after substantial appropriate editing to correct conspicuous errors and gaps.

Fundamentally, the potential setbacks from inaccurate data especially with WEAP application, is the fact that the model validation is based primarily on visual comparison of the observed time series of mean monthly flow at the streamflow gauge and the simulated flow at the nearest node in the immediate upstream reach. To achieve a good semblance between the two, the simulated results may be modified by introducing or adjusting prevailing management scenarios, policies and/or introduction of demand, supply or integrated management policies. Thus the calibration process facilitates the refinement of the resulting model to ensure it represent the system accurately and can be used with confidence for envisaged scenario simulations and evaluations to draw reliable interpretations to steer decision making process in policy formulation and planning (Sieber, 2011). A calibrated model provides reliable foundation to investigate, compare and evaluate various water management scenarios, either for resource usage optimization or policy formulation to guide water resources planning, development and management.

Consequently, future constraints such as changes in demography, economy, climate, land use, irrigation efficiency, or return flow, can be simulated and therefore taken into account through formulation of demand, supply or integrated management policies for timely mitigation of potential adverse effect on catchment water resources sustainability. To calibrate the WEAP model therefore, the model time horizon when both the observed stream gauge time series and the model simulated streamflow time series are available is exploited. The adjudged consistent data for stream flow records obtained from the Ministry of Water and Irrigation[4] (MWI) database for stream gauge 3BA29, located on Nairobi River under a bridge at Museum hill area in the vicinity of Nairobi city CBD, had consistent time series for the period between 1978 and 1992; which were subsequently adopted to represent typical observed streamflow for the river at that section. By specifying 1978 as the base year and 1978 as the first year of use, it was possible to utilize stream flow data for the consecutive fifteen years that was adjudged to be more consistent (see Figure 37 below).

Even in this case, other than just relying on observation, different time intervals could have been chosen alongside the calibration process, expounded prior in this section, to simulate the system over various historical time periods as to select the period with observed flow that presented best consistency with the simulated flow. The year 2010 could not be chosen as the base year as earlier exercised with the meteorological data, since the recent implementation of institutional reforms and the subsequent challenges affecting distribution, smooth transfer, coordination and collaboration in overlapping mandates between WRMA and the parent Ministry, affected data collection and database management. Hence the great inconsistencies and extrapolated gaps

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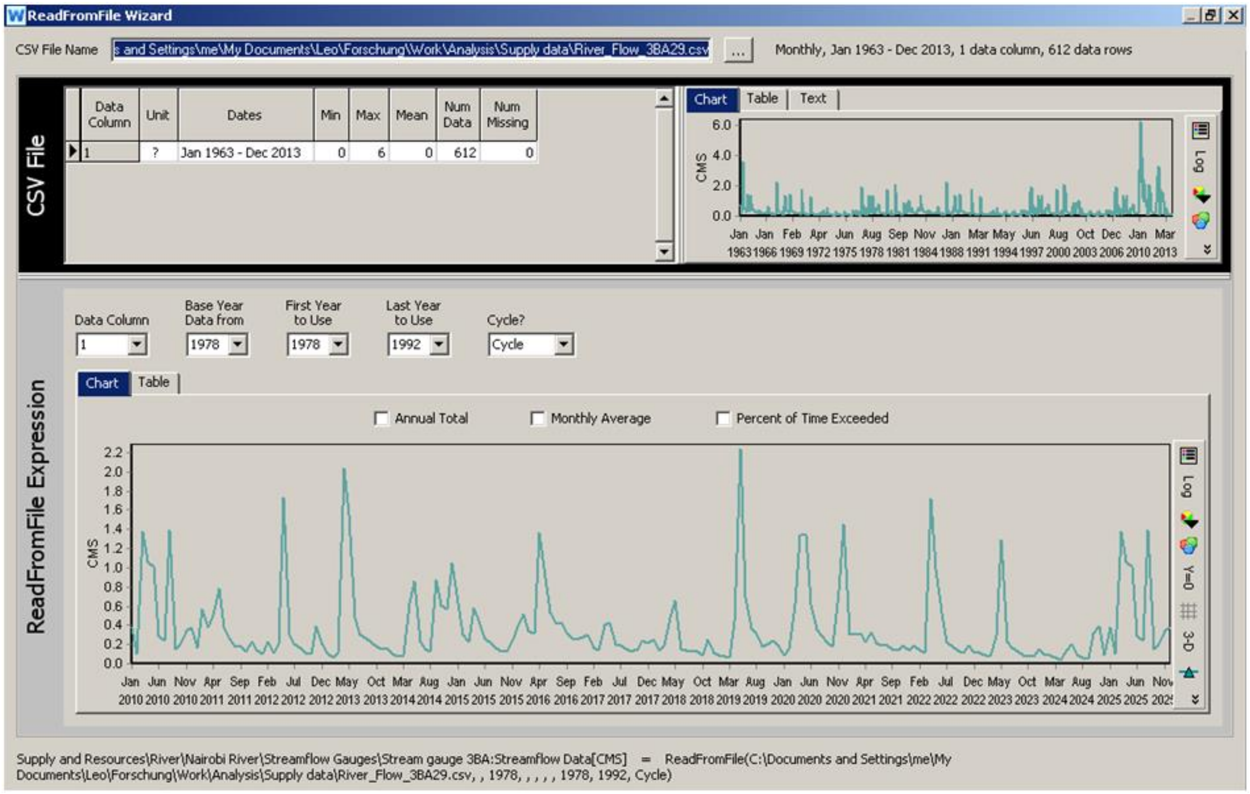
[4] Ministry of Water and Irrigation in Kenya has since been restructured to ‘Ministry of Environment, Water and Natural Resources’ as from June 2013.

apparent from Figure 37 here below. The same approach was adopted in comparison of the observed stream flow time series with the simulated records at Ruiruaka River, which also featured some intermittently consistent but reliable historical data for the period spanning from 1949; the period between 1981 and 1995 being considered. The data pertaining to the other streams were either unreliable or with major gaps that could not be plausibly bridged by interpolations or any other logical data processing approach for use in this case study. However, since the approach adopted in this study to generate flow was simple rainfall coefficient method with the stream flows being generated as the difference between catchment precipitation on one hand and evapotranspiration and groundwater recharge on the other, the calibration of the two main streams would satisfy the study purpose.



CSV File Name: s and Settings\me\My Documents\Leo\Forschung\Work\Analysis\Supply data\River_Flow_3BA29.csv

Monthly, Jan 1963 - Dec 2013, 1 data column, 612 data rows

Data Column	Unit	Dates	Min	Max	Mean	Num Data	Num Missing
1	?	Jan 1963 - Dec 2013	0	6	0	612	0

Data Column: 1
Base Year Data from: 1978
First Year to Use: 1978
Last Year to Use: 1992
Cycle?: Cycle

Supply and Resources\River\Nairobi River\Streamflow Gauges\Stream gauge 3BA:Streamflow Data[CMS] = ReadFromFile(C:\Documents and Settings\me\My Documents\Leo\Forschung\Work\Analysis\Supply data\River_Flow_3BA29.csv, , 1978, , , , , 1978, 1992, Cycle)

Figure 37: Setting gauged stream flow time series for model calibration

Figure 38 below represents the calibrated model average monthly simulated stream flow relative to gauge (absolute) record for a section of Nairobi River and one of the tributaries. The difference between the simulated and the observed flow is not only influenced by the land use and land cover dynamics, but also by some of the assumptions adopted in this study especially on surface water and ground water interaction and routing of total return flows from demand site to the river. This is best reflected by the great disparity between the two rainy seasons since only 10% of the precipitation is considered to recharge the ground water, and the same is assumed to be instantaneously available for withdrawal by local demand site and/or flow to the stream to be used by demand downstream. In this scenario, the entire precipitation safe for the evapotranspired water and amount consumed by the demand sites either through embodiment into products or just unaccounted for and therefore lost from the system, the rest constitute flow in the stream. This assumption has an effect of aggravating floods above normal during the rainy seasons, which is reflected by the high disparity between average simulated and gauge flow for the period around the months of April and November (See Figure 40 below).

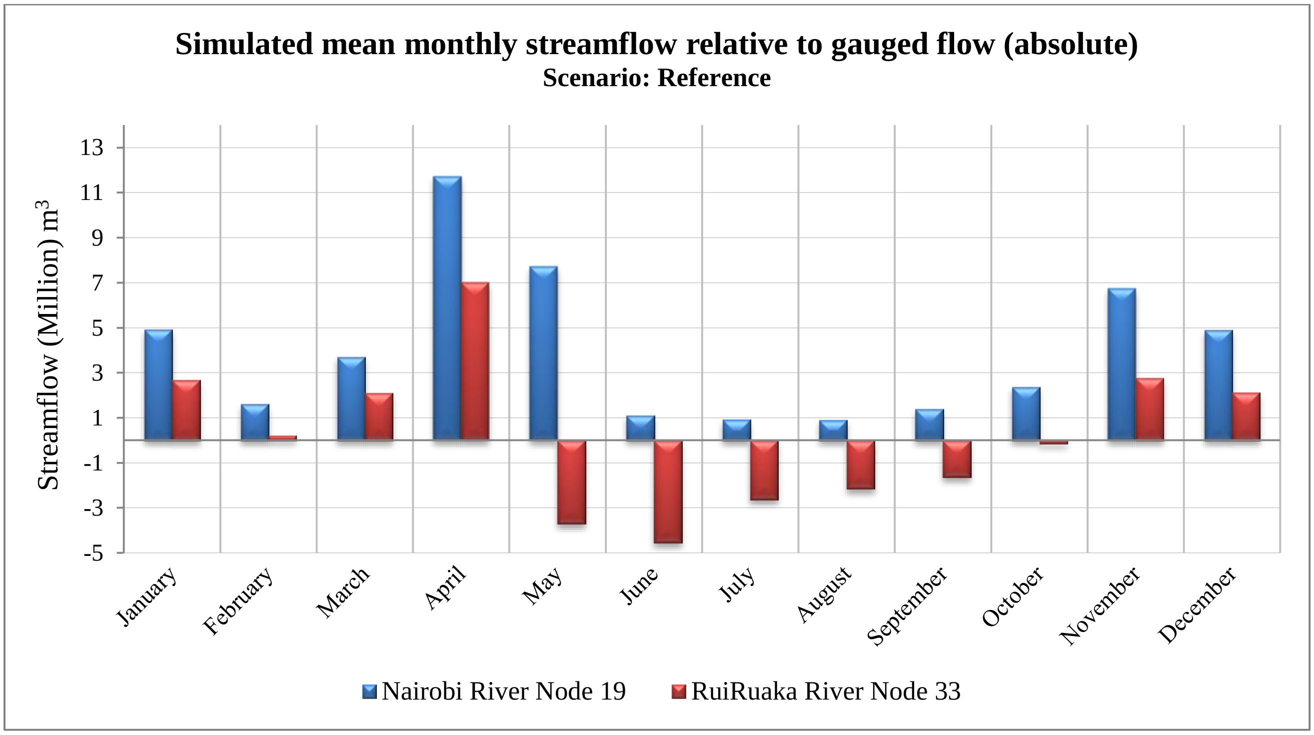


Figure 38: Mean monthly simulated stream flow relative to gauge (Absolute) for Nairobi River and Ruiruaka River, the main tributaries of Nairobi River

The remarkable disparity between the simulated streamflow relative to gauged streamflow for the Nairobi River and its main tributary (Ruiruaka River) could be explained by their apparently different flow regime and diverse catchment land use dynamics. Whereas similar catchment land use scenario were adopted in this case study for simplicity, Nairobi River flows mainly through settlements and agricultural lands that have seen major land dynamics with rapid population growth escalated by rural-urban migration. Ruiruaka River, on the other hand, flow through some conserved forested areas that boost infiltration, during rainy season, and sustain higher water holding capacity in the interstitial subsurface zone and aquifers recharge that avail perennial release of the same during the long dry season ensuring there is more water flowing in the stream throughout the dry season. The observed flow was thus higher during dry seasons than achieved through simulations here where vegetation effects were aggregated and surface water to ground water interaction was not as elaborate as it certainly could be in more pragmatic scenario. This would explain the phenomenal between June and October, where the simulated mean monthly streamflow for the river are lower than the mean monthly observed streamgauge flows.

Figure 39 below illustrate the semblance between the mean monthly simulated flow at the immediate node in the reach upstream of streamgauge 3BA10 and the observed mean monthly flow recorded at the streamgauge.

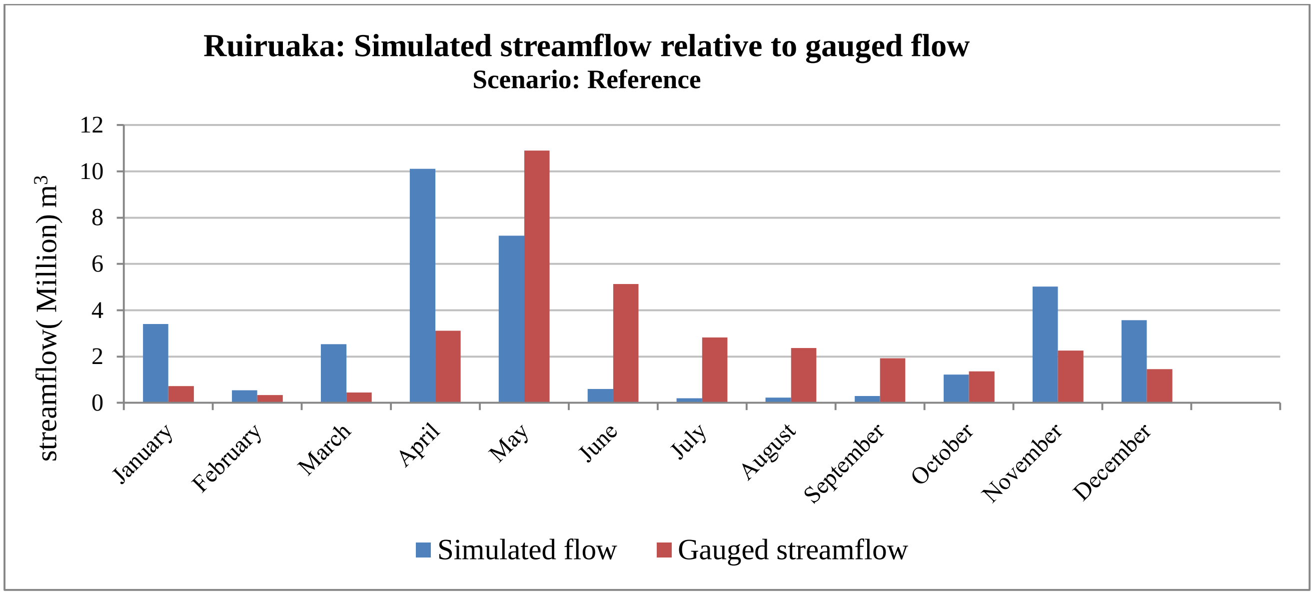


Figure 39: Comparing the observed flow at streamgauge 3BA10 with simulated flow at the return flow node 33 at the immediate upstream in Ruiruaka River.

In the case of Nairobi River, the character of the simulated mean monthly flow at the return flow node immediately upstream of the streamgauge compared relative well with the observed mean monthly streamgauge records, with plausible variations in flow levels attributed to major land use dynamics visited on the catchment courtesy of the expanding settlements and agricultural lands to provide for the rapid growth in the city and satellite towns in the environ. With the settlements and the accompanying infrastructure growth in the city and satellite towns within the catchment, more impermeable surfaces are yielded leading to decreased infiltration of water and characteristic low water retention capacity. With the escalated abstraction of water from the aquifers and low recharge of the same, there is dire need for an adaptive integrated approach in water resources management to arrest the current water crisis and proffer strategies and measures for progressive improvement towards a more sustainable management regime.

Moreover, huge tracts of past conserved public land and forests have been de-gazetted and cleared to provide agricultural land towards creating source of employment in the rural areas and improving food security. The typical attenuated average monthly flow observed during rainy season in April and November during late 1970s up to early 1990s compared to the burst of high flows generated in the simulated reference scenario, is a testimony to the effect of land use dynamics within the catchment over the time. The simulated flow is also accentuated by the subsequent decrease in surface to ground water interaction and absence of water storage structures to hold aggravated runoff during storms, leading to higher floods and conversely lower streamflow in dry season as demonstrated in the Figure 40 below.

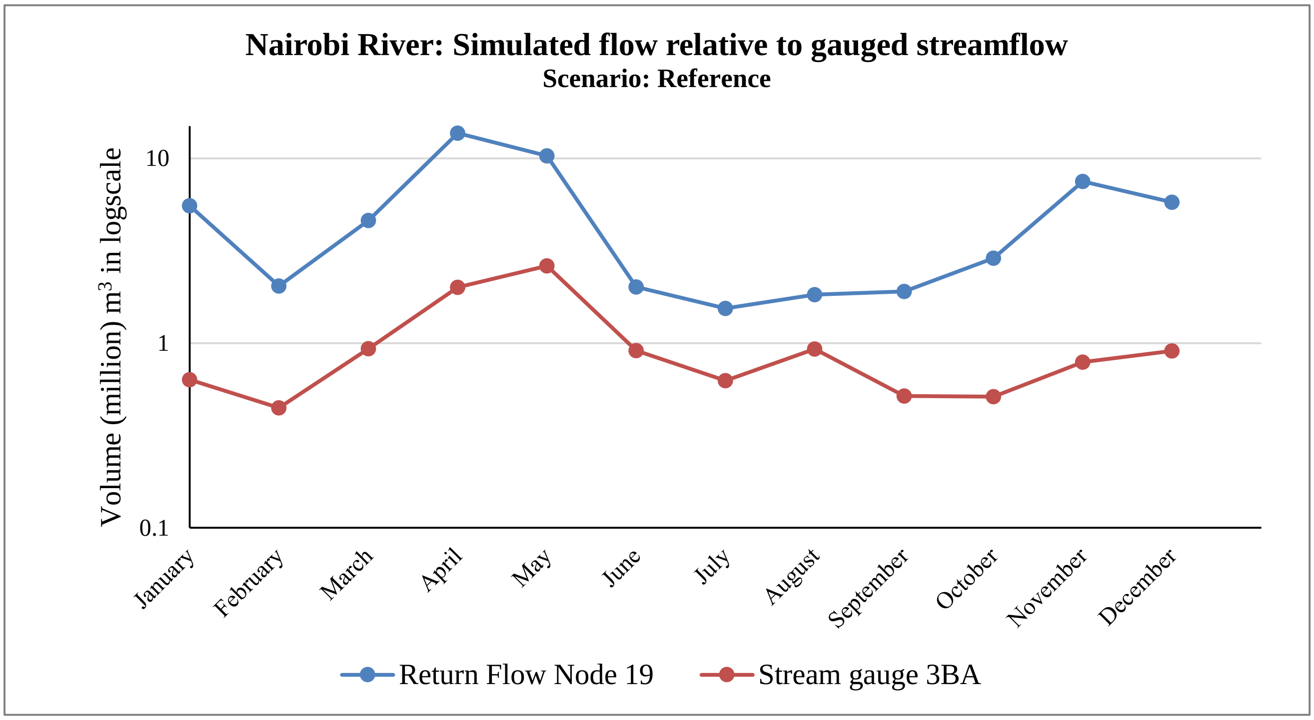


Figure 40: Comparing the observed flow at streamgauge 3BA29 and simulated flow at the return flow node 19 at the immediate upstream in Nairobi River.

WEAP allow users to switch between normal axis and logarithmic axis in order to magnify graph elements for enhanced visual clarity, especially since observation of trend in this case is key to validation of the model as a true representation of the actual catchment system. For instance, the use of log scale in Figure 40 above enhances the visual character that amplify fine details on the two curves illustrating the difference in the simulated mean monthly streamflow at the node just upstream and on same reach as the streamgauge, and the observed mean monthly flow.

6.7 Running various Management and Projected Scenarios

After the model calibration and testing to ensure as precise representation of the system as possible, the simulation and analysis of results for other parameters and variables, especially those crucial for the assessment of catchment water resources demand and supply situation for effective water balancing, were availed as presented and extensively expounded in this section.

When modelling the current and possible scenarios due to the various water resources developments, the prevailing or presumed management and institutional policies and regulations impacts on water resources supply and demand conditions, are the primary objectives of decision support for water managers at the catchment level.

With model simulations, the impact of current and forecasted scenarios due to the various water resources developments, changes in supply and demand conditions on the catchment water resources management were investigated; starting with the reference scenario also referred to as the “business as usual’. In the reference scenario it is assumed that the demand conditions remain static i.e. Population and socio-economic development and environmental requirements continue at the present rate with supply and demand conditions also maintaining the prevailing trend i.e. no additional anthropogenic influences like supply measures (e.g. expansion of water storage, induction of water reuse etc.) and demand measures (i.e. water pricing, minimal system losses etc.). Other scenarios considered include:

- Projected higher population growth within the catchment, especially escalated by increasing rural-urban migration;
- Projected supply management especially through construction of reservoirs in the upstream of the catchment that also offer expanded opportunity for water reuse (see Table 31 below);
- Projected introduction of sustainable land and environmental management measures

The approach adopted in simulations of various scenarios in this study are in conformity with GWP definition of IWRM as “a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems” (GWP, 2000). That is, fostering an approach that highlights the need to strike a balance between economic efficiency and social equity on one hand, with due consideration of environmental sustainability on the other. This is achieved through adoption of management policies and strategies geared towards achieving the objectives of sustainable development. Key assumption, when examining the effect of change of water management policies within a catchment, is that the policy has had enough time to be implemented and take effect.

(i) Projected higher population growth within the catchment

The population growth considered in the ‘business as usual’ scenario of 2.8% was calculated from the data provided by the Central Bureau of Statistics (CBS) for both the 1999 and 2009 National Census. The assessed growth rate within that period pertains to the national population; however, the Nairobi River catchment harbours a capital city and a number of satellite towns that hosts the city work force and other citizens drawn by the better standard of services and opportunities associated with urban environment. Therefore the population growth within the catchment as assessed from the same data was approximately 4% and is expected to grow higher with the departure of government policies on promoting agriculture as the main source of employment in the country.

Previously rural settlements schemes and small scale farming were promoted by the state as a way of creating employment and self-reliance. However, confronted by climate change and its related erratic weather patterns that are increasingly rendering the largely rainfed agriculture unsustainable, posing a perpetual threat to national food security and increasing rural poverty, most government in developing countries have been forced to repackage their economic policies. The agricultural systems have further been weakened by the extreme fragmentations and settlement on the limited arable land as population grows (this is especially prominent in the case study area). The government has thus realised the need to adopt change of tact, and especially stimulate growth of service industry and encourage more urban settlements. As a result, the rural-urban migration is expected to escalate in the near future and urban population is therefore expected to grow at a higher rate that the average national growth. In this study, a forecasted growth of 5% was adopted for the higher population growth scenario in the case study area.

(ii) Projected supply measures especially through construction of reservoirs at the upstream

Appreciating that the projected increase in population translates to a proportionate increase in demand for food; and also in cognizance of the fact that agriculture demands more water than all other sectors put together i.e. the share of rainfall consumed by evapotranspiration is generally 60% in temperate region and 80 – 90% in arid climate (de Fraiture, 2007); there arise the need to envisage expansion of more water efficient agriculture. Water being a finite resource, significant and complex link between land use and available stream and ground water sources shows that river basin management is also about managing evapotranspiration (ET) (Berkoff, 2003).

This scenario is vastly adopted from agriculture water management (AWM) strategies outlined by (Lenton, et al., 2011) and the National water master plan 2030 released by the Ministry of Environment Water and Natural Resources (MEWNR, 2013). AWM involves increasing access to reliable and affordable water supplies, improving management of rainwater, soil moisture, and supplemental irrigation, finding ways to gain higher yields and value from the same water amounts, and enhancing management of the resource as a whole. AWM generally has broader objectives beyond enhancing agricultural productivity, such as improvements in livelihoods and incomes, reductions in risk, and long-term sustainability of the resource.

AWM generally involves the integrated management of both blue water, i.e. water abstracted from rivers, reservoirs, lakes, or aquifers for irrigation purposes and green water, i.e. rainfall stored in soil moisture. While blue water is visible and its role in irrigated agriculture is clearly understood, green water and its crucial role in rainfed agriculture often goes unrecognized (Lenton, et al., 2011). Green water management measures to improve agricultural productivity encompass soil management, crop choices and practices, and water storage. Other than determining share of potential evapotranspiration catered for by rainfall within the catchment, to evaluate irrigation demand, this study did not delve into details of green (soil) water management. Blue water irrigation management could involve water storage, pumping, transportation, delivery, application, and reuse at various levels. Notably, average yields from rainfed agriculture using green water are much lower than those from irrigated agriculture using blue water, and, as a result, only half of the world's food is produced under rainfed conditions practiced by the majority (≈80%) of the world's farmers (de Fraiture, et al., 2007).

Development in green water management can reach relatively large numbers of farmers at relatively low cost, but the productivity gains are relatively small compared to improvement in blue water irrigation management, which can achieve higher productivity gains, but reach relatively smaller numbers of farmers and with a relatively high cost per farmer. International Water Management Institute (IWMI) has played a major role in shaping thinking and action on AWM through research and development. It has subsequently evolved from a narrow blue-water focus on the management of irrigation at the systems level to its current broad mission to "improve the management of land and water resources for food, livelihoods and the environment". Abstraction of groundwater for irrigation has also grown considerably, and continues to play an ever-greater role in efforts to improve productivity, food security, livelihoods, and incomes (Lenton, et al., 2011).

The available data on ground water use in the case study area was limited to borehole inventory on individual wells' abstraction rates used to determine compliance with water permits and total daily abstractions in designated areas (Rural Focus, 2011). Whereas the extent of Nairobi aquifer system has been delineated, the records on number, depth, thickness, recharge rate and hydraulic characteristics of aquifers were missing. It was therefore difficult to ascertain the capacity as to estimate sustainable allocations and therefore the assumption was made that disregarded available storage at the beginning of the scenario. Thus the study could not encompass advanced ground water exploitation that requires adequate resources mapping and historical flow data, which also encompasses surface and ground water interaction.

Fundamentally, in simulation of scenarios, hydrological data, water development projects, policies and other metaphysical aspects of catchment hydrology and socio-economic factors are analysed. In this scenario a consideration for future expansion of storage to improve water availability was adopted, borrowing heavily on the recommendations of the just concluded National Water Master Plan 2030, but also factoring the pumping of treated water from water treatment plants into wetlands upstream for groundwater recharge and supply to rivers feeding the reservoirs. The proposed dams and their reservoirs capacities are as presented in Table 31 below.

Table 31: Proposed Dams within the Nairobi Catchment (MEWNR, 2013)

Name of Reservoir	Storage Volume for Domestic/Industrial (Million m^3)	Storage Volume for Irrigation (Million m^3)	Total Storage Volume (Million m^3)	Remarks
Kikuyu Dam	31.0	0.0	31.0	
Ruaka Dam	4.0	0.0	4.0	Detailed design completed (AWSB)
Kamiti Dam	16.0	0.0	16.0	Government project: Feasibility studies and Master plan ongoing (AWSB)

(iii) Projected shift to sustainable land and environmental management measures

From the climatic data analysis, crop water requirement analysis and from the reference scenario simulations, it was notable that some areas are prone to higher rates of reference evapotranspiration (ETo) and some crops have higher crop coefficient (Kc) that translate to relatively higher water demand than others. Since catchment (land and environment) management is also about managing evapotranspiration (ET), the crops are redistributed in such a manner that, where possible, crop with higher crop coefficient are allocated to zones with lower reference evapotranspiration as to improve on water efficiency.

Environmental management also entails the incorporation of estimated stream flow requirements in scenario simulation to ensure the abstraction from streams does not lead to ecologically unsustainable flows to the detriment of aquatic ecosystem. Flow requirements are derived from the historical stream flow records, with the mean lowest stream flow at a particular reach being adopted as the minimum ecological requirement to sustain aquatic ecosystem within that reach during the potentially driest season affecting that catchment or upstream catchment. Conversely, environment management also provide for the expected extreme high flows to be adequately controlled/ attenuated to mitigate potential damage to lives and property. To capture this scenario, the crop coefficient (Kc), which have been averaged for the entire catchment in the reference scenario, could be disaggregated to achieve greater water use efficiency with favourable crop choice and land management as per the previously discussed green water management measures of AWM.

Essentially, green water management measures are not only intended to improve agricultural productivity, but can encompass rainwater and soil moisture management, crop choices and practices, and water capture; with the stored water providing reliable and affordable supplies to meet the dry season's deficits at the respective catchment demand sites (Lenton, et al., 2011).

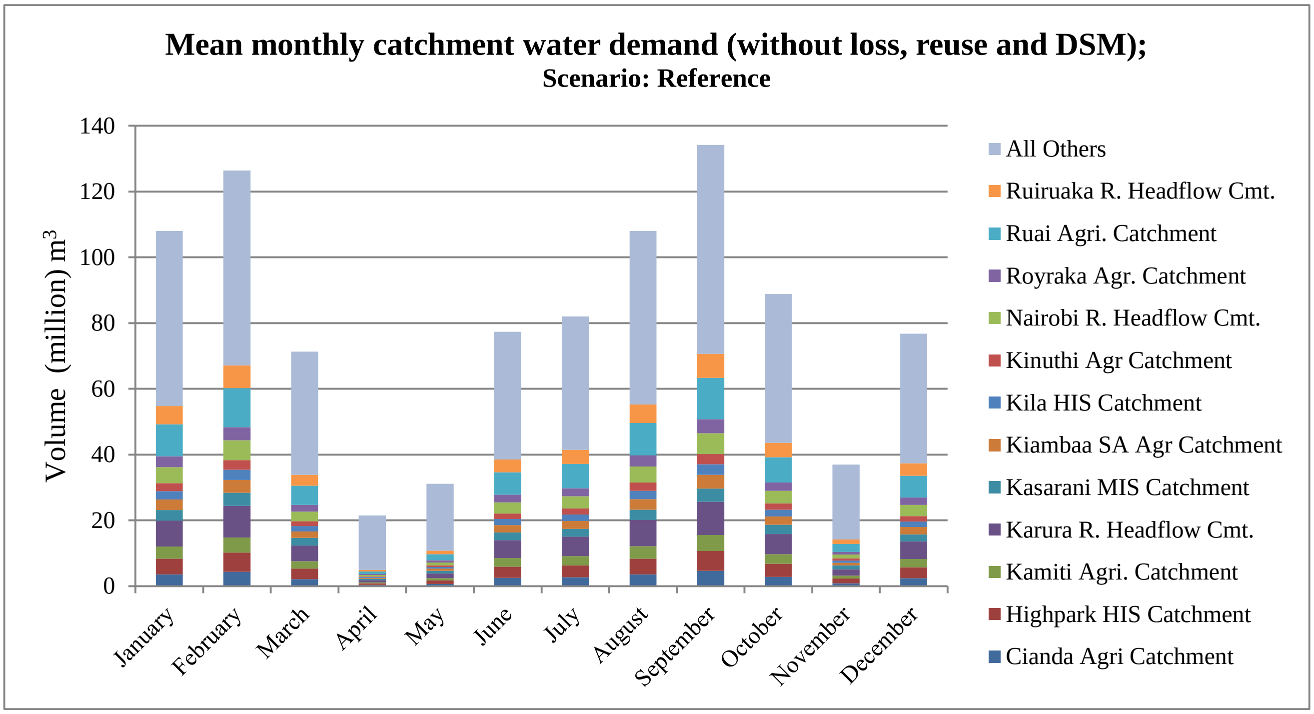


Figure 41: Mean monthly catchment water demand for the reference scenario

The ‘reference’ scenario, as elaborated previously, is adapted from the current account and therefore it represents the ‘business as usual’ management approach where the current population growth, its demography and respectively the demand sites’ activity rate, environmental and water resources management practices are carried over. It is therefore the foundation scenario used in the previous section in the calibration of the model and in illustrating the current state of the system and consequences of preserving the current state of affairs within the catchment.

From the graph of the mean monthly catchment water demand presented in the Figure 41 above it can be demonstrated that evapotranspiration demand constitute the major component of catchment water demand , which in this study is supplied through ‘effective precipitation’ and irrigation. Irrigation was been factored-in for all sub-catchments considering the social-cultural practice where most households have vegetable gardens and areas adjacent to riparian zones in the catchments have increasingly being exploited to provide both agricultural and horticultural products to the local and international market. The proximity to Jomo Kenyatta International Airport (JKIA), and good infrastructure connection to tourist coastal province creates a ready market and high demand for local and exports products and therefore an economic impetus for the mostly small-scale farmers. Moreover, the favourable climate ensures most of these products can be grown all-year-round through irrigations, either in open fields where evaporation losses are higher or in water-friendlier green houses that usually adopt drip irrigation to further boost water efficiency.

It is worthy to note that whereas disaggregation of agriculture sub-catchments to consider the diverse effects of different methods of irrigation adopted in the case study area is considered beyond scope of this study's, it is a very legitimate factor as it pose valid influence on the water loss which lead to an increase in catchment water supply requirements and subsequently reduce the demand coverage for the available water resources. Besides, the allocation of low priority for irrigation demand in all catchment does not exactly capture the reality on the ground, where abstractions for irrigation through numerous small scale diversions in upstream zones within the catchment, has led to unsustainable flows and even stream droughts downstream during long dry seasons. This has been a source of conflict among community water service providers and farmers within the catchment, with the former resigning to ground water abstraction, not only for more reliable supplies, but also to evade costly treatment of stream resources suffering anthropogenic pollution.

The study appreciated the strides already achieved by WRMA in recent times towards mitigating conflicts escalation, especially through delineation and protection of catchment wetlands, water bodies and adopting data-based water allocations towards sustainable usage while ensuring that riverine and ground water ecosystem are conserved and protected. Considering the rapid growth of population in the area and the corresponding demand for water to run industries, municipal and private institutions, and increasing enforcement of environmental protection policies, which collectively forces the agricultural sector to use irrigation water more efficiently, the irrigation fraction was set at 88%. However, this is a very ideal situation, considering conservative estimates suggest that even under optimal management practices the average irrigation efficiency is estimated to be 84 percent (FAO, n.d.). The average water loss under the efficient methods like sprinkler and drip irrigation is estimated at 15 percent. Practically this could drop to over 50 percent under furrow and flood irrigation, though these are not common in the case study area, not only due to water scarcity, but also due to the prevalently unfavourable land terrain.

The reasonably lower efficiency in irrigation would be considered in the demand management scenario, considering prevalent transmission losses, deep percolation losses related to the prevalent loamy and sandy-loam soil in the area. Additionally, the fact that evaporation and run off losses of water under landscape irrigation in leisure and sports fields popular in the city and other urban centres within the catchment are substantial. In comparison to catchment irrigation demand, other catchment demands like household and aggregated 'Stocks[5]' demands are just marginal and especially in typical semi humid zones where effective precipitation fall constantly short of potential evapotranspiration (see Figure 42 and Figure 43 below), and the difference has to be met by irrigation supply. Comparing Figure 41 and Figure 43, it is evident that irrigation demand constitute approximately 70% of the total catchment demand, which is an established phenomenon in arid and semi-arid areas where the proportion ranges between 70-80% (Jabloun, et al., 2012).

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[5] 'Stocks' is a term adopted in this study to aggregate all commercial, recreational and industrial demand within a sub-catchment.

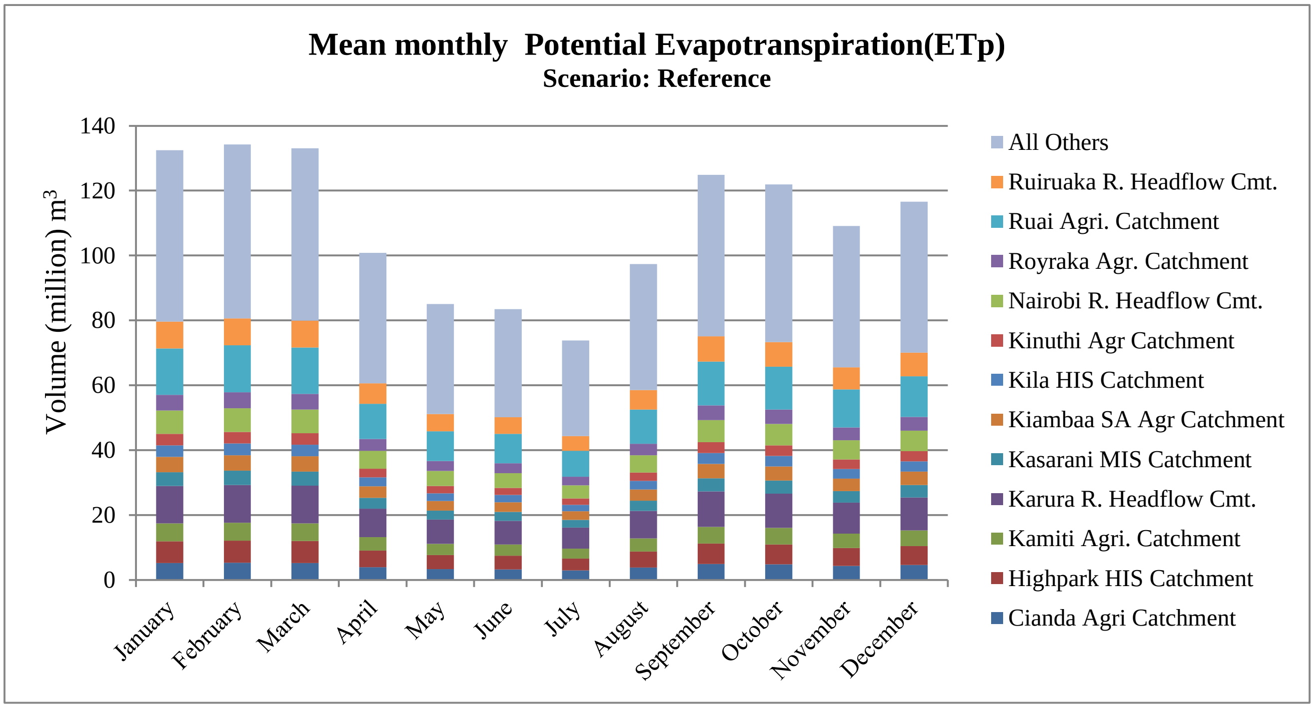

Figure 43: Simulated mean monthly crop potential evapotranspiration demand for the catchment

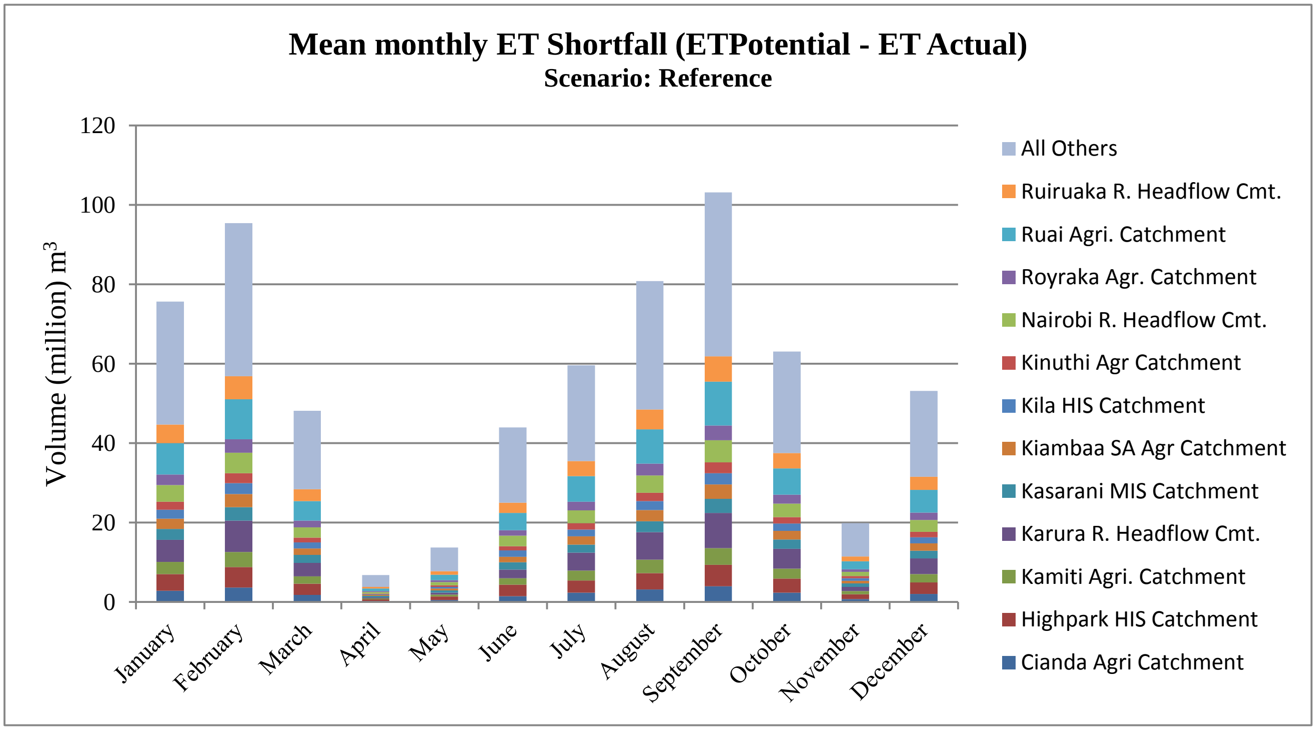

Figure 42: Simulated mean monthly shortfall in potential evapotranspiration demand for the catchment

Since in the reference scenario irrigation is accorded a lower priority to other catchment demand, it accordingly constitutes the lion share of the unmet catchment water demand. To evaluate the actual share of evapotranspiration provided for in the catchment combined mean monthly water demand, WEAP multiplies the residual evapotranspiration amount (ET shortfall) with the ratio of precipitation to 'effective precipitation' (88%), which equals to 1.136 in this case. This yields the remaining amount that would have been supplied through irrigation if adequate supplies were available, which added to the amount available for irrigation yields the total shortfall in precipitation or otherwise irrigation demand. That is:

$$\textbf{Supply Requirement} = \textbf{Irrigation demand}$$

$$\textbf{Irrigation demand} = (\textbf{ET shortfall}) * \left({}^{\mathbf{1}}/_{(\textbf{Irrigation fraction})}\right) + (\textbf{Irrigation supplied})$$

Adopted from the Mabia method discussed in the earlier section of this study, where sub-catchments are termed as hydrological unit and the supply requirement for a catchment where irrigation is considered is a summation of individual HU supply requirements (Sieber, 2011).

$$\textbf{Supply Requirement}_{\mathbf{LC,I}} = \left({}^{\mathbf{1}}/_{(\textbf{Irrigation fraction})_{\mathbf{LC,I}}}\right) * \ \textbf{PrecipShortfall}_{\mathbf{LC,I}}$$

$$\textbf{Supply Requirement}_{\mathbf{HU}} = \sum \mathbf{LC, I}\ \textbf{Supply requirement}_{\mathbf{LC,I}}$$

Adaptation to water scarcity and the recent appreciation of the need to sustain the ecosystem, has presently led to adoption of river basin oriented management with a three tier water allocation system in order of priority, starting with water reserve for basic human needs and environment; reserve for productive uses to promote social welfare; and finally reserve for productive uses in commercial agriculture and urban developments. Considering decision to manage water on the basis of river basins is a political choice, river basin becomes the scale of governance in which tensions arise between effectiveness, participation and legitimacy (Blomquist & Schlager, 2005). To appease the diversity of competing values, livelihoods and economic interest, all depending on the same hydrological cycle, and for the system to be socially acceptable, societal actors and other stakeholders must be given a voice and be encouraged to participate in determining water entitlements.

This study appreciate the ongoing departure from the previous trend, which has been transfer of water from nature to agriculture and from agriculture to urban uses, making nature the ultimate loser (Molle & Berkoff, 2006). Accordingly, irrigation has been allotted the last priority, as is typical in other water scarce areas, the catchment total mean monthly unmet water demand graph (see Figure 44) is typical of the catchment water demand graph albeit with minimal reduction in quantities. Household and "Stocks' demands, in order of priority and contingent to available supply, may be fully met but they have marginal effect on the overall unmet catchment demand. Considering the assumption adopted in this catchment disregarding aquifer storage at the beginning of the study and providing only 10% recharge from precipitation, ground water resources supply was insignificant in serving the catchment irrigation demand.

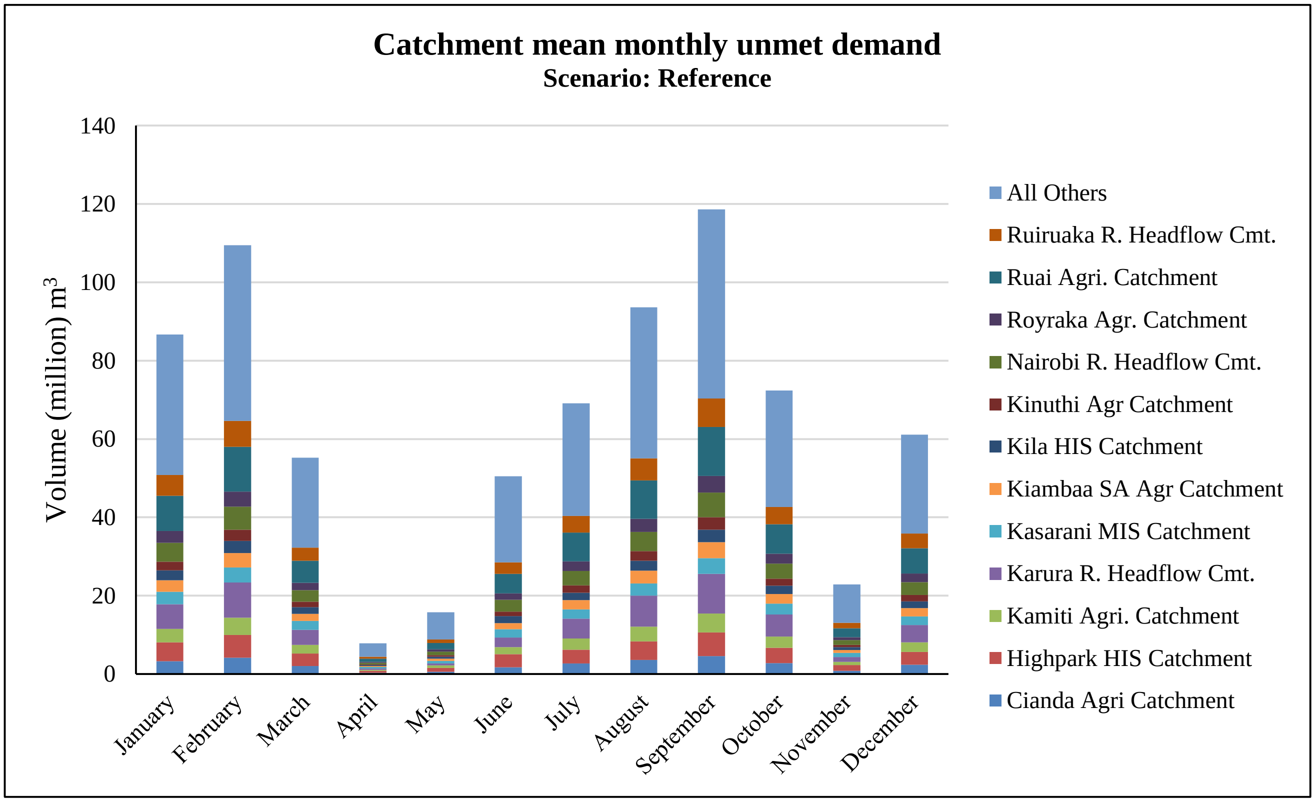

Figure 44: Illustration of the combined mean monthly unmet catchment water demand

In the reference scenario, the catchment supply requirement is also similar to catchment demand since no supply management measures like loss or reuse and/or demand management measures are considered. Thus, to appreciate the prevailing exploitation of catchment water resources to satisfy catchment demand and water transfers (if any), the supply delivered graph (see Figure 45) demonstrate how the available water is allocated among various catchment demands. It is rather appreciable that the lion share of the available water resources is allocated to catchment house hold demand due to the superior priority over other demand nodes as illustrated in Figure 46 and Figure 47 below. WEAP uses linear programming approach in allocating water to various nodes according to their priority.

Since the model uses monthly time steps, it implies that a particular quantity of water is abstracted by a given demand site located upstream of the catchment, from a given source i.e. a stream, ground water or other supplies source (which may represent imported water or water from a desalination plant); the water passes through a transmission link where any loss in transit is accounted for and a given quantity is delivered to the demand site. Any amount lost from the system through embodiment to demand site product is accounted for as loss from the system and the remainder is routed back to the stream or ground water source, either through a water treatment plant or directly as raw effluent. The return flow is instantaneously available to any other demand site downstream that requires it and by the end of the month residue amount exit the system at the last node of the catchment.

To ensure that demand nodes with higher priority to the modeller but which lay downstream of the catchment are accorded the precedence in water allocation, the demand sites with lower priority but located upstream of the catchment are accorded respective rank, and the model will allocate water to them with due consideration of satisfaction of the higher priority demand sites first, regardless of their location. This is to ensure that if adequate water is available for the demand site with higher priority in the catchment, its satisfaction is not affected by losses in lower priority demand sites located upstream if they were to be allocated similar or higher demand priority. This is why Eastland household demand is fully met (see Figure 50) while the Kinuthi household demand located along the same stream at an upstream position is not covered fully.

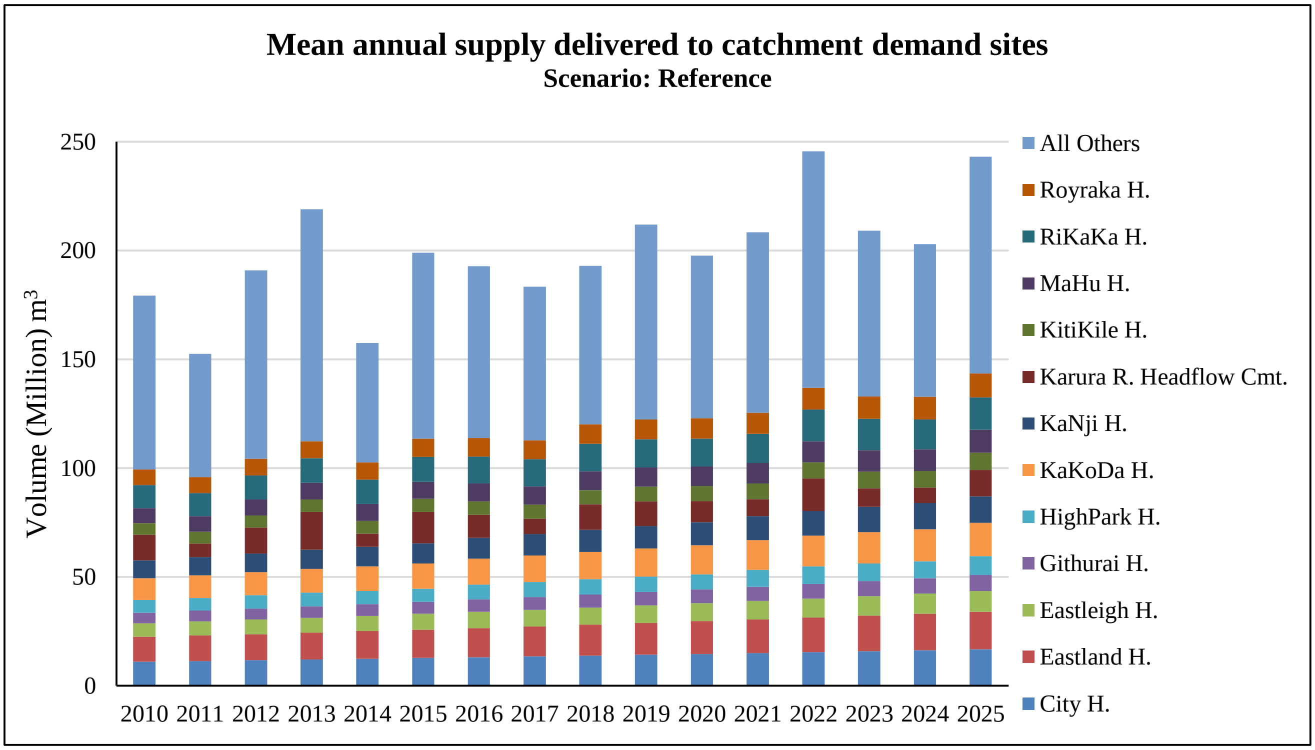

Figure 45: Supply delivered to Nairobi River catchment household demand

When reuse of water is considered as in reference scenario here, WEAP's linear programming approach in water allocation allows the demand site located downstream to have advantage of getting full coverage even when they have lower priority than some other demand sites in the upstream that may not have been fully covered. This happens when there are, as in this case, many demand sites with equal priority at upstream, which then get equal precedence in water allocation and therefore with scarce resources may not be fully covered; but they all rout their return flow back into the stream and the same is available to downstream demand sites, which may therefore have advantage of more water availability and therefore full coverage of their demand. These two case are best illustrated by Figure 50 and Figure 51 here below, where Eastland livestock demand is fully covered but Kikuyu household demand is not fully covered due to water scarcity in the sub-catchment shared by many demand site with equal priority in the upstream zone, which rout their return flow back to Nairobi River and the same is available for use by Eastland livestock demand site located further downstream.

It can also be illustrated (see Figure 46 and Figure 47) that in absence of demand side management measures (DSM), household water demand increases proportionally with population growth from the first to the last year of scenario. This information would help the water managers and societal actors to deliberate and formulate policies to increase water supply and/or proportionally lower the demand activity rate, to ensure progressive increase in demand coverage for the catchment from the current scenario into the projected future. In this case the, with the Nairobi catchment already experiencing closure

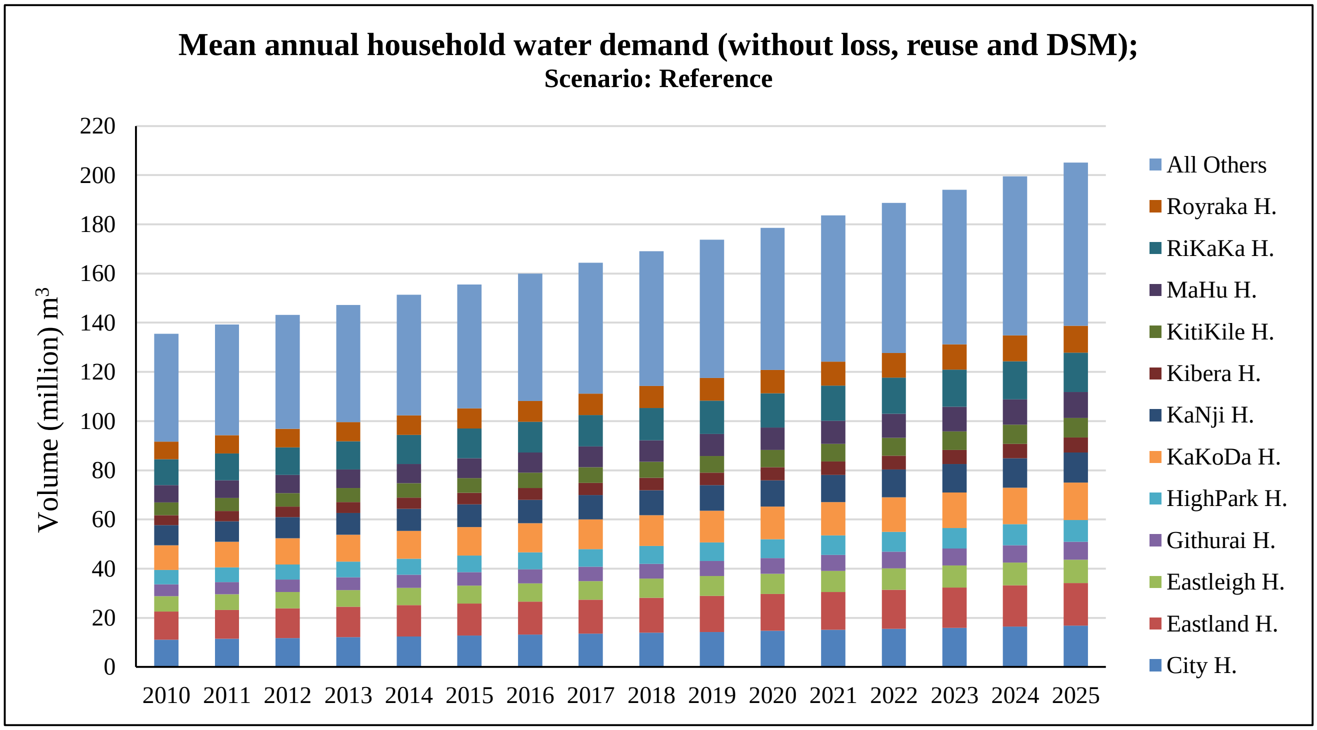

Figure 46: Illustration of increasing Household demand as population continue to grow at current rate

This being an urban catchment where household and commercial demands are interrelated, they were both allotted equally first priority. In this case, the modeller is obliged to evaluate and to provide for their adequate coverage in consistence with the available resources and due consideration of other economic and social obligation. The commercial demand is allocated high priority since it covers both the social, institutional administrative and economic welfare in urban development, which has huge implication on the ability to provide for other societal good and services. Accordingly, Nairobi city, adjacent industrial area (Viwandani) and

(Eastleigh) a business district in the neighbourhood have been classified as commercial districts for the purpose of this study.

Inter-basin transfers, as practised in the study area, can enhance the absolute water supply to the river basin by taking water from 'surplus[6]' to deficit basins (Berkoff, 2003). Due to the high importance attached to Nairobi catchment (50% of National GDP is generated within the area (Rural Focus, 2011)), huge amount of water resources (approx. 90% of the entire household and 'stock' demand) from the adjacent Tana River basin are imported daily and distributed within the catchment with clear bias on ensuring the prime demand sites are covered before other legitimate demand sites are considered. It is therefore important to maintain a coordinated statistical database on expansion of the commercial districts demand activities and to provide for integrated management policies to ensure the prevailing trend is consistent with catchment resource availability and sustainability, as they pose direct impact on resources development, exploitation and also on the sustainability of other legitimate enterprise with lower priority in catchment water allocations.

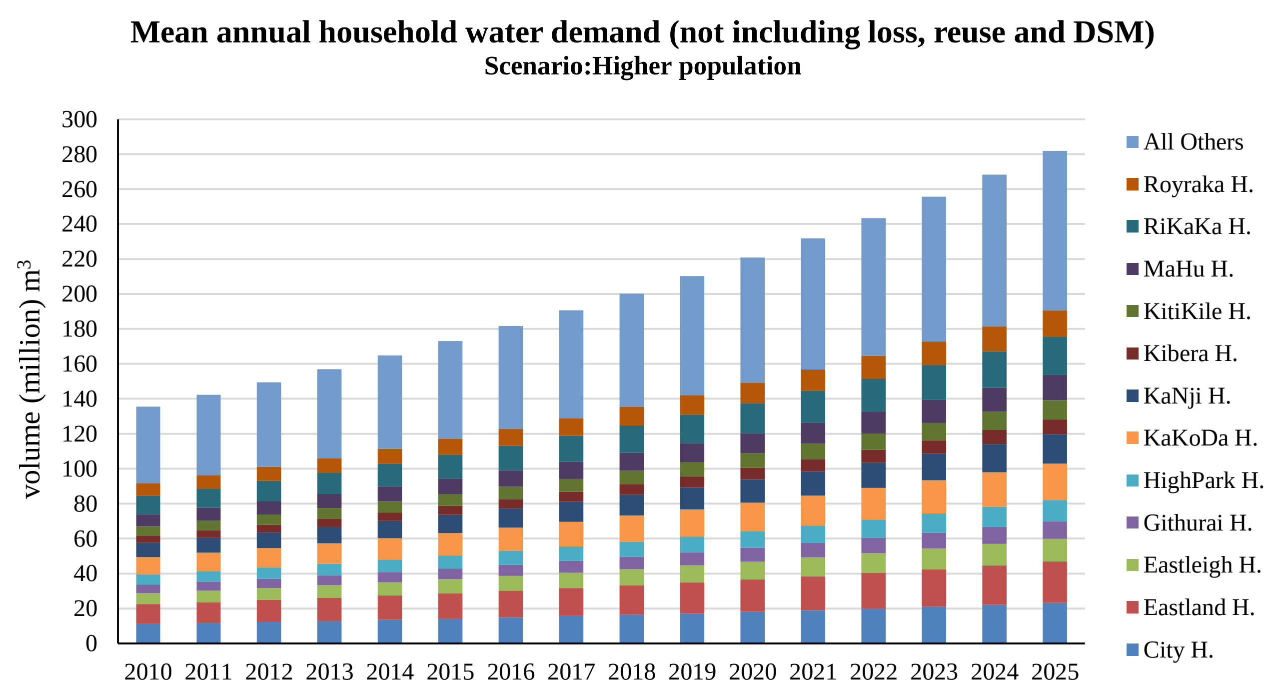

Figure 47: Illustration of corresponding increase in exploitation of catchment supplies by household demand as population grows at double the current rate

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[6] In the world of rapid basin closure, it is increasingly rare that existing flows are surplus to the full range of ecological as well as human requirements at the full basin level (Molle, et al., 2010).

Given that currently the database on existing good and services industries and manufacturing enterprises is not coordinated to include their character, size, level of activity i.e. estimated water consumption; waste generation and its related treatment and/or raw disposal; future projected expansion; and technology dynamics; this posed a critical hurdle in evaluating their current and future impacts on catchment water resources development, use and management for a pragmatic planning purposes. Therefore the activity levels adopted for related demand sites in this study are lumped estimated figures, which can be improved or reduced with availability of hard data amassment. In the study, water allocation to irrigated agriculture has been accorded a universal lower priority, yet the sector employs the bulk of the working population in the case study area.

Agriculture is still the backbone of most industries and service enterprises in this catchment, which is typical of most developing countries. Thus with the increasingly erratic climate and a rapidly growing population, both of which poses a great challenge to the majority peasant farmers, the demand for more dynamic strategies to ensure food security and tame rising rural and urban poverty have been escalating. In the future allocation to irrigation could be prioritized in some sub-catchment; implying need for management policies to ensure demand sites use water more efficiently or reorganisation of current infrastructure to ease pressure on the already overstretched resources. This approach would also ensure moderation and consistency between the key social and economic interests within the case study area, which would mitigate future conflict between farmers and municipal water services providers.

A feasible approach appreciated in light of the huge quantity of water imported into the area, which in practise is discarded as waste water in the water treatment plants in the lowermost extreme of the case study area and therefore not available for reuse by other demand site, is to consider the economic costs and benefits of making this water available to more demand sites. In the reference scenario this has been envisaged by ensuring all demand site rout their return flow to a node on the nearest stream point, which has ensured downstream demand sites have better chance than exist in the current system.

The assumption had little effect on the calibration of the system, since the area above the stream gauges considered is currently not connected to the sewer network. Most households depend on septic tanks and improved latrines where most of the water either evaporate, percolate to recharge ground water or compose interflows that recharge the stream. Worse still is the situation within a few poor urban settlement districts, where riparian zones in exploited and raw sewage is routed directly into the river or wetlands. Thus the system as calibrated was by and large authentic in light of the scenarios and when only the mass balance equation is considered. One of the recommendations from just concluded National Water Master Plan 2030 (MEWNR, 2013), which could be converged with water reuse, was to construct reservoirs from large and small dams and water pans at strategic locations upstream of select streams to impound water during floods for use in subsequent intermittently long dry seasons.

The planning of the large dams as shown in (appendix Figure 70) is to ensure they are located in zones posing minimum evaporation loss and where sedimentation rate is not at impeding rate. But this has the potential of lowering the capacity of the respective storage due to a reduced area of the catchment generating flow. This is evident in this study as 10% of the flow from precipitation in a few upstream catchment that is apportioned to groundwater, is not sufficient to supply respective sub-catchments demand sites. Hence the need to factor in water reuse, not only to augment inflows, but also to ensure consistent inflows throughout the year. This could be effected through establishment of the economic efficacy of constructing a series of reservoirs to impound heavily silted flood water, which could be used to generate energy in the first instance, and allowed to settle in the subsequent reservoir.

The generated energy could then be applied in pumping the supernatant water mixed with accumulated clear fully treated effluent from the water treatments plant's retention basins back for storage in the reservoirs upstream, increasing water availability in the catchment. Conversely, two systems can be maintained where treated water is not routed back to the reservoir, but to upstream infiltration basins to recharge ground water resources, which has similar effect on catchment resources availability.

To evaluate the efficacy and sustainability of prevailing policies on water resource development, allocation, use, management and conservation, illustrations of the current level and future trend of satisfaction of key demand sites within the catchment was studied. The satisfaction of household demand illustrated by Figure 48 is a critical testament to a catchment's chronic water scarcity. Since households have a higher priority and have to be satisfied first before other legitimate demands are allocated water, the failure in their demand coverage implies water is unavailable for other important ventures. This information is vital to location of the spatially moveable demand sites which can be relocated downstream to benefit from return flows from other demand sites if the basin is not experiencing closure[7]. Growth in population without any management measures in place to control demand and/or increase supplies has the same proportional effect on unmet demand as on the catchment demand (see Figure 49).

Through this illustration water managers would be able to reason with the society actors and other stakeholders on measures that need to be adopted, both from the societal actors' side e.g. measures to tame rapid population growth and accountability in water usage efficiency, and also from the experts side in crafting acceptable policies to implement integrated management measures to impact on both supply and demand for the resource as to ensure water balance within the catchment.

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[7] Closure occurs when the supply of water within a particular basin falls short of commitments to fulfil demand in terms of water quality and quantity within the basin and at the river mouth, for part or all of the year (Molle, et al., 2010).

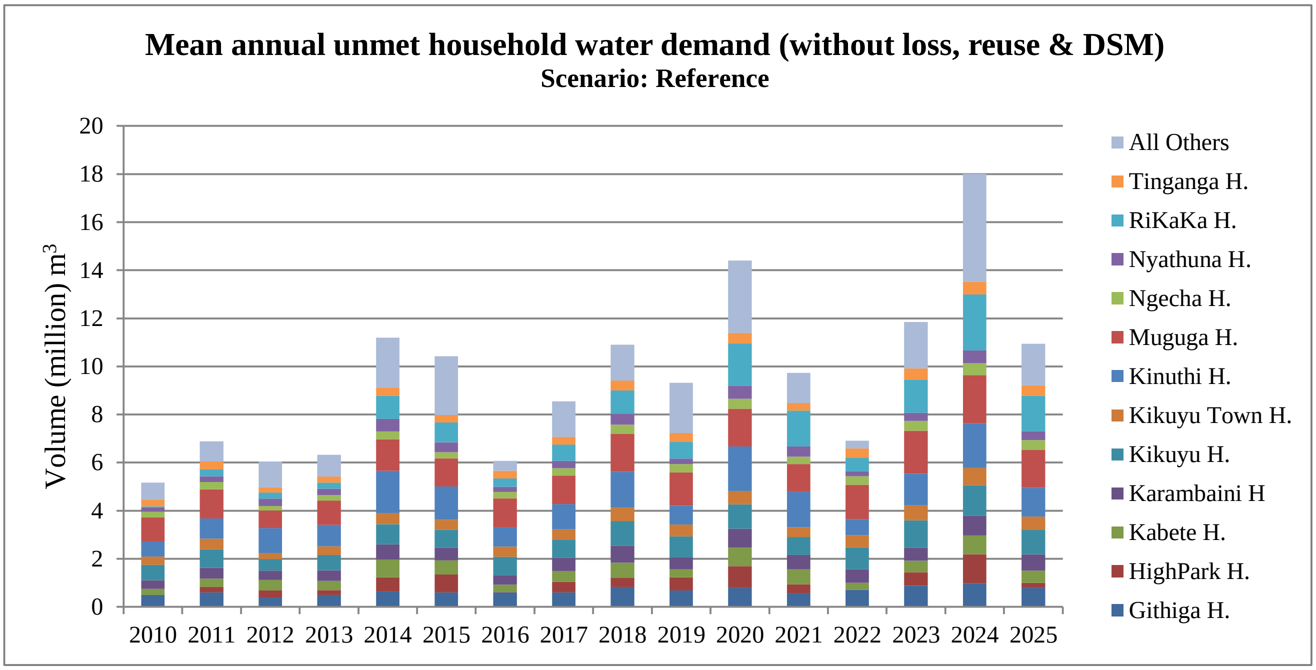

Figure 48: 'Business as usual' trend in unmet household demand within Nairobi River catchment

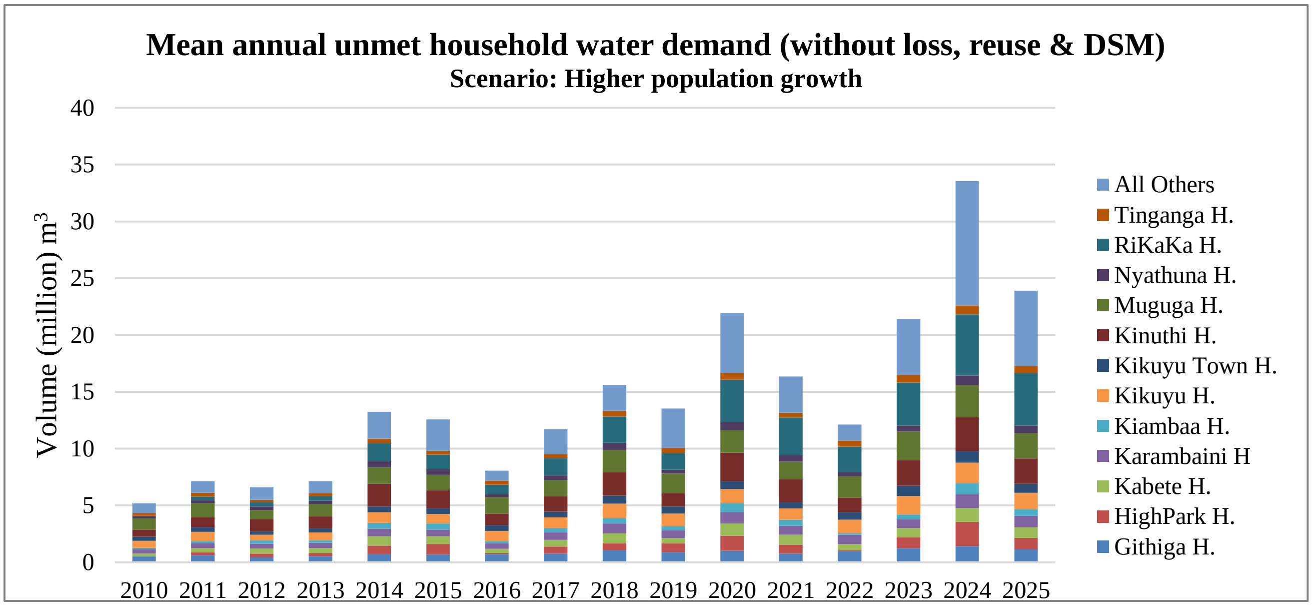

Figure 49: Effect of higher population growth on household demand in the Nairobi River catchment

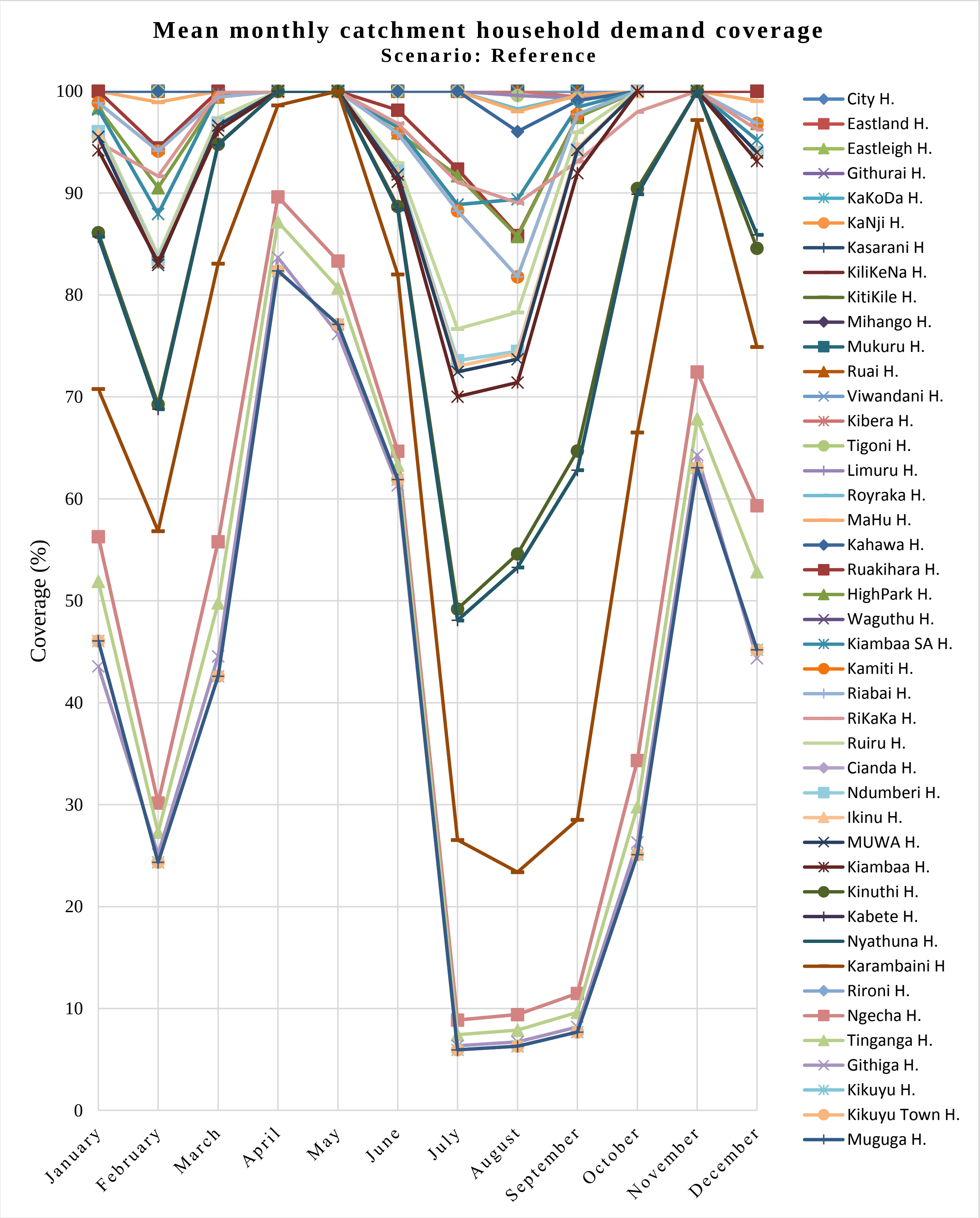

Figure 50: Demand coverage for household demand in the catchment

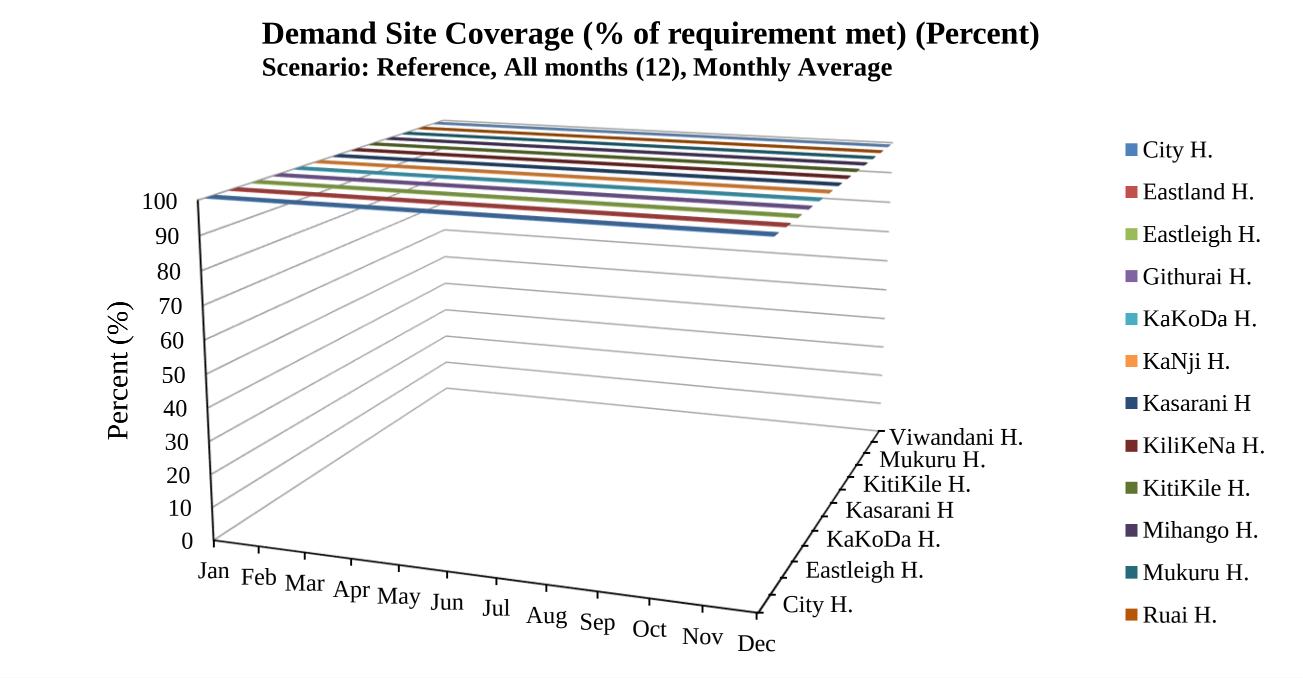

Figure 52: Full coverage for a section of household demand in the catchment

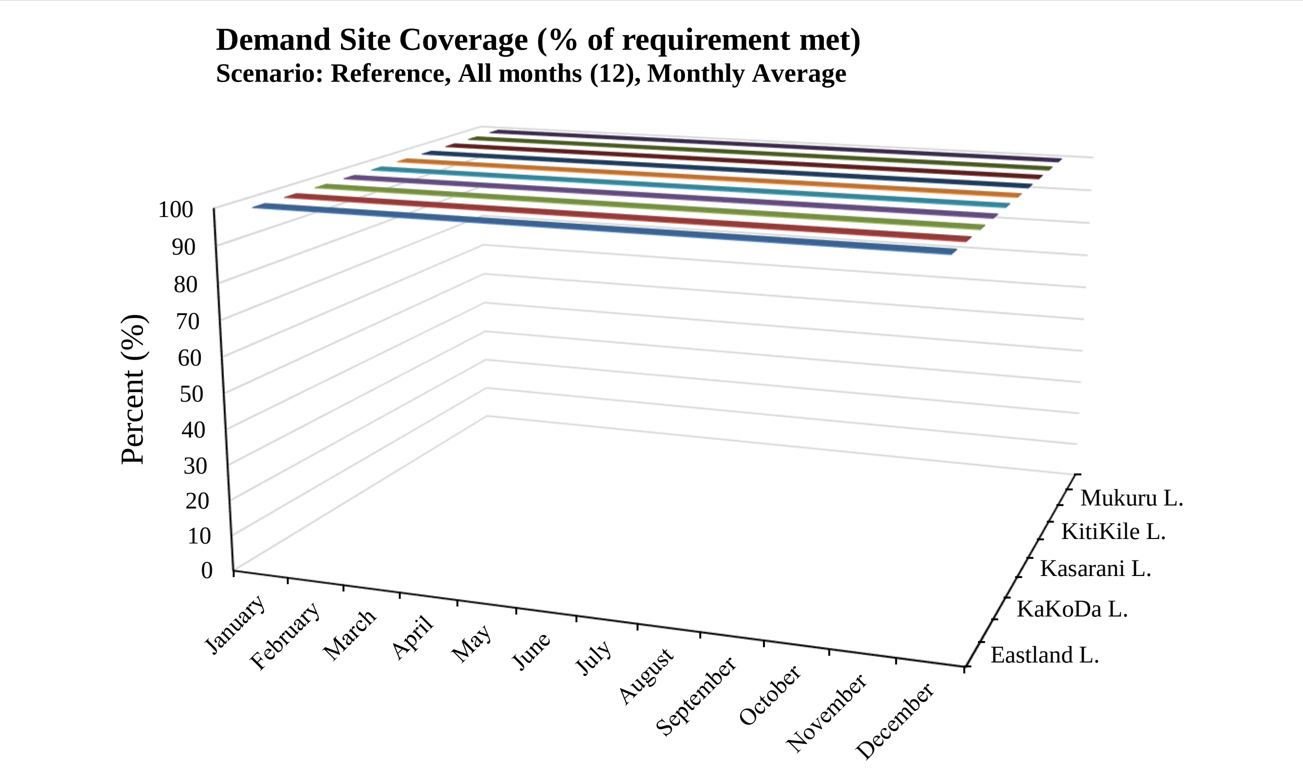

Figure 51: Full coverage for a section of Livestock demand sites within in the catchment

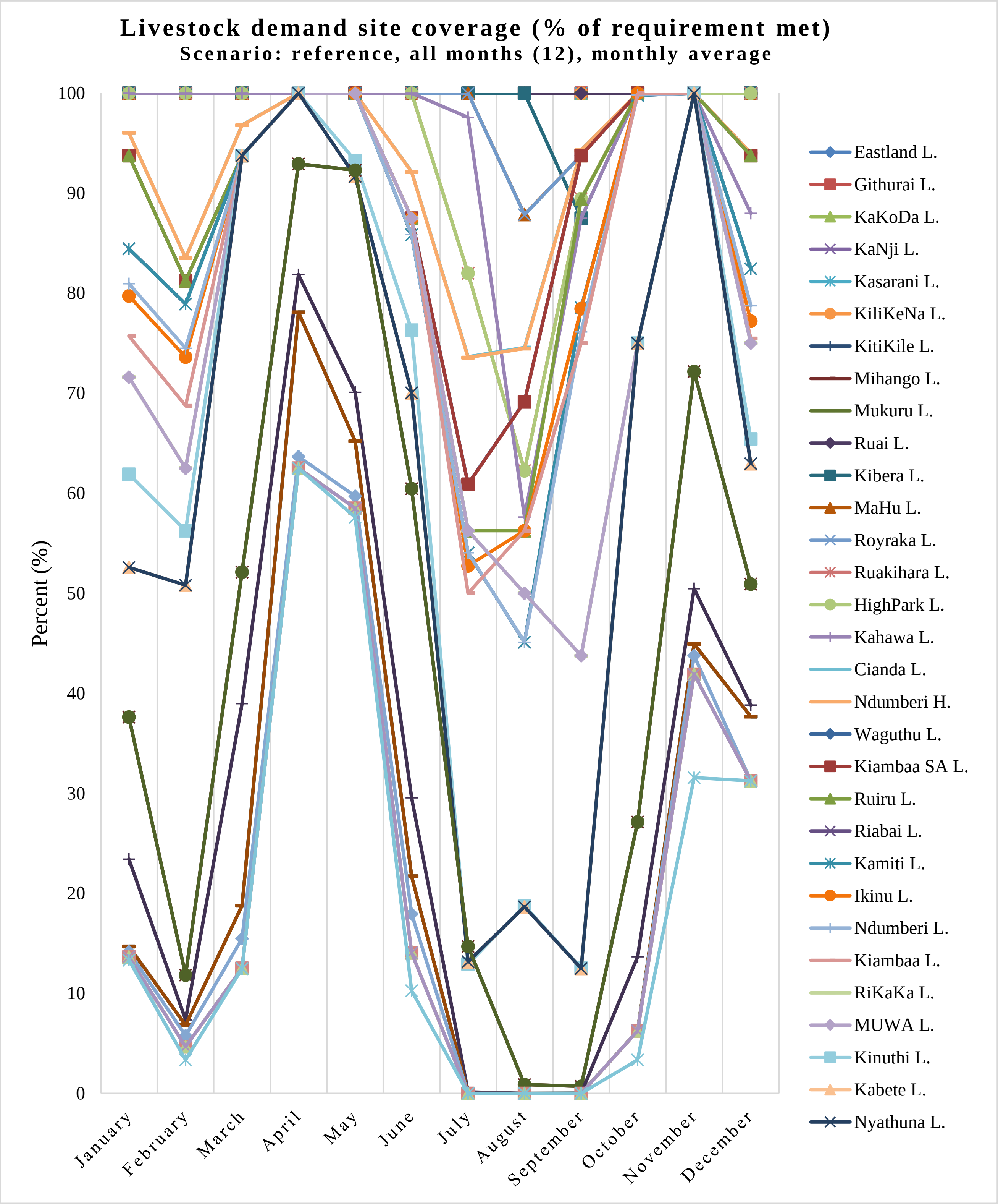

Figure 53: Coverage for Livestock demand sites within the catchment

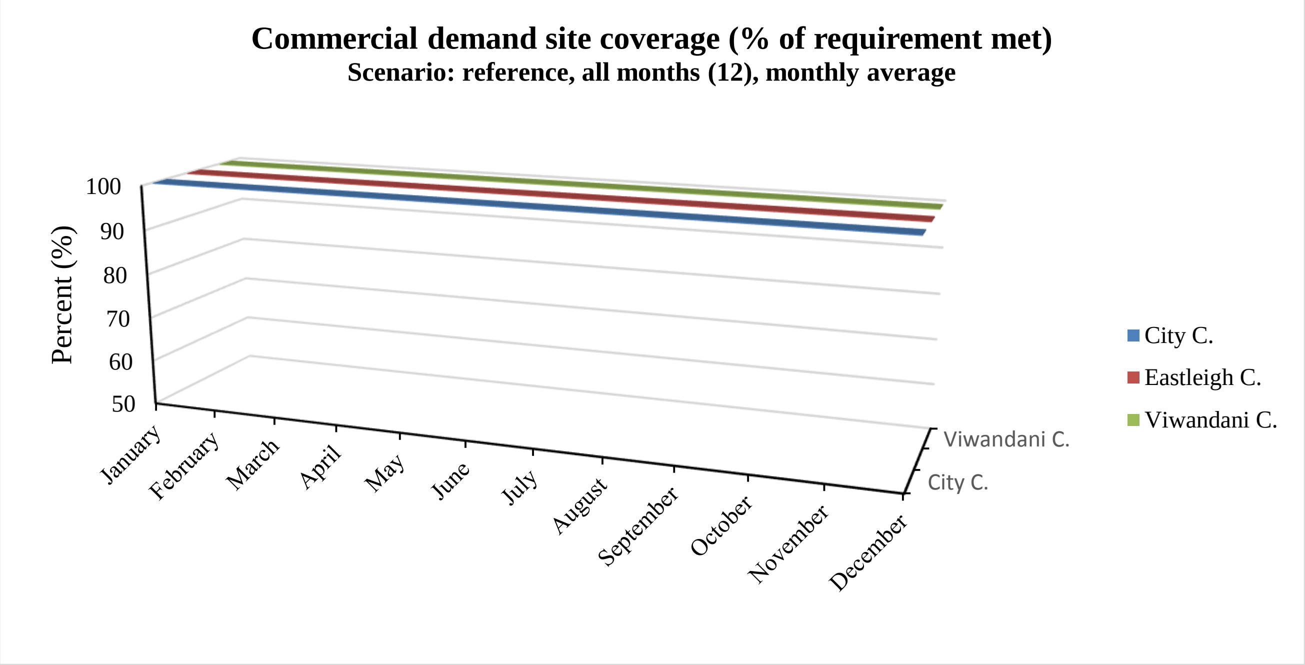

Figure 54: Coverage for designated commercial demand sites within the catchment

By representing the individual demand sites coverage as show in Figure 50 - Figure 54 above, it is possible to assess the capacity of various sources as to apportion them to various demand sites according to respective priority. As hereby illustrated some livestock demands have been fully covered while adjacent household sites with higher priority facing low coverage. To alleviate this situation, other scenarios where reservoirs are added to the model, or increasing the number sources and/or controlling the activity rate through pricing, reuse etc. for the affected demand nodes would be among a few plausible solutions available. However supply and demand management measures have costs as discussed previously. Thus the efficacy of adopting any of them or an integrated approach should be founded on a cost-benefit analysis that is also integrated within WEAP.

From Figure 55 below it is appreciable that imported water resources from the adjacent TCA, represented by various Nairobi water distribution zones (identified with their geographical location), already constitutes (and are envisaged to continue delivering) the bulk of supply to all demand nodes, safe from irrigation, within the Nairobi city and it’s environ. The graph also illustrate the importance of the rivers in the catchment areas and project how even in the ‘business as usual’ scenario, they form a key resource for future catchment demand, though most are current in disuse due to human-induced pollution. Though in this study the model is set to demonstrate catchment water balance through a basically quantitative approach, and therefore the quality of water and the admissibility of any source to actually serve demand is assumed, this graph illicit vital future research questions on the economic benefit accruing from ongoing and potential intensification of catchment waste water disposal infrastructure, river rehabilitation and revitalisation and how the engagement would help contribute to catchment water demand solution in the near future.

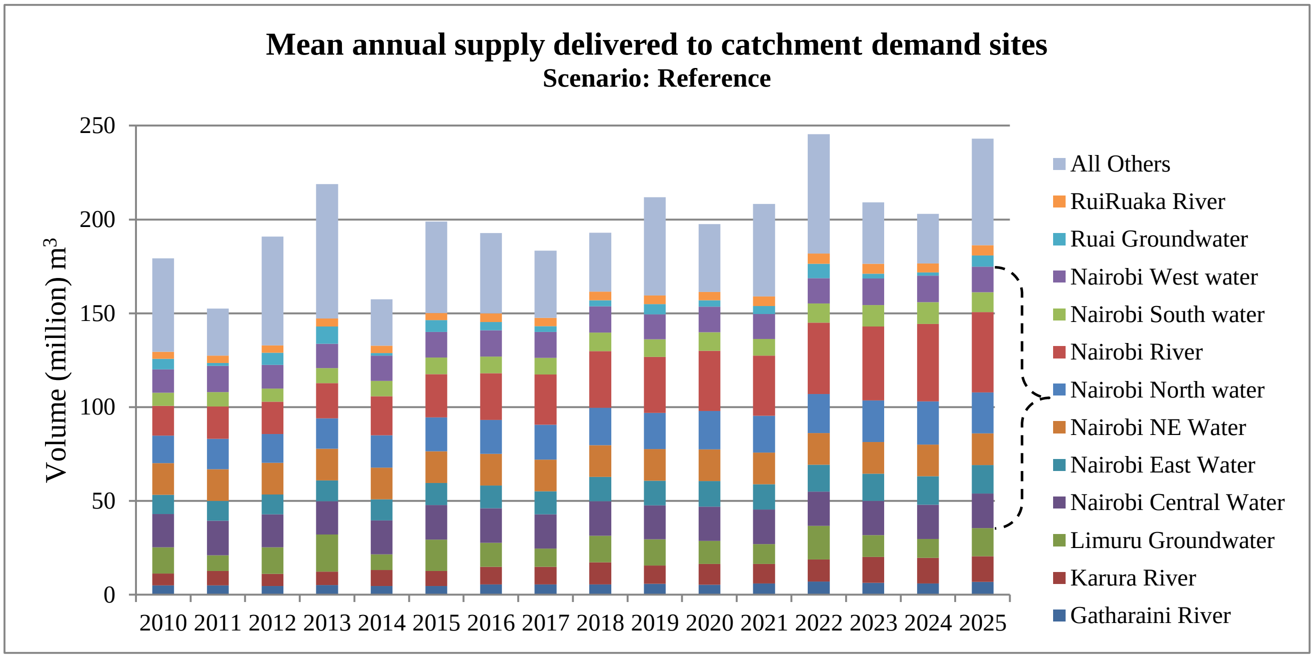

Figure 55: Illustration of the major supply sources for the catchment and their respective share

As previously expounded, the head flow sub-catchments were delineated to represent zones that generates head flow for the respective Nairobi River tributaries and were thereby labelled accordingly. They were essentially modelled as agriculture catchment with irrigation factored in to augment respective precipitation supply to meet potential crop evapotranspiration. Therefore head flow catchment water demand represents the balance between potential and actual crop evapotranspiration multiplied by inverse of the irrigation fraction (1.136 in this case), and then adding the available irrigation supply to get the total supply requirement that should be met through irrigation. However, irrigation demand has lower priority than other catchment demands and considering the catchment is under chronic closure i.e. water footprint within the catchment exceed the available resources (van Oel, et al., 2011), irrigation demand is therefore largely unmet and is captured in the catchment's unmet demand (see Figure 56 here below).

The same case applies to agricultural catchments (see Figure 57 below) where the shortfall between the recorded precipitation and the simulated catchment potential crop evapotranspiration constitute the major portion of respective catchment demand, which is apportioned lower priority among other water footprints within the sub-catchments and therefore remains largely unmet. This approach, more so considering the aggregation of crop evapotranspiration demand generate extremely magnified irrigation demand situation. In more pragmatic scenario irrigation would only be considered in simulation of cultivated agriculture cropped areas and generally ignored in simulation of sub-catchments under natural vegetation (e.g. forests, grasslands etc) unlike the generalised practice adopted in this case study. This approach has been adopted in this case to bridge the gap elicited by absence of information on actual acreage of various crops in spatial and temporal terms within the catchment annually; and also to simplify a rather tedious exercise of disaggregating various agricultural demand sites, which would have precipitated the need to apportion different Kc values to characterize diverse crops impacts on evapotranspiration.

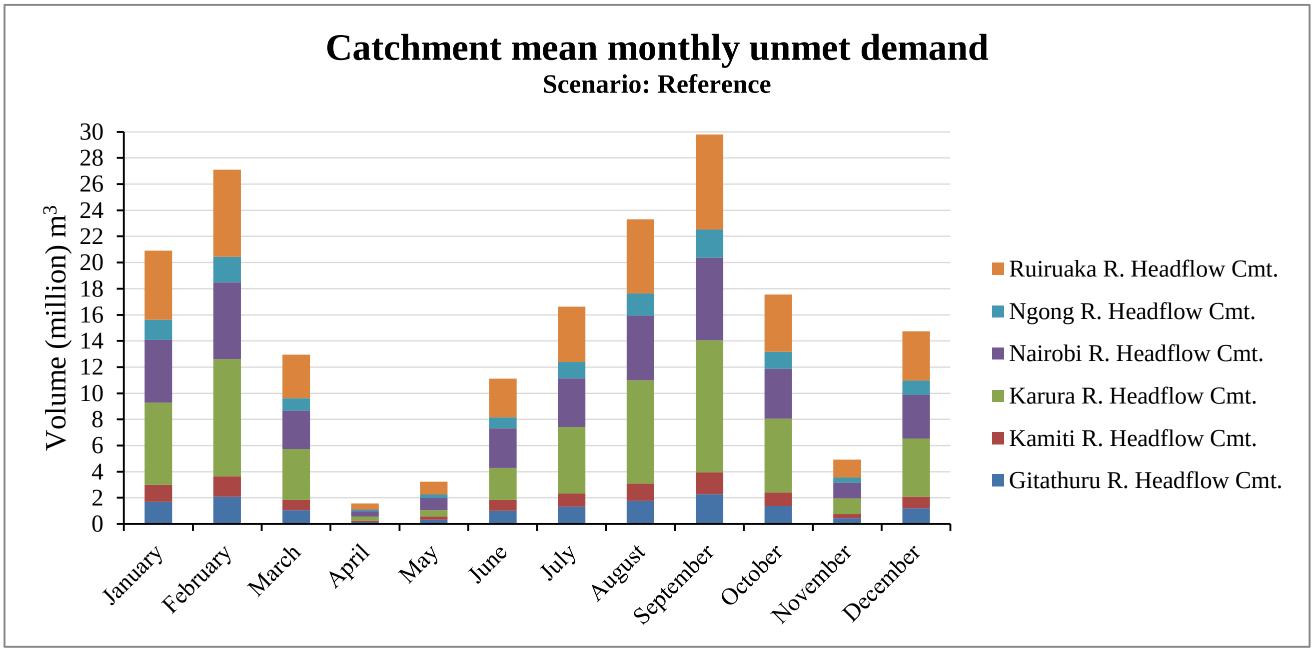

Figure 56: Mean monthly headflow catchments water demand

This approach would have been more pragmatic and precise in evaluating potential evapotranspiration, but was considered superfluous to the scope of this study which is confined to generating a methodology for exploiting the available data series in catchment scale modelling for logical but progressively adaptive and collaborative decision support process. In any case, the available data presented by the ministry of agriculture offices in both Nairobi and Kiambu counties exhibited major gaps and inconsistencies. In addition to the fact that data collection in the agriculture sector, mostly rainfed, is not oriented towards helping in water resources management, but on maintaining crop statistics in term of acreage, production and market prices at lumped up spatial and temporal context. It could therefore not be relied upon to capture the factual character of the catchment's cultivated crops, specific crop zoning or actual diversity in natural vegetation, which could use to facilitate comprehensive and precise vegetation water consumption assessments.

This could be explained from the nature, and thereupon, the orientation of the records, which are meant to evaluate general agriculture land usage and to link farmers with various markets by providing prices for respective products at different towns and markets. Pointedly, the data availed had reliable acreage estimate time series for major cultivated crops (Maize, beans, tea, coffee etc.) and related future projections, albeit in lumped up figures for districts within the counties (see appendix Table 33). This was the same case for major horticultural crops, especially those cultivated on established public and private irrigation schemes for local and international markets.

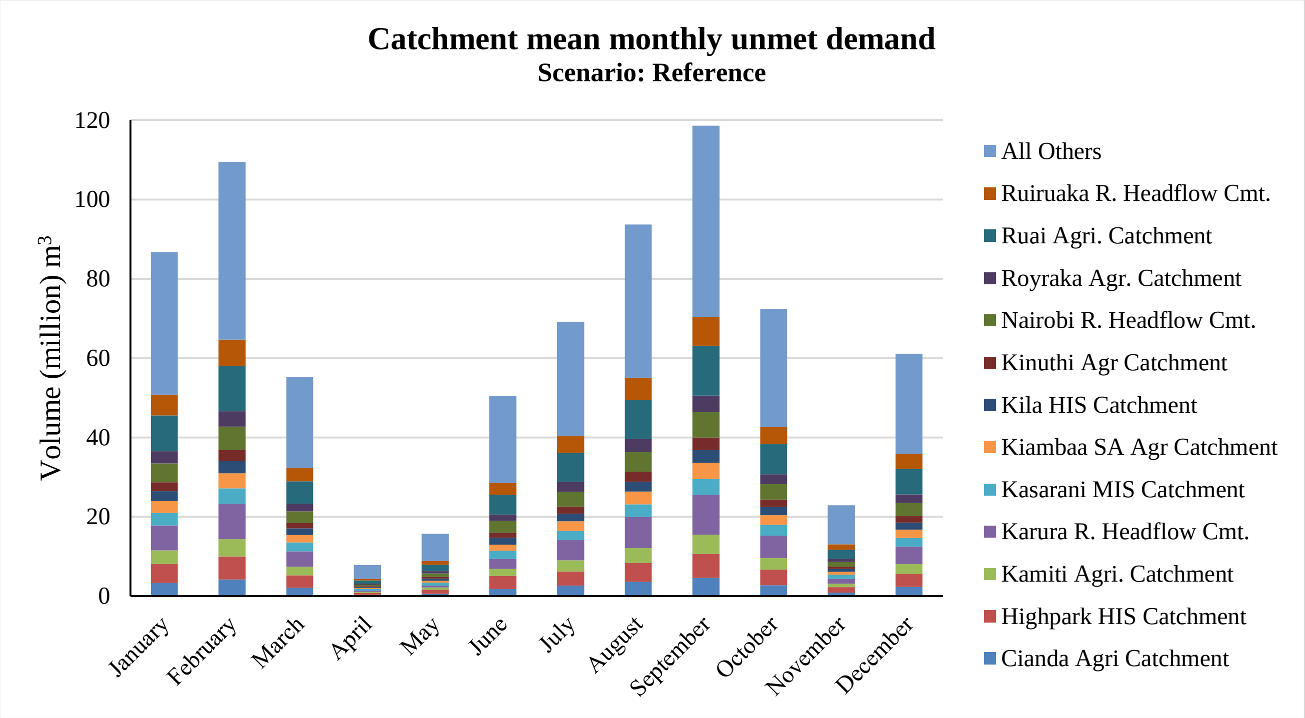

Figure 57: Mean monthly irrigation water demand with agricultural catchment

However, time series for the other crops that are rather temporally dynamic were either inconsistent or missing altogether. This include: data related to minor subsistence crops (potatoes, peas, sorghum, millets etc.) that are usually affected by crop rotation, zoning and seasonal weather dynamics; horticultural and vegetable crops cultivated through small scale irrigation schemes by peasant farmers in reclaimed wetlands, riparian zones and between major crops during extended rainy season; and perennial crops (e.g. Mangoes, pawpaw, oranges, lemon etc.) that are sparsely planted in agricultural land making it difficult to ascertain their actual coverage. On the other hand, the available land use and land cover GIS data were too general to meaningfully bridge the gaps in details provided by the ministry of agriculture.

The main challenge to availability of catchment data management infrastructure and a well-coordinated database at the time of this study could be rooted on the conflict of interests as a result of amorphous fragmentation of responsibilities between government ministries, departments and authorities mandated with natural resources management. For instance, Forestry and Wildlife departments being separately in-charge of diverse ranked habitats meant that records related to forests in national parks and game reserves as well as wildlife in the conserved forest habitats could not be coordinated without due collaboration network linking the two departments.

Similarly, National Environment Management Authority (NEMA), Water Resources Management Authority (WRMA) and Kenya Meteorological Department (KMD) all rely on related data and data infrastructure, but were considered independent, with no binding obligations to ensure collective mandates are achieved through collaboration and networking. This represented a major break in an important loop that could ensure optimal performance of their individual and collective mandates and optimal usage of public finance by avoiding the duplication of data collection infrastructure through synchronising databases for easy correlation and authentication; while also enriching collective capacity to deliver individual mandates by maintenance of reliable feedback lines that would also serve to curb the bureaucracy involved in obtaining crucial data and information from across department's databases.

It was therefore determined in the interest of this study, an average crop coefficient (Kc) representing a simulated representative crop bearing the average canopy characteristic of the listed catchment crops and covering the entire catchment would suffice. It is worthy to note that disaggregation of the catchment to sub-catchments in accordance to respective catchment general land use practices in this study, would have allowed for corresponding disaggregation of the catchment vegetation to reflect the actual diverse sub-catchments vegetation characteristic for a more precise crop potential evapotranspiration assessments. This evidently would have resulted in steep decline of catchment residual evapotranspiration (irrigation demand), as irrigation would not be factored in catchment under rainfed agriculture, as is predominantly the case in the case study area; and also in forests and naturally vegetated sub-catchments; predominantly built-up settlement zones; industrial areas; and in some commercial districts where irrigated landscaping is not practiced.

All the same, the assumption adopted in this case study was considered admissible to the scope of the study and the exaggerated water demand/supply requirement could be managed without undermining the important deductions relevant to the study objective. The graphs (Figure 42 and Figure 43) illustrate the simulated mean monthly catchment crop evapotranspiration demand, which is mainly a characteristic of catchment climate and crop effect on crop water consumption (Allen, et al., 1998); and evapotranspiration shortfall, which is the balance between potential evapotranspiration (ETp) and actual evapotranspiration (ETa). The later represent the achieved crop evapotranspiration provided by 'effective catchment precipitation' and, for irrigated an irrigated catchment, the irrigation supply further increases the actual evapotranspiration. To calculate the evapotranspiration shortfall for a catchment, irrigation supply multiplied with the factor representing 'irrigated fraction' i.e. factor representing the fraction of the applied irrigation supply that is actually available for crop evapotranspiration, is subtracted from ETp together with ETa.

Chapter 7. **Formulation of a Methodology to an Adaptive Collaborative DSS**

7.1 **Introduction**

Adaptive water management provide the system's flexi-function in the ability to offer appreciable solutions and functionality within the prevailing socio-economic, cultural and technical constraint especially the related data inadequacy in developing countries; while providing ample room for progressive learning, innovation and implementation. Collaborative management on the other hand entails deliberate system inclusivity through promotion of roundtable decision making process featuring experts, water and land users, and other interested societal actors and sectors stakeholders. The system is designed to proffer a friendly seamless interface between experts and societal actors (implementers) at the field, through shared learning in system conception, design, analysis, evaluation, consensus building, policy formulation and implementation at local (water users) level. Conventionally, experts have restricted deliberations and decision making amongst themselves, leading to lack of social acceptability and support of some policies at implementation stage. The new approach is in concurrence with the other research findings that 'shared learning has potential to empower local people and strengthen their participation in adaptive collaborative management' (Kamau & Kimberly, 2014).

IWRM has been appreciated as a wide range of approaches to manage water and related resources – a meta-approach or meta-concept, as it were, which both transcends the various levels of decision making and recognizes the importance of integrating decision making at each level. In watershed management the need for a close integration of land and water management activities with upstream and downstream considerations is imperative. Reflecting these key features, the World Bank has defined watershed management as ''the integrated use of land, vegetation and water in a geographically discrete drainage area for the benefit of its residents, with the objective of protecting or conserving the hydrologic services which the watershed provides and of reducing or avoiding negative downstream or groundwater impacts''. Combining the measures of the three management approaches, results in a favourable resources management paradigm where ''adaptive, multilevel, collaborative governance arrangements'' are entrenched and currently appreciated as the best able to deal with the complexities of issues that arise at the basin level (Lenton, et al., 2011).

Notably, the World Summit for Sustainable Development in Johannesburg (WSSD, 2002) arrived at a related consensus, stating that ''the river basin should be used as the basic unit for integrating management.'' This involves management of a range of resources, including soil, crops; forests, livestock systems, and water in the form of overland flow, streams, and soil moisture. The goals are usually economic, social, and environmental in nature, and relate both to communities in the upstream (principally the increase in productivity and income levels) and to downstream (chiefly flood management and drought mitigation). Therefore, the instruments involved in watershed management usually involve a combination of institutional, socio-economic, and environmental measures (Lenton, et al., 2011). However, for the system to be socially acceptable, stakeholders must be given a voice and be encouraged to participate in determining resource entitlements (Berkoff, 2003).

7.2 Setting- up or Re-alignment of the Institutional Structure

Experience proves that countries starting to reform their water sectors first focus on the preparation of policies, laws and regulations. These pave the way for the institutional set-up, definition of institutional roles and the development of capacities to take on these roles (Hübschen, 2011). It is assumed that the new management instruments and capabilities needed to manage water resources in an integrated manner can only be developed within the essential institutions. It can thus be argued that the enabling environment and institutional roles form a precondition for the implementation of management instruments in the sense of IWRM (see Figure 63). These management instruments include the operational instruments for effective regulation, allocation, monitoring and enforcement that enable decision-makers in the institutions in collaboration with the societal actors as well as other interested stakeholders to make informed choices between alternative actions.

However, in the Comprehensive Assessment of water management in agriculture (CA, 2008), IWMI and GWP notes that in developing countries, what is usually passed-off in the name of IWRM has tended to have a very narrow blueprint package focused essentially on:

- National water policy,
- A water law and regulatory framework,
- Recognition of the river basin as the unit of planning and management,
- Treating water as an economic good, and
- Participatory management

Although these measures represents a shift in paradigm, the vagueness of the entailed requirements only allows the existing institutions to rebrand themselves and continue with their business as usual, thus making IWRM initiatives ineffective or counterproductive. All the same, creation or restructuring of institutions to meet a particular requirement helps reduce uncertainty and enhance the predictability of rational human behaviour by structuring actions. As such, institutions help to equilibrate claims and preferences of bargaining actors, if they provide all individuals involved with the needed information as well as a cost scheme for compliance and non-compliance (Hanisch, 2004).

In light of these considerations, in formulating a methodology to an effective adaptive collaborative decision support system for watershed management, primary consideration is to facilitate a good institutional structure especially in guiding data collection, correlation, coordination, storage and management. This encompasses:

- The means, mode, sequence and related intra- and extra-institutional collaborations in data collection correlation and coordinating both in temporal and spatial scale. This approach is guided by the fact that water is a common pool resources amenable to sharing between multiple uses and users and data informed trade-offs are paramount to mitigation of allocation related contestations and conflicts.
- A data processing approach that factor propensity of social-cultural, economic and environmental rationale to change, and is therefore adaptive to progressive improvement of the system from the onset

where fundamental assumptions could be adopted to bridge the gaps availed by data and technical inadequacy, until such a time when precise time series data is availed to the system.

- Proactive engagement of catchment water users in organised regular discourses on all aspects from conception, design, and formulation to policy implementation.

The institutional structure foster clear collaboration networks for data flow and information dissemination; feedbacks and systematic solutions communication both vertically and horizontally. It clearly outline both the individual and collective mandate and responsibilities of various sectoral institutions in water resources data collection, correlation, coordination, processing, database management, information dissemination, feedback analysis and related attendance and policies and regulations implementation at various levels. The formulation and networking of the institutions should be informed by the demand for efficiency in service delivery, and the need to facilitate viable decision support framework for, among other processes, water allocations for social equity, economic viability, environmental sustainability and water balance within the particular catchments (see Figure 62 and Figure 63 here below).

With the formulation of the national water policy in Kenya (MoWI, 1999) and Water Act 2002 (Leg., Ass., 2003), the water resources management institutional structure has already been put in place, but their collective and individual performance has been mired by: amorphous fragmentation, ineffective networking for coordination and collaboration; inadequate funding and ambiguous assignment of individual and collective mandates that often ignore corresponding resource requirement and the implicit and explicit interdependencies between various institutions for effective performance. Moreover, most of the new institutions have been set-up with major consideration being to fulfil the requirements of the national water policy and the Water Act, without adequate capacity building to apprise the employees and sector players on their specific duties and expected performance deliverables. Consequent to the malfunctions of both the implied and essential interdependencies between water and land management institutions as a result of the fuzzy institutional networking, it is currently a daunting task to appraise individual performance and/or benefits accredited to establishment a specific institution.

Therefore the accountability of individual institutions is compromised mainly due to bureaucracy encountered while procuring vital data and other resources from government departments and independent institutions. On the other hand, implementation of the policy setting-up community based groups such as Water Resources Users Association (WRUA) has not been accompanied by adequate capacity building and financing to enable catchment water resources users clearly understand their roles and responsibilities, and to muster the clout to influence society behaviour toward water resources. To achieve the required credibility, legitimacy and influence, there is need to appreciate water allocation and trans-disciplinary engagements as political processes. Even the decision to manage water on the basis of river basins is a political choice and river basin thus becomes the scale of governance in which tensions arise between effectiveness, participation and legitimacy (Blomquist & Schlager, 2005).

Therefore local culture, public administration and political interests should be considered both in cultivating a proactive discourse in decision making process for sustainable and equitable catchment water allocations and developing collectively acceptable water resources development and management policies (Kulkarni, 2010). The community-based organisation's capacity should be boosted through capacity building and inclusivity to play their rightful role in forecasting and mitigating water allocation conflicts rather than arbitration centred agenda in catchment water management.

To facilitate this study, 20 years' time series of climatic data was procured from Kenya Meteorological Department (KMD), while hydrological data (essentially streamflow) were in parts obtained from the Ministry of Environment Water and Natural Resources (MEWNR) (data centre), and Water Resources Management Authority (WRMA), with the later also facilitating the gathering of water use data from catchment water service providers. Detailed agro-hydrological data was expected from Ministry of Agriculture (MoA), but the data obtained from her two relevant counties data centres was mainly biased to cropping and market statistics. The lumped data on actual acreage and seasonal variations for different crop and their respective market prices in various towns is only meant for use in economic models to evaluate counties food security and helping farmers get the better income. The available data in its current form has to be manipulated with assumptions based on background information to be of use in water balancing model.

MoA is mandated with ensuring favourable farming environment for socio-economic purposes and national food security, by supporting farmers with improved farm technology, capacity building, information on crops choices and zoning, and best farming methods for optimal production. To achieve this mandate, close collaboration with ministry of water through Water Resources Management Authority, Meteorological Department and National Environmental Management Authority is implied though not explicitly required. This system poses a great hurdle in coordination and correlation of data collection between the two sectors, with real collaboration taking place intermittently and only during crisis. Considering the interdependence between the two ministries in their individual and collective mandates, the need for cross-ministerial data linkages and coordination cannot be overstated. However, to ensure accountability within the unfamiliar institutional manifestation, policy formulated to govern these inter-departmental collaborations would have to cross the traditional jurisdictional and institutional boundaries, which is workable challenge only complicated by the increased number of actors (Radin & S., 1996).

With IWRM strive for an integration of water, land and related resources, institutional structure need to attend to the concerns on how an integration of the responsible institutions, which are often entangled in power struggles, can be reached without jeopardising the two tenets of accountability i.e. answerability on individual performance and responsiveness in adopting essential changes (Weber, 1999). The Ministry in-charge of water resources, which is responsible for implementing IWRM-strategy require, for instance, some jurisdiction over relevant data collected and maintained by interrelated institutions such as agriculture and meteorological department. But considering the "intense inter- and intra-ministerial rivalries over mandates that have always been present in many countries" (Biswas, 2004), the feasibility of an integrated development, allocation, use, and management of water resources continue to be compromised. The major contestations rest on the fact that actions striving for IWRM often have low priority because different groups have biased opinions to a given problem; often perceiving it to be someone else's problem or responsibility (Kennedy, 2009).

Trans-disciplinary participation in resources management is an approach that entails cross disciplinary engagement with common goal setting; with involvement of both academic (researchers) participants and non-academic (societal actors such as policy makers, representatives of administration or interest groups, locals or the broader public) participants in developing new social and scientific knowledge and theory (Narayanan, 2011). Adopting this approach in inter- and intra-ministerial and public discourses would persuade other stakeholders like the ministry of agriculture to appreciate the need for a more comprehensive agricultural land use and land cover data, more so with spatial and temporal scales, that could be adopted within a model to help evaluate various crops water resources consumption and catchment's overall agriculture water balance. Other than aiding IWRM efforts, this data would allow simulations of various crop choices and farming methods within the catchment as to help farmers and other stakeholders appreciate the opportunity cost of every choice and therefore arrive at optimal trade-offs, between short-term costs and long-term gains. Especially with regards to crop choices, zoning and farming methods that are both socially acceptable and economically efficient in water use.

7.3 Determining and Delineating the Appropriate Scale of Catchment for the Model

The approach used in this study to delineate the Nairobi River catchment, and which seems quite pragmatic for recommendation in modelling typical catchments, is informed by (among others references) the Global Water Partnership Technical Committee lessons from integrated water resources management in practice (GWP, 2009). Among the key lessons drawn from practical experiences with IWRM include:

a) Water management must ensure that the interests of the diverse stakeholders who use and impact on water resources are taken into account. Stakeholders should be engaged in the entire policy dialogue and implementation, recognizing their divergent opinions, potential conflicts and the need for tools to mitigate and resolve conflicts.
b) Adaptive collaborative management approaches to water-resources management will keep on evolving as the pressures on the resource and social priorities change. The challenge is to support the development of institutions and infrastructure that can meet the challenges of new circumstances.
c) Water-resource planning and management must be linked to a country's overall sustainable development strategy and public administration framework;

That is, as much as modelling of a catchment along its closed hydrological boundaries would be the best approach, water development and management and especially water allocation is heavily influenced by the area social and political processes and interests. Therefore engagement of water users and other stakeholders should be moderated with calculated acknowledgement of catchment hydrological confines, geographical and public administration boundaries to avoid collision of interests and potential impediments in IWRM implementation. Also the adopted policies should primarily comply with the existing national master plan on water development to strengthen the existing institutional structure and yield adaptive collaborative systems.

d) Whereas the river basin is an important and useful spatial scale at which to manage water, the importance of stakeholders' participation is central to IWRM approach, and therefore it is vital that water resource allocation decisions are taken at the lowest appropriate level.

Accordingly, there are often circumstances where it is appropriate to work at smaller sub-catchment (hydrological unit) scale. This is especially important when modelling catchments within the developing countries where there exist a vast number of small-stakeholders, making engagement for real participation of stakeholders and consensus building very complex and time consuming. It is more pragmatic to subdivide the river basin into a number of successively smaller hydrological units which can be classified according to respective size in geographic area representation (Seaber, et al., 1994) see Figure 58 below. A Regional unit, also referred to as a catchment area or basin, is a geographical area based on surface topography, which represents an inland basin comprised of a network of streams draining into one or several constituent inland Lakes; a Lake basin with its network of feeder streams or a major river drainage system with its network of tributaries from source to its coastal outlet (e.g. Athi River CA).

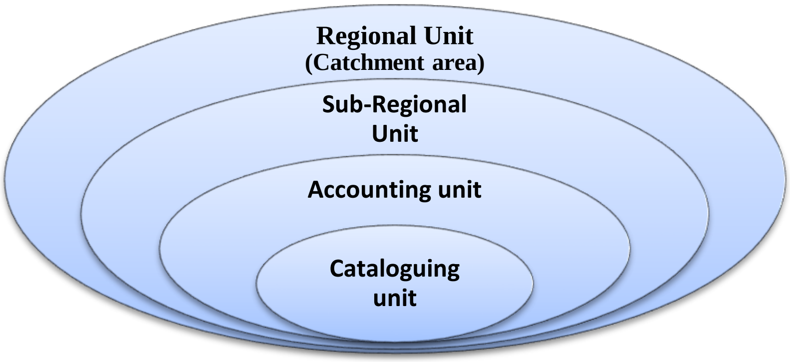

Figure 58: Hierachy of hydrologic units shown on Hydrologic Maps adopted from (Seaber, et al., 1994)/ (MEWNR, 2013)

The Catchment Area is then sub-divided to several sub-regional units, which depending on geographical area may encompass the area drained by a closed basin (e.g. a Lake basin within an inland catchment area), rivers and their network of tributaries within a reach of the main catchment river, or a group of streams forming a coastal drainage area (Seaber, et al., 1994). The sub-region, as is the case in the case study area, can serve as the data collection centre where collection and coordination, correlation, documentation and dissemination of field raw data is administered and where detailed raw data (i.e. metadata) is stored so that the users of the data can access the details about how the data was gathered and any processing manipulation carried out on the data. Diligent execution of a sub-region office mandate is therefore vital in configuring the basis for planning, design and management of the catchment area and national water resources data network.

Consequently, for effective water development and management the relevant water resources administration institutions, technical staff, data management technology and infrastructure should be cascaded and seamlessly coordinated from national level to at least this level. Thus the sub-regional offices fashions and manages interactions between experts and community stakeholders represented by the water resources users' association committee members. It is therefore the institutional foundation for water resources management policy formulation, and the launch pad for all sector policy implementation and regulations enforcement. It coordinates water developments, evaluations, issuances and documentations of water allocation permits at the local scale.

The sub-regions are subdivided into accounting units which are essentially the lowest level in the hierarchy of hydrologic units with respect to water resources data consolidation and coordination. An accounting unit (AU) is a geographical area representing part of, or an entire upstream river catchment (Nairobi River catchment); a combination of several river catchments, which are part of the reach of a major river or a distinct hydrological feature (Seaber, et al., 1994) and (MEWNR, 2013). It mainly represent a geographical area where water users depend on same resources and therefore their water use pattern impacts directly on each other, while they also have to observe the environmental base flow besides the requirement for downstream demand. These units are used by water resources management authority as the foundation for water resources data acquisition and coordination; platforms for facilitating local users' capacity building and information dissemination for water allocation and efficient use within the local community and industries (see Figure 60 here below). The boundaries of an accounting unit is delineated to encompass the entire area drained by the river and, where necessary, could also be manipulated to represent the totality of local users interests. This is because in most cases hydrological boundaries are not consistent with the local public administration boundaries, whereas residents are served by the same resource.

The lowest hydrologic unit in the hierarchy is the cataloguing unit, which represent a geographical area that constitutes the head flow catchment of a river, a part or an entire reach of a river, where local users' main water use and pattern of use can be ascertained and classified either through demography, economic activity, land use or land cover. It is the smallest hydrologic unit where statistical data on land and water resources, water demand and water use pattern are generated and assimilated within a water planning or balancing model etc. It therefore serves as the basis for simulation and evaluation of the impacts of the prevailing water resources situation and existing water management policies and regulations on water allocations, demand satisfaction and systems' sustainability. Subsequently it is the basis for data collection on various demand nodes water requirement and their related time variations, water management policy formulation on water allocation trade-offs to conflicting or competing uses and also the smallest unit that can be administered by a community water resources user association (WRUA). For seamless data coordination from the cataloguing unit to the national level, the hydrological units are identified by a unique mixture of numeric and alphabetic codes in an orderly consistent manner.

In the case study zone, the cataloguing units are yet to be official delineated and distinctly identified, thus the modeller has to delineate them subjectively within an accounting unit of interest. Presently the accounting unit constitute the basis of hydrological data management, with each bearing a unique code blend from a digit and two alphabets. The first code (numeric) represents a catchment area (Regional unit); with Kenya having been divided into six distinct catchment areas as discussed previously, and the additional two unique consistently blend alphabetic codes represent a specific accounting unit.

Athi catchment area is comprised of five (5) sub-regions which are correspondingly comprised of varied number of accounting units (AUs); that is upper Athi sub-region (4 AUs); middle Athi sub-region (7 AUs); Nolturesh-Lumi sub-region (1AU); Coastal Athi sub-region (16 AUs) and Nairobi sub-region (4AUs) as shown in Figure 59 below. The case study area, Nairobi River and its tributary system within two accounting units No. 3BA and 3BB, constitutes the upstream river catchment of the larger Athi River drainage basin and cut across Nairobi and Upper Athi sub-regions presented in the Figure 59 here below.

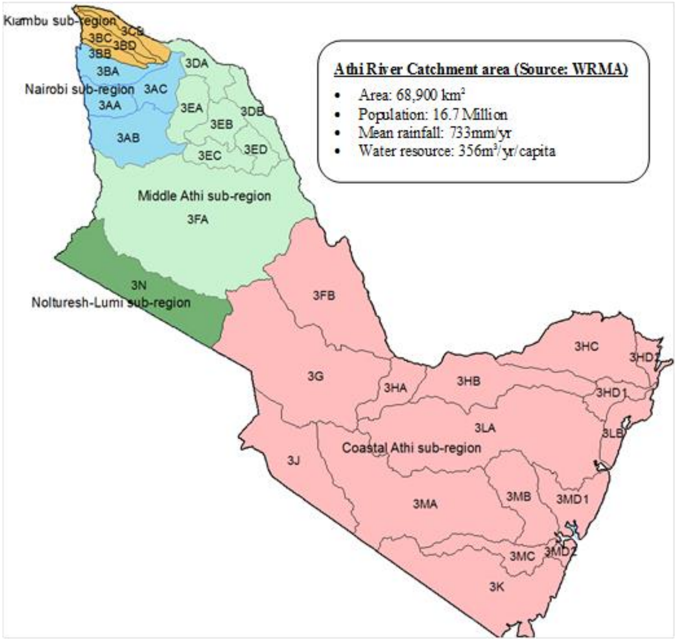

Figure 59: The hydrologic units within Athi River Catchment area

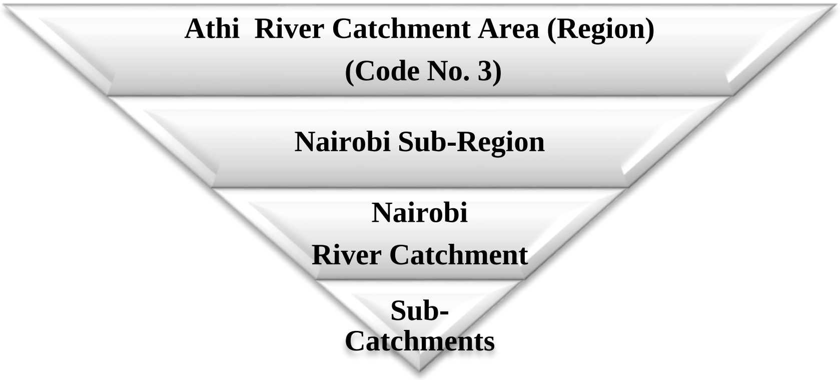

Figure 60: Hierachy of hydrologic units for Water resources Management (MEWNR, 2013)

Therefore in this case, regions and sub-regions do not represent consistently larger hydrologic unit, but are essentially institutional management levels charged with complementary responsibility in data collection, correlation, coordination and management and respectively with policy and regulations implementation. A sub-region office administers one or more accounting units depending on geographical extent, hydrologic subsidiarity or complementarity of the drainage system, and complexity due to number of small scale stakeholders involved that is often a factor of population density and socioeconomic impacts.

While basin boundaries provide a useful way of delimiting the supply side of the water balance equation, they are not necessarily the best means to integrate the demand side, especially since basin boundaries usually do not coincide with political or administrative boundaries. To effectively integrate natural and human systems, other levels beyond the basin are therefore generally required. For instance in the current study, the case study area essentially encompassed two accounting units, but the actual modelled extent was adaptably expanded to include strips of the adjacent area that were complementary to both local water supply and demand interests. This approach was informed by the fact that local interests are driven to a large extent by local political needs, which in a large extent also inform the public administration boundaries and impact indisputable influence on water resources allocation and management.

The following two principles as espoused by Ostrom (Ostrom, 1992) as pre-requisites for organizations design for effective management of common pool resources like water were considered in this study:

- Clearly defined boundaries, in order to know what is being managed and for whom (in addition to closing the boundaries to exclude non-members from usage, supported by rules limiting use and/or mandating provision (as in the case for urban poor), especially in cases of water scarcity;
- Including most individuals affected by the operational rules into the group that can modify these rules in collective-choice arrangements, to enable the organization to better tailor the rules to the local circumstances;

Consequently, on imperative areas the model delineation was so aligned as to ensure a public administration unit partially falling within the catchment area was either adopted or omitted in totality. The sub-catchment were also grouped into various classes depending on local economic activity and majority resident status i.e. agricultural catchment, high-income/middle-income/low-income settlement, commercial zone catchment. This classification allow allocation of water in the model to be tailored to the local realities.

In light of these considerations, the modelled catchment should generally be delineated in such a way that both supply-oriented and demand-oriented key components are incorporated in their entirety, noting that whereas water resources supply is related to hydrological and anthropogenic processes of water transportation, water demand processes are to a big extent influenced by political interests especially in water allocations to various local and external interests and/or corresponding financial allocation to facilitate water transfer to meet the demand shortfall. In this study the hydrological confine of the Nairobi River catchment was first delineated and then the subsidiary areas, especially in demand perspective, were considered to ensure water resource allocation decisions at the lowest appropriate level were practically representative.

7.4 Setting-up a Database within the Model Decision Support GUI Framework or other GUI Platform

Once a model is developed it can be operated from other Graphical User Interfaces (GUIs) or within a DSS (Jensen, 2013). For a decision support model operating on its own GUI framework there is an added advantage especially in leveraging flexibility in capacity required to model increasingly complex catchments and socio-economic systems. GUIs allow storage and representation of all the relevant spatial-temporal, qualitative and quantitative data through representative schema availed by a decision support tool and/or assimilation of the collected data and information that can be uploaded in vector or raster forms, after relevant pre-processing and geo-referencing using GIS software.

Control over GUI framework also allows the developer a lee way to promptly attend to users' feedbacks through progressive unimpeded updates on the capacity, gaps and efficiency of a DSS to process increasingly complex model simulations (Jensen, 2013). Since memory requirement increases with the complexity of the model and the complexity of scenarios being simulated, modeller's operating system capacity could also be a limiting factor. However, some DSS allows the modeller to choose scenarios to be simulated at any given run and therefore reduce the task at hand, which enhances the capacity of processors to handle complex systems through separation of various scenarios under comparison and iterative simulations (Sieber, 2011).

Uploading of all the relevant information within the decision support framework, not only provides an information hub (database) for comprehensive and integrative system analysis, but also enhances modeller's and stakeholders' comprehension of the catchment water resources realities. Hence it provides a platform for launching stakeholders' discussions on the system and a point of reference in arbitration of water resources conflicts. Comprehensible depiction of a catchment water supply and demand network enriches the decision making process by triggering proactive deliberations by all stakeholders regarding current and potential future water resources development, allocations and use in the catchment. Their opinion on various causes and effects and proposed changes that could be incorporated to make the current system economically viable, socially equitable and environmentally sustainable facilitates formulation of unanimously acceptable water management policies and strategies.

Moreover, the proactive participation of societal actors and other stakeholders in the decision making process facilitates the conceptualisation and design of DSS model in such a manner that accommodates majority's comprehension of the system and needs that should be addressed in performance of various forecasted and presumed scenario simulation. The subsequent analysis and evaluation of various potential options (different potential management strategies) to address the catchment management issues, would also follow an agreeable criteria leading to a consensus solution that is easy to implement. This is a vital approach in developing acceptable catchment management strategies for integrated management of catchments (DWAF, 2004).

However, it is also worthy to appreciate the reservations raised by other researchers like Bates (Bates, et al., 1993), who describes the trans-disciplinary approach in water resources management as a "Gordian Knot[8]". More recent findings shows that the meaningful involvement of the interests of every person or group that affects or is affected by a resource (e.g. watershed), even those separated by distance and time, combined with a requirement of consensus-based decision making, would actually cut the Gordian knot rather than pull it tighter. But there are still remain reservations on tangibility of the achievements in term of equity in resource allocation and the value of time needed to arrive at a broad consensus. This is due to the fact that affluent members of the society may still influence the consensus building and have their way in resource allocation. There is also uncertainty on how disputing citizens could challenge decisions made through collaborative efforts (Tarlock, 2000).

By and large, a broad understanding of the actual water resources situation and appreciation of prevailing and potential future impacts on quality of life for both human and environmental systems, as afforded by an effective DSS, would potentially arouse the required support for water allocation trade-offs, especially in water scarce areas to ensure allocation of water primarily to meet basic household demand and environmental reserves; and subsequent allocation be made priority-wise, starting with the demand site that offer greatest value to the society.

7.5 Data Collection, Correlation and Management

Good management of water resources should be based on an insight into the evolution of past water use, as well as an understanding of current demand and an awareness of possible future trends (Molle, 2003). Irrespective of the supply/demand-oriented approach on water resources management that is pursued, data on the available and abstracted water resources is imperative. Systematic and regular recording and control of water resources supply

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[8] "Gordian Knot" – a phrase used to describe an apparently insurmountable challenge (Fekete, 2011).

and demand trends facilitates the adjustment and alignment of the development and management of water resources to the dynamics social-cultural and environmental conditions. The success depends on the reliability and accuracy of the available gauging and monitoring systems. Failure to keep track of changes in actual status of the available and demanded water resources, compromises the evaluation of water resource allocations and efforts to strike a balance between social equity and economic efficiency on one hand and environmental reserve on the other.

One of the aims of regular data collection is to identify problematic areas and keep track of changes in local demand priorities in water allocation management. According to the (GWP, 2000), the development of an effective water resource knowledge base is an indispensable prerequisite for effective evaluation and balancing between its availability and quality against demand, pursuant to its efficient management. It is vital that this knowledge base also contains data on the variables that influence water demand, to pre-empt too optimistic or pessimistic predictions about the development and requirements for the water sector being made. This is because demand and supply measures undertaken in mitigation against future adverse effects have cost implications and therefore should be justified through precise economic evaluation against the opportunity cost of investing the resources elsewhere. Furthermore, information management system might be necessary to ensure that data and information are promptly made available to professionals, practitioners and the general public for effective usage and to encourage the implementation of IWRM-principles.

During this case study, concern has been raised regarding data inadequacy, data unreliability, bureaucracy and high cost of accessing the available data for analysis. The need to maintain detailed documentation of the data (metadata), so that the users of the data know the details about how the field data has been gathered and any manipulation carried out in the process has also been a touchy issue. The need to incorporate micro data sources especially for agriculture and water services have also been appreciated leading to the inclusion of data held by the irrigation districts and water services providers in water demand evaluation. This is because inadequacy or unavailability of the data on water consumption, especially with corresponding volumetric tier-pricing (step-pricing), has consistently made it difficult to understand users’ behaviour in response to increased water scarcity or water costs (Ayoo, et al., 2007).

To calculate the agricultural water demand, the engineering-agronomic approach was herein adopted; where water demand was determined using FAO Penman-Monteith formula (less comprehensive formulas could also apply depending on the data available) to calculate reference evapotranspiration, which is a factor of the climate (precipitation, temperature, relative humidity, sunshine, wind etc.), anthropogenic input (irrigation), soil type and system efficiency. The reference crop evapotranspiration is multiplied with crop coefficient for the vegetation (which is a factor of crop type), to get the potential crop evapotranspiration (PET). PET is the maximum amount of water drawn by a particular crop for optimal productivity in absence of the any limiting factor (Sieber & Purkey, 2011).

Some drawbacks of this approach are that the demand quantities achieved are lumped up; hence, disregarding zonal variability of climatic parameters even within the confines of a hydrologic unit. The output choices and investment are not modelled, so it only captures changes in water use at the intensive margin, rather than also considering how water use changes at the extensive margin through changes in land use. Considering that man is a rational being, a behaviour-target approach where farmers, either individually or within an irrigation district, are examined for their crop choices, inputs and irrigation methods as a function of output, market prices and preferences, would capture more reliable data for assessing both the current and future agriculture water consumption.

This is why some water planning models consider the individual behaviour of farmers, recognizing that farmers are heterogeneous and may use private information about their farm characteristics and practices to behave strategically. Additional benefit accrued from this type of modelling is the support in understanding policy feedbacks including the heterogeneous response of producers to policy variables as well as behaviour that influences the design of policy (Dridi, 2007). Market dynamics generally dictates farmers' preferences, and therefore adopting this approach also within an economic model, assumptions about profit maximizing behaviour could be tested rather than assumed (Dupont & Renzetti, 2007). However, this approach would be very tedious, if not impractical for the developing countries due to the vast fragmentation of land to numerous small pieces under peasant farmers, with varied capacities, preferences and an amorphous relationship with each other. Thus in the developing countries, local water user associations would be best suited to provide a structure to organise the societal actors and leverage in data correction through guidance on necessary societal behaviour towards water resources in tandem with the environment.

Through regular precise hydro-climatic, human and environmental systems' monitoring over the years, time series data for different parameters are availed, which help discern a historic trend of year-to-year variations. This trend could be projected to the future, with and without escalations, to help analyse and evaluate potential catchment systems' behaviour and their impacts on water and environment systems' sustainability. In this study, 20-years of monthly time series for stream flows and climatic data were exploited to help envision the natural hydro-climatic processes and their spatial-temporal variations within the case study area.

7.6 Formation of WRUA at Community Level and Capacity Building for Real Participation

IWRM promotes change from the sector-oriented to integrated management approach; from top-down bureaucratic mainly supply management system to an inclusive stakeholder and demand driven management approach; from command and control to decentralized forms of governance; from conventional expert driven management organizations to an adaptive collaborative system with more transparency and sharing of information (Rogers & Hall, 2003). The new approach is typified by valuable trans-disciplinary engagements that feature collaborative interdisciplinary modelling efforts that help structure complex problems, identify important gaps, explore novel solutions, demonstrate detailed thought, and provide and support insights that would be otherwise unavailable for complex systems. In this regard, models allow experts and stakeholders to explore complexities beyond the intuitive limits, that greatly aid decision making for holistic water resources development and management (Lund, 2007).

However, the holistic management approach of IWRM and the simultaneous inclusion of decisions taken at the lowest possible level (devolution) can result in a conflict between national, regional and local aspects (Hübschen, 2011). Nevertheless, participation and decentralization are essential for the implementation of IWRM and its underpinning values, as a lasting consensus and understanding of sustainable management as well as an optimal and equitable allocation of water resources can only be reached by the involvement of all stakeholders (van Edig & van Edig, 2005). In addition to the principle of participation and decentralization, IWRM is based on the principle of subsidiarity, which promote transfer of decision making processes to the lowest level where they proffer optimal productivity. Decisions based on local interest (e. g. local water allocation, permit issuance, supervision of compliance and sanctions, conflict resolution etc.) should be founded at the local level where the policy and rules could best be tailored to the local circumstances.

This is the foundation of the common form of stakeholder participation at the community level in demand driven water resources management, through Water Users Associations (WUA), that have been established in countries worldwide. WUA usually consist of a group of water users, for example irrigating farmers, who assemble their available resources for an ideally more efficient operation and maintenance of water system (Hübschen, 2011). Legislation provides a legal basis for the exercise of power at the local level and enables citizens to actively participate and thereby influence local policy-making. All the same, for these grass-root bodies to be effective and achieve their objectives, they require recognition of their right to organize, without these rights being challenged by external governmental authorities, for them to be able to hold members accountable for their actions (Ostrom, 1992). In this regard, all three IWRM principles are interlinked, as decentralization recognizes subsidiarity which on the other hand support and enhance wider participation of the water users in decision making process (Polte, et al., 2011).

In the past, water resources planning and development has been an exercise based primarily on engineering convention where societal actors were just funding agents, who are occasionally consulted through interviews during investigations, and who finally receive and apply the incontestable results. With the expansion of the democratic space and entrenchment of citizens' rights in many facets of conventional social and political domains (Wester & J., 2002), the traditional approach has now metamorphosed into a component within a complex, trans-disciplinary approach which is both interdisciplinary and participatory. In the new paradigm, societal actors and interest groups are not just funding agents to be consulted, or handed over the results, but are actively involved in the planning, design, analysis as well as the implementation of the research report (Narayanan, 2010). Subsequently, (Cap-Net; GWP, 2005) envisions IWRM as a systematic process centred on stakeholders participation, transparency, cost-effective allocation and monitoring of water resources use in the context of social, economic and environmental objective for sustainable development.

Despite their much publicized successes in practice, community water users’ associations encounter major challenges in developing countries (Hübschen, 2011), due to lack resources for effective participation, such as adequate information, appropriate contacts, funding and often time (Huntington & Nelson, 1976). Local politics also impacts a major influence especially in water allocation, and considering that the poor usually have low or no stake in shaping local politics, participation often seems irrelevant to their primary concerns. This attitude is also encouraged by the general perception that their requests or pressures would not be accorded respect by the authorities. Moreover, people in low-income strata are often divided by race, tribe or religion making consensus building, even in constitution of bodies to guard their interests, a daunting task.

These problems escalate especially in the rural areas, where most people already feel marginalised and might be unaware or simply cynical of national government policies and programs. Therefore, for participation through community water users’ associations to be meaningful, it should primarily involve empowerment; increasing levels of citizen power over decision-making process with clear illustration of the balance of responsibilities between the competent authority and stakeholders. Empirical research shows however, that this power is more often about being consulted or having a say in decisions than actual decision making (Ker Rault & Jeffrey, 2008). However, regarding the management of water resources, participation goes beyond influencing the concepts and decisions which one is affected by and includes the sensitization on questions of water resources management, raising awareness and increasing the sense of ownership (Hübschen, 2011).

Multi-stakeholder platforms like the previously elucidated WUAs, have lately become popular way to encourage water and related resources management dialogues even in the developing countries. Stakeholder participation are envisaged to provide vital information required to mitigate catchment adversities, and bolster timely resolution of local conflicts, reduce misdemeanour in water use and mobilize for socially equitable, economically efficient and environmentally sustainable use of local resources (Bandaragoda, 2005). The trans-disciplinary approach engaging both academic (researchers) and non-academic (societal actors such as policy makers, representatives of administration or interest groups, locals or the broader public) participants has also expanded the scope for collaboration in research, where different participants can make valuable contributions according to their unique strengths and comparative advantage, thus proffers a shared solution-driven approach (Narayanan, 2010).

Its multi-disciplinary and participatory setting brings together a wide array of individuals and organizations with varied interests, technical expertise, and priorities, which elicits the need for system models that can clarify complex issues and thus facilitate deliberations for successful planning (Loucks, 1995). Decision support systems are key to bridging the gap by integrating the diverse understanding and ideas to conceptualize a representative system through clear illustration within a graphical user interface. Thus proffering clarity on issues at hand and informing the all-inclusive panels' choices on multifaceted decision problems; mainly regarding water resources development, equitable allocation, use, management and conservation with due regard to sustenance of fragile ecosystems.

Appreciating that water resources management, especially water allocation, is a political process driven majorly by local economic and social interests, the substance of participation by members within water users associations is very vital. Various categories of participation have been classified (see Table 32 below) according to what they entail to members (Ker Rault & Jeffrey, 2008). Participation process is divided into three different levels, corresponding to an increasing sense of ownership of a public resources management system; mainly based on both power to influence decisions and their implementation and the details of communication availed during the decision process (Hübschen, 2011):

- Informative participation;
- Consultative participation; and
- Decisional participation

The attributes of different levels of participation are further discussed by (Narayanan, 2010) as depicted in Figure 61 here below, with stakeholders at the lowest level just being informed about decision making but have absolutely no stake in the processes. At the second level, stakeholders are at least consulted and may provide data and input for a study; however, they are not represented in the decision making table. At the top level, stakeholders are involved in a decision making process right from the onset and have tangible influence on its course; and at the highest scale on this level, stakeholders actually steer the decision making process and determine the course of action.

Table 32: Arnstein's eight categories of participation (Ker Rault & Jeffrey, 2008)

Level of participation	**Category**	**Description of the form of public participation**
Non-Participation	Therapy	A public relation exercise organized by authority to gain people support.
	Manipulation	A meeting where people express and share their problems, but there is no intention from the organizers of solving them.
Tokenism	Informing	Giving information to the citizen about a project that has been done or will be done.
	Consultation	Gathering information and opinion of the citizen on a project or a problem that concerns them.
	Placation	Citizens are allowed to advise and propose solutions to a local authority, but have no power to implement it.

Level of participation	**Category**	**Description of the form of public participation**
Citizen Power	Partnership	Citizens and power holders agree to share planning and decision-making responsibilities.
	Delegated power	Negotiation between citizens and public officials, which can also result in citizens having a dominant decision-making authority over a specific plan or programme.
	Citizen control	Citizens have a degree of power and control which guarantees that participants or residents can govern a program or an institution and are in full charge of policy and managerial aspects.

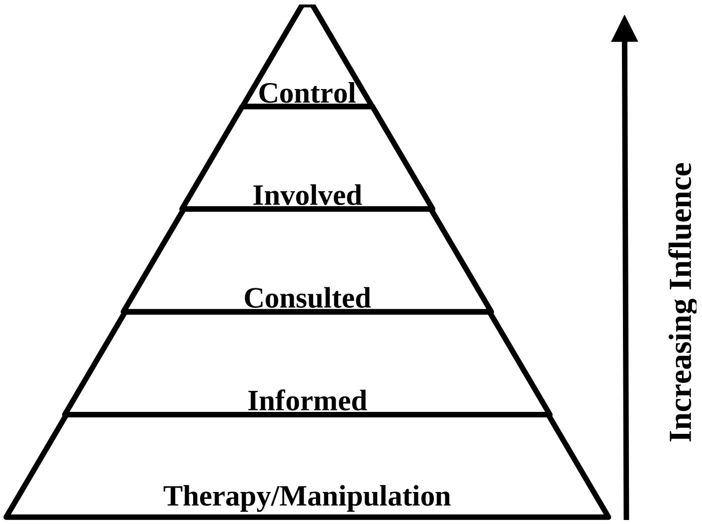

Figure 61: Levels of stakeholder participation – modified from (Narayanan, 2010)

The preferred tenets for real participation involve consultation, information and partnership; in the developing countries however, the main reason for participation in decision making from the local perspective has been about expression of one's opinion. The ideology of partnership in decision making has been lacking and need to be inculcated, to enhance consensus building in conflict resolutions and water allocation/management problem solutions. This can be achieved through (Ker Rault & Jeffrey, 2008):

- Bringing on board and facilitating the involvement of those potentially affected by policies at all levels of society;
- Providing participants with the information they need to participate meaningfully; a decision support tool would potentially aid comprehension of complex systems.

- Creation of forum for proactive discourse and interaction between water users, interested groups, the scientific community and policy decision-makers.[9]

Although the involvement of stakeholders can considerably improve the quality of decisions as well as compliance with them, it needs to be noted that increased participation can be a time-consuming process escalating the transaction costs of water resources management (Hübschen, 2011). Moreover, the information provided by societal actors could be biased to favour subjective positions; often short-term political objectives that are inconsistent with long-term management goals for sustainability. The involvement of academic actors, who are considerably impartial, should provide the leverage in moderation of these round-table consultations to guarantee the most optimal compromise.

7.7 Running Scenarios, Analysis, Evaluation and Choosing Optimal Management Option

There is an abundance of planning and management models currently in application world-wide, developed either for simulation and/or optimization of various resources management objectives. They are all anchored in the analysis of the prevailing “state of resources”, hence establishing the effectiveness of existing management policies and regulations. Both simulation and optimization models have often complementary role; simulation models help us understand the physical properties of the system while optimization models are necessary to evaluate the costs and benefits of policy options such as water pricing and trade-offs, establishing in-stream flow objectives, investment in storage capacity, and conjunctive management (Howitt, 2007). Where values, preferences, and/or the resource base is changing, optimization will have a greater role because of the need to evaluate the public and private values from new management approaches.

For instance, this study delved specifically on water allocation planning and balancing models, that in essence facilitates estimate of the quantity of water available to different users within a river basin at different times. These models facilitate the analysis and evaluation of allocation problems involving complicated hydrological, environmental and socio-economic constraints vis-à-vis water users’ and other stakeholders’ often conflicting preferences and management objectives (McCartney, 2007). Through simulation the models allow policy-makers and managers to gain insight into the potential consequences of policy changes, changes to physical infrastructure and changes in processes that affect runoff (e.g. land-use modifications). They can also help set the expectations of different water users with respect to the reliability and security of supply, which can help secure investment in water dependent enterprises. In some instances these models have been integrated with an economic framework, thereby enabling an assessment of the potential economic consequences of different options (scenarios) proposed for the management of water resources (McCartney & Arranz, 2007).

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[9] Declaration of the International Conference on Participatory Processes in Water Management (PPWM) – Satellite Conference to UNESCO’s World Conference on Science in Budapest, Hungary in 1999, (Bandaragoda, 2005)

Some DSS are multifaceted allowing integration of multiple management objectives in their frameworks; for instance WEAP model adopted in this study proffer not only simulation for both water balance and allocation management, but also optimization to maximise socio-economic or environmental benefits accrued from various management options through an in-built cost-benefit evaluation module. The said module facilitates assessments of economic productivity from various allocations and the related impacts (opportunity cost) of trade-offs between competing allocations, and could be optimized to ensure priority in water allocation starting with demand with greatest value to the society. Simulation of the opportunity cost for the unmet demand help approximate economic cost of failing to allocate water to a given demand for comparison with corresponding economic benefit of allocating the water to an alternative use. The iterative analysis and evaluations help ascertain the potentially most beneficial allocation for the scarce water resources; hence guide the formulation of catchment water allocation priorities and/or desirable trade-offs between various water demand sites.

Although economic efficiency alone should not guide decisions about water resources development, modelled scenarios results nevertheless provide a useful starting point for comparison of feasibility in alternative water development and allocations management. Use of scenarios facilitate precise predictions while investigating complex systems that are inherently unpredictable or insufficiently understood. Each scenario provides a coherent, internally consistent and plausible description of water demand within the catchment (Sieber, 2011). However, selected scenarios are not absolute possibilities for future water resources development within the catchment and it is not possible to attach probabilities to them (Mugatsia, 2010). In most instances, especially in the developing nations, knowledge of prevailing water demand is incomprehensive; and subsequently there is considerable uncertainty about future water needs. This is due to lack of (or inadequate) monitoring and gauging devices and sometime lack of coordination of historical data time series leading to paucity of data that make it impossible to precisely discern historical trends as to simulate future demand with certainty.

All the same, scenarios are valuable hypotheses that provide bases for discussions and evaluation of different options for meeting possible future water demand challenges; hence providing a framework for strategic planning. The commonly used scenarios in IWRM, especially in water balance and water resources allocation, revolve around the two main management measures i.e. Demand and supply. Within these models, scenarios facilitates determination of the impacts of natural phenomena (e.g. climate change) and the effectiveness of various supply-side and demand-side management measures in stabilising the systems.

I. Demand-side management measures

Besides water tariffs, the other measure used to control water demand is the enhancement of efficiency, meaning less water consumption per output unit. For instance, through measures reducing non-revenue water (leakages, illegal connections etc.) or water-saving irrigation technologies. However, the key to improved efficiency lies in setting up mechanisms for changing people's attitudes and behaviour towards water use (Hübschen, 2011). Water tariffs and especially tiered prices, i.e. water tariffs subject to increasing rates commensurate with the cumulative quantity of water consumed within an accounting period, could help to set incentives for a more sustainable and efficient use of the scarce water resource. Some models allow disaggregation of demand management measures to capture individual options savings or losses within a demand site, others provide for aggregated values for each demand site. Others like WEAP are more versatile allowing the modeller both options, which allows the model to be suited to the data available. However, a general demand-orientation in water management does not exclude measures to augment water supply.

I. Supply-side management measures

In the past this has been the key approach adopted by the authorities, often without involvement of water users and other stakeholders, to deal with challenge in water resources management. These has entailed, mainly due its political correctness, continuous expansion of storage infrastructure to capture water during rainy season as to avail it for multi-purpose uses during the dry season. Modern measures like water reuse have also shown substantial potential to deal with scarcity from the supply-side when accompanied by quality improvement through treatment of effluent from one demand sites before application in other demand sites (Hübschen, 2011). For instance, clarified or treated effluent or storm drainage from households and the agricultural sector can be reused for irrigation purposes or for industrial use, where quality standards are not prohibitive.

To comply with the requirements of an integrated system, the reuse of wastewater should not pose a health hazard or threaten sustainability of ecological systems (Neubert, 2005). The quality requirements and stringent regulations for wastewater treatment; the corresponding expertise and technology; and the associated costs by and large renders water reuse as an option for augmenting water supply economically unfeasible for many developing countries. Thus the need to progressively develop local capacity in operation, monitoring and management of the systems to ensure water reuse is both safe and effective cannot be overstated. Meanwhile, low technology options of using domestic and agricultural effluents for irrigation and ground water recharge in controlled infiltration basins could be a feasible alternative. Also feasible is rainwater harvesting with storage in the soil profile to check evaporation (e.g. sand dams or ground water system), or in water pans and tanks to provide safe water for household or irrigation application for an extended period of time (Hübschen, 2011).

To boost feasibility of water reuse in water scarce urban catchments like Nairobi, where large quantities of water are imported from adjacent basin, thus guaranteeing corresponding disposal of effluent, multipurpose dams could offer an alternative solution. The efficacy of ploughed-back economic benefits from non-consumptive water use (e.g. hydropower generation, navigation, recreation etc.); in tandem with income from sales of treatment plants' by-products, to cover treatment and pumping costs should be evaluated. In relevant catchments, water supply could also be augmented via desalination of water from sea, lake or groundwater sources. However, desalination plants are both technically and economically beyond the developing nations' capacity. Even in developed nations, these systems are yet to exude favourable economic returns, whereas accumulated salt from the plant is potentially hazardous to the ecosystems (Schönewald, 2005).

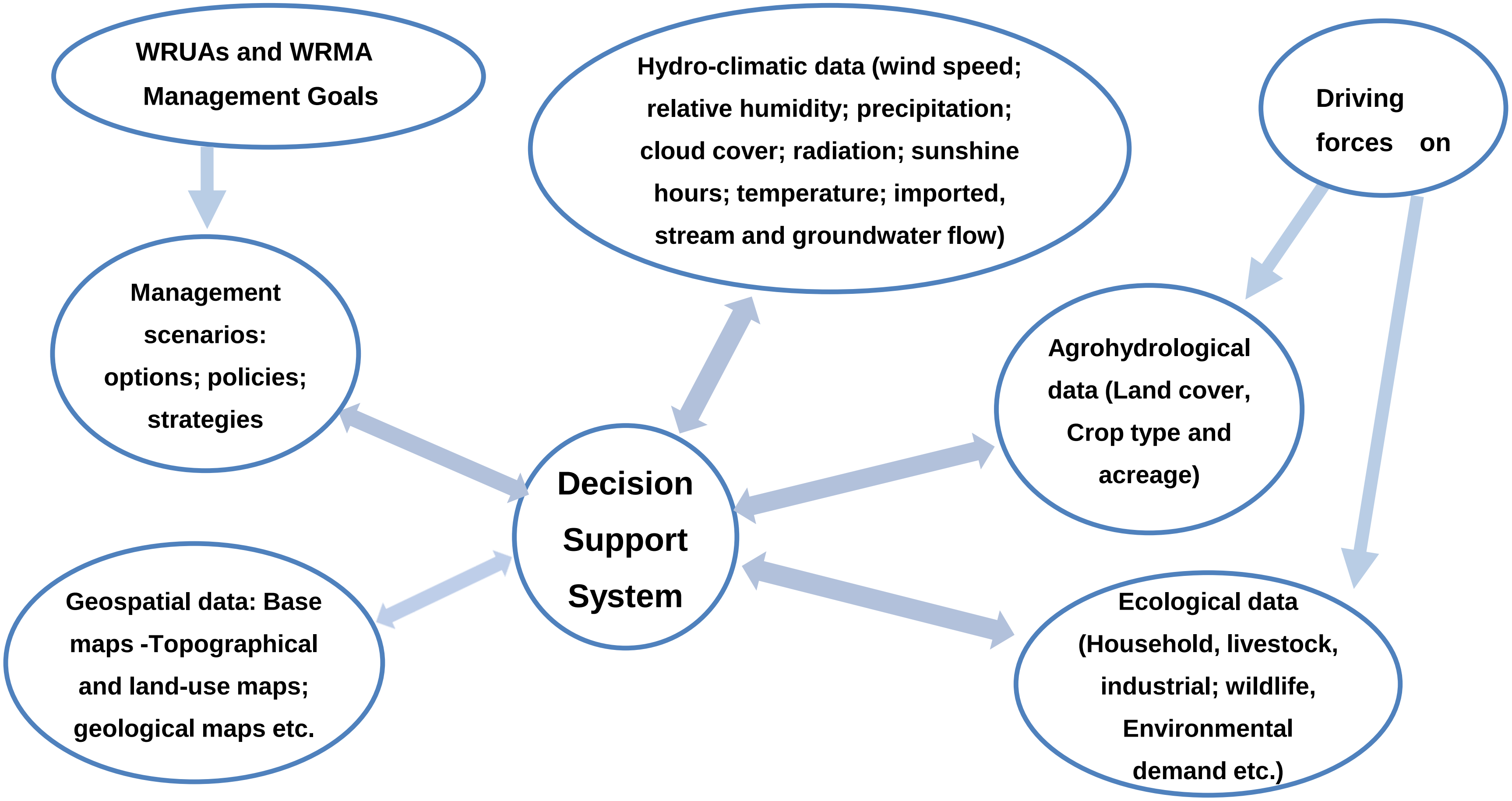

Figure 62: Decision support framework for effective data collection, processing and management and feeback management

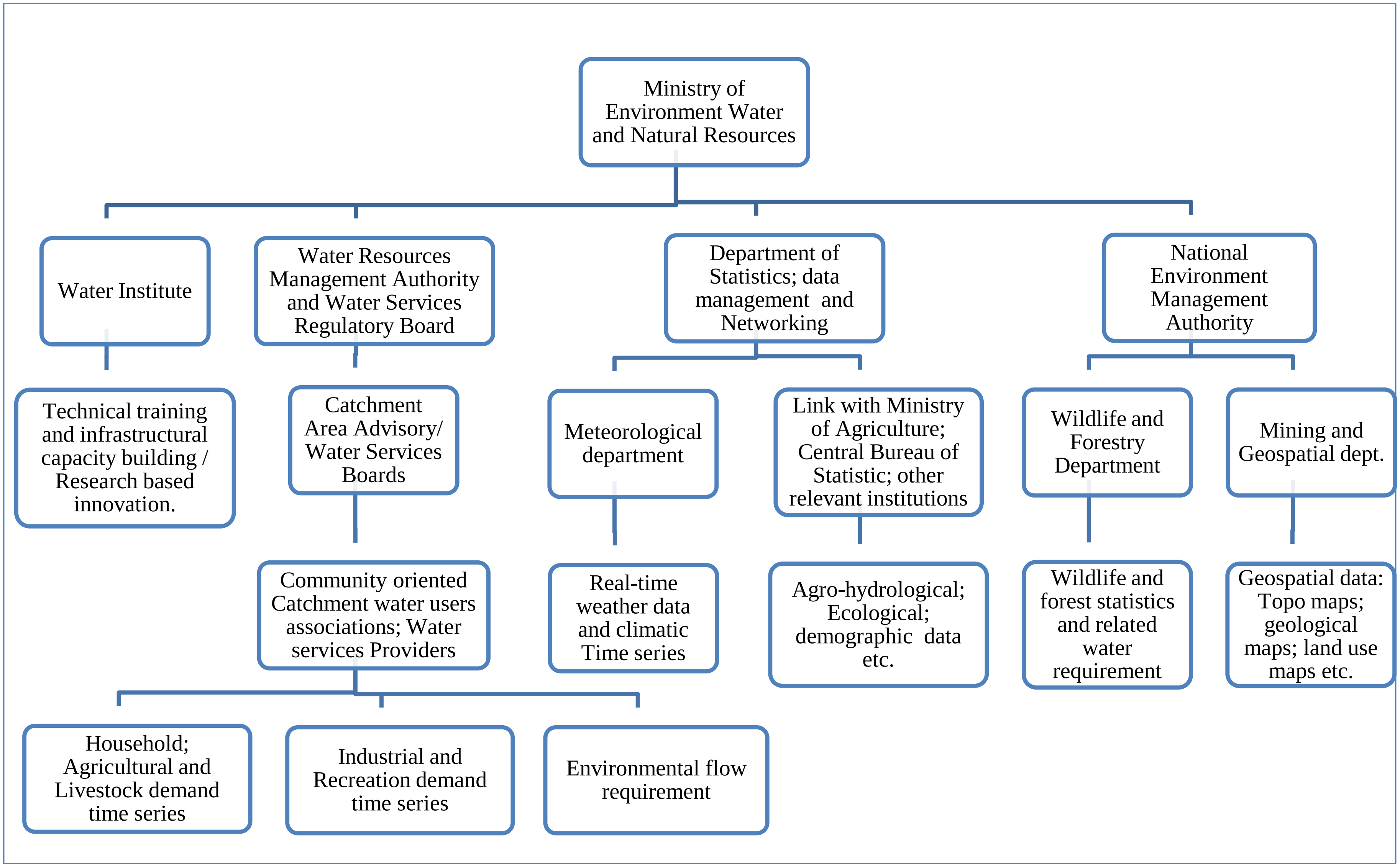

Figure 63: Institutional structure for an effective proactive decision making process

Chapter 8. **Discussion and Recommendation**

8.1 **Highlights**

The starting point for improving water management is to ensure that societal actors, water managers and policymakers have the information, expertise, and resources they need to identify, shape, and implement water reforms (Hanak, et al., 2011). By impacting the awareness of the interdependence between the human and environmental systems within a basin, the case for prudent water resources management and conservation is furthered. Hence, availing and dissemination of information on water related issues is part of broader strategy for sustainable development (Ehrensperger & Wiesmann, 2006).

In the case study area, this has been facilitated by the inauguration of National Water Master Plan 2030 in the year 2010, which led to development of not only reliable base maps (schemas) of the nation's six catchments that constitute national water management system, but also the provision of planning frameworks to steer both the future collaborative resources development by local, county, regional and state agencies and further studies on the comprehensive water and related resources' management. It worthy to note that this study is among a number of studies recommended by the recently released National Water Master Plan 2030, as per the local demand (MEWNR, 2013).

Previously, base maps have been embedded in fragmented planning and research models which provided incomplete, overlapping, and often inconsistent representations of the national water management system. This is due to the fact that the need for both modelling as a planning tool and collaborative management approach have only recently taken root. In earlier efforts, water managers engaged societal actors at field reconnaissance and then at implementation stages; hence, creating a gap in information flow and with it loss of ground support on authenticity of new policies. In addition, most studies often represented the water management system at a general level that did not always provide information at the scale needed for local planning (Alfarra, 2004).

Since water resources endowment vary both spatially and temporally, their sustainability hinges on the ability to select the "best practices" (IHP, 1999) to steer management of the quantity, quality and reliability of the resources at a catchment scale; so as to achieve optimal, short and long-term social-economic benefits without compromising environmental sustainability. Since the quantity of available water is finite, and a realistic reduction of the demand for the resource is also finite, IWRM has emerged as an attempt to shift attention to the key issues pertinent to sustainable catchment water allocation management i.e. adaptive systems, efficient water infrastructure, and participatory approach in water resources management.

In many developing countries, the institutional structure have already been set up, but the essential IWRM initiatives still remain at national policy level and are yet to be cascaded down the institutional systems to the grass root. Meanwhile water authorities continues being undermined by outdated techniques, inadequate human capacity both in statistics and expertise, inefficient and/or inconsistent data collection leading to inadequate and poor quality data. Moreover, data needed for water resources assessment is uncoordinated as hydro-climatic data is collected by a number of different organizations, whose systems are yet to be attuned in terms of standards, quality assurance, electronic access and transfer. This situation undermines the efforts to study historical trends in water resources supply, development, allocation (demand), use, management and conservation; which would steer simulation and/or optimization of future scenarios for planning and formulation of adaptive management measures.

Lack of effective forecast and subsequent failure to timely adopt appropriate management measures to mitigate adverse impacts of future events, aggravates the challenges already elicited by water scarcity and the highly variable resources distribution. This often leads to water conflicts between competing sectors and enterprises. To resolve this problem, shared learning (inclusivity) has shown potential to empower local people and strengthen their participation in adaptive collaborative management (Kamau & Kimberly, 2014). Accordingly, water managers need to shift their management policies from the archaic top-down command and control, to a consensus process involving local stakeholders in developing innovative locally applicable policies. The new approach will support the watershed management strategies by guiding stakeholders, through dissemination of relevant information in an comprehensible manner, especially in determination and evaluation of trade-offs for effective water resources allocation management (Ochola & Kerkides, 2003).

The need for collaborative management strategies have necessitated adoption of decision support systems that would facilitate roundtable deliberations in an inclusive and constructive environment where interdisciplinary experts and societal actors are proactively engaged in:

- Conceptualisation of the prevailing problems within a catchment;
- Devising modes of data collection, coordination and management of database on key water issues
- Devising accurate analytical means of estimating the size and impact of various demand on catchment water resources, e.g. relative crop evapotranspiration, to inform farmers and water managers decision on crop zoning, at relatively little cost, and without inconvenience to farmers (Hanak, et al., 2011)
- Devising criteria for evaluating the efficacy of existing management policies and assessment of alternative water allocation management solutions. This entails assessments of various stakeholders' conflicting interests and the potential impacts of management options on those interests; that leads to
- Making informed choices that strike a balance between environmental sustainability, social equity and economic efficiency for optimal trade-off in allocation of catchment scarce water resources

As highlighted by (Hanak, et al., 2011), the most urgent and overarching challenge for water management in the modern era is to reconcile the demands of the environment with the large and evolving demands for water for human activities. To this end, DSS are being embraced to steer collaboration process as water authorities seek to enhance consensus building in developing management policies for equitable resources allocations';

economically efficient usage towards ensuring full investment recovery on water developments and services; and catchment water balance without compromising ecological sustainability. Owing to the improved understanding of the essence of sustainability, water users are able to adopt efficient water use practices and assist water managers in timely implementation of essential management policies.

8.2 Deductions

The study was principally intended to help evaluate the efficacy of various DSSs available in the water industry in proffering adaptive and collaborative water resources management within the developing countries. Especially identifying and devising a methodology to guide propagation of a favourable tools that could function within the typical data-related, technical and institutional limitations, as to promote adaptive, participatory catchment-based decision making process.

From the results of this case study, it can be affirmed that DSS when founded on consistent, comprehensive, and coordinated data management; adaptive technology; and collaborative management systems, could competently proffer customised policies for sustainable water resources management. The core strength of DSS is the comprehensive schematic illustration of water systems in GUI frameworks. Moreover, a seamless interface with geographical information systems (GIS) enhances data pre-processing, management and, on demand, uploading on the model for outputs in map, tables and graphs.

Among various potential DSS evaluated in this study, WEAP emerged among the proficient tools for possible adoption, especially due to the capacity to traverse the most fundamental constraint i.e. data inadequacy, and to solve marginalisation question facing majority of societal actors within the developing countries. Accordingly, the model was utilised in furthering the other interest of the study in fashioning a simple methodology to guide propagation of adaptive and collaborative decision support tools for typical catchment background. The case study was focussed on catchment water resources balancing, with particular emphasis on environmental conservation and socio-economic stability in water resources allocation management within the Nairobi River Catchment. The results obtained for WEAP in this study:

- demonstrate DSS tools as ample management instruments that facilitate evaluation of various policies within a catchment and guide water managers, in collaboration with water users and societal actors, in making informed decision on trade-offs in water allocation for optimal resource use, economic return, without compromising the social and environmental interests;
- Underscore the importance of collaboration between academic (researchers) and non-academic (societal) actors in decision making process, to guarantee comprehensive data collection, overboard analysis, evaluation and acceptance of preferred management options;

As demonstrated in application of WEAP in this study, DSS through its GUI framework makes it possible to use a common (base map) schematic view for comprehensive water resources assessments. The use of the same schematic view for diverse water management assessments permits simultaneous analysis of different management attributes (e.g. quantity, allocation, demand satisfaction, quality, economic viability etc.) for the same polygon. A polygon in this case represents the entire catchment, a constituent hydrologic unit or other delineated management units of the catchment. Thus enabling the interpretation of a range of interrelated geographical information for the same area. Hailed by (Ochola & Kerkides, 2003), this approach proffers holistic planning, by either direct or derived integration of water and related resources.

As per (GWP, 2000), availability of water and its balance with the demand within a catchment for socio-economic and ecological sustenance, is primarily influenced by both quantitative and quality distribution in time and space, which is largely a factor of temporal and spatial variations in the precipitation. More so due to the fact that transport of water to other areas exhibits technical, socio-economic limitations. However, for already closed sub-basins like the Nairobi catchment, water transfers are the only way to balance inequity in water distribution and also in servicing fundamental urban and industrial demands. Nevertheless, fiscal prudence prescribe that before water transfers are considered, local resources that are more economical to develop should first be optimally exploited leaving only the physical and economic deficits to be imported from other catchments. This would ensure optimal use of available resources, justified quantities of water transfer and accountability in its use; while also ensuring water import to one area does not translate to scarcity exportation to the donor basin.

In this study it was established that Nairobi city and the satellite towns in her environ import almost 90% of their municipal water from the adjacent Tana River basins. The imported water quantities translate to a steadily rising figure that currently stand at i.e. approx. 600,000m^3/day. The ensuing wastewater is also disposed directly into the rivers as raw sewage predominantly in low income settlements where wastewater disposal infrastructure is still a mirage. This aggravates pollution of the available water resources rendering local rivers utterly untenable sources, and increasingly poses risk to future integrity of groundwater sources. Besides, wastewater treatment plants that serve approximately 40% of the urban residents, are located at the lower extreme of the catchment; hence, return flows effluent into Nairobi River are not available for use by other demand sites within the catchment as envisaged by WEAP model. This situation call for urgent redress, considering that little has been done so far to ensure available local water resources are conserved, protected and optimally exploited to ease the current and potential future strain on the catchment.

Adopting a decision support tool for this catchment to guide an all-inclusive survey of the hitherto disused local water resources, would proffer a two prong initiative. First in raising awareness on water as a finite resources with social and economic value, which should not be wasted more so in chronically water scarce catchment like Nairobi. Involving all stakeholders from the onset would help garner local support and influence behavioural change toward water and the environment, especially in stemming water pollution. Secondly, a decision support tool would provide a database for comprehensive catchment's water supply and its attached interests by various demand sites both within and without the catchment, which would facilitate evaluation of catchment water balance and formulation of acceptable policies its sustainable management.

Previous conventional models have entailed complex structures and illustrations that could only be grasped by the experts; hence collaborations has been confined within interdisciplinary expert roundtables, which are not bound to consider the societal actors opinions. Therein, diverse disciplines would share notes and experiences on probable approach to adopt in pursuit of a common goal, which could end in new theory development and new knowledge on the subject matter (Narayanan, 2010). In essence this approach suit the command and control system of governance where societal actors, who are most affected by the problems within a catchment and directly bear the consequences from policy implementations, have little role to play within the decision process apart from being interviewed and receiving results for implementation.

On the other hand, in embracing IWRM paradigm, water authorities appreciate the benefits of inclusivity in decision making, which is pertinent to every research leading to formulation of policies and regulation to govern water development, allocations, uses, conservation and management in a catchment. Subsequently, the governance regime within the water sector has shifted to a consensus process involving water managers, local users and other interested stakeholders.

To this end, decision support systems, for instance WEAP as demonstrated in this study, are increasingly being accepted as vital tools for fashioning inclusive roundtable experiences involving academic participants and societal actors. The roundtable deliberations are crucial in building consensus in:

- Conceptualization and configuration of water management problems at every level;
- Selection of various management options for solving the identified problems;
- Determination of choice criteria to compare various options;
- Analysis and evaluation of various selected option against selected criteria, as to inform the ultimate choice i.e. the most optimal compromise option.

To effectively execute this intricate processes within the IWRM objectives, as typified in this study through the use of schema to represent catchment water system, key assumptions and scenarios to represent management situation and options, models (in concurrence with (Lund, 2007)) play crucial role in:

- Helping integrate pragmatic and deductive knowledge;
- Generating complex testable hypotheses i.e. scenarios;
- Exploring and comparing different potential options available to solve the problem;
- Avoiding costly trial and error associated with testing policy “in the field”; and
- Reducing uncertainty and providing assurances

The value of modelling in a collaborative process is in the capacity to structure complex system problems into simple comprehensible illustrations, demonstrating detailed line of thought, and therein identifying important gaps. Models allow users to exploit vast amount of data to explore complexities beyond modellers' intuitive limits (Lund, 2007); thus providing and supporting insights that would be otherwise unavailable for complex systems. Moreover the graphical user interface framework exploited by models allows visualisation of the catchment systems, layouts of various problems in charts or schemas and presentation of results in simple graphs and flow charts that most societal actors can identify with. This ensures transparency of the process and proactive contribution by all stakeholders, thus building trust between the authorities and the societal actors for long-term collaboration in the management process.

The study results ascertained that, prevailing constraints notwithstanding, DSS in the developing countries would supports innovative catchment-specific management strategies by guiding experts and societal actors through the decision making process; presenting participants with data and information in a logical manner that help them understand their water resources situation and proactively engage them in informed decision making and implementation of essential practices in water resources development, management and conservation. Simulation of the current and possible future scenarios due to changes in supply and demand conditions and various proposed water resources developments within the Nairobi catchment not only support the case for optimal use of local resources but also put forward a legitimate cause for adopting water reuse to solve water scarcity equation within the catchment.

8.3 Recommendation

In ideal situation where these huge quantities of water resources availed daily to the catchment were managed more sustainably by invigorating the treatment process and inculcating water reuse as a supply management measure, they could provide a vital options to augment supply to current unsatisfied demand in the catchment. Wastewater should be treated in a way that simultaneously accomplishes a recycling concept for the nutrients and preserves the scarce water resources. By adopting the modern cogeneration technology to harness energy utilizing substrates generated at the WTPs in Nairobi, the plants would potentially have enough power to run own operations and complement the off-peak power excesses in pumping the treated effluent into reservoirs or infiltration basins upstream. The new supply availed upstream could subsequently supplement the catchment agricultural supply and enhance recreation, especially in making the section of Nairobi River flowing through the city's central business district (CBD) navigable for recreation and leisure commuter services (appendix Figure 70). This is in addition to boosting ground water storage and augmenting stream flows through ground to surface water interaction, that also supplement the environmental base flows.

However, before adoption of this measure further studies are pertinent, since the basis for the implementation of a sustainable disposal concept is the development of a material flow model of the region (Nestmann, et al., 2010). This would not only help establish the spatial-temporal quantities of waste matter generated in the catchment (i.e. substrates available at the plants), but also I ascertaining all relevant water-bound nutrient flows in both influents and effluents at the WTPs. Thus the model should reveal existing deficiencies in the treatment process and help to determine potential starting points for improvement to comply with the stringent regulations governing wastewater reuse. To evaluate the related economic viability of the project, a favourable economic model should be adopted in evaluating the economic benefits accruing from cogenerations, sale of by-products and application of better quality effluents to multipurpose use either directly or through ground water recharge; against the entire cost of incorporating stringent treatment techniques, plant installations, human capital, operation and maintenance and extra energy for water pumping. This could help open prospects for funding towards a potentially legitimate water scarcity solutions for the catchment.

Rated as an inherently adaptive approach, IWRM accommodates emerging challenges, constraints, changing social priorities and dynamic societal preferences. Though in the past, reuse especially related to wastewater has locally been anathema, the growing population relying on the same finite renewable water resources, has yielded a shift in norms. All the same, unlike in conventional supply measures where authorities could develop new sources without engaging the communities, success of water reuse is pegged on full and real participation of societal actors in the entire process. This would allow room for all to tender their reservations, pragmatic or cultural, and for the experts to alleviate all legitimate concerns through clear, audience-customised demos and explanations on the treatment process. That is, how the treatment plant will handle influent from arrival to the effluent release; the plant's by-products and both their beneficial use and detrimental consequences if any; and the recommended application of the effluent and any precautionary measures to be observed. To accentuate the participatory element in application of DSS within IWRM regime, this study espouses various system and social networking approaches that need be adopted:

(i) Collaborative engagement featuring all stakeholders to develop shared physical schematic of local, regional and national water management systems that are stored, updated, documented, accessible and transferable electronically. Data collected by different organisations should be well coordinated and compatible to ensure standards, quality assurance and essential data protection.

(ii) Review the catchment water management base maps to strike a balance between hydrologic units' extents and administrative interests while delineating water resources management units.

(iii) Formulate strategies for effectively cascading the shared management base maps to every management level, besides capacity building to encourage water planners to apply them in assessing the status and trends in water supply in agriculture, households, urbanization, and environmental base flows or reserves for a range of plausible scenarios.

(iv) Consider the prevailing local, regional and national strategies on water demand, supply and quality management, flood risk mitigation, and environmental resource management.

(v) In collaboration with societal actors, provide institutional structure to host a network of experts to boost analytical capacity in support of water management decisions and investments.

In addition to the procedures proffered in this study, which are especially pertinent to the developing countries, the general modelling guidelines are already integrated within various available tools and comprise iterative steps as illustrated by (Jakeman et al. 2006):

1. Define model purpose and specify modelling context (scope and resources)
2. Conceptualise the system, specify data and other prior knowledge
3. Select model structure and features
4. Identify model parameters and variables
5. Select estimation performance criteria and techniques
6. Quantify uncertainty
7. Model calibration, evaluation and testing

The preferred evaluation criteria, arrived at in a participatory process, should be realistic in relation to local conditions (social-economic, cultural, and environmental interests); while the modelling software should be affordable; practical; simple; adaptive and efficient. Results of every study should constitute a progressive representation of water management system to build on common linkages of information shared among local, regional, state authorities. To facilitate data analysis and policies implementation, systematic increase in state resources allocation are essential to assemble data from local to national agency within a coherent accessible framework. In some regions, the main problem is not the lack of data but the bureaucratic hurdles in accessing the data for analysis by other agencies or groups (Hanak, et al., 2011).

To harness the benefits of structural reforms, as highlighted by challenges experienced in data collection during this study, the state should promote greater coordination among agencies mandated with managing water, land and related resources at all institutional levels. Given the increased complexity of water challenges and the abundance of agencies, often with fragmented jurisdiction over water, a single agency may find that its jurisdiction does not extend to all issues or areas that must be addressed to achieve effective reform. For instance, collaboration between water authorities and meteorological department is imperative to effective water resources management, which is also the case between wastewater treatment and water agencies for effective implementation of water reuse/recycling projects.

A fundamental attribute of decision support tools, such as WEAP, in providing flexibility to accommodate the evolving needs of the user, is among the key footprints of an adaptive and collaborative model. Data analysis is customised to accommodate gaps in information without compromising admissibility of the process, which provides workable solutions while ensuring improved accuracy on availability of better information, changes in policy, planning requirements or local constraints and conditions (Mounir, et al., 2011).

Chapter 9. **Conclusion**

With the increasingly erratic climate and the impacts of climate change being registered world over, there is an escalating societal desire to depart from the 'rule of the thumb' especially in interrogating natural phenomena and interpreting the interfaces and interdependence between the human and environmental systems. The modern society yearns for a seamless interface between science and practice; clearer communication between scientists and societal actors for deeper shared understanding of issues at hand; heralding more pragmatic and inclusive approaches that could provide reliable information based on legitimate study of historical trends and impacts. This is envisaged to inform choices on human and environmental resources management policies and adoption of authentic measures not only to facilitate sustainable interdependencies between the systems, but also to curb or mitigate future impacts from typical adverse occurrences and set institutional structure and infrastructure for disaster preparedness and management.

The fundamental hypothesis at the onset of this study was that adoption of an effective, adaptive and collaborative DSS would not only accentuate real time resources assessment, forecast and management, but would also be a safe vehicle to carry societal actors and other interested stakeholders along. The results of the study overwhelmingly approves the hypothesis though with stipulation that the engagement of societal actors ought to be objective in ensuring their stakes, interest and skills are analysed to ensure contradictory aims and interest are censored at the onset. This would ensure water managers and all stakeholders are reading from the same script and guarantee real proactive participation that exploits the diverse competencies in generation and integration of knowledge on the system. Only then would it be pragmatic to build consensus on priority targets and formulate acceptable policies to steer the required system's transformation.

That clear illustrations of the system has been identified as the underpinning element of a decision support system, especially as the interface between experts and societal actors in cultivating a shared comprehension of the system. This underscores (Agarwal, et al., 2000) inference that using modern advancement in IT, combined with knowledge of environmental sciences, hydrology, hydraulics, economics, sociology and other disciplines pertinent to IWRM, concrete strategies for communication with all actors and stakeholders could be devised. All this bearing in mind that the most appropriate method of configuring the system, in any case, needs to take account of local social-economic, political, cultural and other subjective factors. Societal actors are crucial not only in mobilizing support for implementation of policies, but also in influencing change in behaviour and actions towards water resources.

WEAP system, as demonstrated here, through its in-built GUI and a seamless interface with GIS, allows uploading of geo-referenced spatial data alongside its corresponding non-spatial data. This provides an effective integration of the physical and agro-hydrology, human and environmental systems and the management policies within a basin that help simulate prevailing and projected water balance within the catchment. The hosting of the model within a GUI framework facilitates simple interactive construction, illustration and modification of the system under study, which proffers a vital user-friendly interface between non-academic actors' and the system. Illustrations are structures that turn data into comprehensible information; thus the clearer they are the more they aid perception of prevailing problems in a system and elicits proactive participation of stakeholders in consensus building and tendering the influence required in implementation of essential management policies.

The experienced at the data collection phase of the study, underscores the concerns over bureaucracy and high untenable cost of accessing the available data across government agencies. This aggravates the already acute problem elicited by data inadequacy, unreliability, and weak legitimacy. As such, the need to ensure that data needed for water resources assessment that is collected by different agencies is assembled in systems that are well attuned in terms of standards, quality assurance and electronic access and transfer, to ensure requisite analysis are not impeded cannot be overstated. So is the maintenance of detailed documentation of the data (metadata), so that users of the data could know the details about how the field data has been gathered and any manipulation carried out in the process. Also imperative, especially for an adaptive water balance model in the developing countries where agriculture is still the chief water user, is the incorporation of data collected at farm-scale for small-scale (peasant) farmers' districts, at irrigation districts for schemes, and community water services providers' data in water demand evaluation. Unavailability or insufficiency of water consumption data and corresponding absence of metering devices in water supply systems, has consistently made it difficult to understand users' behaviour in response to increased water scarcity or water pricing (Ayoo, et al., 2007).

The study has established huge physical imbalance between available water resources and the demand to meet both human and environmental systems requirements at the Nairobi River catchment. However, the escalated importation of water from the adjacent river basin to meet the deficit, while ignoring conservation and optimal use of the meagre local resources, has inculcated societal indifference towards efficient use, conservation and protection of water resources. If locally available resources were to be adeptly safeguarded from apathetic use and pollution; if their usage was principally optimized before considering transportation of legitimate deficit from the adjacent basin; if, and only if in addition to these two measures, demand and supply management measures like water reuse and conjunctive use of surface and groundwater were adopted to optimize benefits from each unit of the available resource, then a potentially legitimate solution to a significant margin of the prevailing water deficit in the catchment could be realised.

Groundwater, in contrast to surface water, is not exposed to evaporation and pollution; does not suffer from reduction of storage capacity because of siltation; is seldom harmful to environment and offers a natural water distribution up to the users. However, groundwater aquifers seldom offer large storage capacity able to absorb large volumes of flood in a short period of time, and are unable to return them as significant discharge per unit production system of well or borehole. Moreover surface water storage is often preferred because it offers a much higher political visibility, opening the way for improper influence through advocacy based on short-term objectives rather than the most sustainable option in decision making (Stewart, 1989). Conjunctive use, a harmonious blending of both sources of water in order to minimize the undesirable physical, environmental and economic effects of each solution and to optimize catchment water balance, would be the best option for the case study area; allowing integration of water reuse that is envisaged to optimize use of available resource.

Using WEAP or typical model in tandem with GIS application to set up a coordinated database for the catchment water system, could certainly help progressive assessment, management and conservation of the overall catchment water resources. Besides it could also help evaluate the impacts of the potential human interventions, for instance water harvesting and impoundment in large dams, small dams or water pans; artificial ground water recharge in infiltration basins, and reuse of treated wastewater, to demand site or through recharge of ground or surface sources. There is however, need for further research to establish hydrogeological and hydraulic attributes of the catchment, especially with regard to their impact on general hydrological cycle, and natural recharge, storage capacity and productivity of aquifers, and the comparative environmental and economic implication of various potential options for conjunctive water management.

Thus it is apparent that DSS will inspire all-inclusive participation in decision making process, especially if the methodology of application is customised to accommodate local socio-economic, cultural, technical and data constraint reality, but of course without adversely compromising system’s capacity to deliver optimal solutions to the catchment management problems. In the long run, administration will build capacity to sustain research and development, thus improve data accessibility, information flow and extensive stakeholders’ participation in decision making process. This will ensure optimal and sustainable exploitation of available resources while allaying water related conflicts by making upstream users cognizant of the downstream users’ right, ecological reserve i.e. conservation of stream base flows.

Nairobi catchment, being an already closed catchment i.e. available local supply is less than catchment’s sum total water footprint, water transfers are the only way to balance inequity in water distribution in space and time; especially in servicing fundamental urban and industrial demands. However, fiscal prudence prescribe that before water transfers are considered, local resources that are more economical to develop should first be optimally exploited, leaving only the physical and economic deficits to be imported from other catchments. This would ensure optimal use of available resources, justified water transfer and accountability in its use; while also ensuring water import to one area does not translate to scarcity exportation to the donor basin.

Simulation of the current and possible future scenarios due to changes in supply and demand conditions and various proposed water resources developments within the Nairobi catchment would not only support the case for optimal use of local resources but also put forward a legitimate cause for adopting water reuse to solve water scarcity puzzle within the catchment. The key contention aroused by this study is how modelling would aid collaborative decision making process in developing countries yet majority local water users are peasant farmers with little technical know-how. However, the study ascertained that, constraints notwithstanding, DSS in a typical developing country would supports innovative catchment-specific management strategies by guiding experts and societal actors through the decision making process; presenting participants with data and information in a logical manner that help them understand their water resources situation and proactively engage them in informed decision making and implementation of essential practices in water resources development, management and conservation.

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List of Tables

List of Figures

Acronyms

ACA	Athi River Catchment Area
ASAL	Arid and Semi-arid Land
ASL	Above Sea Level
AWRM	Adaptive Water Resources Management
CBD	Central Business District
CBS	Central Bureau of Statistic
CI	Consistency index
CR	Consistency ratio
DM	Decision Making
DPS	Driving force-Pressure-State
DPSIR	Driving force-Pressure-State-Impact-Response
DSS	Decision Support Systems
ENSO	El Niño Southern Oscillation
EU	European Union
FAO	Food and Agriculture Organisation
GDM	Group Decision Making
GIS	Geographical Information System
GUI	Graphical User Interface
GWP	Global Water Partnership
IRBM	Integrated River Basin Management
ITCZ	Inter Tropical Convergence Zone
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
JICA	Japan International Cooperation Agency
KMD	Kenya Meteorological Department
MAA	Multi-Attribute Analysis

MADM	Multiple-Attribute Decision Making
MCA	Multicriteria Analysis
mDSS	MULINO Decision Support Systems
MEWNR	Ministry of Environment Water and Natural Resources
MODM	Multiple-Objective Decision Making
MULINO	MULti-sectoral INtegrated and Operational
MWI	Ministry of Water and Irrigation
NetSyMoD	Social Network Analysis, Creative System Modelling and Decision support approach
NWMP	National Water Master Plan
OWA	Order of Weighting Average
PET	Potential Evapo-Transpiration
PMs	Programme of Measures
QBO	Quasi-Biennial Oscillations
RBMPs	River Basin Management Plans
RI	Random index
SAW	Simple Additive Weighting
TC	Tropical Cyclones
TCA	Tana River Catchment Area
TOPSIS	Technique Order of Preference by Similarity to the Ideal Solution
WASREB	Water Services Regulatory Board
WEAP	Water Evaluation and Planning System
WEP	Water Efficiency Plan
WFD	Water Framework Directive
WRMA	Water Resources Management Authority
WTP	Water Treatment Plant
WUA	Water User Association

Appendices

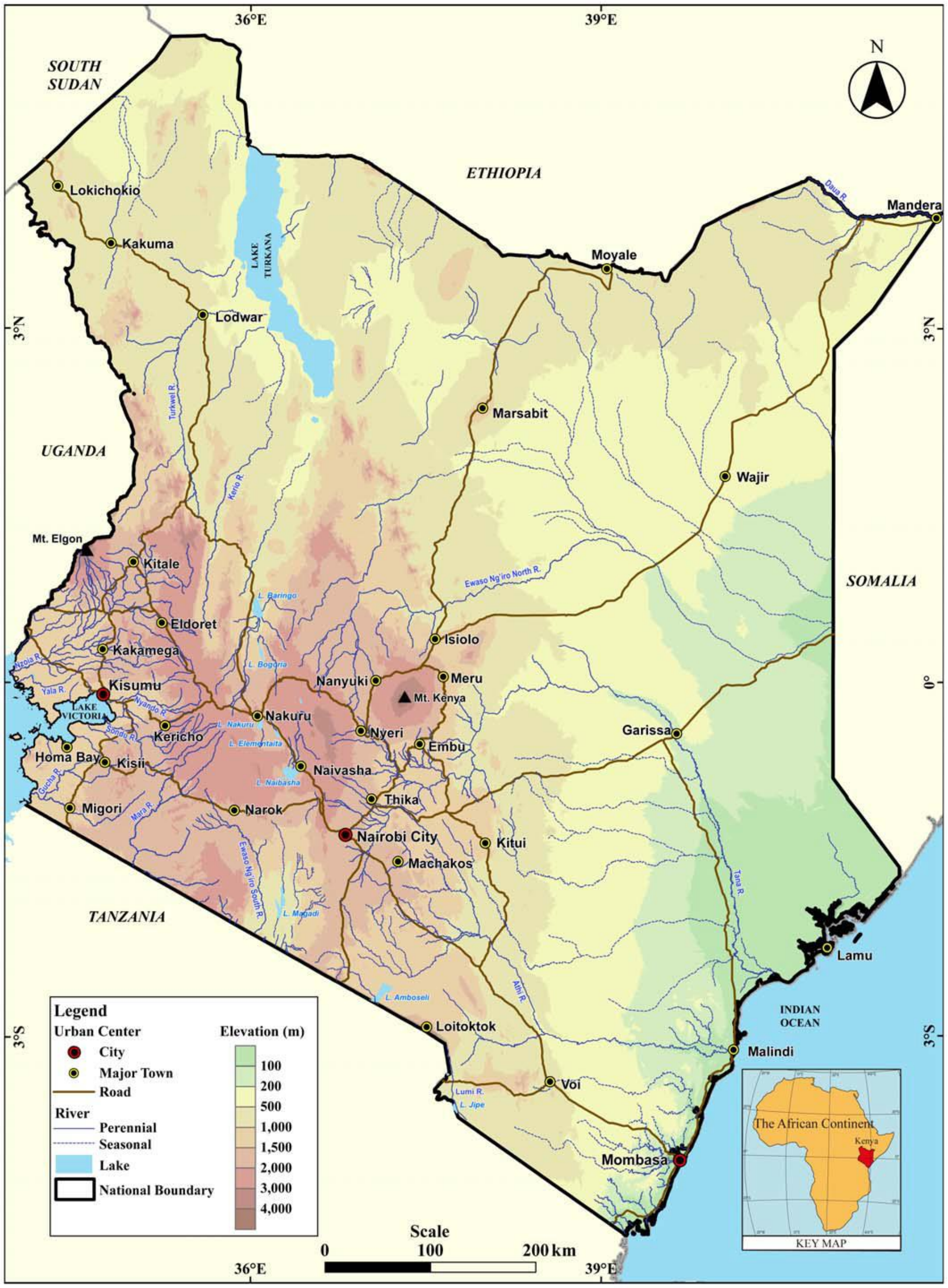


Figure 64: Map of Kenya with Key Urban centers and road connections (Source: WRMA)

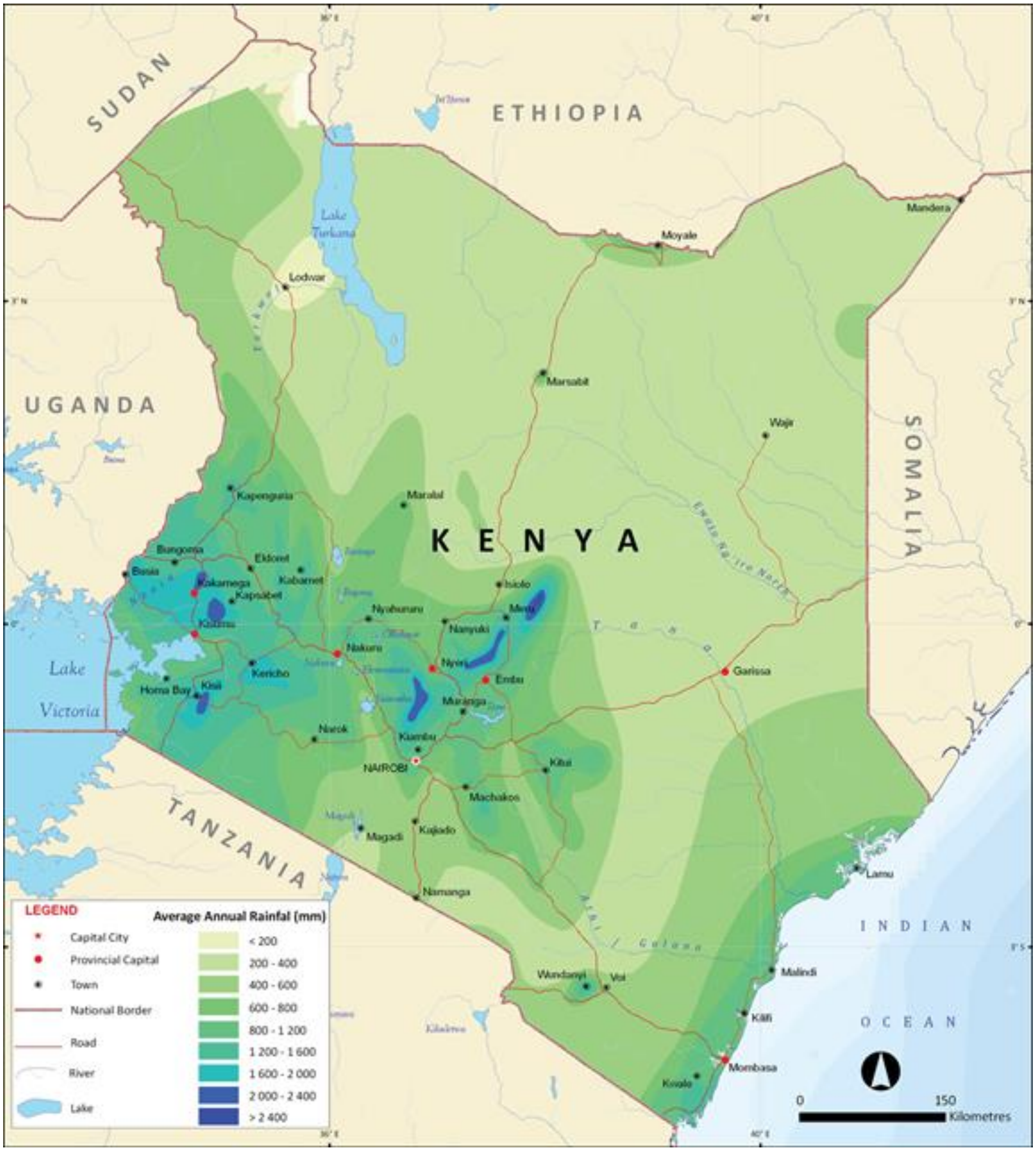
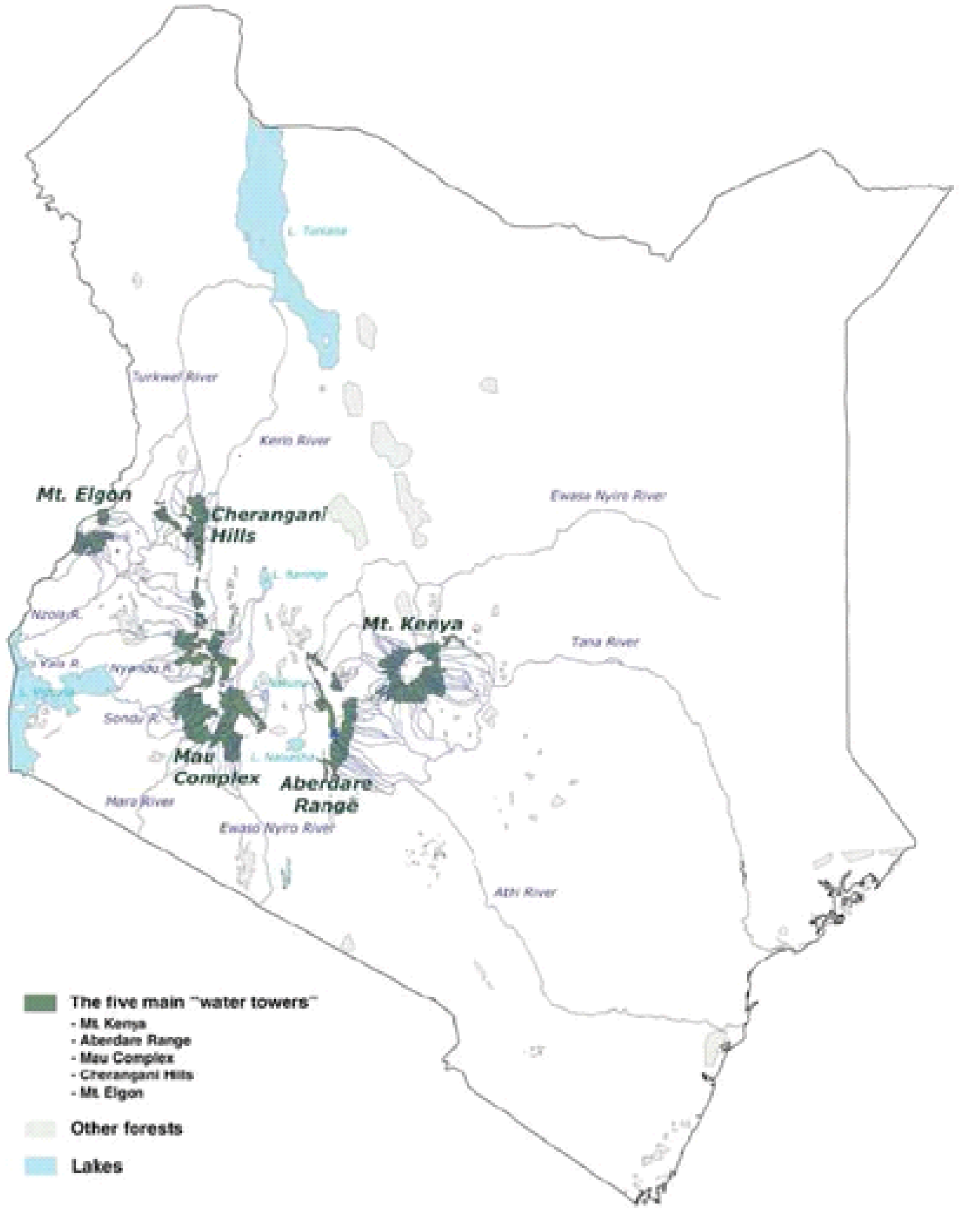


Figure 65: Distribution of mean annual rainfall – 80% arid and semi-arid land (CBS, 2012 - modified)



Source: Mogaka et al. 2006

Figure 66: The Five Major "Water Towers" of Kenya (MEWNR, 2013)

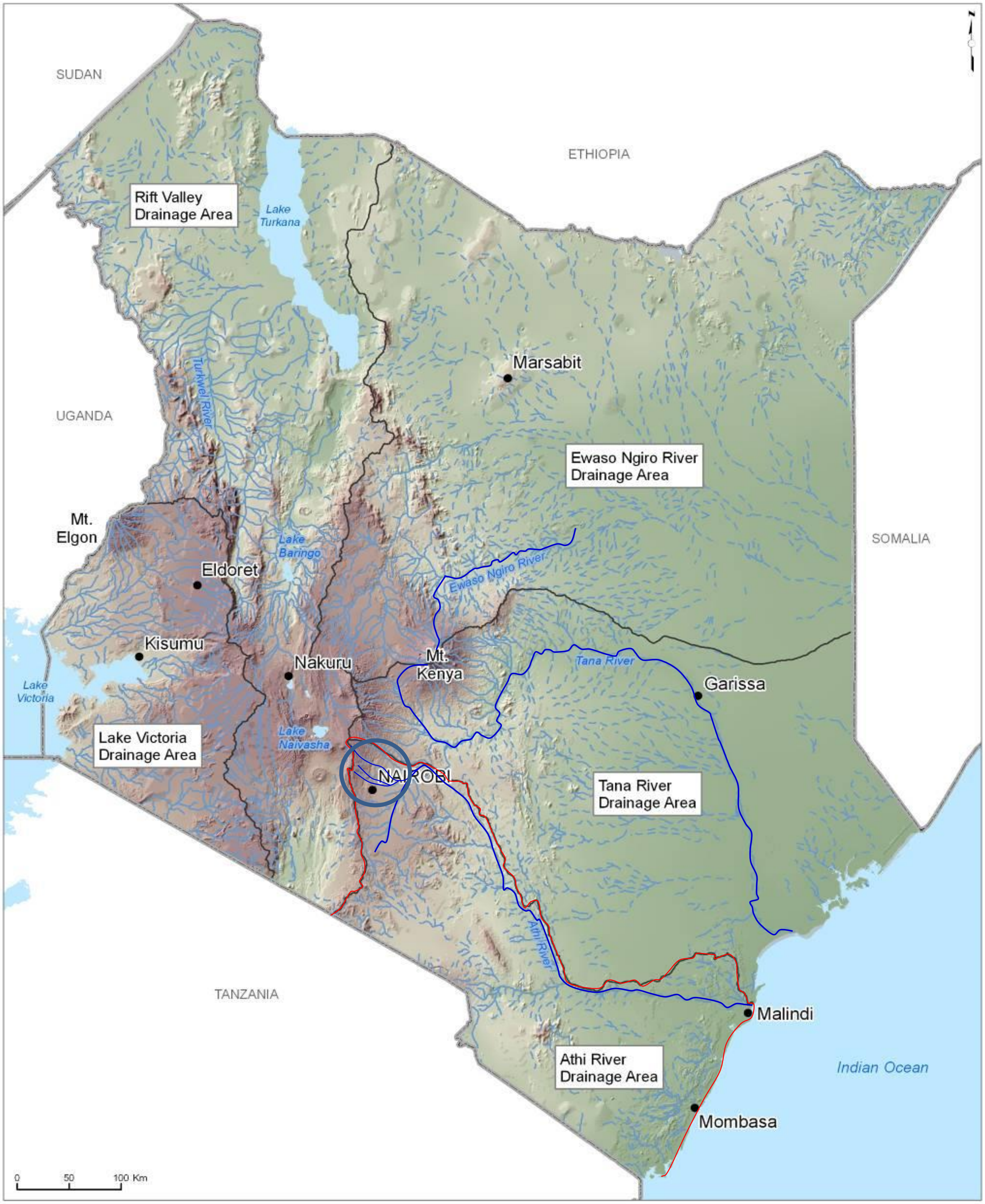
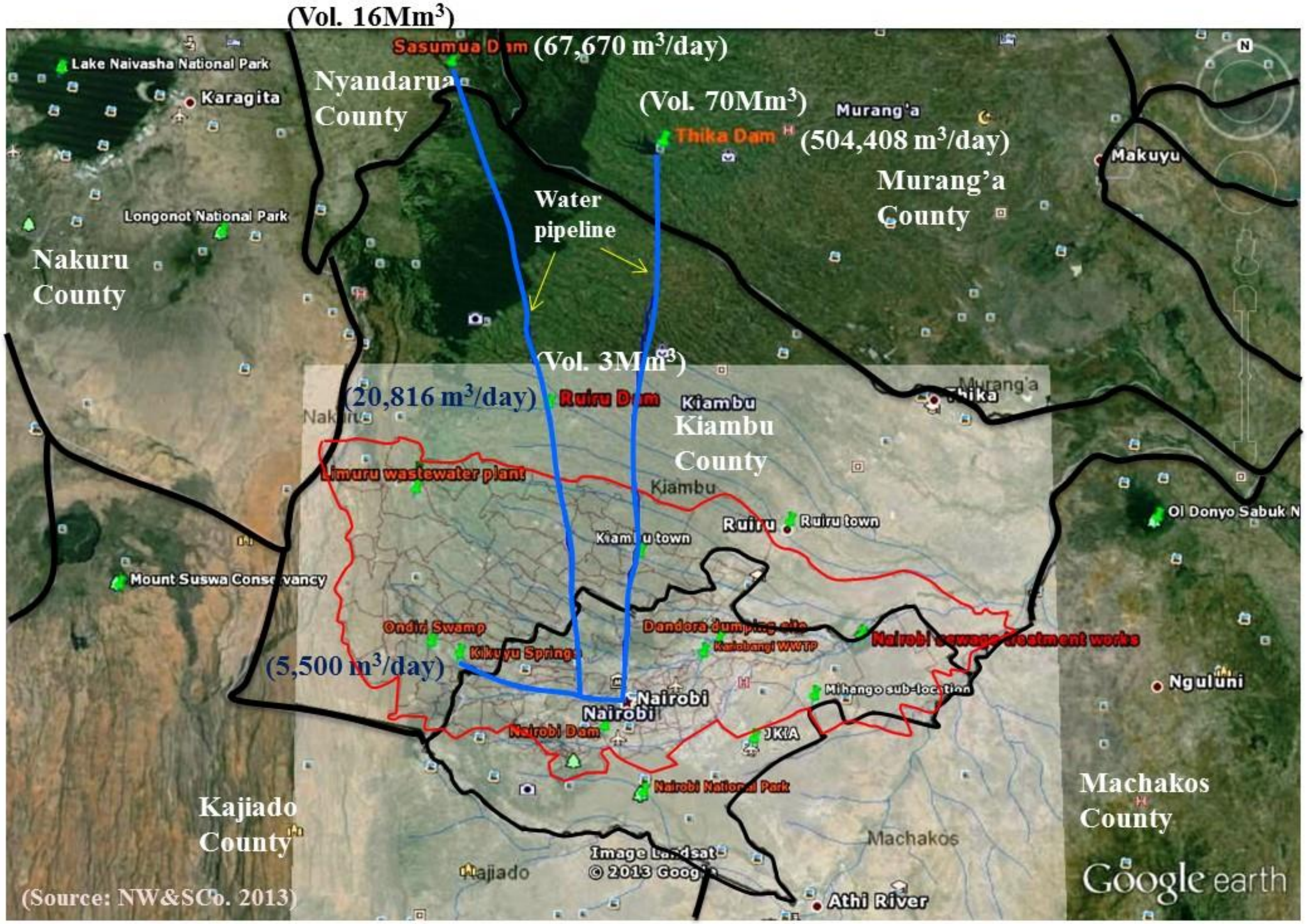
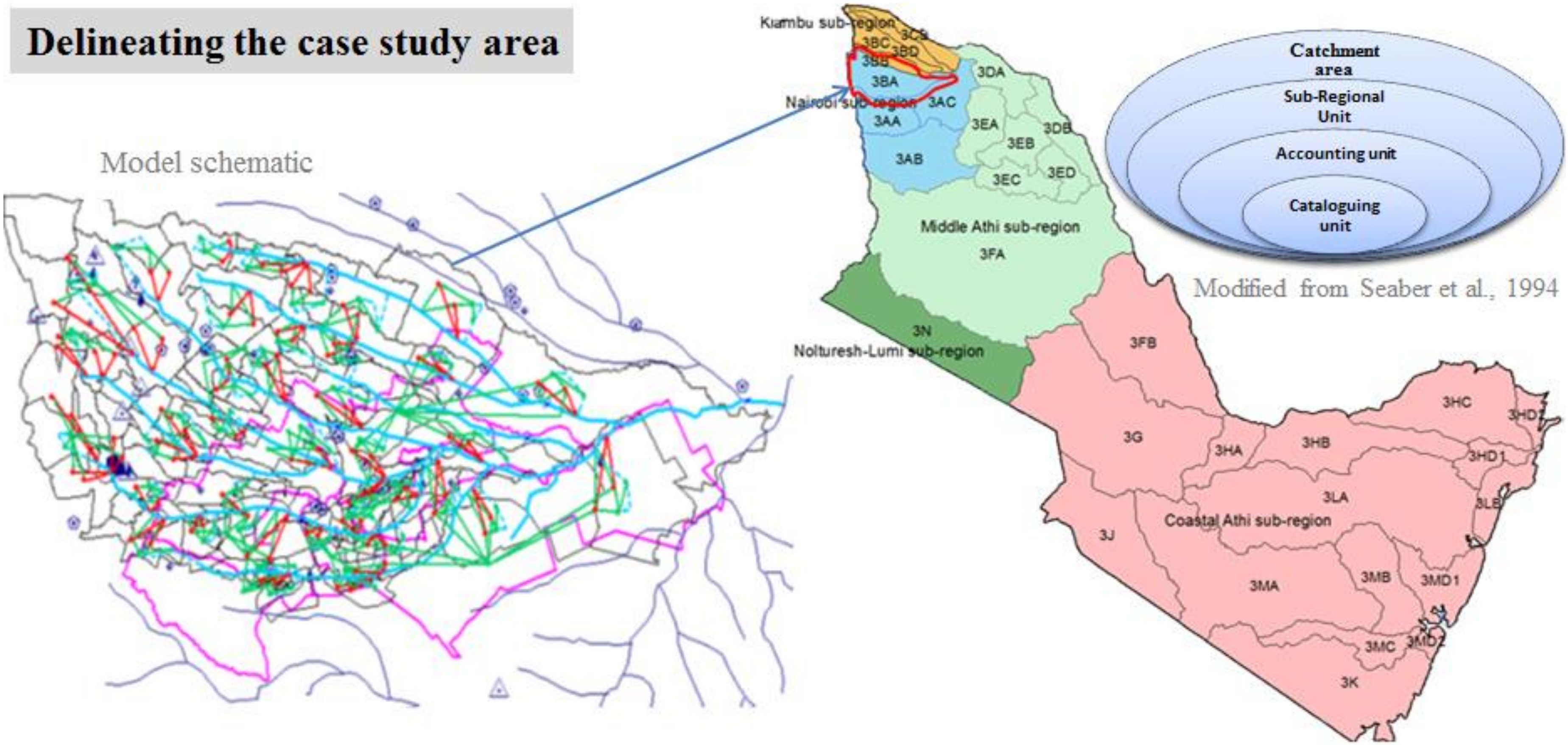


Figure 67: Delineating the Athi River basin with highlight on the case study area - (JICA, 1992) modified



(Source: NW&SCo. 2013)

Figure 68: Sources of water for the case study area whose extent overlaps Kiambu and Nairobi Counties



Modified from Seaber et al., 1994

Figure 69: Delineation of the Nairobi River catchment for modelling purposes (Model schema)

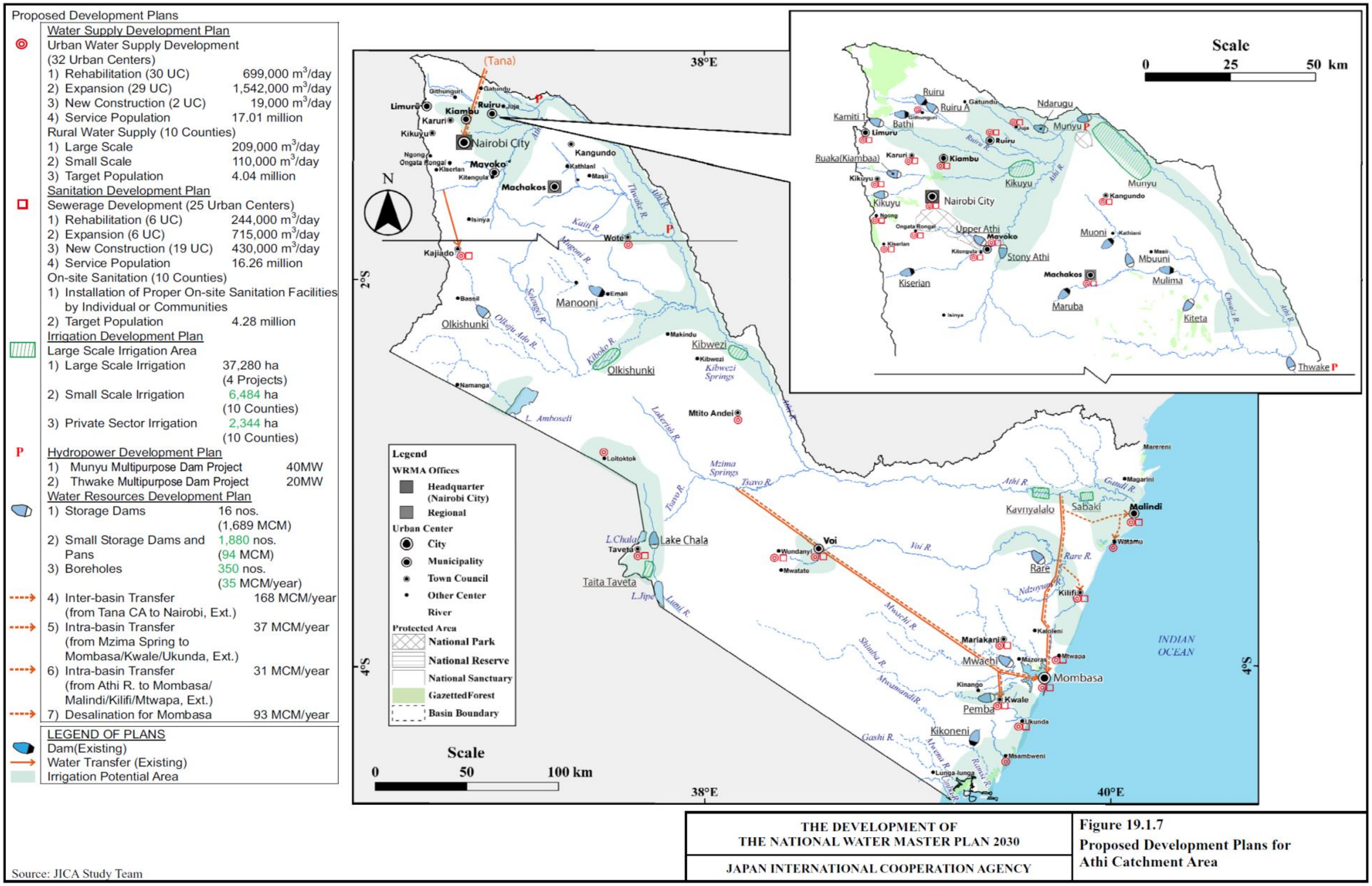


Figure 70: Proposed Development Plans within the case study area (MEWNR, 2013)

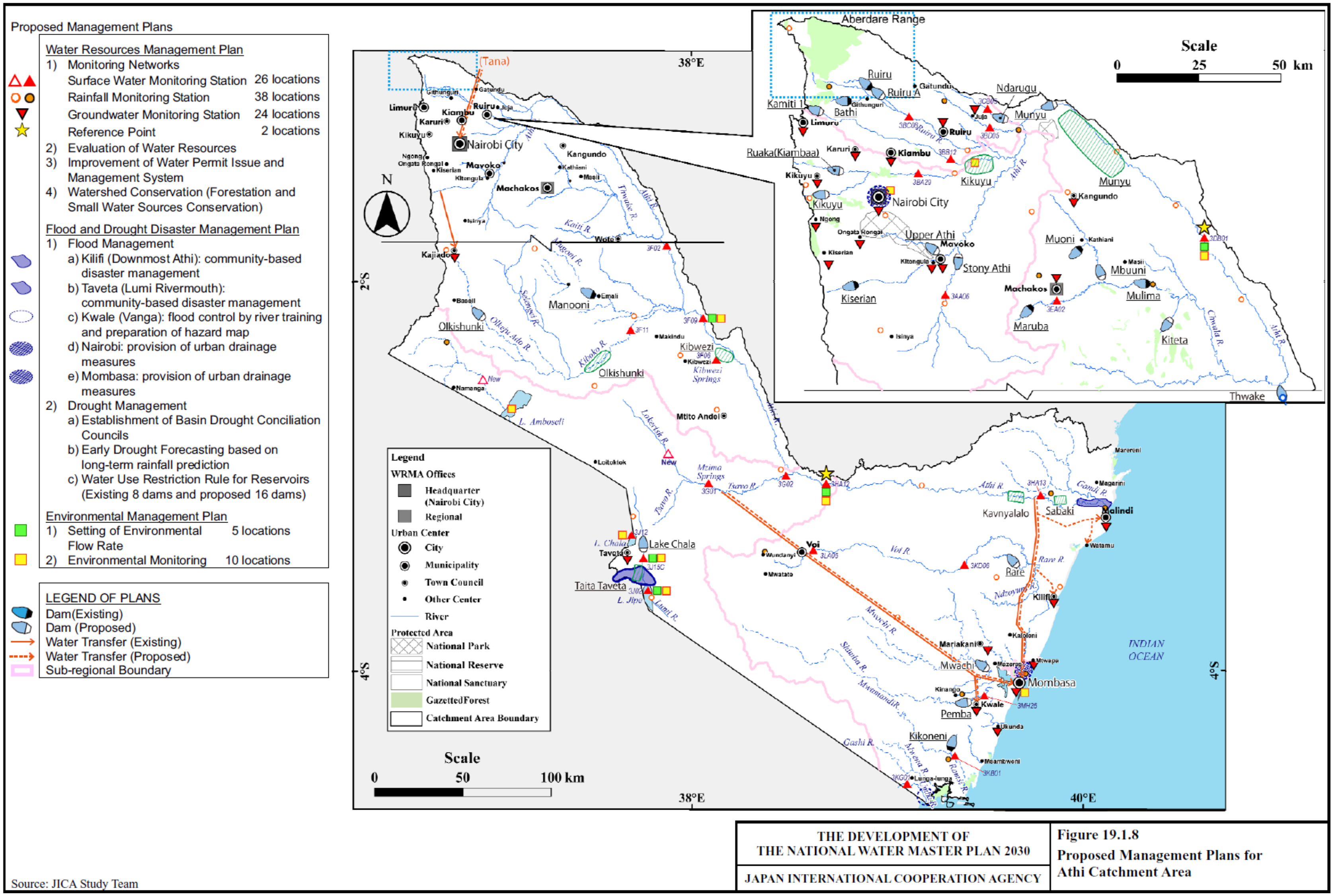


Figure 71: Proposed management plans for the case study area (MEWNR, 2013)

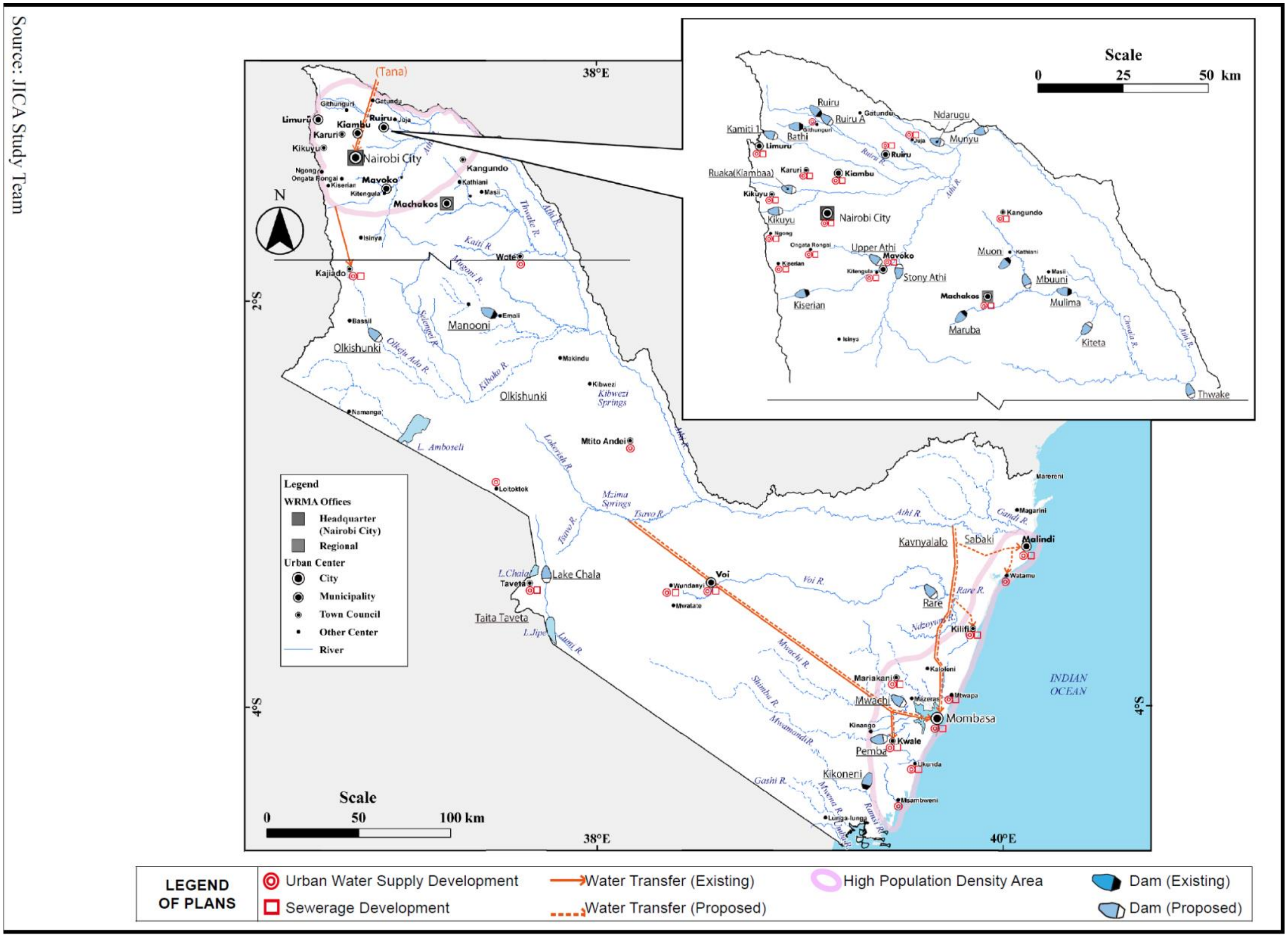

Source: JICA Study Team

Figure 72: Proposed Urban water supply and sewerage development plan (MEWNR, 2013)

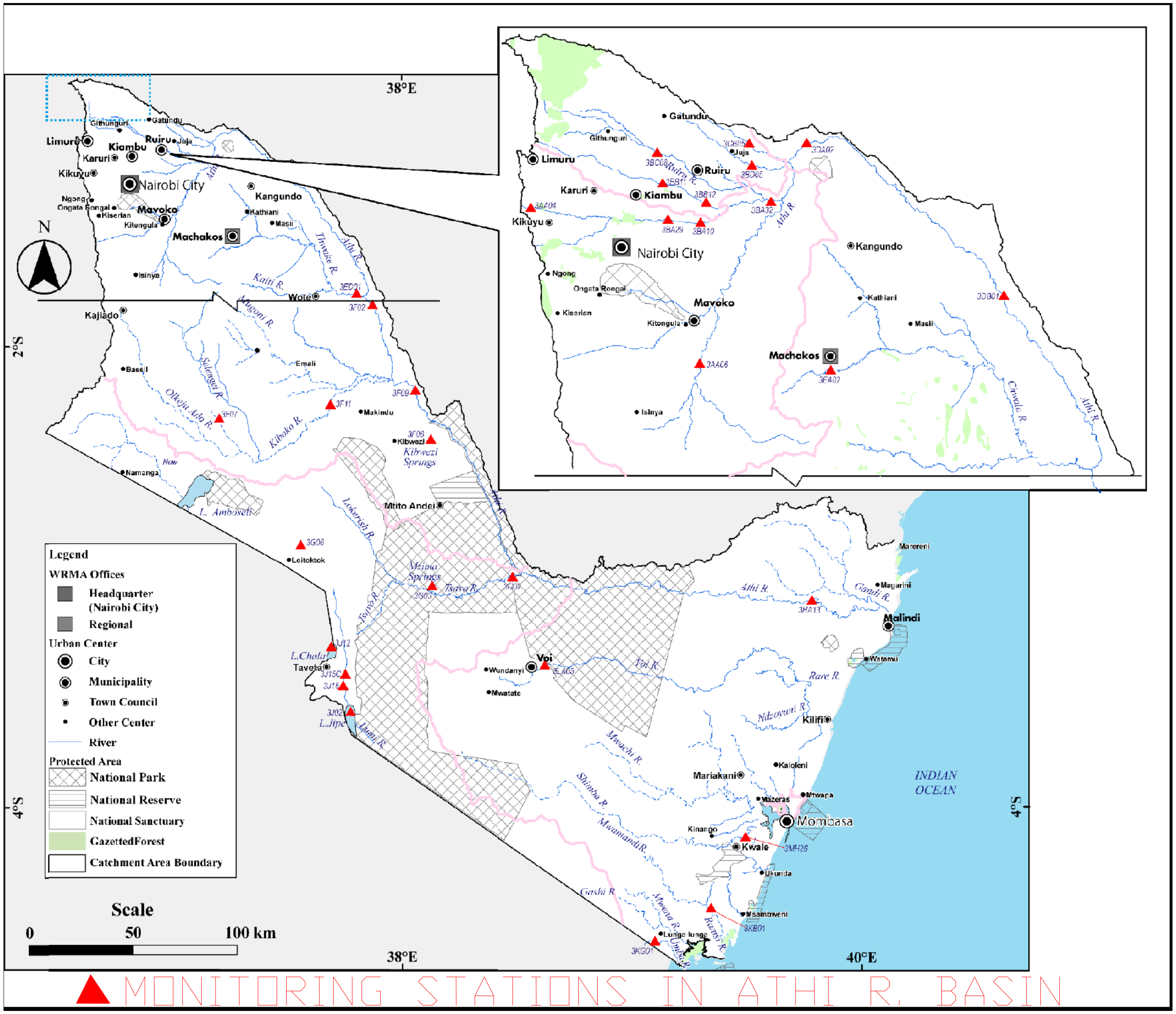


Figure 73: Proposed monitoring stations in Athi River Basin (MEWNR, 2013)

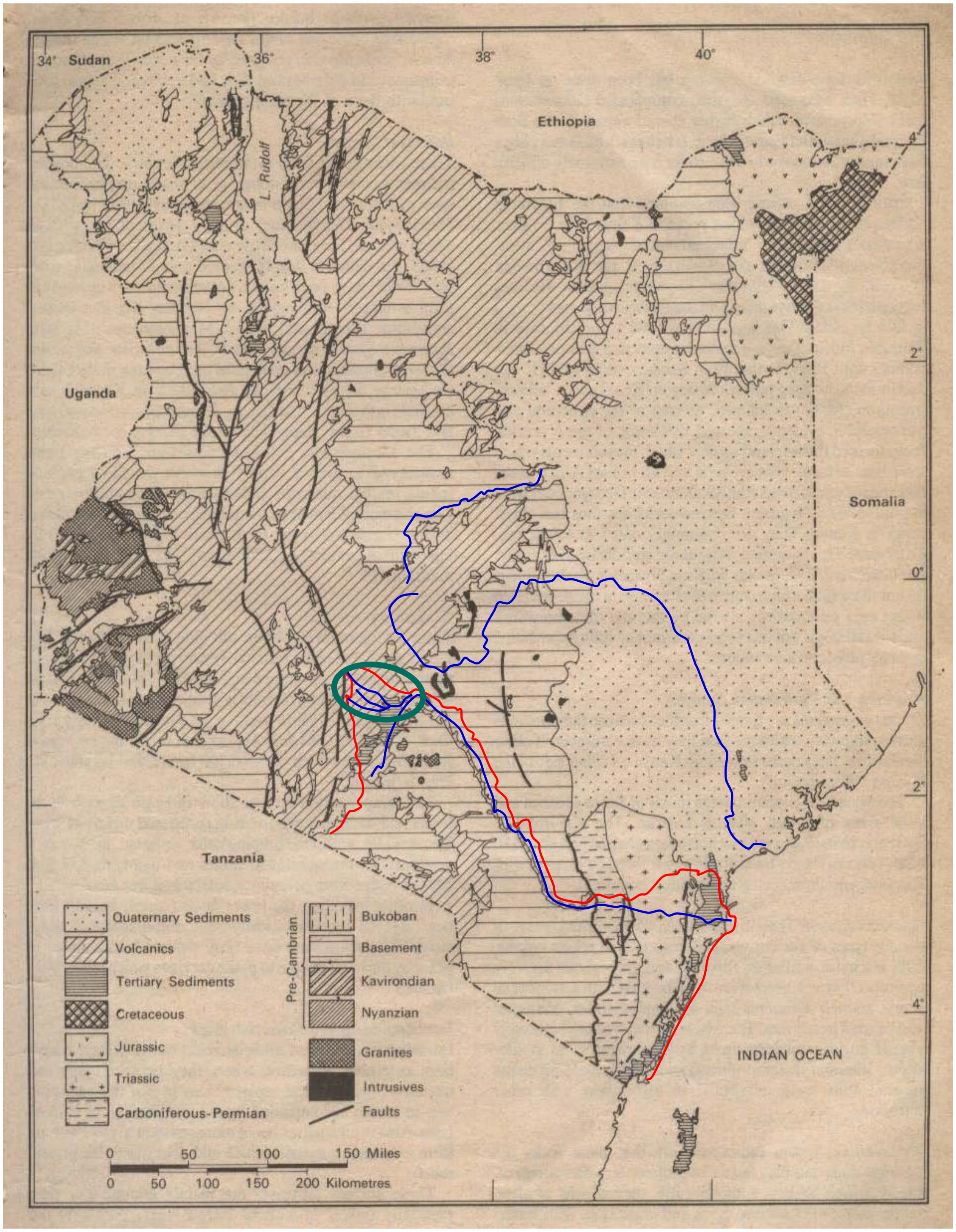


Figure 74: Geology map of Kenya showing lithology of the case study area: Modified from (MoWI, 1999)

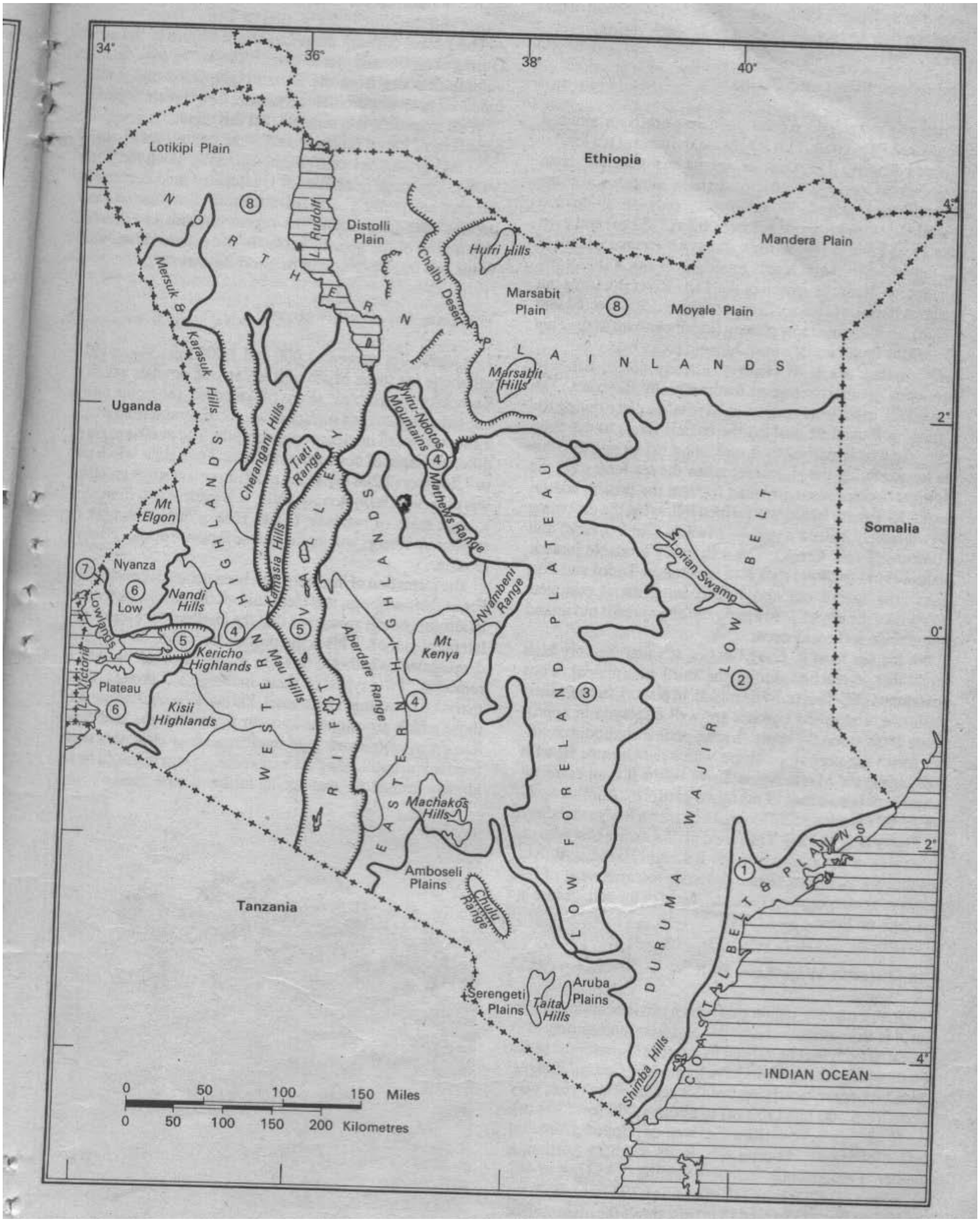


Figure 75: Physiographic Map of Kenya (Source: (MWI, 2008)

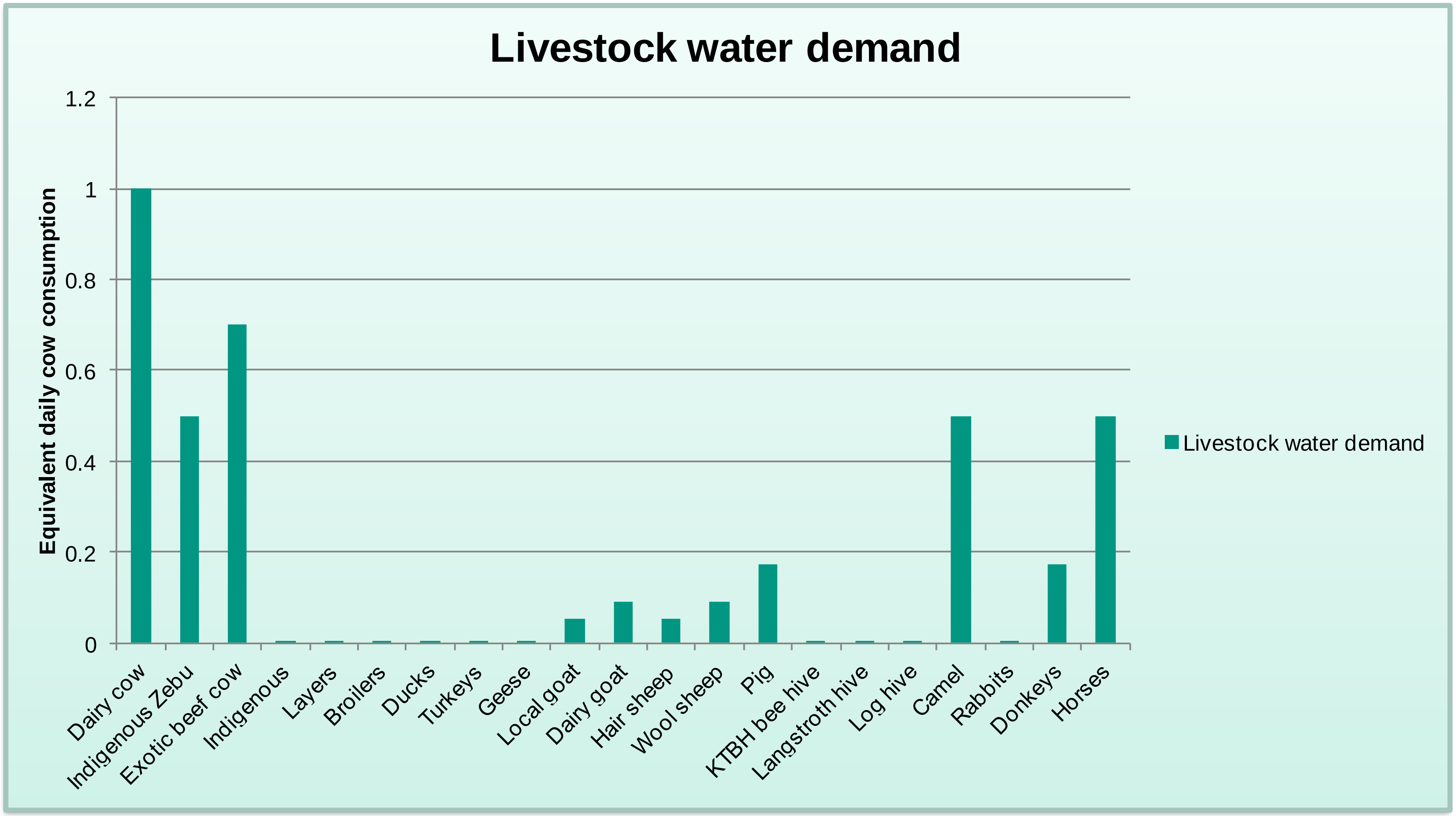


Figure 76: Livestock average daily water demand ratio to typical 'daily cow' water demand Adopted from (Ward & McKague, 2007) and (Stewart & Rout, 2007)

Table 33: Typical Agricultural crop data (Extracted from Ministry of Agriculture – Nairobi County office, 2013)

CROPS GROWN UNDER IRRIGATION	AREA UNDER IRRIGATION(HA)	IRRIGATION POTENTIAL (HA)	REMARKS
KALES , SPINACH & COWPEAS	800 Multi-storey gardens	1000 Multi-storeys	Kamukunji district
KALES & SPINACH	2 HA	8 HA	Makadara district
KALES	10 HA	50 HA	Langata district
HORTICULTURAL CROPS	50 HA	2500 HA	Njiru
VEGETABLES	8	8	Westland

CROPS STATISTICS Crop……MAIZE……….

DISTRICT	(2010)						(2011)					
	Targets Area in Ha			Achieved Area in Ha			Targets Area in Ha			Achieved Area in Ha		
	LR	SR	Total(LR+SR[10])	LR	SR	Total(LR+SR)	LR	SR	Total(LR+SR)	LR	SR	Total(LR+SR)
NJIRU	180	300	480	183	200	383	180	300	480	200	220	420
KAMUKUNJI	4.5	3.5	8	4	4.5	8.5	4.5	3.5	8	3.5	2.5	6
MAKADARA	8	6	14	7.5	4	11.5	8	6	14	6	2.5	8.5
LANGATA	56	28	84	55	21	76	56	28	84	55	4	59
KASARANI	94	65	159	50	30	80	94	65	159	45	34	79
EMBAKASI	15	10	25	10	5	15	15	10	25	70	25	95
WESTLAND	60	50	110	80	20	100	60	50	110	60	40	100
DAGORETI	82	75	157	78	69	147	82	75	157	48	58	106
STAREHE	2	1	3	0.7	0.6	1.3	2	1	3	2	1	3
TOTAL	**503.5**	**538.5**	**1040**	**468,7**	**354.1**	**822.8**	**503.5**	**538.5**	**1040**	**489.5**	**387**	**876.5**

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[10] LR stands for 'Long rains'; while SR stands for 'Short rains'

Table 34: Nairobi River Catchment: A section of water services providers: – a field questionnaire with WRMA (2013)

Item	Name	Location/ Target zone	Water sources	Spatial reference (Geo-Ref)	Availability of storage: - Capacity (m^3)	Daily abstraction approx. (m^3)	Water Loss (%)	Competing Demands	Approx. No. of served Households	Remarks
1	**Gitaru Self Help W/P**	Kikuyu: Gitaru and Kinoo	Borehole		-	500	Unmetered	2 schools (@ 50 m^3/month)	800 HH @5p/HH	Small satellite towns at the outskirt of Nairobi
2	**Kahuho Sub Location Water Project**	Kikuyu	Spring	0241349; 9867722; 1913	160	150	Unmetered	Only Household	1000 HH @ 5p/HH	Water kiosks are untenable as everyone want house connections
3	**Ondiri Water Group**	Kikuyu: Ondiri Sublocation	Borehole		-	70	Unmetered	Only household	200 HH @5p/HH	Exclusively household water supply
4	**Sigona Water Project**	Kikuyu	Borehole	0239457; 9861399; 1905	-	330	40	Household; 3 schools (@10cm/month)	400 HH;	1 water kiosk which is virtually dormant due to low demand
5	**Kamirithu Water Project**	Limuru: Kamirithu sublocation	Borehole	0236253; 9876100	-	300	Unmetered	H/H; 2 school @10 m^3/day	700 H/H	Exclusively household water supply@5p/HH; 5 water kiosk
6	**Karuri Water Company Bibironi Water Project**	Limuru	Borehole		-	150	Unmetered	HH; industry @ 70 m^3/day /water kiosks/ irrigation	2300 H/H @ 8p/HH; 5 water kiosk	Irrigation: Approximately .3 Greenhouses; Crops: Flowers and vegetables
7	**Nderu Water Project**	Limuru: Nderu sublocation	Borehole	0232915; 9872778	-	300	Unmetered	Household; 3 water kiosks; schools@25cm/day	1500 H/H; 9 School: 1 dispensary	Exclusively household supply
8	**Ngecha Community Borehole**	Limuru: Ngecha sublocation	Borehole	0240711; 9870572		50	Unmetered	Households/ 2 School	180 H/H @ 7p/HH; 1 water kiosk	Rural community water supply
9	**Mlolongo Water Supply**	Mavoko	Borehole	0270774; 9846158; 1562	-	70	25	Households; 20 water kiosks; water tankers	10 commercial buildings	Serves household and commercial supply at Mavoko municipality
10	**Karuri Water Company**	Kiambaa: Karuri Twn; Kiambaa, Muchatha, Ndenderu, Kihara,	Boreholes and NRB Water Company	0297831; 9922590	-	Mothly: 60000 – NRB 35000 -BH	40	HH/Livestock/Institutions (1 school @ 200 m^3/month)	4000HH@ 10p/HH	Serve both rural and satellite towns household connections and commercial centres and institutions: in addition to 5 water kiosks

Item	Name	Location/ Target zone	Water sources	Spatial reference (Geo-Ref)	Availability of storage: - Capacity (m^3)	Daily abstraction approx. (m^3)	Water Loss (%)	Competing Demands	Approx. No. of served Households	Remarks
11	**Kikuyu Water Company**	Kikuyu: Kikuyu Twn	Boreholes	0240348; 9861722	-	12000	40-50	H/H; Industry @5 m^3/day; commercial 70 m^3/day; schools@30 m^3/day universities (@180 m^3/day	22000 H/H; 3 Kiosks; 11 schools; 2 universities	Water kiosks not popular as house connections are preferred
12	**Limuru Water Company**	Limuru: Bathi; Mathithia; Tigoni; Ithanji	Boreholes	0238478; 9878314	-	4000	34	H/H; commercial; 5 school	6500 HH	Water treatment plant currently operating beyond capacity
13	**Rironi Self Help Water Project**	Limuru: Gatimu; Rironi: Kiroe	Boreholes		-	4090	Unmetered	Irrigation; H/H; 5 schools@17 m^3/school/month	929 HH	Resident use water for irrigation of vegetable farms
14	**Tigoni Water Project**	Limuru	Boreholes	0241752; 9874983; 2115	-	600	20	HH, institutions, recreation facilities and poultry farm	115HH	Kenchic @ 2200 m^3/month; Limuru country club @ 600 m^3/month; Tigoni school@100 m^3/month;
15	**Mavoko Water Company**	Mavoko	50% Transfer/ 35% Athi River/ 15% Boreholes	0275075; 9838173; 1562	1 million	6700	Unmetered	75% to HH and 25% to 13 No. Industries; 37 water kiosks @20 m^3/day	5500 HH	Commercial water loss 60%; Technical water loss 40%
16	**Nairobi Water & Sewerage Company Ltd**	Nairobi		0240693; 9861829; 1925	88 million in 3No. Reservoirs		40	Households; Institutions; Industries; Recreation centres	794495 HH,	Main water service provider importing 600000 m^3/day from TCA
17	**Runda Water Company**	Runda; Old-Runda; Mimosa	R. Ruaka and NRB Water Co.	0257375; 9864612; 1682	Abstraction weir: No storage	2500 River; 2500 NRB Water Co.	25	Majorly HH; 1 Hotel @ 50 m^3/m and School @ 100 m^3/m	1000 HH@ 8p/HH	Challenge of river water quality due to waste disposal; septic for waste disposal
18	**Gitangu Self Help Group**	Kikuyu: Ngecha sublocation	Spring		-	200	Unmetered	H/H	380 H/H; 4 water kiosk; 3 schools; 1 hospital	No means of evaluating water losses. Livestock major water consumer
19	**Kamuguga Water Project**	Kikuyu: Muguga	Borehole	0239929; 9866116; 2076	-	100	Unmetered	H/H; 1 water kiosk	350 HH	Water kiosks are being phased off

Table 35: Typical rates of water use for various establishments: extracted from (Metcalf, et al., 2003)

User	**(l/person or unit/day)**	**User**	**(l/person or unit/day)**
Airport, per passenger	10-20	**Institution**	
Assembly hall, per seat	6-10	Average type	400-600
Bowling alley, per alley	60-100	Hospital	700-1200
Camp		Office	40-60
Pioneer type	80-120	Picnic park, with flush toilets	20-40
Children's, central toilet and	160-200	**Country clubs**	
Day, no meals	40-70	Resident type	300-600
Luxury, private bath	300-400	Transient type serving meals	60-100
Labour	140-200	Dwelling unit, residential	
Trailer with private toilet and bath, per unit (2 1/2 persons)	500-600	Apartment house on individual well	300-400
Restaurant (including toilet)		Apartment house on public water supply, unmetered	300-500
Average	25-40	Boarding-house	150-220
Kitchen wastes only	10-20	Hotel	200-400
Short order	10-20	Lodging house and tourist home	120-200
Short order, paper service	4-8	Motel	400-600
Bar and cocktail lounge	8-12	Private dwelling on individual well or metered supply	200-600
Average type, per seat	120-180	Private dwelling on public water supply, unmetered	400-800
Average type, 24 h, per seat	160-220	Factory, sanitary wastes, per shift	40-100
Tavern, per seat	60-100	Fairground (based on daily attendance)	2-6
Service area, per counter seat	1000-1600	**School**	
Service area, per table seat	600-800	Day, with cafeteria or lunchroom	40-60
Store		Day, with cafeteria and showers	60-80
First 7.5 m (25 ft) of frontage	1600-2000	Boarding	200-400
Each additional 7.5 m of	1400-1600	Self-service laundry, per machine	1000-3000
Swimming pool and beach, toilet and shower	40-60	**Theatre**	
		Indoor, per seat, two showings per day	10-20
		Outdoor, including food stand, per car (3 1/3 persons)	10-20

Table 36: Mean monthly household demand coverage at the Nairobi River catchment

Demand Site Coverage (% of requirement met) (Percent); Scenario: Reference												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
City H.	100	100	100	100	100	100	100	100	100	100	100	100
Eastland H.	100	100	100	100	100	100	100	100	100	100	100	100
Eastleigh H.	100	100	100	100	100	100	100	100	100	100	100	100
Githurai H.	100	100	100	100	100	100	100	100	100	100	100	100
KaKoDa H.	100	100	100	100	100	100	100	100	100	100	100	100
KaNji H.	100	100	100	100	100	100	100	100	100	100	100	100
Kasarani H	100	100	100	100	100	100	100	100	100	100	100	100
KiliKeNa H.	100	100	100	100	100	100	100	100	100	100	100	100
KitiKile H.	100	100	100	100	100	100	100	100	100	100	100	100
Mihango H.	100	100	100	100	100	100	100	100	100	100	100	100
Mukuru H.	100	100	100	100	100	100	100	100	100	100	100	100
Ruai H.	100	100	100	100	100	100	100	100	100	100	100	100
Viwandani H.	100	100	100	100	100	100	100	100	100	100	100	100
Kibera H.	100	100	100	100	100	100	100	100	99	100	100	100
Tigoni H.	100	100	100	100	100	100	100	100	99	100	100	100
Limuru H.	100	100	100	100	100	100	100	100	99	100	100	100
Royraka H.	100	100	100	100	100	100	100	98	100	100	100	100
MaHu H.	100	99	100	100	100	100	100	98	100	100	100	99
Kahawa H.	100	100	100	100	100	100	100	96	99	100	100	100
Ruakihara H.	100	94	100	100	100	98	92	86	97	100	100	100
HighPark H.	98	91	99	100	100	96	92	86	97	100	100	97
Waguthu H.	98	88	100	100	100	96	89	89	98	100	100	95
Kiambaa SA H.	98	88	100	100	100	96	89	89	98	100	100	95
Kamiti H.	99	94	99	100	100	96	88	82	98	100	100	97
Riabai H.	99	94	99	100	100	96	88	82	98	100	100	97
RiKaKa H.	95	92	100	100	100	97	91	89	93	98	100	96
Ruiru H.	96	84	97	100	100	93	77	78	96	100	100	94
Cianda H.	96	84	97	100	100	92	74	74	94	100	100	94
Ndumberi H.	96	84	97	100	100	92	74	74	94	100	100	94
Ikinu H.	96	83	97	100	100	92	73	74	94	100	100	94
MUWA H.	96	83	97	100	100	92	72	74	94	100	100	94
Kiambaa H.	94	83	96	100	100	91	70	71	92	100	100	93
Kinuthi H.	86	69	95	100	100	89	49	55	65	90	100	85
Kabete H.	86	69	95	100	100	88	48	53	63	90	100	86
Nyathuna H.	86	69	95	100	100	88	48	53	63	90	100	86
Karambaini H	71	57	83	99	100	82	27	23	29	67	97	75
Rironi H.	56	30	56	90	83	65	9	9	11	34	72	59
Ngecha H.	56	30	56	90	83	65	9	9	11	34	72	59
Tinganga H.	52	27	50	87	81	63	7	8	10	30	68	53
Githiga H.	44	25	45	84	76	61	6	7	8	26	64	44
Kikuyu H.	46	24	43	82	77	62	6	6	8	25	63	45
Kikuyu Town H.	46	24	43	82	77	62	6	6	8	25	63	45
Muguga H.	46	24	43	82	77	62	6	6	8	25	63	45

Table 37: Typical available streamflow time series data: - Nairobi River (Sources: WRMA, 2013)

Year	Month	Gauged Streamflow (m^3)	Year	Month	Gauged Streamflow (m^3)	Year	Month	Gauged Streamflow (m^3)	Year	Month	Gauged Streamflow (m^3)
1960	1		1962	4		1964	7	0.419	1966	10	0.084
1960	2		1962	5		1964	8	0.434	1966	11	0.256
1960	3		1962	6		1964	9	0.310	1966	12	0.112
1960	4		1962	7		1964	10	0.260	1967	1	0.083
1960	5	0.884	1962	8		1964	11	0.251	1967	2	0.078
1960	6	0.265	1962	9		1964	12	0.282	1967	3	0.063
1960	7	0.221	1962	10		1965	1	0.300	1967	4	0.441
1960	8	0.194	1962	11		1965	2	0.160	1967	5	2.234
1960	9	0.186	1962	12		1965	3	0.135	1967	6	0.701
1960	10	0.202	1963	1	0.732	1965	4	0.408	1967	7	0.366
1960	11	0.253	1963	2	0.198	1965	5	0.434	1967	8	0.313
1960	12	0.202	1963	3	0.208	1965	6	0.204	1967	9	0.172
1961	1	0.110	1963	4	1.302	1965	7	0.185	1967	10	0.206
1961	2	0.039	1963	5	3.575	1965	8	0.153	1967	11	0.242
1961	3	0.148	1963	6	2.404	1965	9	0.128	1967	12	0.195
1961	4	0.306	1963	7	0.583	1965	10	0.150	1968	1	0.084
1961	5	0.481	1963	8	0.446	1965	11	0.238	1968	2	0.156
1961	6	0.187	1963	9	0.328	1965	12	0.219	1968	3	0.616
1961	7	0.169	1963	10	0.260	1966	1	0.253	1968	4	1.343
1961	8	0.184	1963	11	0.522	1966	2	0.136	1968	5	1.337
1961	9	0.189	1963	12	1.430	1966	3	0.194	1968	6	0.616
1961	10		1964	1	0.519	1966	4	0.486	1968	7	0.354
1961	11		1964	2	0.346	1966	5	0.663	1968	8	0.289
1961	12		1964	3	0.313	1966	6	0.146	1968	9	0.217
1962	1		1964	4	1.362	1966	7	0.142	1968	10	0.180
1962	2		1964	5	0.895	1966	8	0.129	1968	11	0.760
1962	3		1964	6	0.528	1966	9	0.120	1968	12	1.448

Excerpt break-- ‘continued’ --- Turn over

Year	Month	Gauged Streamflow (m^3)	Year	Month	Gauged Streamflow (m^3)	Year	Month	Gauged Streamflow (m^3)	Year	Month	Gauged Streamflow (m^3)
1983	9	0.132	1986	1	1.542	1988	5	21.331	1990	9	2.970
1983	10	0.121	1986	2	1.190	1988	6	12.298	1990	10	2.555
1983	11	0.239	1986	3	1.764	1988	7	4.783	1990	11	6.851
1983	12	0.385	1986	4	14.749	1988	8	3.078	1990	12	
1984	1	0.198	1986	5	24.986	1988	9	2.107	1991	1	3.509
1984	2	0.067	1986	6	1.772	1988	10	1.672	1991	2	1.585
1984	3	0.536	1986	7	1.235	1988	11	5.655	1991	3	5.625
1984	4	0.328	1986	8	1.464	1988	12	7.400	1991	4	8.882
1984	5	0.876	1986	9	0.854	1989	1	2.267	1991	5	17.644
1984	6		1986	10	0.672	1989	2	1.190	1991	6	6.739
1984	7		1986	11	1.044	1989	3	2.267	1991	7	3.157
1984	8	0.405	1986	12	0.627	1989	4	8.351	1991	8	2.683
1984	9	0.608	1987	1	0.953	1989	5	24.819	1991	9	1.886
1984	10	0.161	1987	2	0.498	1989	6	7.895	1991	10	1.421
1984	11	0.251	1987	3	1.474	1989	7	8.959	1991	11	1.851
1984	12		1987	4	3.925	1989	8	4.464	1991	12	
1985	1	0.722	1987	5	4.908	1989	9	4.495	1992	1	1.341
1985	2	2.784	1987	6	1.772	1989	10	4.307	1992	2	1.058
1985	3	2.835	1987	7	1.235	1989	11		1992	3	1.009
1985	4	69.198	1987	8	0.868	1989	12		1992	4	1.230
1985	5	7.814	1987	9	0.605	1990	1	12.229	1992	5	12.037
1985	6	2.301	1987	10	0.567	1990	2	3.353	1992	6	4.057
1985	7	1.856	1987	11	1.044	1990	3	37.195	1992	7	3.745
1985	8	0.807	1987	12	0.627	1990	4		1992	8	2.820
1985	9	0.729	1988	1		1990	5	19.225	1992	9	1.526
1985	10	1.009	1988	2		1990	6	8.813	1992	10	1.083
1985	11	7.530	1988	3	2.762	1990	7	7.212	1992	11	
1985	12		1988	4	14.597	1990	8	4.271	1992	12	

CURRENCY UNITS, WEIGHTS AND MEASURES

Currency Unit = Kenya Shilling (Kshs.)

USD 1 = KES 85.00 (Date, source: CBK)

EUR 1 = KES 115.00 (Date, source: CBK)

1 kilogram (kg) = 2.204 pounds (lb)

1 hectare (ha) = 10,000 m^2

1 hectare (ha) = 2.47 acres

Per Capita = per person/head

Fiscal Year = 1st July 2013 to 30th June 2014