APPLICATION OF THE WEAP MODEL IN INTEGRATED WATER RESOURCES MANAGEMENT OF THE NYANDO RIVER BASIN, KENYA

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A thesis submitted in partial fulfillment for the degree of Master of Science in Agricultural Engineering in the Jomo Kenyatta University of Agriculture and Technology

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DECLARATION

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

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This thesis has been submitted for examination with our approval as the University Supervisors.

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DEDICATION

Dedicated to my dear wife Grace and our loving children David, Joan, Ezra and Ruth-Esther for their perseverance, prayers and support during my entire study period.

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ABBREVIATIONS

CBS	Central Bureau of Statistics
DEM	Digital Elevation Model
DSS	Decision Support System
D_W	Lower storage Zone
DS	Demand Sites
f	Soil, land cover, topography parameter.
FAO	Food and Agriculture Organization
GIS	Geographical Information System
GWP	Global Water Partnership
HEC	Hydrologic Engineering Centre
ILRI	International Livestock Research Institute
ITCZ	Inter-Tropical-Convergence Zone
JICA	Japanese International Corporation Agency
KMD	Kenya Meteorological Department
KSS	Kenya Soil Survey
Kj	Root zone Hydraulic Conductivity
K_c	Crop coefficient
LAI	Leaf Area Index
MCM	Million Cubic Metres
MWI	Ministry of Water and Irrigation
R^2	Coefficient of Determination
RMSE	Root Mean Square Error

SEI	Stockholm Environmental Institute
Sw_j	Total Soil Moisture Storage Capacity
SWAT	Soil and Water Assessment Tool
UNEP	United Nations Environmental Programme
WAB	Water Appeals Board
WEAP	Water Evaluation and Planning Systems Model
WRMA	Water Resources Management Authority
WSB	Water Service Boards
WSP	Water Service Providers
WSRB	Water Services Regulatory Board
WSTF	Water Services Trust Fund

ABSTRACT

The Nyando River Basin experiences highly variable weather patterns which pose a challenge to water resources availability and distribution. There is need to store flood water for use during drought especially for irrigation. The potential of the three dams proposed by JICA to meet the irrigation water requirements for rice irrigation in the Kano Plains needs to be investigated. There is need to develop long term and sustainable water resources management strategies for the basin. This study was therefore undertaken to evaluate the current and future water supply, demand status, water allocation and the ecological water requirements in the basin in a sustainable way.

Rural, urban, livestock, industrial and Irrigation water demands were calculated and the in-stream flow water requirement set. Irrigation water demand for the basin was simulated at current, half and full irrigation potential. Scenarios were then developed to evaluate the unmet irrigation water demand.

Results of the study revealed that the basin presently has high unmet water demand. The total Current Unmet Water Demand was estimated at 15.33 MCM. The Unmet ecological flow requirement with two dams in place was highest in January at 5.0 MCM during extreme low flows. With the expansion of basin irrigation area to its full potential, the total unmet irrigation water demand would be 482 MCM. Scenario studies revealed that with establishment of the three proposed dams, it is possible to satisfy the full irrigation potential development in Ahero and S.W. Kano from the current 1600 ha to 25000 ha.

CHAPTER 1

INTRODUCTION

1.1 Overview

Water scarcity and poorly managed water resources have become major threats to food security, human health and natural ecosystems. People in developing countries are particularly at risk in areas experiencing high population growth and limited means of managing water resources. An estimated 1.4 billion people, amounting to a quarter of the world's population in developing countries, live in regions that will experience water scarcity by 2025 (Seckler et al., 1999).

Water is a key resource whose use and development will determine the rate of social and economic development of our country. With the increasing growth in population and the economy including urbanization, industrial production, agricultural and livestock production, demand for water has increased rapidly over the years. Precipitation varies immensely over time and space and most tropical and subtropical regions of the world are characterized by huge seasonal and annual variations in rainfall (GWP, 2000). The above factors have further compounded the water scarcity problem. The increase in water demand has reduced water availability during dry seasons and has as well increased water conflicts in the watersheds.

There is a need to involve representatives of all local stakeholders in decision making processes on water allocation. This would improve their understanding of the water allocation processes that affect water quality and quantity and the interdependencies between upstream and downstream water uses in the watersheds. It is also increasingly important to provide quantitative information about the state of water resources. Demand and supply of water could also change over space and time as a result of changes in land-use, population growth, demographic shifts within the watershed, industrial development and water development initiatives such as dam construction

In evaluating the range of available management tools the role of conceptual level models and forecasting systems should be considered in the achievement of sustainable water resources management. These can allow better prediction of temporal and spatial variations in the quality and quantity of available water resources. An effective water management tool must address the two distinct systems that shape the water management landscape i.e. the biophysical and socio-economic management systems. The biophysical system is driven by, climate, topography, land cover, surface water hydrology, groundwater hydrology, soils, water quality and the ecosystem. However, the socio-economic management system is driven largely by human demand for water. These systems determine how available water is stored, allocated and delivered within or across watershed boundaries.

1.2. Statement of the Problem

The world population has increased by a factor of about three during the 20th century whereas water withdrawals have increased by a factor of about seven. It is estimated that currently one third of the world's population live in countries that experience medium to high water stress. This ratio is expected to grow to two thirds by 2025 (GWP, 2000). It is estimated that Kenya has 19,500 MCM of renewable water. The current per capita availability of renewable water is estimated as 750 cubic meters. By the year 2025 when the population is expected to be 60 million, the per capita is forecast to drop to 235 cubic meters (Hirji et al., 1996). Therefore Kenya is considered a water scarce country. There is an urgent need to lay down strategies to deal with the water scarcity.

People living in the Nyando River Basin with highly variable weather patterns experience droughts and floods and often have insecure livelihoods. Water resources availability and use, especially information on floods, droughts, water allocation, water resources planning and water quality are key concerns in the Basin (Samez Consultants, 2005).The population is rapidly increasing at the average rate of 3.4% (Republic of Kenya, 1999a) thereby giving rise to decreasing per capita available water. In addition the existing water supplies are threatened in quality and quantity by land use and land cover changes, pollution from point and non-point sources and climatic change. There is therefore potential for water use conflicts especially between communities upstream and downstream of the basin mainly due to wide disparities in natural resource base. Communities in the upper part of the catchment are richly endowed with land and water resources while those in the lower parts have generally lower rainfall, and remain vulnerable to extreme weather conditions such as drought and floods. The lower reaches are also continuously subjected to decreasing per capita food production, due to unfavourable weather conditions and inappropriate farming practices. Therefore, there should be long term and sustainable water resources management strategies for the basin. The prevailing short term planning does not consider future demands and how shrinking water resources can be allocated. The long term plans should include an approach to water management that considers the Nyando as a river with unlimited potential to satisfy current and future needs. This would help to tap the huge and largely unexploited irrigation potential in the basin that can contribute to food security especially in the lower catchment.

It is internationally agreed that the economic base of an individual can influence his vulnerability to natural disasters. A strong economic base improves the resistance of an individual to natural disaster (UNEP, 2004). There is high poverty incidence in the Nyando Basin (Figure 1.1), ranging from an average of 58% in Kericho district, 63% in Nandi district and 67% in Nyando district (Samez, 2005). There is therefore the need to maximize the use of available land and water resources as a means of enhancing agricultural activities for improved livelihood and poverty reduction. The maximization of the use of land potential and the use of water in an integrated approach are critical issues to basin management, sustainable economic development, environmental management and poverty reduction. The irrigation undertaken in the lower reaches of the basin has not reached its maximum potential and the canals are mostly silted up due erosion load from upstream. The Ministry of Water and Irrigation has proposed several dams for use in the basin (MWRMD, 2004) There is need to use the proposed dams in the catchment for irrigation and domestic water allocation, flood management and silt reduction. The exploitation of rice cultivation to its full potential would enhance food self-sufficiency, increase the local rural income and provide employment opportunities. Contributions to food security are more pronounced in group-based irrigation and

National Irrigation Board (NIB) Schemes, where rice is the main crop accounting for 90 per cent of rice produced in the country (Kimani and Otieno, 1992). Kenya produced 70,000 tonnes of rice in 2005 against a demand of 280,000 tones and imported 210,000 tonnes of rice the same year (USDA, 2006).

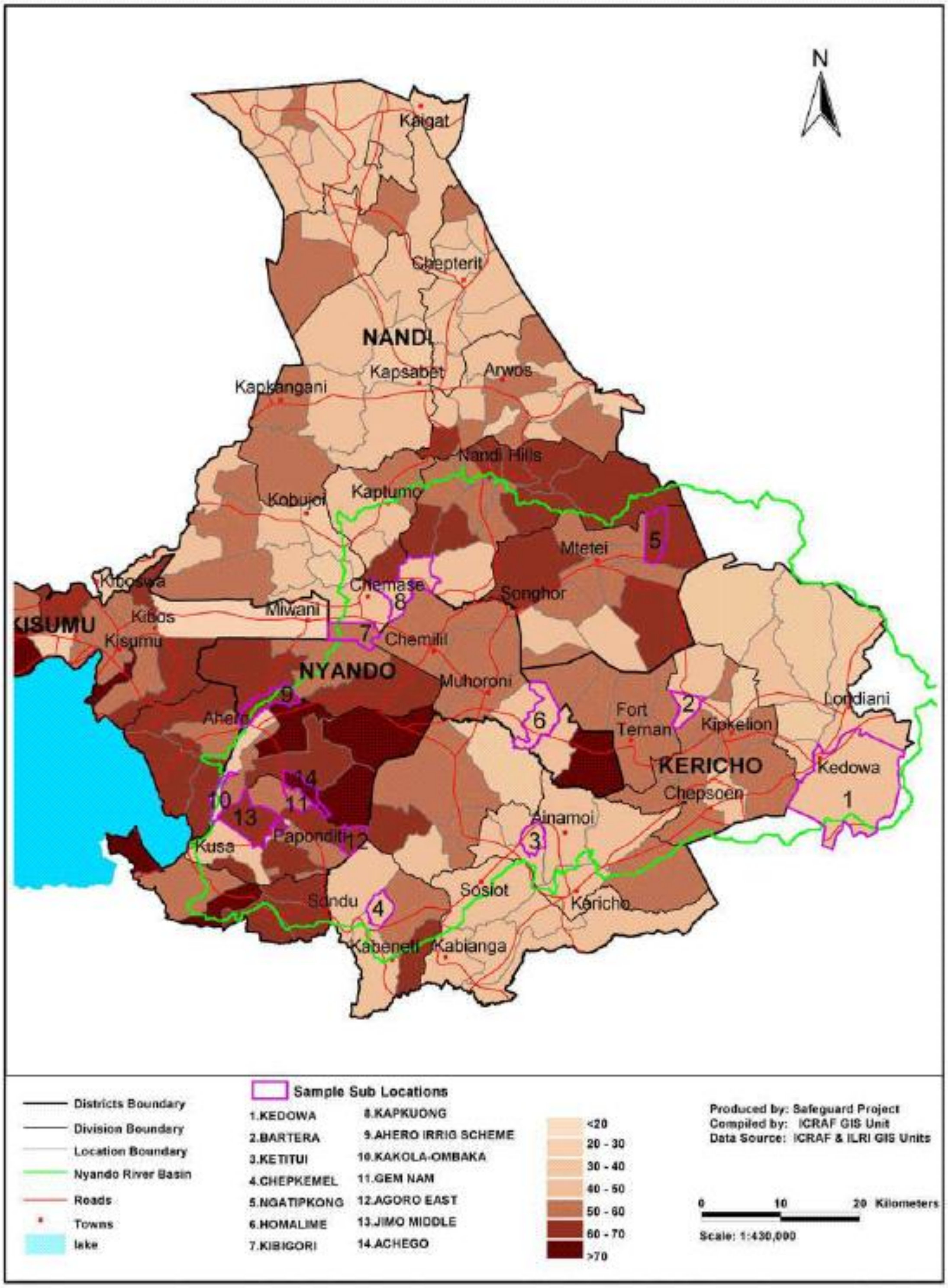

Figure 1.1. **Percentage of population below poverty line in the Nyando Basin.**

(Source: Onyango et al (2005))

This study is therefore aimed at answering the following research questions:

- What integrated water resources management options can be used to optimize water utilization in the basin?
- How can the proposed dams in the upper catchment be used to meet irrigation water requirements if area under rice irrigation in the Kano Plains is expanded to half and full of the potentially irrigable area?
- How can the future water supply and demand be predicted in relation to envisaged development strategies?

1.3 Objectives:

The main objective of this study was to develop a tool that can be used for sustainable integrated water resources management in the Nyando River Basin. The specific objectives were:

- To determine spatial and temporal distribution of available river water resources and the current domestic, urban, irrigation and ecological water demands.
- To evaluate future domestic, urban, irrigation and ecological water demand scenarios in the basin.
- To evaluate the WEAP model as an integrated water resources management strategy tool for balancing water supply and demand for current and future conditions in a sustainable way.

CHAPTER 2

LITERATURE REVIEW

In this chapter various kinds of relevant literature have been reviewed. Firstly, there is a discussion on Integrated Water Resources Management (IWRM) and Water Balance in the Water Evaluation and Planning System (WEAP). Secondly there is a discussion on the Nyando Basin Water Resources. Finally there is a discussion on Modeling and the key aspects of the WEAP Model.

2.1 Integrated Water Resources Management

IWRM is 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 (Global Water Partnership, 2000). The key aspect is the acceptance that water comprises an ecological system which is formed by a number of interdependent components (Mitchel, 1990). Each component may influence other components and therefore needs to be managed with regard to its interrelationships. Management of water resources requires an understanding of the nature and scope of the problem to be managed. An integrated approach to water resources management entails identification of conflicts of interest between upstream and downstream stakeholders. Recognition of downstream vulnerability to upstream activities is imperative. Water resources management involves both natural and human systems.

The involvement of the concerned stakeholders in the management and planning of water resources is universally recognized as a key element in obtaining a balanced and sustainable utilization of water (GWP, 2000). The stakeholders are best involved at project inception and commencement by seeking their views on the management methods envisaged. The pollution loads discharged upstream will degrade river water quality. Land use changes upstream may alter groundwater recharge and river flow seasonality. Consumptive uses upstream may also alter downstream river flows. Flood control measures upstream may threaten flood-dependent livelihoods downstream. Such conflict of interest must be considered in an integrated water resources management strategy with full acknowledgement of the range of physical and social linkages that exist in complex systems. To deal with such conflicts a water-resources management strategy should develop operational water balancing tools for the evaluation of trade-offs between different objectives, plans and actions. The GWP (2000) notes that the management instruments for Integrated Water Resources Management are the tools and methods that enable and help decision-makers to make rational and informed choices between alternative actions. These choices should be based on agreed policies, available resources, environmental impacts and the social and economic consequences.

The IWRM framework and approach is based on three complementary elements i.e. the enabling environment, the institutional role and the management instruments. This study focuses on the management instruments including operational instruments, for effective regulation. These enable decision makers to make informed choices between alternative actions. The Dublin principles which aim to improve water resources management are fundamental to this study. The principles are:

- Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment.
- Water development and management should be based on a participatory approach, involving users, planners and policymakers at all levels.
- Women play a central part in the provision, management and safeguarding of water.
- Water has an economic value in all its competing uses and should be recognized as an economic good

Nevertheless, for a comprehensive water resources management to be achieved, a thorough assessment of the available water resources has to be undertaken. In most cases however, available information about the water resources situation is scarce, fragmented, outdated and inconsistent. Without adequate access to scientific information concerning the hydrologic cycle and the associated ecosystems, it is not possible to evaluate the available resource or to balance its availability and quality against demands. Hence, the development of a water resources knowledge base is a precondition for effective water management. It takes stock of the resource and establishes the natural limits for management. The water resources knowledge base must therefore include data on the variables which influence demand such as population and per capita water use. Only with such data can a flexible and realistic approach to assessing water demands be taken. The use of scenario building for water demand projections may be advantageous and serve to identify possible ranges for various categories of future water demands (Smits et al., 2004).

2.2. Water Evaluation and Planning System (WEAP).

The Water Evaluation and Planning System (WEAP) is a microcomputer tool for integrated water resources planning (SEI, 2005). It places the demand side of the equation – water use patterns, equipment efficiencies, re-use, prices and allocation – on an equal footing with the supply side – streamflow, groundwater, reservoirs and water transfers. Operating on the basic principle of water balance accounting, WEAP is applicable to municipal, rural, agricultural, single sub-basins and complex river systems. The WEAP model was chosen for this study because of its integrated approach to simulating water systems and its policy orientation. It is comprehensive, straightforward and easy to use. It also acts as a database for maintaining water demand and supply information. WEAP has an intuitive graphical interface which provides a simple yet powerful means for constructing, viewing and modifying the system and its data.

2.3. Water Balance in WEAP

The Water Balance is an accounting of the inputs and outputs of water. The analysis is done to account for all the water entering or leaving any hydrologic system. It can be determined by calculating the input and output and storage changes of water at the earth's surface (Ritter, 2006). Water balance may be desired for drainage to remove excess surface and subsurface water, to estimate safe yield at a site for a ground water aquifer, to compute evaporation from a reservoir and for purposes of water abstractions from the rivers. Inputs into a water balance may constitute precipitation, streamflow and surface runoff, while outflow may constitute streamflow discharge, sub-surface discharge and evapotranspiration. To assess a water balance, a careful selection of both the area boundaries and time period is essential and all the water quantities need to be expressed in the same units. The Nyando Basin for example is a whole unit that comprises of irrigation farms, domestic and industrial demand sites, river reaches and reservoirs. These are very useful in planning, regulations and management of the entire hydrologic system. Mass balance equations are the foundation of monthly water accounting in WEAP, where total inflows equal total outflows, net of any change in storage. Every node and link in WEAP has a mass balance equation. The equation is given as follows:

$$\sum Inflow = \sum Outflow + Addition\ to\ Storage \tag{1}$$

The amount supplied to a demand site *(DS)* is the sum of the inflows from its transmission links. The inflow to the demand site from a supply source (*Src)* is defined as the outflow from the transmission link connecting them (equation 2).

$$DemandSiteInflow_{DS} = \sum_{Src} TransLinkOutflow_{Src,DS} \tag{2}$$

Every demand site has a monthly supply requirement for water as computed in demand calculations. The inflow to the demand site equals this requirement (equation 3).

$$DemandSiteInflow_{DS} \leq SupplyRequirement_{D} \tag{3}$$

Some fraction of the water received by a demand site will be unavailable for use elsewhere in the system (i.e. because the water is consumed- lost to evaporation, or otherwise unaccounted for – it disappears from the system). This consumption fraction is shown as follows (equation 4).

$$Consumption_{DS} = DemandSiteInflow_{DS} * DemandSiteConsumption_{DS} \quad (4)$$

Of the inflow that is not consumed, the remainder flows out of the demand site either to another demand site for re-use or to surface or ground water. Any demand sites directly re-using this outflow will take what they need. The remainder is sent to the various return flow destinations. These return flow routing fractions are input and are expressed as:

$$DemandSiteReuseOutflow_{DS1} = \sum TransLinkOutflow_{DS1,DS2} \quad (5)$$

$$DemandSiteReturnFlow_{DS} = DemandSiteInflow_{DS} - Consumption_{DS} - DemandSiteReuseOutflow_{DS} \quad (6)$$

The dynamic balance between surface water and groundwater in WEAP can also be illustrated in the following schematic module. When groundwater is depleted, a stream contributes to aquifer recharge, while a stream is considered to be gaining when there is substantial recharge to the aquifer across the watershed and flow is from the aquifer to the stream (Yates et al., 2005a). The aquifer is a stylized wedge that is assumed symmetric about the river (Figure 2.1) with the total aquifer storage estimated under the assumption that the ground water table is in equilibrium with the river.

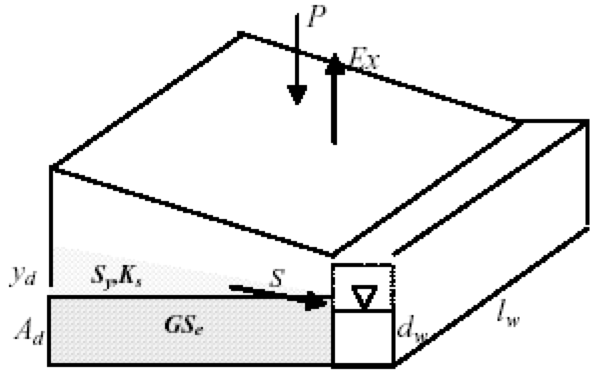

Figure 2.1. Schematic of Groundwater-Surface water balance. (Source: Yates et al, 2005)

Thus the equilibrium storage for one side of the wedge, GS_e is given as,

$$GS_e = h_d * l_w * A_d * S_y \tag{7}$$

Where h_d (m) represents the normal distance that extends horizontally from the stream, l_w (m) is the wetted length of the aquifer in contact with the stream, S_y is the specific yield of the aquifer and A_d is the aquifer depth at equilibrium. An estimate of the height which the aquifer lies above or is drawn below the equilibrium storage height is given by y_d, so the initial storage GS in the aquifer at $t=0$, is given as,

$$GS(0) = GS_e + (y_d * h_d * l_w * S_y) \tag{8}$$

The vertical height of the aquifer above or below the equilibrium position is given as

$$y_d = \frac{GS - GS_e}{(h_d * l_w * S_y)} \tag{9}$$

and the more the aquifer rises relative to the stream channel, the greater the seepage back to the stream and vice versa where total seepage, *S* from the side of the river (m^3/time) is defined by

$$S = (K_s * \frac{y_d}{h_d}) * l_w * d_w \tag{10}$$

where K_s (m/time) is an estimate of the saturated hydraulic conductivity of the aquifer, and d_w (m) is an estimate of the wetted depth of the stream. Once seepage is estimated, then half of the aquifer's total storage for the current time step is given as

$$GS(i) = GS(i\text{-}1) + (1/2\ P\text{-}1/2\ Ex - S) \tag{11}$$

Where E is the water withdrawn from the aquifer to meet demands, *i* is the period, and R is the watershed's contributing recharge.

2.4 Past Studies in the Basin

Numerous studies have been done on the Nyando River Basin mostly tackling the flood menace, land degradation and the debilitating poverty. A recent study by Samez Consultants (2005) for the Japanese International Cooperation Agency (JICA), has suggested many areas for research with regard to Integrated Water Resources Management. The study has noted that an overview of water resource utilization must be given, in order to assess the sources and demands, land use categories and areas of conflict. It further suggests that long-term sustainability, available alternatives and opportunities also need to be explored and that forecasting and prediction of demands and trends is also necessary for forward planning. The baseline data can then be entered into a GIS database or modeled in order to generate what-if scenarios, i.e. with business-as-usual or 'if things change'. In this case modeling can be used for data storage and update and as a planning and decision support tool. A Study by Njogu (2000), found out that there exists uncertainty in the projection of water demand, the actual water use and the unaccounted for water in the Nyando Basin. It further found out that the actual water supply potential is not precisely known because of its lateral flow and un-gauged tributaries. The Study suggested the application of systems approach in the water resources potential and demands assessment using spreadsheet models. Other studies done on the Nyando Basin include, the use of United States Geological System Stream flow Model (USGS-SFM) for Flood Simulation by Muthusi (2004) and Muthusi et al (2005) which evaluated the use of the USGS Model as a flood simulation tool and explored the use of satellite based rainfall data. Sang (2005) used Geographic Information System (GIS) based version of Soil and Water Assessment Tool (SWAT) to evaluate the effect of changes in land use/land cover, climate and reservoir storage on flooding in the Nyando Basin and concluded that conversion of forests into agricultural land would result into increased flooding.

The knowledge gap is therefore clearly about sustainable water resources management with regard to water allocation based on supply and demand side management. This requires the use of a spreadsheet model capable of data storage and prediction of future demand scenarios. Such a model would also tackle policy issues such as water rights through prioritization and preference based water demand and supply. WEAP model is capable of undertaking measures that can bridge the gap.

2.5. Description of the study area

2.5.1. Location

The Nyando River Basin is situated in the western part of the Republic of Kenya in Eastern Africa (Figure 1.2). It is one of the sub-basins that drain into Lake Victoria. It covers an area of approximately 3600 km^2 (Njogu, 2000).

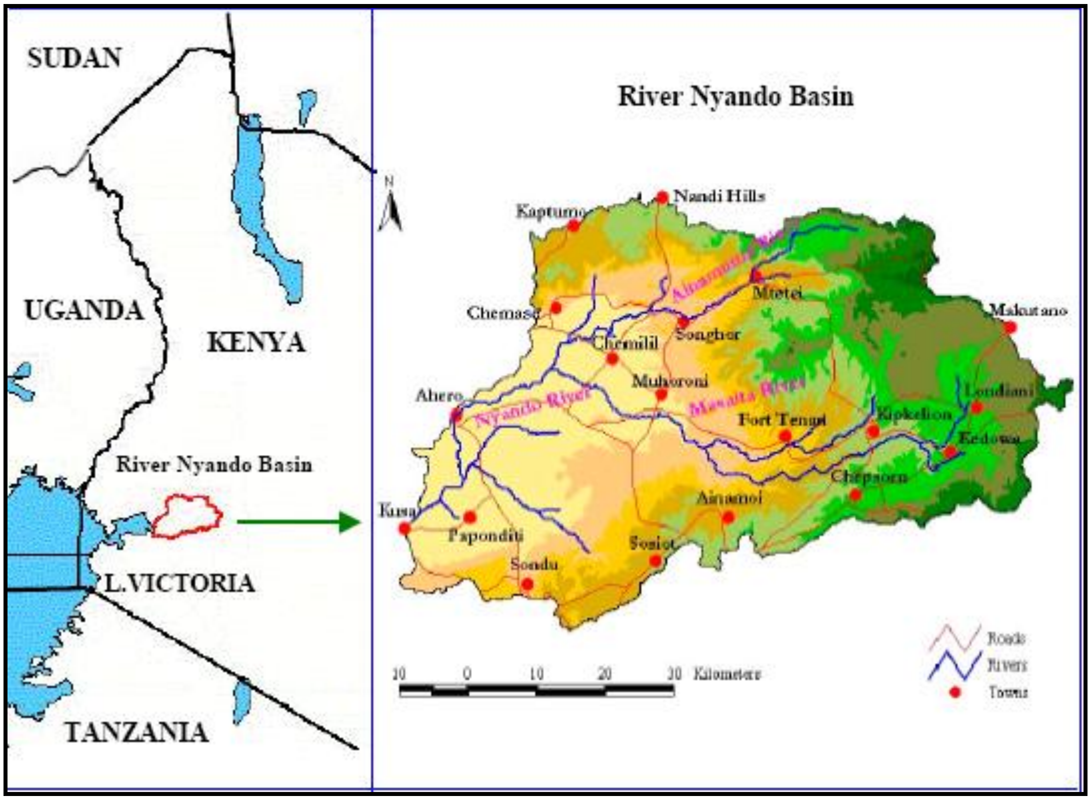

Figure 1.2. Nyando River Basin. (Source: Muthusi, 2004)

The basin covers the entire Nyando District and parts of Kisumu District all in Nyanza Province, and South Nandi and Kericho Districts in the Rift Valley Province (Figure 1.3). The basin is bounded by latitudes 00 7’ 48”N and 00 24’ 36”S and longitudes 340 51’E and 350 43’ 12”E. It is located between Lake Victoria to the west, Tinderet Hills to the east, Nandi escarpment to the north and Mau escarpment to the South-East. The land generally slopes in the North East - South West direction.

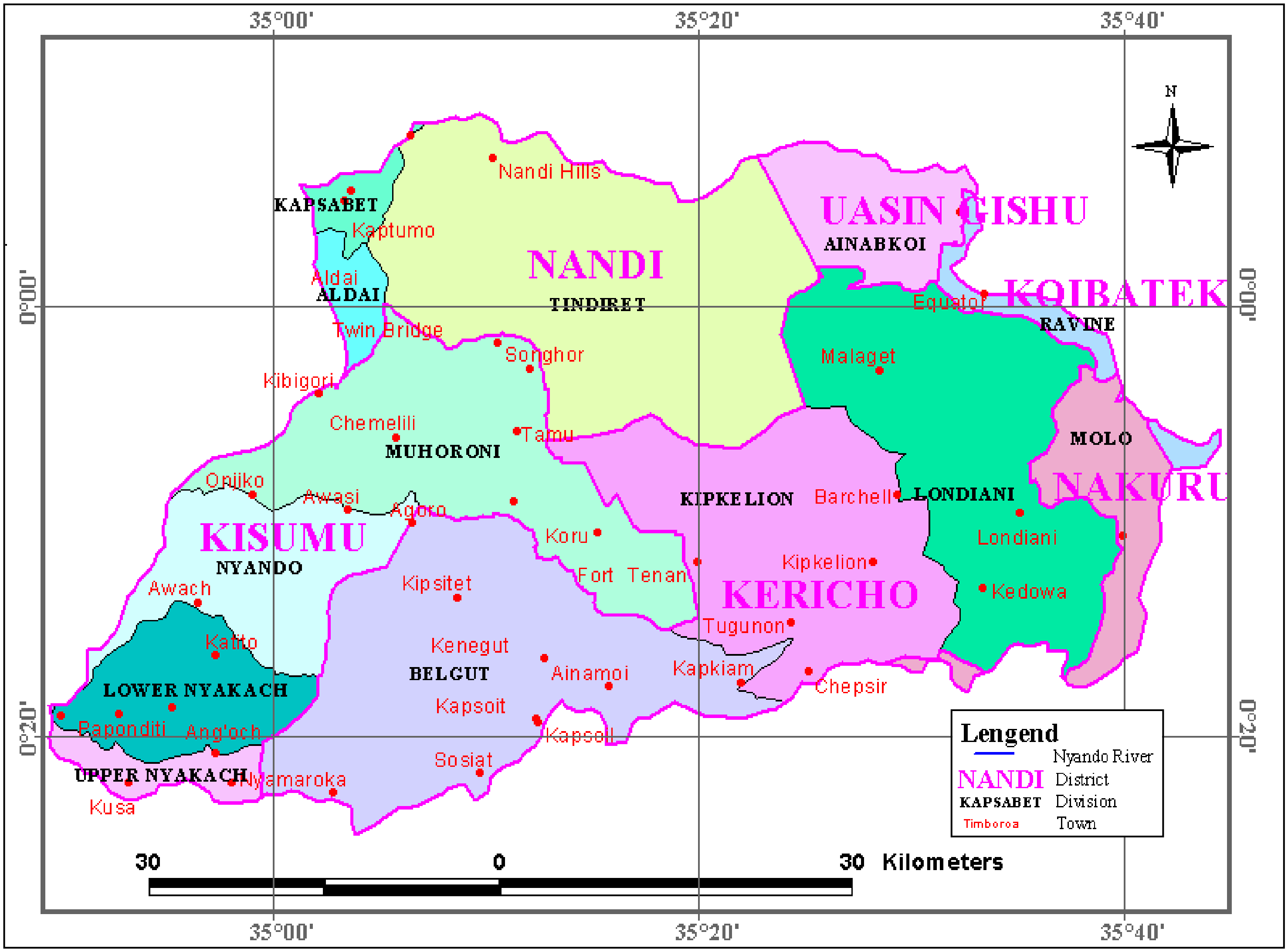

Figure 1.3. Nyando Basin District Boundaries

2.5.2. Topography

The Nyando Basin can be divided into three regions depending on the river profile (Onyango et al., 2005). These are the upstream, midstream and downstream regions which lie between 1800 – 3000m, 1300 – 1800m and 1000 – 1300m above sea level respectively. The basin physiography consists of scarps formed by the rift faults, which shape the Kavirondo Rift branching from the main north-south oriented Rift Valley System. Foot slopes are typically along the Nandi escarpment in the north and Mau escarpment in the south. A gently shaped piedmont plain and a very flat alluvial plain are mainly found in the surface of alluvial deposit and Pleistocene deposit (JICA, 1992a).

2.5.3. Climate

Climate in the basin is diverse due to altitude differences from the upstream to downstream regions. The rainfall regime is bi-modal with long rains falling between March-May while short rains fall between September-November. In the upstream and midstream reaches, the average annual rainfall ranges from 1200mm to 1600mm and the temperatures range from 5^0 C to 27^0 C. In the downstream regions the average annual rainfall ranges from 800mm to 1200mm, and the temperatures range from 12^0 C to 31^0 C. The Inter-Tropical Convergence Zone (ITCZ), Lake Victoria proximity and the high altitudes in the upper parts of the basin are the driving force behind the spatial-temporal variations of rainfall. Generally, the rainfall decreases from the high altitude to the lowlands round the lake.

2.5.4. Soils

In the mountainous upstream reaches, the dominant soils are excessively drained to well drained and deep to very deep. The soils range from the fertile dark reddish brown Humic Nitisols to friable clay and Humic Cambisols. In the gently undulating to the undulating slopes of the midstream, the soils are moderately well drained to imperfectly drained, deep to very deep. The soils here are also cracking sandy clay to clay and in some places shallow and stony. The soils are classified as Eutric and Calcic Vertisols, Vertic Luvisols and Gleyic Cambisols. In the flat to very gently undulating slopes of the downstream reaches, the soils range from imperfectly drained to poorly drained grayish black to black cracking clay. The soils are classified as Eutric Vertisols and stagnic Luvisols with sodic phases (Waruru et al., 2003).

2.5.5. Hydrology

Nyando catchment is mainly drained by the River Nyando. Its main tributaries are Ainapngetuny and Kipchorian Rivers, which originate from Nandi and Tinderet hills, Londiani, and West Mau forests respectively. They are perennial rivers while minor tributaries such as Nyaidho, Awach, Namuting, Mbogo and Kapchorua are seasonal. River Nyando traverses highlands (Londiani, Kipkelion, Kericho, Koru and Muhoroni) and lowlands (Chemelil, and Nyando plains), a distance of approximately 170km with a western flow direction up to the north of Awasi market after which it meanders south westwards through the Kano plains. It finally dissipates into swamps in Kusa area before discharging into Lake Victoria at Winam gulf.

2.5.6. Water Management

The major water uses in the Nyando Basin include domestic, industrial, irrigation and livestock watering purposes. Water Management and Provision has in the past been the preserve of the Government under the Ministry of Water and Irrigation. Presently the Nyando Basin falls under the management of the Lake Victoria South Water Services Board. The Board has constituted Water Companies to manage water supply in the basin. The Companies provide water and sanitation services to their customers and collect revenue. Water Resources and Water Catchments in the basin are managed by the Water Resources Management Authority. The potential surface water resources in the Nyando Catchment are estimated at 702 MCM/Year. This is an average of 60MCM/ Month (Njogu, 2000).

2.5.7. Sub-watersheds

The basin is divided into 7 sub-watersheds according to the river gauging stations designation (JICA, 1992b), namely, GA, GB, GC, GD, GE, GF, and GG . The main river tributaries (namely, Nyando-Ainabng'etuny, Nyando-Kipchorian and the main Nyando River) fall in the sub-watersheds GA, GB, GC and GD. These cover, Kipkelion, Londiani, Tinderet, Buret, Nandi South, Chemelil, Muhoroni, Kibigori and Ahero areas. The sub-watersheds are shown in Figure 1.4.

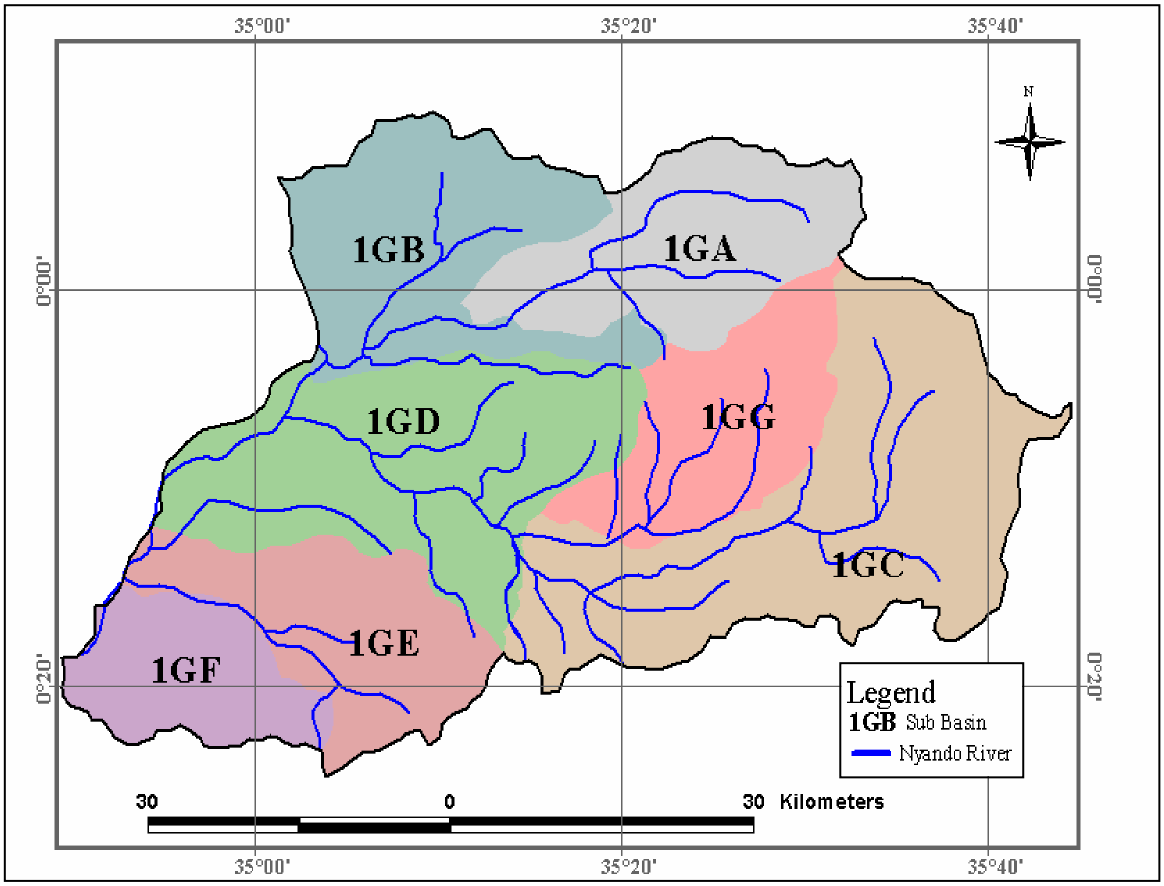

Figure 1.4. Nyando Basin Sub-watersheds

2.5.8. Land Use/Land cover

According to Samez Consultants (2005), about 65% of the arable land in the upstream region is utilized for active farming. The region is mostly under grassland, woodlots, natural forest and cultivation of tea, coffee and annual crops. More than 50% of the land in the upstream region is under grassland, woodlots and cultivation. Figure 1.5 shows a generalized land use pattern for the basin.

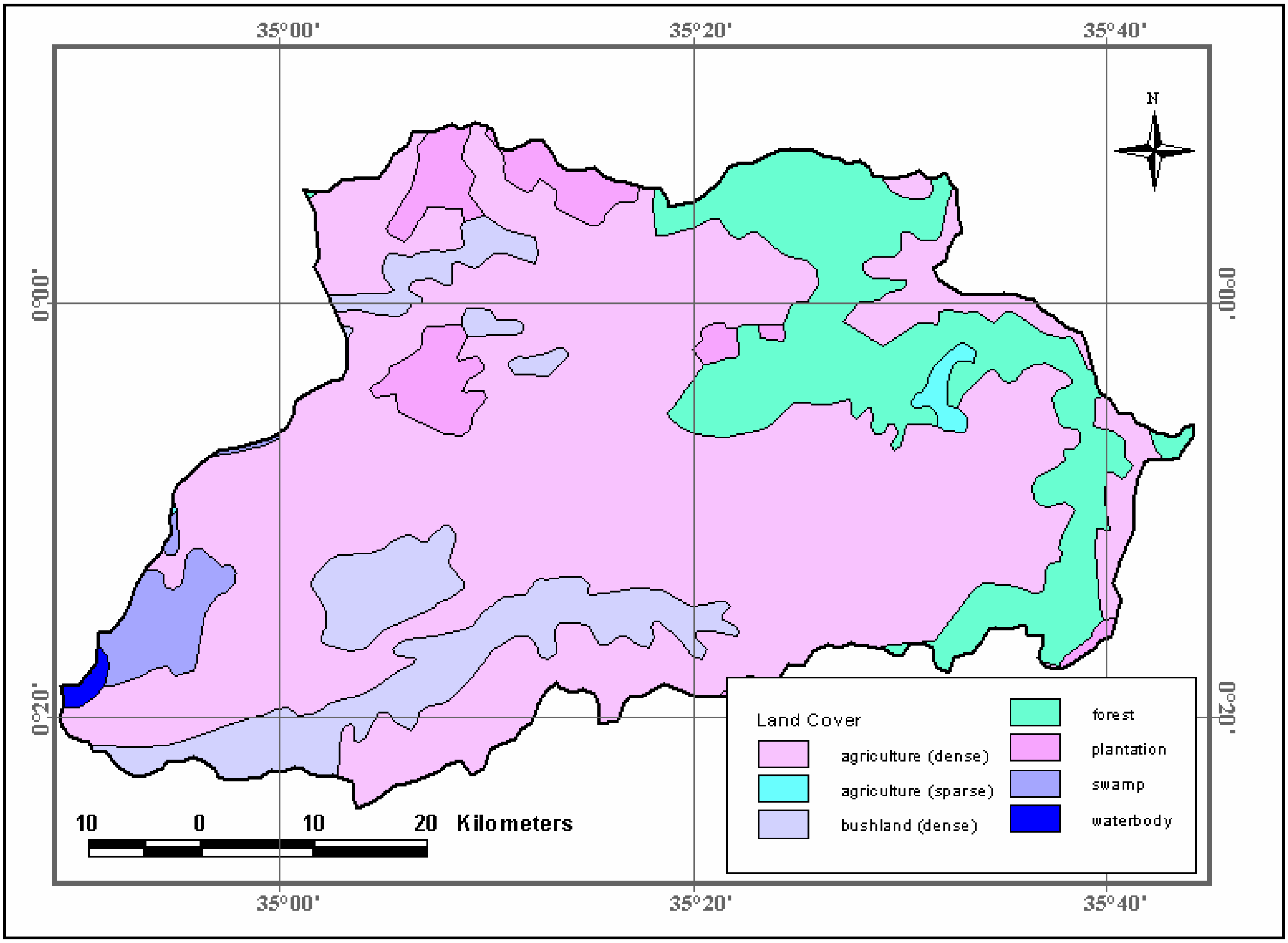

Figure 1.5: Nyando Basin Land-use Map. (Source: ILRI)

The common grass species include Kikuyu grass (*Pennisetum clandestinum)* and Couch grass (*Digitaria scalarum)*. Forestland is predominantly found in Tinderet, Londiani and Mau regions. These are the indigenous forests that are government protected for conservation purposes. The dominant woody tree species are the *Juniperus procera* and the *Olea europoea* (Wagate and Macharia, 2003).

Maize cultivation is also predominant in Kipkelion and Londiani and parts of Tinderet and Nandi regions. The most profitable crop in the highland zone is coffee, which is limited to only a few areas of Kipkelion and Fort Ternan divisions. The average farm size in Nandi South and Kericho districts are 1.85ha and 1.5ha, respectively. Land in the two districts has consistently been converted from large-scale farming to intense smallholder cultivation, as people move in to occupy the subdivided farms (Samez Consultants, 2005).

In the midstream catchment, sugar cane is the predominant cash crop. It is mostly grown in Koru, Muhoroni, Soin, Chemelil and Songhor. The downstream catchment has 43% of the area being utilized for agricultural production. This zone is dominated by grazing lands, marshes/swamps, the cultivation of sugarcane, rice and other annual crops. Rice is the most profitable crop, grown mainly around Ahero, occupying approximately 5% of the region. The other land use types include fallow/grazing land, bushes and woodlots, Sugar cane, hedges and bare ground. The permanent and seasonal swamps of the sedge *Cyperus papyrus* occupy about 5%. There are virtually no forests in this area. Sugarcane remains the dominant commercial crop in the lower parts of the basin, interspersed with grassland and bushes. Crop production in the downstream region is basically subsistence farming of maize with an average production of 20bags/ha (Samez, 2005). Sorghum is also relatively popular due to its potential in marginal areas of the downstream region.

2.6. Water Resources in the Nyando River Basin

The available water resources in the basin include perennial rivers, ground water, springs, reservoirs, rainfall and the Lake. The water resources in the basin vary spatially and temporally due to rainfall, climatic and geological variability. This confirms the need for river water storage in the form of reservoirs. The renewable ground water potential of the Nyando basin is about 256 MCM/year while the potential surface water resources are estimated at 702 MCM/year (Njogu, 2000). The ground-water recharge is dependent on the land use/land cover and storm characteristics. In most parts of the Nyando catchment groundwater has generally been considered to be readily available and a good source for drinking water. However, the stress on this key resource has been growing rapidly. Contamination may occur whenever potential exists for transport of matter into the groundwater environment, either from the ground, polluted surface water or through human action.

2.7. Water Use and Demand Forecasting

Water use refers to the amount of water applied to achieve various ends, while water demand is the scheduling of quantities that consumers use per unit of time (Mays and Tung, 1992).Water use can be divided into two categories, consumptive use, and non-consumptive use. Consumptive use includes municipal, agricultural, rural and industrial use. Non-consumptive use includes in-stream uses such as hydropower, transportation and recreation. Demand forecasting is used to forecast water use in the future based upon previous water use and the socio-economic and climatic parameters of past and present water use. Water demands in the Nyando catchment consist of public water supply, industrial demands, irrigation demands, Environmental Flow Requirements and demands for livestock watering purposes.

Forecasting water demand is an important task in water resources management. It involves three activities. The first activity is supply management which refers to forecasting water demand so that investments in new supply facilities can be planned. A second interrelated activity is demand management to determine the impact of inefficient water use, conservation measures and rationing. The third activity is demand-supply management which uses water use forecasts to integrate and coordinate supply and demand management policies (Mays and Tung, 1992).

Water demand forecasts are used in many areas of utility planning. From small utility models to long term inter state resource management; reliable forecasts are critical components of water planning and policy. To be reliable water demand forecasts must include social, economic and environmental factors. Two of the most common models for forecasting water demands are based on “per capita consumption” and econometric considerations. The “per capita” consumption method calculates the total water demand per person per year and applies a forecast population factor to project future consumption per person (Kame’enui, 2003). Although simple, this method is often sufficient for calculating demands and impacts on water supply. The econometric models use factors such as billing rates and personal income as variables for calculating water demands.

2.8. Hydrologic Modeling

A hydrologic system model is an approximation of the actual system (Chow et al, 1988). The objective of hydrologic system analysis is to study the system operation and predict its output. Its inputs and outputs are measurable hydrologic variables and its structure is a set of equations linking the inputs and outputs. Models have contributed much to hydrology (Luijten et al, 2000). According to Maidment (1993), models deal with three distinct areas of the environment: pollution control, flood control and water utilization. Water utilization looks at the supply and allocation of the limited amount of water among competing demands in domestic, industrial and agricultural sectors. Hydrologic models have also been used in urban drainage studies, reservoir simulation studies, flood control studies and watershed management studies among other fields of hydrology.

Hydrologic models can be broadly classified into three categories; empirical models, physical models and conceptual models. Empirical models do not utilize physical laws to relate input to output. They are based on identifying statistically significant relationships between assumed important variables where reasonable database exists (Morgan, 1986). In empirical models, the variation within the watershed characteristics is not accounted for directly. Regression analysis and the classical unit hydrograph developed by Sherman (1932) are two examples of empirical models. Empirical models cannot be generalized to other locations and scenarios without reducing their accuracy since they are not based on the physical characteristics of the watershed.

Physical models are miniature representations of the real world system. They include, scale models which represent the system on a reduced scale and analog models which use another physical system having properties similar to those of the prototype (Chow et al, 1988). Physical models are based on complex physical laws and theories. They have logical structures which are similar to the real hydrologic process in the field. These models therefore can improve understanding of hydrologic systems (Singh, 1988).

Conceptual models fall in a category between physical models and empirical models. They usually represent physical formulas in a simplified form. Singh (1988) noted that these models are able to provide useful results efficiently and economically for some problems. These models are capable of reflecting changes in the watershed characteristics if the parameters used are physically based.

Hydrologic models can also be generally grouped into surface and groundwater models. These models can also be empirical, physical or conceptual models. Most surface water models deal with the management and control of floods, soil erosion, water quality and water allocation. Common surface water models include, TOPMODEL, which is a rainfall-runoff model using an analysis of catchment topography as its basis for predictions (Beven, 1989). There are others such as, the (USGS-SFM) for flood forecasting and the Hydrologic Engineering Centre-6 (HEC-6) Model for sediment transport, erosion and deposition in rivers.

There are also a number of Integrated Water Resources Management (IWRM) Models. These models have tended to focus on understanding how water flows through a watershed in response to hydrologic events and on allocating the water that becomes available in response to these events. Such models include the Soil Water Assessment Tool ((SWAT), Arnold and Allen (1993)) which has sophisticated physical hydrologic watershed modules that describe among others, rainfall-runoff processes, irrigated agriculture processes and point and non-point water watershed dynamics but a relatively simple reservoir operations module. The RiverWare™ DSS can be used to develop simulations of river and reservoir systems such as storage and hydropower reservoirs, river reaches, diversions and water users but requires upstream flows derived from a physical hydrologic model (Zagona et al, 2001). The US Army Corp of Engineers, HEC-ResSim (USACE, 2003) is a reservoir simulation model that can describe operating rules such as release requirements and constraints, hydropower requirements and multiple reservoir operations, but it too requires prescribed flows from other models.

The Water Evaluation and Planning (WEAP) IWRM Model attempts to address the gap between water management and watershed hydrology and the requirements that an effective IWRM Model be useful, easy to use, affordable and readily available (Yates et al., 2005). It integrates a range of physical hydrologic processes with the management of demands and installed infrastructure in a seamless and coherent manner. It allows for multiple scenario analysis, including alternative climate scenarios and changing physical stressors such as land use variations, changes in water demand and alternative operating rules. WEAP's strength lies in addressing water planning and resource allocation problems and issues. WEAP however is not designed to be a detailed water operations model, which might be used for example to optimize hydropower based on hydrologic forecasts.

2.9. Model Calibration

The values for the model parameters are selected once a suitable model for a given watershed has been defined. The process by which the parameters are selected is called model calibration (Sorooshian et al., 1993). Calibration is an iterative exercise used to establish the most suitable parameter in modeling studies. The exercise is vital because reliable values for some parameters can only be found by calibration (Beven, 1989). It involves the identification of the major model parameters and changing the parameter set. Model parameters changed during calibration are classified into physical and process parameters. Physical parameters represent physically measurable properties of the watershed; while the process parameters are those not directly measurable. Model calibration can be manual, automatic and a combination of the two methods (Refsgaard , 1996). Manual calibration makes use of trial and error techniques in parameter adjustment through a number of simulation runs. It is subjective to the modeler's assessment and can be time consuming. Computer based automatic calibration involves the use of a numerical algorithm which finds the extreme of a given numerical objective function. The purposes of automatic calibration are to speed up the process and to assign some measure of objectivity and confidence to model predictions (HEC, 2000). A combination of the two methods involves initial adjustment of parameter values by trial and error to delineate rough orders of magnitude of the parameters followed by a fine adjustment using automatic optimization within the delineated range of physical realistic values. Model performance is assessed statistically by comparing the model output and observed values. The statistical measures commonly used are the coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE) and the Root Mean Square Error (RMSE) (Loage and Green, 1990).

2.10. Model Validation

Model Validation is the process of demonstrating that a given site specific model is capable of making accurate predictions. This is done by applying the calibrated model using a different set of data without changing the parameter values. The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits (Refsgaard, 1996). Observed and simulated hydrograph values are again compared as in the previous calibration procedure. If the resultant fit is acceptable then the model's prediction is valid and reliable.

2.11. WEAP Model Overview

The Water Evaluation and Planning (WEAP) model was developed by the Stockholm Environmental Institute-Boston, Tellus Institute, U.S.A. It is an integrated Decision Support System (DSS) designed to support water planning that balances water supplies and multiple water demands. WEAP incorporates issues such as allocation of limited water, environmental quality and policies for sustainable water use unlike the conventional supply oriented simulation models. It gives a practical integrated approach to water resources development incorporating aspects of demand, water quality and ecosystem preservation (SEI, 2005).

2.11.1. WEAP Area

An "area" in WEAP is defined as a self-contained set of data and assumptions (SEI, 2005). Its geographical extent is typically a river basin. An "area" is sometimes referred to as a "data set". A study area can be a set of demand sites or a water supply system such as a river basin. Nyando Basin "area" is both a set of demand sites and water supply system. The study area contains a distinct set of information and assumptions about a system of linked demands and supplies. It is where different sets of water supply and demand data are stored, managed and analyzed.

2.11.2. WEAP Schematic

The Schematic View is the starting point for all activities in WEAP. It is formed from the setup “area”. It defines the physical elements comprising the water demand-supply system and their spatial relationships, the study time period, units and the hydrologic pattern. The graphical interface is used to describe and visualize the physical features of the water supply and demand system (SEI, 2005). The system formed is a spatial layout called the schematic. GIS Vector or Raster Layers (ArcView Shape files or GRID) may be added as overlays or backgrounds on the Schematic.

2.11.3. Demand Sites

A demand site is defined as a set of water users that share a physical distribution system that are all within a defined region or that share an important withdrawal supply point (Sieber et al., 2005). Demand sites may be urban centres, rural water supplies, individual users, industrial facilities or irrigation farms. Each demand site has a transmission link to its source and where applicable a return link directly to a river. The Nyando Basin Demand Sites are depicted on the Schematic Map (Figure 3.2).

2.11.4. Priorities for Water Allocation

Two user-defined priority systems are used to determine allocations from supplies to demand sites: Demand Priorities and Supply Preferences. Demand Priority determines the demand site's priority for supply. Competing demand sites and catchments, the filling of reservoirs and flow requirements are allocated water according to their demand priorities. Priorities can range from 1 to 99 with 1 being the highest priority and 99 the lowest. Demand sites with higher priorities are processed first by the WEAP Allocation Algorithm. Reservoir priorities default to 99, meaning that they will fill only if water remains after satisfying all other demands. Many demand sites can share the same priority. These priorities are useful in representing a system of water rights and are also important during a water shortage (SEI, 2005). Supply Preferences indicate the preferred supply source where there is more than one source to a demand site. Using the demand priorities and supply preferences, WEAP determines the allocation order to follow when allocating the water. The allocation order represents the actual calculation order used by WEAP for allocating water.

2.11.5. Current Accounts

The Current Accounts represent the basic definition of the water system as it currently exists. The Current Accounts are also assumed to be the starting year for all scenarios. The Current Accounts include the specifications of supply and demand for the first year of the study on a monthly basis.

2.11.6. Scenario Analysis

At the heart of WEAP is the concept of scenario analysis. Scenarios are self-consistent story-lines 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 (SEI, 2005). Using WEAP, scenarios can be built and then compared to assess their water requirements, costs and environmental impacts. Scenarios can address a broad range of questions. The basic scenarios explored in this study are about the impacts of the proposed dams upstream on the irrigation schemes in the Kano Plains. An important concept of WEAP is the distinction between a reference or “business as usual” scenario and alternative policy scenarios (Raskin et al., 1992). The “business-as-usual” scenario incorporates currently identifiable trends in economic and demographic development, water supply availability, water-use efficiency and other aspects. No new water conservation measures or supply projects are included in the “business-as-usual scenario. This scenario provides a reference against which the effects of alternative policy scenarios may be assessed. In any study the current water accounts and the reference or “business-as-usual” scenarios are outlined based on the continuation of current patterns. Population growth as demand driving variable is relied on for this purpose. “What-if” scenarios based on the reference scenario are then introduced.

2.11.7. GrowthFrom function

This is a function that the model uses to compute the population in any given year using a growth rate from the start-value in the start-year. The start-year can be any year, past present or future (SEI, 2005). The last census year was taken as the start-year and a growth rate of 3.4% was used (Republic of Kenya, 1999a).

2.11.8. ReadFromFile function

This function allows the system to be modeled using a sequence of real monthly streamflow data. The model uses this function for any variable that requires a time series, monthly or yearly such as streamflow or precipitation. Streamflow data are entered as a comma-separated value text file and the ReadFromFile function is used to import the data into the "Area" directory. A text file can contain one or more columns of data for each year or month. The format of the WEAP expression is:

ReadFromFile(FileName, DataColumnNumber, YearOffset) (12)

YearOffset can use data from different years. For example, to use historical streamflow data (starting in 1950) for future values (2005-2025), the YearOffset is -55 (SEI, 2005).

2.12. Proposed Reservoirs

Several reservoirs have been proposed by JICA along the courses of the major Nyando River tributaries. The primary function of reservoirs is to smooth out the variability of surface water flow through control and regulation and make water available when and where it is needed (Mays and Tung, 1992). The use of reservoirs for temporary storage would result in an undesirable increase in water loss through seepage and evaporation. However the benefits that can be derived through regulating the flow for water supplies, hydropower generation, irrigation, recreation uses and other activities would offset such losses. Reservoir systems may be grouped into two general operation purposes: conservation and flood control. Conservation purposes include water supply, low-flow augmentation, irrigation and hydroelectric power. Generally the total reservoir storage space in a multi-purpose reservoir consists of three major parts (Figure 2.2): The dead storage zone, mainly required for sediment collection or hydropower generation, the active storage used for conservation purposes including water supplies, irrigation and navigation, and the flood control storage reserved for storing excessive flood volume to reduce potential downstream flood damage (Mays and Tung, 1992).

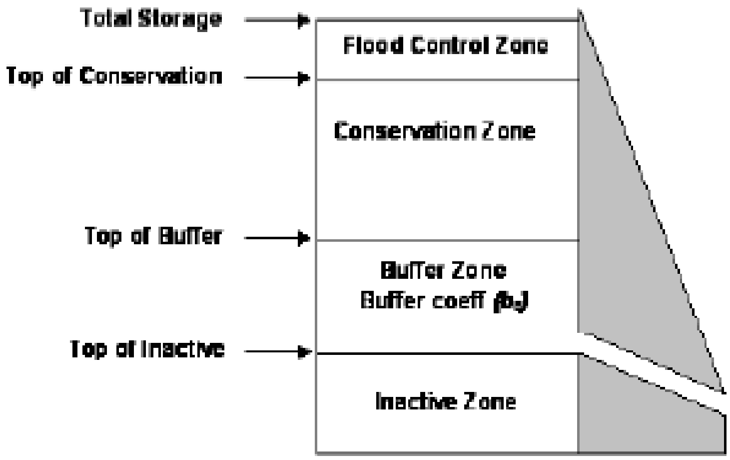

Figure 2.2. The different reservoir storage volumes used to describe reservoir operating policies. (Source: Yates et al., 2006).

A reservoir's (*Res*) storage in the first month (m) of the simulation is input and is expressed as in the following equations:

$$BeginMonthStorage_{Res,m} = InitialStorage_{Res}\ for\ m=1 \tag{13}$$

Thereafter, it begins each month with the storage from the end of the previous month as follows:

$$BeginMonthStorage_{Res,\,m} = EndMonthStorage_{Res,m-1}\ for\ m>1 \tag{14}$$

This beginning storage level is adjusted for evaporation as follows:

$$BeginMonthElevation_{Res} = VolumeToElevation\ (BeginMonthStorage_{Res}) \tag{15}$$

The elevation is then reduced by the evaporation rate and results in the following equation:

$$AdjustedBeginMonthElevation_{Res} = BeginMonthElevation_{Res} - EvaporationRate_{Res} \qquad (16)$$

Then the adjusted elevation is converted back to a volume, thus,

$$AdjustedBegMonthStorage_{Res} = ElevationToVolume(AdjustedBegMonthElevation_{Res}) \qquad (17)$$

A reservoir's operating rules determine how much water is available in a given month for release to satisfy demand and in-stream flow requirements, and for flood control. These rules operate on the available resource for the month. This "storage level for operation" is the adjusted amount at the beginning of the month, plus inflow from upstream and return flows from demand sites (*DS*). It is expressed in the following equation:

$$StorageForOperation_{Res} = AdjustedBeginMonthStorage_{Res} + UpstreamInflow_{Res} + \sum_{DS} DSReturnFlow_{DS,Res} \qquad (18)$$

The amount available to be released from the reservoir is the full amount in the conservation and flood control zones and a fraction of the amount in the buffer zone. Each of these zones is given in terms of volume. The water in the inactive is not available for release. The water available for release is expressed as follows:

$$StorageAvailableForRelease_{Res} = FloodControlAndConservationZonesStorage_{Res} + BufferCoefficient_{Res} * BufferZoneStorage_{Res} \qquad (19)$$

All of the water in the flood control and conservation zones is available for release, and equals the amount above Top of Buffer. This is given by,

$$FloodControlAndConservationZonesStorage_{Res} = StorageForOperation_{Res} - TopOfBuffer_{Res} \quad (20)$$

or zero if the level is below Top of Buffer

$$FloodControlAndConservationZoneStorage_{Res} = 0 \quad (21)$$

Buffer zone storage equals the total volume of the buffer zone if the level is above Top of Buffer, such that,

$$BufferZoneStorage_{Res} = TopOfBufferZone_{Res} - TopOfInactiveZone_{Res} \quad (22)$$

Or the amount above Top Of Inactive if the level is below Top Of Buffer, so that,

$$BufferZoneStorage_{Res} = StorageForOperation_{Res} - TopOfInactiveZone_{Res} \quad (23)$$

or zero if the level is below Top Of Inactive.

$$BufferZoneStorage_{Res} = 0 \quad (24)$$

The change in storage is the difference between the storage at the beginning and the end of the month. It is an increase if the ending storage is larger than the beginning, a decrease if the reverse is true. This is expressed as follows:

$$IncreaseInStorage_{Res} = EndMonthStorage_{Res} - BeginMonthStorage_{Res} \quad (25)$$

2.13. Ecological Flow Requirement

The need to regulate the amount of water that flows in streams for ecological reasons is very important. During the past century, the global human population quadrupled, the area of irrigated agricultural land multiplied more than six-fold, and water withdrawals from fresh-water ecosystems increased eight –fold (Gleick, 1998; Postel, 1999). Natural river systems around the world were heavily modified to serve a variety of human purposes including, supplying water to cities and farms, generating electric power and controlling floods (Richter et al., 2003). Dams capture high river flows and release the water in a carefully controlled manner for water supplies downstream, to protect settlements from floods or to generate electric power. Consequently, river flows below dams commonly bear little resemblance to their natural flow regimes. This has caused considerable ecological damage and the loss of important ecosystem services valued by society (Baron et al., 2002; Postel and Richter, 2003; Fitzhugh and Richter, 2004). River ecosystem health deteriorates when natural flows of water, sediments, and organic materials through a river system are substantially disrupted or modified by human activities (Poff et al., 1997; Richter et al, 2003). There is need therefore to protect the natural river flow conditions necessary to support ecosystem health. WEAP has a provision for a Minimum Flow Requirement which defines the minimum monthly flow required along a river to meet water quality, fish and wildlife, navigation, recreation, downstream or other requirements. The flow requirement in WEAP will be satisfied depending on its demand priority. A priority of 1 is normally appended to the in-stream flow requirement. Depending on its priority a flow requirement will be satisfied either before or after other requirements in the system. The minimum flow is achieved either by restricting withdrawals from the river or by releasing water from reservoirs (SEI, 2005). Virtually all models and methods for setting in-stream flow requirements in common use today have been criticized for their overly simplistic treatment of complex ecosystem processes (Mathur et al., 1985). WEAP's in-stream flow requirement method however adopts the use of long term stream flow data to set ecosystem based management targets.

There are several other methods for developing in-stream flow based river management. One such method is the Range of Variability Approach or RVA which incorporates the concepts of hydrological variability and river ecosystem integrity (Freshwater Biology 37, 1997). RVA begins with a comprehensive characterization of ecologically relevant attributes of a flow regime and then translates these attributes into more simple flow-based management targets. These targets are subsequently used as guidelines for designing a workable management system capable of attaining the desired flow conditions. Another method is the 'Montana Method', (Tennant, 1976) wherein environmental flow regimes are prescribed on the basis of the average daily discharge or the mean annual flow (MAF). In general 10% of the MAF is recommended as a minimum instantaneous flow to enable aquatic life to survive. One of the most technologically sophisticated and widely applied modeling approaches is the In-stream Flow Incremental Methodology (IFIM) developed by the USA Fish and Wildlife Service (Bovee, 1982). The method uses (across river) transect based hydraulic analyses to evaluate basic habitat conditions (such as depth and velocity) associated with varying levels of flow.

2.14. Water Year Method

This is an in-built model in WEAP that allows the prediction of hydrological variables based on historical analysis of streamflow data. It uses statistical analysis to identify the coefficients which are used to replace real data for future projection. It may be used to test a hypothetical event or set of events or to approximate historic patterns. For example the method may be used to test the Nyando Basin system under historic or hypothetic drought conditions. WEAP uses five water year types that characterize hydrologic conditions over the period of one year. The five types are, Normal, Very Wet, Wet, Dry and Very Dry. They divide the years into five broad categories based on relative amounts of surface water inflows. The Water Year Method allows one to use historical data in a simplified form and to easily explore the effects of future changes in hydrological patterns (SEI, 2005). It projects future inflows by varying the inflow data from the Current Accounts according to the Water Year Sequence and Definitions. The method is a simple way to explore sensitivity to climate change. River flows have been altered with extensive use and irrigation development and many hydrological records cannot serve as proxies for historical hydrological patterns (Raskin et al., 1992). Therefore in order not to depend entirely on hydrologic processes, this simpler option may be adopted to depict the basin's basic climatic pattern.

2.14.1 Water Year Definition

Five categories of water-year types, Very Wet, Wet, Normal, Dry and Very Dry are used to represent hydrological patterns (Raskin et al., 1992). To define each non-Normal water year type, the amount of water that flows into the system in that year is specified relative to a Normal water year. For example if a Wet year has 25% more inflow than a Normal year, 1.25 is entered for the Wet year. These fractions are derived from a statistical analysis of historical streamflows. The years are first grouped into five groups (quintiles), and then their variation from the normal year is computed.

2.14.2. Water Year Sequence

The Water Year Sequence specifies the sequence of water year types (Very Dry, Dry, Normal, Wet, and Very Wet) in the study. The defined sequence of water year types will set inflow values for future years by applying the appropriate fluctuation coefficient to the streamflows.

CHAPTER 3

METHODOLOGY

The Water Evaluation and Planning (WEAP) model is designed to support water planning that balances water supplies generated through watershed scale physical hydrologic processes and multiple water demands and environmental requirements. The model deals with a varied range of issues that include climate, watershed condition, water supply, ecosystem needs and anticipated demands.

3.1. Determination of spatial and temporal distribution of river water resources

3.1.1. Data collection

The data used in the study were varied and were obtained from different sources. Data were collected through site visits, from Government Agencies, research institutions, NGO's and from the internet.

Table 3.1. Climatic Summary of the lower basin at Ahero Irrig. Scheme (JICA, 1992)

Parameter	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall (mm)	84	77	140	192	126	77	77	75	72	76	101	87	1204
Evap.(mm/day)	8.4	8.1	8.1	7.2	7.1	6.7	6.8	6.8	7.1	7.4	7.1	8.2	7.4
R H (%)	63	66	68	72	74	73	73	70	64	62	64	65	68
Max temp (°C)	31.3	31.4	31.3	29.4	29.0	28.7	28.7	29.2	30.4	31.0	30.3	30.3	31.3
Min. temp (°C)	14.2	14.6	15.5	15.9	15.9	14.8	14.5	14.3	14.1	14.7	14.8	14.4	14.8
MeanTemp (°C)	30.9	31.3	31.4	29.4	28.8	28.5	28.7	29.2	30.1	30.8	30.3	30.3	30.8

3.1.1.1 Population Data

The population Data of the Nyando Basin were obtained from the Central Bureau of Statistics. Divisional, Locational and Sub-locational population data were considered for some demand sites in order to capture the actual basin water demand. Such population data were input as the Activity Levels to be multiplied by the Annual per capita water use rate in order to obtain the total annual water demand.

The per capita water demands for the various demand levels based on the Ministry of Water and Irrigation Design Manual, (MWI, 2006) were as shown in Table 3.2.

Table 3.2.Summary of Per Capita Water Demand

Demand Level	Per Capita Water Demand (L/S)
Rural	25
Urban	60
Livestock	50

An Activity Level is the level of any activity that drives demand e.g. population. Table 3.3 shows the population data of the various divisions in the basin as obtained from the 1999 population census report.

Table 3.3: Summary of Divisions Population Data (Source: CBS, 1999).

Division	Male	Female	Total
Lower Nyakach	23395	25852	49247
Miwani	28128	29901	58029
Muhoroni	33516	29901	63417
Nyando	30571	33940	64511
Soin	12929	12864	25793
Ainamoi	62268	57428	119696
Chilchila	187762	18221	205983
Kipkelion	31986	32491	64477
Londiani	29443	29998	59441
Nandi Hills	40779	36735	77514
Tinderet	29732	29193	58925
Total	510509	336524	847033

A growth rate of 3.4% percent (Republic of Kenya, 1999b) was assumed for the entire basin and the "GrowthFrom" function of the model was used to compute the current population for each demand site. The GrowthFrom function calculates a value in any given year using a growth rate from the Start Value in the Start Year, entered as,

GrowthFrom (GrowthRate, StartYear, StartValue) (26)

The forecast population was used to calculate the demand.

3.1.1.2. Streamflow data

Streamflow is an important aspect of modeling a water system and helps in understanding how it operates under a variety of hydrologic conditions. Natural variation in hydrology can have major effects on simulation results. Streamflow is depleted through natural watershed processes and human demands. In WEAP these were linked to a schematic of stream network and water allocation components which accounted for streamflow depletions and accretions.

Three sections of the Nyando River were considered in the study. These were named here as Nyando-Ainapngetuny, Nyando-Kipchorian and the Main-Nyando rivers. Data available for the river gauging stations, namely, 1GC05, 1GD03 and 1GB03 were used (Figure 3.1). Monthly mean streamflows from the three gauging stations have been adopted for use in the model (Table 3.4).

Table 3.4. Streamflow data summary for the three main gauging stations

Gauging Station	River	Monthly mean (MCM)	Period
1GC05	Nyando-Kipchorian	2.8	1965-1995
1GD03	Main-Nyando	16.1	1950-2000
1GB03	Nyando-Ainapngetuny	13.9	1968-1990

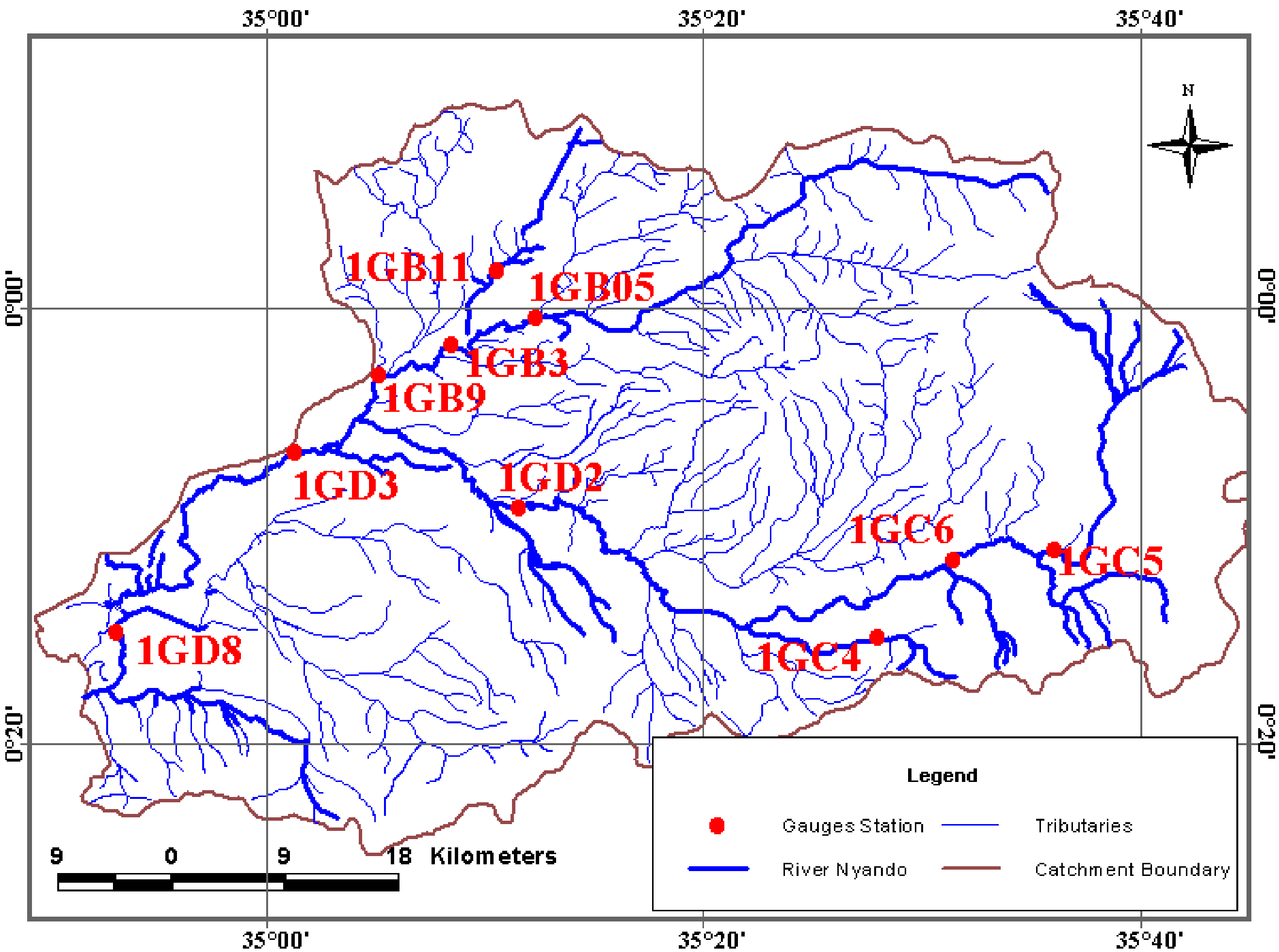

Figure 3.1. Working Stream-gauge stations in Nyando River Basin

The ReadFromFile method was used to project surface water hydrology over the study period. Monthly streamflow was read into WEAP from a comma-separated value (CSV) text file. Data available from the stream gauging stations were from 1950 to 2000. The model allows for the use of historical data (e.g. starting in 1950) for future values (2002-2014). In order to model streamflow for later years the YearOffset function was used. YearOffset of 50 years was used for 1GD03 since data for this gauging station starts from 1952 and the current accounts year was taken as 2002. 32 years was used for 1GB03 in order to offset the 1970 data to 2002.

3.1.1.3. Rainfall data

The WEAP model is based on the premise that at the most basic level, water supply is defined by the amount of precipitation that falls on a watershed (Yates et al., 2005). This supply is progressively depleted through natural watershed processes and human demands. The watershed itself is the first point of depletion through evapotranspiration and deep percolation. Rainfall data is therefore of utmost importance for the simulation of the catchment processes. The rainfall data obtained from the Ministry of Water and Irrigation covered the period between 1960 and 1990. The locations of rainfall network in and around the basin are depicted in Figure 3.2.The main rain-gauge stations used are shown on Table 3.5.

Table 3.5. Summary of rainfall gauging stations (Source: MWI, 2005)

Station	Name	Year	Lat/Long.
8935112	Nandi Forest Stn.	1960 – 2004	012N 35 4E
8935013	Nandi, Cematin	1960 – 2004	05N 35 16E
9034009	Miwani European Quarters	1960 – 2001	035N 34 57E
9034086	Ahero Irrigation Scheme	1960 – 2004	031N 35 16E
9035046	Chemelil Plantations	1960 – 2002	04S 35 9E
9035150	Tinderet Estate	1960 – 2004	08S 35 23E
9035240	Londiani Keresoi Forest St.	1960 -2004	017S 35 32E
8935033	Savani Estate Stn.	1962 - 1999	05N 35 10E
9035199	Kericho, Ainamoi	1963 - 2002	018S 35 16E

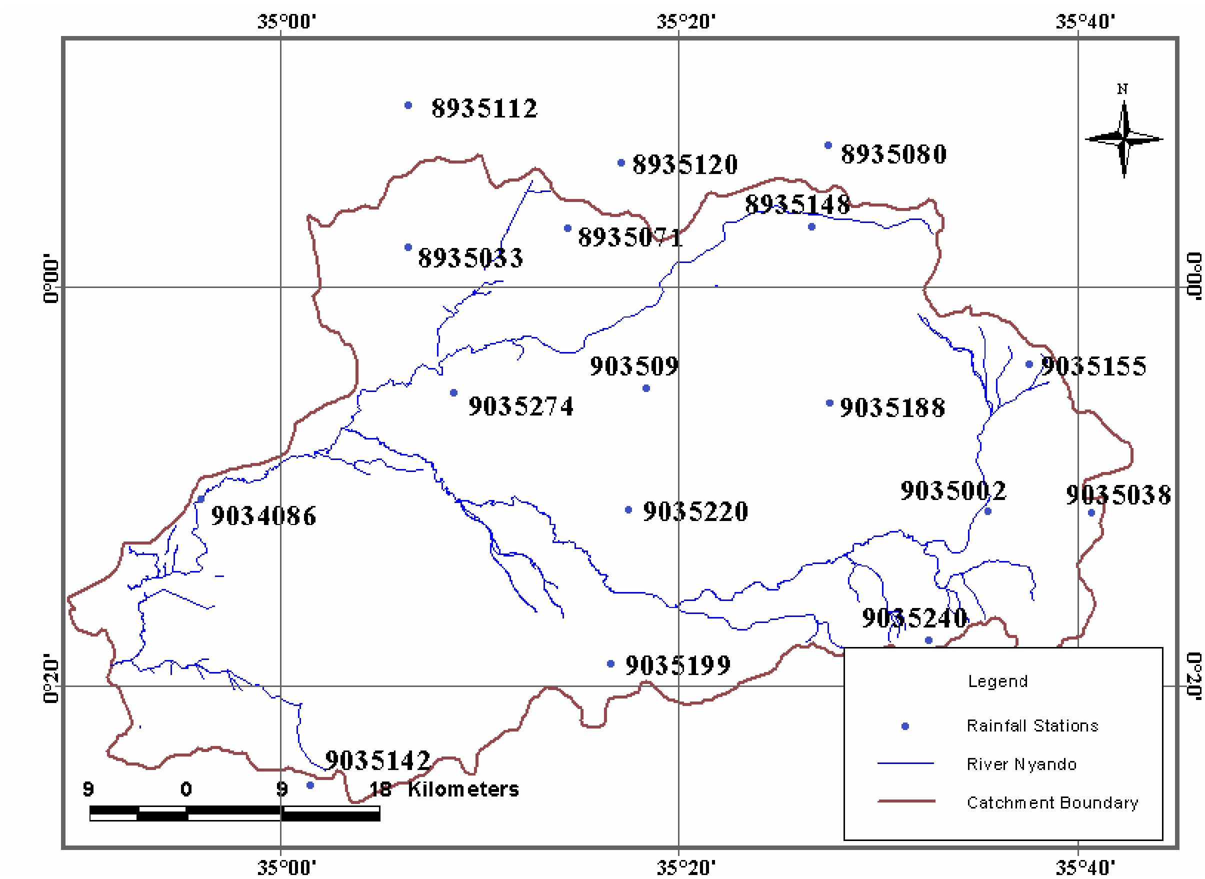

Figure 3.2. Rain-gauging Stations in and around the Nyando basin

3.1.2. Demand Sites Schematic Development

The create-Area menu option was used to create the Project Area. GIS-based vector boundary, rivers and towns shapefiles for the Nyando River Basin were imported to the Project Area to orient the system and refine the area boundaries. This provided the outline for the Schematic which is the view used for system configuration The major river water courses were digitized starting from source going downstream. Data for each river tributary was entered using the WEAP data tree, e.g. minimum flow requirement (to meet ecological needs), return flow, stream gauge and transmission link for demand sites and supply source. Demand sites were entered on the schematic and demand priorities set based on MWI water allocation priorities. Demand priorities represent the level of priority for allocation of constrained resources among multiple demand sites. Demand sites with the highest priorities will be supplied first. For each demand site, the Annual Activity Level, Annual Water Use Rate and Consumption were entered to be used in calculating the water demand. Different levels of disaggregation were created for each demand site, e.g. rural, urban, livestock and industry. The final demand site schematic is shown in figure 3.3.

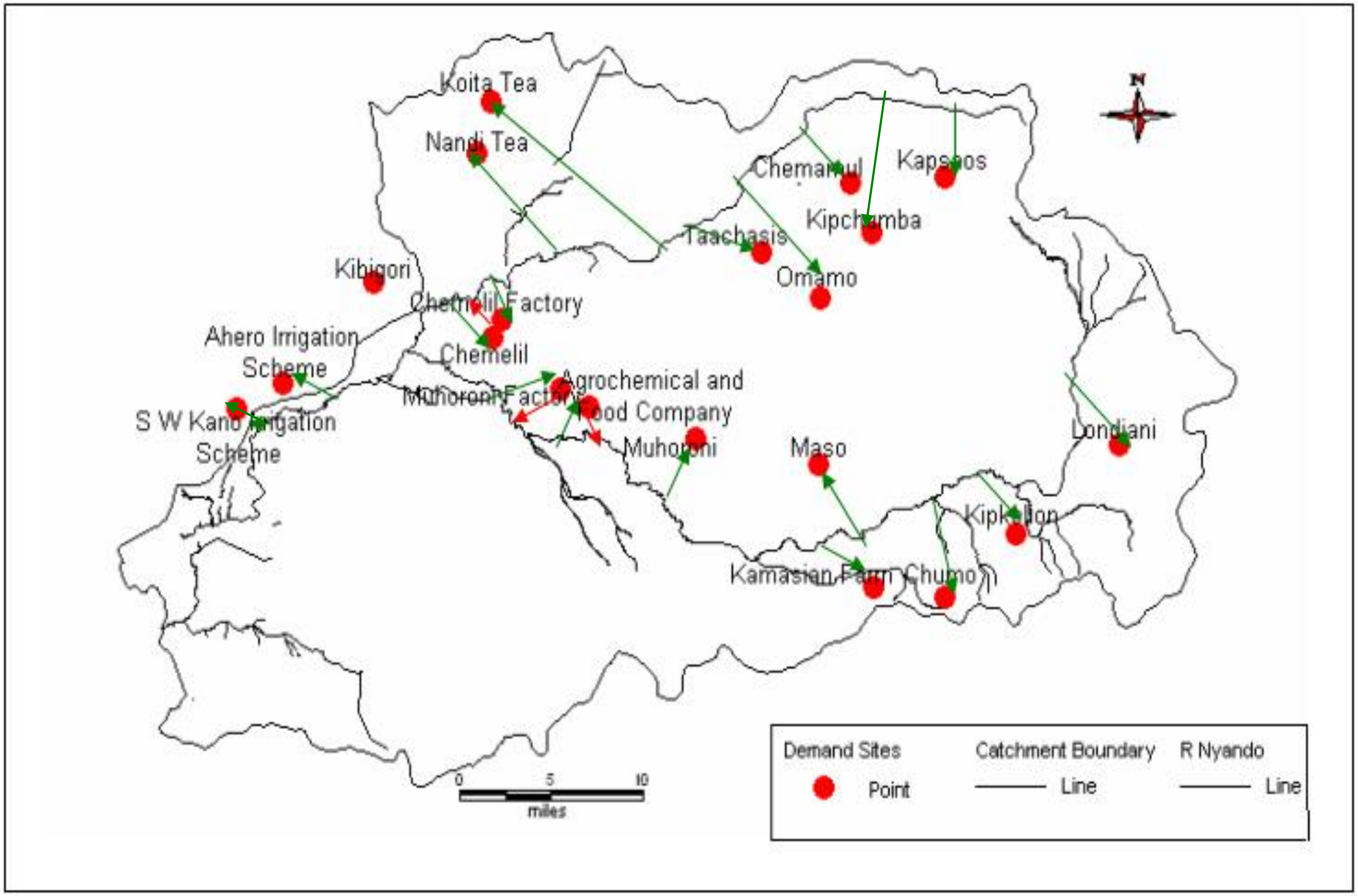

Figure 3.3. Nyando Basin Demand Sites Schematic Map

3.2. Evaluation of the WEAP Model

3.2.1. WEAP Model Calibration

The WEAP planning model is spatially oriented with a study area configured as a set of sub-catchments that is overlaid with rivers, reservoirs and demand centres (Yates et al, 2005a). Within each sub-catchment, the area is fractionally sub-divided into a unique set of independent land use/land cover classes. At the most basic level in WEAP, water supply is defined by the amount of precipitation that falls on the watershed. This supply is progressively depleted through natural watershed processes, human demands and interventions. The watershed itself therefore is the first point of depletion through evapotranspiration. The model's water balance hence defines watershed scale evaporative demands, rainfall-runoff processes, groundwater recharge and irrigation demands. These form the basis for the calibration process that assesses the hydrologic response of the basin to climate changes.

The Nyando Basin was subdivided into various sub-catchments. The sub-catchments 1GB and 1GD that define the upper and lower portions of the watershed were used in model calibration of the watershed responses. For the 1GB Sub-catchment the period 1970-1980 was used to calibrate the model and the period 1981-1990 was used for validation. For the 1GD Sub-catchment the period 1952-1964 was used for model calibration and the period 1965-1972 was used for validation. The initial parameter estimate was done by separating the baseflow. This was done by using the SWAT automated method for estimating baseflow and ground water recharge from streamflow. The average of the outputs Baseflow Pass1 and Baseflow Pass 2 was taken as the final separated baseflow. Based on the research done by Samez Consultants (2005), the sub-catchments were further subdivided into several land covers fractions (Tree cover, grassland, irrigated rice, sugarcane and maize) which are the computational elements of the conceptual water balance model (Yates et al., 2005a). Table 3.6 shows the total area of each sub-catchment with estimates of percent land cover fraction for each (Samez Consultants, 2005).

Table 3.6. Total sub-catchment areas and the percentages of land cover fractions

Item	1GB	1GD
Area (km^2)	518	720
Grassland (%)	40	45
Irrigated Sugarcane (%)	2	0
Rainfed Sugarcane (%)	18	20
Tree cover (%)	40	30
Rice (%)	0	5

Source: Samez (2005).

Only the lower sub-catchment 1GD has been considered to have irrigated rice covering about 5 percent of the 71269 ha total land area of the sub-catchment (Samez Consultants, 2005). The two-layer soil moisture scheme (Figure 3.4) was applied to both sub-catchments.

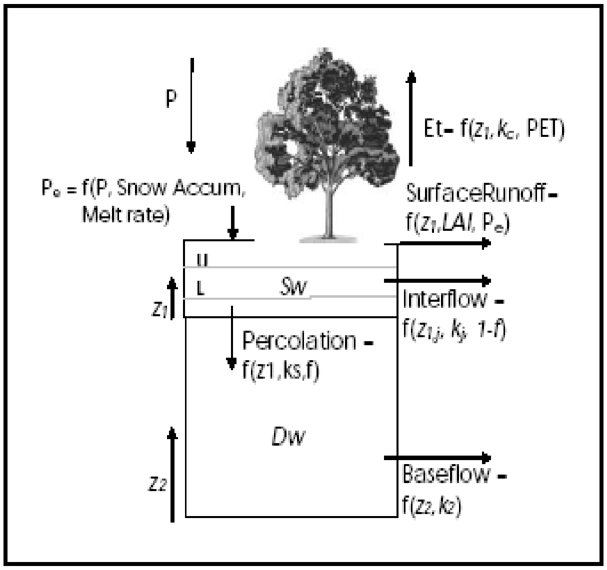

Figure 3.4. Schematic of two-layer soil moisture store

Source: (Sieber et al., 2005)

The model was run on a monthly time-step and tracked the relative storage z_j and z_2 based on water balance dynamics that include infiltration, evapotranspiration, surface runoff, interflow, percolation and baseflow (Yates et al., 2005a). z_j is the relative storage given as a percentage of the total effective storage of the root zone water capacity. z_2 is the relative storage given as a percentage of the total effective storage of the lower soil bucket (deep water capacity).

The climatic data considered include, total monthly precipitation, average monthly temperature, relative humidity and wind speed. For each land cover fraction *j* several parameters are required. Estimates of LAI which was used to specify the hydrologic response of the upper soil moisture store and crop coefficients (k_c) for describing potential evapotranspiration requirements were obtained from FAO (2006). Sw_j (mm) is the total soil moisture storage capacity and is conceptualized as an estimate of the rooting zone depth. The parameter k_j (mm/month) is an estimate of the root-zone hydraulic conductivity while k_2 is the lower store hydraulic conductivity. Since the water balance model was run on a monthly time-step, precipitation was given as a total accumulation (mm/month) as opposed to daily average (mm/day). Hydraulic conductivity of the upper (k_j) and lower (k_2) stores is therefore the maximum possible water flux at full storage (maximum z_j and z_2). The parameter f known as the flow direction factor is a quasi-physical tuning parameter related to soil, land cover type and topography that fractionally partitions the upper and lower store to discharge water either horizontally or vertically. A large f value means more horizontal flow contributing to streamflow than deep percolation.

3.2.2. Calibration Process

Model calibration was done manually via trial and error seeking to minimize the RMSE; maximize the correlation coefficient R and reproduce the average annual flow volume. The calibration procedure began by approximating the values of Sw_j and LAI based on estimates from referenced sources (Jackson et al., 1996; Allen et al., 1999; Scurlock et al., 2001; Gordon et al., 2003). The lower storage zone Dw was set at 2000mm (Yates et al., 2005b). Calibration then proceeded by making initial estimates of k_2, k_j and f; and subsequently adjusting the parameters to improve the RMSE and R values. The initial estimates of k_2 and k_j were made by separating the baseflow and computing the average monthly equivalent water depth. For the 1GB03 streamgauge the monthly average baseflow volume was $12.3*10^6$ m^3 . The total contributory area was 518 km^2. The equivalent baseflow depth was then given as, $12.3*10^6/518km^2 = 24mm$.

The discharge rate from the lower store is given as,

$$DR = k_2 * z_2^2 \tag{27}$$

The average relative storage z_2 has been taken as 25% of the total effective storage of the root zone water capacity (Sieber, 2006). Therefore the first estimate of 1GB's lower store hydraulic conductivity was, $k_2 = 24/0.25^2 = 384$mm/month. k_j was estimated from the difference between the observed average monthly baseflow and the monthly average peak discharge. For 1GB the average monthly peak discharge was $18.2*10^6m^3$ while the average monthly baseflow was $12.3*10^6m^3$ which gives a difference of $6*10^6m^3$. The equivalent baseflow depth is hence, $6*10^6m^3/518km^2= 12mm$

Assuming z_j (Upper store average relative storage) is 60% for the entire watershed (Yates et al., 2006), a first estimate for the upper store hydraulic conductivity is $k_j = 12/0.6^2 =$ 33mm/month.

The flow direction factor *f* was assumed to be 0.6 for all land cover fractions to allow greater contribution to streamflow (Gordon et al., 2003). The LAI was increased for all the land cover fractions to reduce the surface runoff. The second store hydraulic conductivity k_2 was reduced to 300mm/month and the upper store k_j to 30mm/month to reduce sub-surface storage, since the lower storage zone *Dw* had been set high at 2000mm in order to create a balance between subsurface flow and run- off into the river. Streamflow recharge was increased by increasing the flow direction parameter *f* to 0.8 for all the land cover fractions. The average relative storage for both the upper and lower stores was reduced to 30%. Adjustments were made until it was observed that the simulated flow volumes were agreeable with historical values. A similar procedure was followed for 1GD.

3.3. Evaluation of future water demands in the basin

3.3.1. Water Demand

Water demand analysis in WEAP is either by the disaggregated end-use based approach of calculating water requirements at each demand node or by the evapotranspiration-based irrigation demand in the physical hydrology module. Demand calculations for urban, rural, livestock and industrial entities were based on a disaggregated accounting for various measures of social and economic activity such as population served, livestock population and industrial production units. These are referred to as the Activity Levels. The Activity Levels were multiplied by the water use rates of each activity defined as water use per unit of activity. Each Activity Level and water use rate was individually projected into the future using exponential growth rate function. WEAP calculates water mass balance for every node and link in the system on a monthly time step. Water is dispatched to meet instream and consumptive requirements subject to demand priorities, supply preferences, mass balance and other constraints (SEI, 2005)

3.3.2. Demand Calculation Algorithm

A demand site (*DS)* demand for water was calculated as the sum of the demands for all the demand site bottom level branches (*Br).* A bottom-level branch is one that has no branches below it. For example in Chemelil Factory, under industrial demand as the main branch are production and cooling as bottom level branches. Annual water demand was then calculated as follows:

$$Annual\ Demand_{DS} = \sum_{Br}(TotalActivitylevel_{Br} * WateruseRate_{Br}) \qquad (28)$$

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*). The Total Activity Level was given as:

$$TotalActivityLevel_{Br} = ActivityLevel_{Br} * ActivityLevel_{Br'} * ActivityLevel_{Br''} * \ldots \qquad (29)$$

The activity levels for each branch and the water use rates for all the bottom-level branches are inputs into the model. Monthly demands were calculated based on each month's fraction specified as data under Demand\Monthly Variation of the adjusted annual demand as follows:

$$MonthlyDemand_{DS,m} = MonthlyVariationFraction_{DS,m} * AdjustedAnnualDemand_{DS} \quad (30)$$

For irrigation water demand, the Soil Moisture Method was used. The method represents the catchment with two soil layers. 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 (SEI, 2005). Baseflow routing to the river and soil moisture changes are simulated in the lower soil layer (Figure 3.4). Each watershed unit was divided into N fractional areas representing different land uses (Table 3.6), and a water balance was computed for each fractional area, j of N. Climate was assumed uniform over each sub-catchment, and the water balance of the sub-catchment was given as,

$$Rd_j \frac{dz_{1j}}{dt} = P_e(t) - PET(t)k_{cj}(t)\left(\frac{5z_{1j} - 2z_{1j}^{\;2}}{3}\right) - P_e(t)\, z_{1j}^{\;LAI_1} - (1\text{-}f_j)k_j\, z_{1j}^{\;2} - f_j k\, z_{1j}^{\;2} \qquad (31)$$

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. P_e is the effective precipitation. *PET* is the Penman-Montieth reference crop potential evapotranspiration where k_{cj} is the crop/plant coefficient for each fractional land cover. The third term $(P_e(t)\, z_{1j}^{\;LAI_1})$ represents surface runoff, where LAI_j is the Leaf Area Index of the land cover. Lower values of LAI_j lead to more surface runoff. The third and fourth terms are the interflow and deep percolation terms, respectively, where the parameter k_{sj} 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. The total runoff *(RT*) from each sub-catchment at time t is,

$$RT\,(\mathrm{t}) = \sum_{j-1}^{N} A_j\, (P_e(\mathrm{t})\, z_{1j}^{\;LAI_j} - (1\text{-}f_j)\mathrm{k_j}\, z_{1j}^{\;2}) \qquad (32)$$

Baseflow emanating from the second bucket is computed as:

$$S_{max}\frac{dz_2}{dt} = \{\sum_{j-1}^{N} f_j k_j z_{1j}{}^2\} - k_2 z^2{}_2 \qquad (33)$$

Where the inflow to this storage, S_{max} is the deep percolation from the upper storage and k_2 is the saturated conductivity of the lower storage (mm/time), which is given as a single value for the catchment.

3.3.3. Demand Sites:

Different levels of aggregation were considered for the various demand sites. These include urban, rural, livestock and industrial demands. The main water withdrawal points from the Nyando River have been considered as the supply draw off points for the various demand regions. Table 3.7 shows the major draw-off points.

Table 3.7: **Major water draw-off points**.

Draw-off point	Type	Source	Abstraction Method	Abstraction (m^3/day)
Londiani W/S	Pumping	Nyando-Kipchorian	Pipeline	169
Chemamul W/S	Pumping	Ainabng'etuny	Pipeline	15.4
Taachasis W/S	Pumping	Ainabng'etuny	Pipeline	756.4
Muhoroni W/S	Pumping	Nyando	Pipeline	720
Agrochemical Co.	Pumping	Nyando	Pipeline	680
Ahero Irrig. Scheme	Pumping	Nyando	Canal	105408
Maso W/S	Pumping	Nyando	Pipeline	74
Kibigori W/S	Pumping	Nyando	Pipeline	200
Nandi Tea W/S	Pumping	Ainabng'etuny	Pipeline	40.8
Muhoroni Factory	Pumping	Nyando	Pipeline	1920
S.W. Kano Scheme	Gravity	Nyando	Pipeline/Canal	146880
Chemelil Factory	Gravity	Ainabng'etuny	Pipeline	564.5

Source: (MWI Abstraction Permits

The major draw-off points represent various levels of water use. Londiani, Kipkelion and Muhoroni have both rural and urban domestic water users. Agrochemical and Food Company, Chemelil and Muhoroni Sugar Factories are industrial water users. The rest of the draw-off points are rural water users. All the draw-off points have their sources from the major Nyando River Tributaries. In order to give the true water demand picture each draw-off point represents users in a region or division. Londiani Water Supply covers Londiani Division and includes Kedowa, Masaita, Sorget, Lomotit, Tendeno and Kipsirchet. The other supply draw-off points and their coverage are shown in appendix B 1.1.

3.3.4. Reservoir-added Scenario at Ahero and S.W. Kano Schemes

Ahero and S. W. Kano Irrigation Schemes currently cover 830 ha and 800 ha of irrigated area respectively. Due to rapid expansion the schemes will soon reach their full potential irrigation coverage with a corresponding increase in water demand. The present level of streamflow in the Nyando River might not sustain future water demand from the two schemes. The possibility of the use of the proposed reservoirs for future sustainable irrigation water supply was evaluated. The Scenarios illustrated in Table 3.8 were in-put in the model and run to assess the results of the intervention measures. The model's ability to depict unmet water demand was used to portray the two schemes' irrigation status. Firstly, the current irrigation status was considered. Other scenarios were developed that illustrated irrigation status in the schemes at half potential and at full potential. Other scenarios considered the introduction of reservoirs as an intervention measure.

Table 3.8. Reservoir scenarios summary for input into WEAP.

Status	Ahero Irrigation Scheme	S.W. Kano Irrig. Scheme
Current Status	830 ha	800 ha
Half Potential	5500 ha	7000 ha
Full Potential	11000 ha	14000 ha
Half Potential with dams	Unmet Water Demand	Unmet Water Demand
Full potential with dams	Unmet Water Demand	Unmet Water Demand

3.3.5. Scenario Reservoirs

Several reservoirs have been proposed for development in the basin. However the three reservoirs *DS2*, *DS5* and *DS20* were chosen because they were initially proposed for irrigation and water supply (JICA, 1992a) and because of their proximity to the irrigation area. Table 3.9 summarizes the characteristics of the proposed reservoirs. A feasibility study was done by JICA (1992a) for the Ministry of Water and Irrigation to assess the viability of 16 dam sites on the Nyando River. This recommended a number of dam sites for further investigation. Some of the proposed dams have been shown in Table 3.9. The three reservoirs at DS2, DS5 and DS20 have particularly been chosen due to their viability based on the JICA proposal and proximity to the targeted irrigation area in the Kano Plains.

Table 3.9. Proposed Reservoirs and their Characteristics (Source:JICA (1992a)

DS	River	RGS	Catchment area (km^2)	Capacity $x10^6(m^3)$	Length(m)	Height of dam(m)	Usage
03	Ainaposiwa	1GB01	120	33	200	50	Flood control
05	Ainabngetuny	IGB05	404	65	-		Irrigation
10	Nyando	1GG02	220	710	-	60	Flood control, Water Supply
11	Nyando	1GC06	867	50	-	50	Irrigation
13	Kipchorian	1GC04	526	21	300	80	Water supply and Flood control
02	Ainabngetuny	1GB03	518	90	210	70	Irrigation and water supply
20	Nyando	1GD07	720	30	150	55	Irrigation, flood control and water supply

3.3.6. Reservoir Storage Capacity Algorithm

The reservoir storage capacities and heights shown in Table 3.8 were estimated from topographical surveys carried out by the Ministry of Water and Irrigation (MWI). WEAP calculated reservoir storage capacities as follows; the estimated storage capacities were entered as the initial storage for the first month as shown in the equation

$$BeginMonthStorage_{Res,m} = InitialStorage_{Res} \text{ for } m = 1 \quad (34)$$

Thereafter, it began each month with the storage from the end of the previous month as shown in the equation below:

$$BeginMonthStorage_{Res,m} = EndMonthStorage_{Res,m-1} \text{ for } m > 1 \quad (35)$$

The beginning storage level was adjusted for evaporation. Since evaporation rate is specified as a change in elevation (SEI, 2005), the storage level was converted from a volume to an elevation. This was done using the volume-elevation curve obtained from the model's in-built reservoir capacity algorithm. The volume-elevation curve was interpolated on entering zero, the estimated storage capacity and the estimated dam height (SEI, 2005). The conversion was done as in the following equation;

$$BeginMonthElevation_{Res} = VolumeToElevation(BeginMonthStorage_{Res}) \quad (36)$$

The elevation was reduced by the evaporation rate as follows:

$$AdjustedBeginMonthElevation_{Res} = BeginMonthElevation_{Res} - EvaporationRate_{Res} \quad (37)$$

Then the adjusted elevation was converted back to a volume as follows,

$$\mathrm{AdjBeginMonthStorage_{Res}} = \mathrm{ElevationToVolume(AdjBeginMonthElevation_{Res})}. \quad (38)$$

The final calculated reservoir storage capacities were then obtained.

3.3.7. Ecological flow requirement

Flow requirements were created along Nyando-Ainabngetuny River downstream of *(D2)* dam-site, along Nyando-Kipchorian River downstream of *(D20)* dam-site and along the main Nyando River downstream of the South-West Kano Irrigation Scheme abstraction point. The mean flows in the streams at 1GB03, 1GD03 and 1 GC05 were entered as the flow requirements at the three points (Table 3.4, section 3.1.1.2.). In the Flow Requirement Calculation Algorithm, the minimum flow is achieved either by restricting withdrawals from the river or by releasing water from reservoirs. The flow out of the node equals the flow in from upstream, plus demand site (*DS*) and the return flows *(RF)* that come in at that point. This flow is given by the following equation:

$$DownstreamOutflow_{FR} = UpstreamInflow_{FR} + DSReturnFlow_{DS,FR} + ReturnFlow_{RF,FR} \quad (39)$$

3.3.8. Water Year Method

Hydrological fluctuation patterns are important in estimating future water availability. While the WEAP model is designed to utilize historic time based data, a second simpler option has also been adopted based on a representative streamgauge at 1GC05. This was used to estimate the basin sensitivity to climate change. The 1GB03 and 1GD03 were however used to simulate hydrological alterations in the upper and lower sections of the basin.

In this method, five categories of water-year types, Very Wet, Wet, Normal, Dry and Very Dry were used to represent hydrological patterns. A frequency analysis of the monthly streamflow at 1GC05 from 1965 to 1985 was carried out. The years were grouped into five quintiles and the annual average inflows for each water year type were calculated. The ratios of monthly fluctuations for the four non-normal years to the normal year were then computed to form the fluctuation coefficient. The base year (the first year in the planning period) monthly inflow was input as data and the values for the future years monthly inflows were set by the water type sequence by applying the fluctuation coefficients to the base year inflows.

CHAPTER 4

RESULTS AND DISCUSSION

4.1. Evaluation of the WEAP Model

4.1.1. Baseflow Separation

Baseflow was separated using the SWAT automated baseflow estimation sub-model. Summary values for baseflow fractions, alpha and baseflow days are automatically printed out. The alpha factor is a baseflow recession constant which the model uses in baseflow estimation. Baseflow days are the number of days for the baseflow recession to decline through one log cycle. Baseflow Passes 1, 2 and 3 are streamflows contributed by baseflow. In general the fraction of water yield contributed by baseflow should fall somewhere between the value of Baseflow Pass 1 and Baseflow Pass 2 (Arnold and Allen, 1999). Therefore, the average of the outputs of Baseflow Pass 1 and Baseflow Pass 2 was taken as the final separated baseflow. Figure 4.1 shows a sample baseflow separation hydrograph for 1GB03 using 1976 streamflow data.

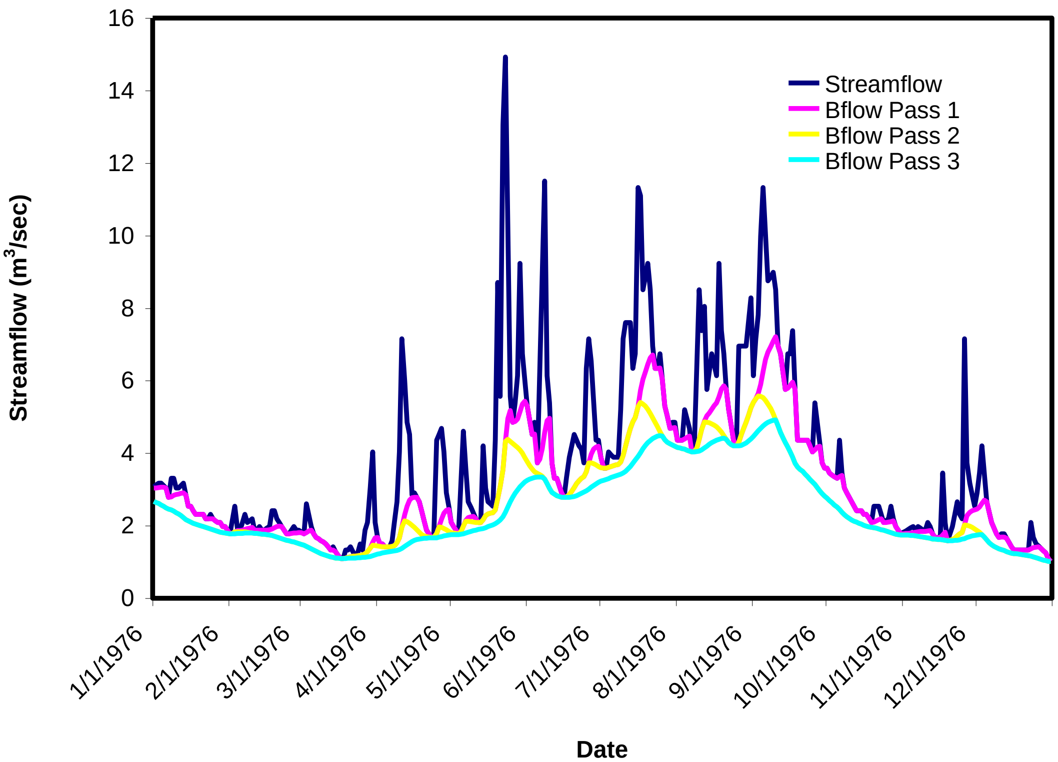

Figure 4.1: Hydrograph at 1GBO3 depicting Streamflow and baseflow separation for 1976.

A summary of the baseflow separation results is shown in Table 4.1

Table 4.1: Baseflow fractions results summary

Gauging station	Baseflow Pass 1	Baseflow Pass 2	Baseflow Pass 3	Alpha factor	Baseflow Days
1GB03	0.78	0.78	0.65	0.0124	81
1GD03	0.58	0.55	0.70	0.0118	84

4.1.2 Calibration of the WEAP model

Calibration of the WEAP model was based on the flow at the gauging stations 1GB03 and 1GD03. It was done for the period 1970 -1980 for 1GB03 and 1952 – 1964 for 1GD03. The period 1981-1990 was used to validate flow at 1GB03 while the period

1965-1972 was used to validate flow at 1GD03. 1GB03 data were offset by 32 years while 1GD03 data were offset by 50 years in order to simulate the study period from 2002 to 2022. The final calibration parameters for both stations are summarized in Table 4.2.

Table 4.2: Summary of calibration parameters

Initial	**Grassland**	**Tree Cover**	**Sugarcane**	**Rice**	**Irrigated Sugarcane**
LAI	7	8	10	20	10
Sw_j	900	1500	1400	900	1400
	1GB03	1GD03			
f	0.6	0.6			
k_j	33	40			
k_2	384	500			
Dw	2000	2000			
Z_1	30	30			
Z_2	40	40			

Final	**Grassland**	**Tree Cover**	**Sugarcane**	**Rice**	**Irrigated Sugarcane**
LAI	8	9	10	30	10
Sw_j	1000	2000	1700	1000	1700
	1GB03	1GD03			
f	0.2	0.3			
k_j	25	30			
k_2	1200	432			
Dw	1000	1000			
Z_1	20	40			
Z_2	20	30			

LAI and Sw_j values are land cover specific and each land cover has to have a value applied to it since the LAI and the Rooting depth depend on specific land covers. The other parameters are applicable to all land cover types.

The initial parameter values gave R^2 of 0.57. The parameters were adjusted to improve the correlation coefficient and the R^2 value of 0.82 was obtained. A similar procedure was repeated for the flow at 1GD03.

Figure 4.2 shows the observed and modeled streamflow for the IGD03 gauging station. The model over-predicted peak discharge volumes and medium flow volumes particularly those within $10*10^6$ m^3. The low flows were however under-predicted in all the cases. Flow volumes above about $300 * 10^5$ m^3 also tended to be under-predicted. Medium flows between $10*10^6$ m^3 and $20*10^6$ m^3 were fairly well estimated but tended

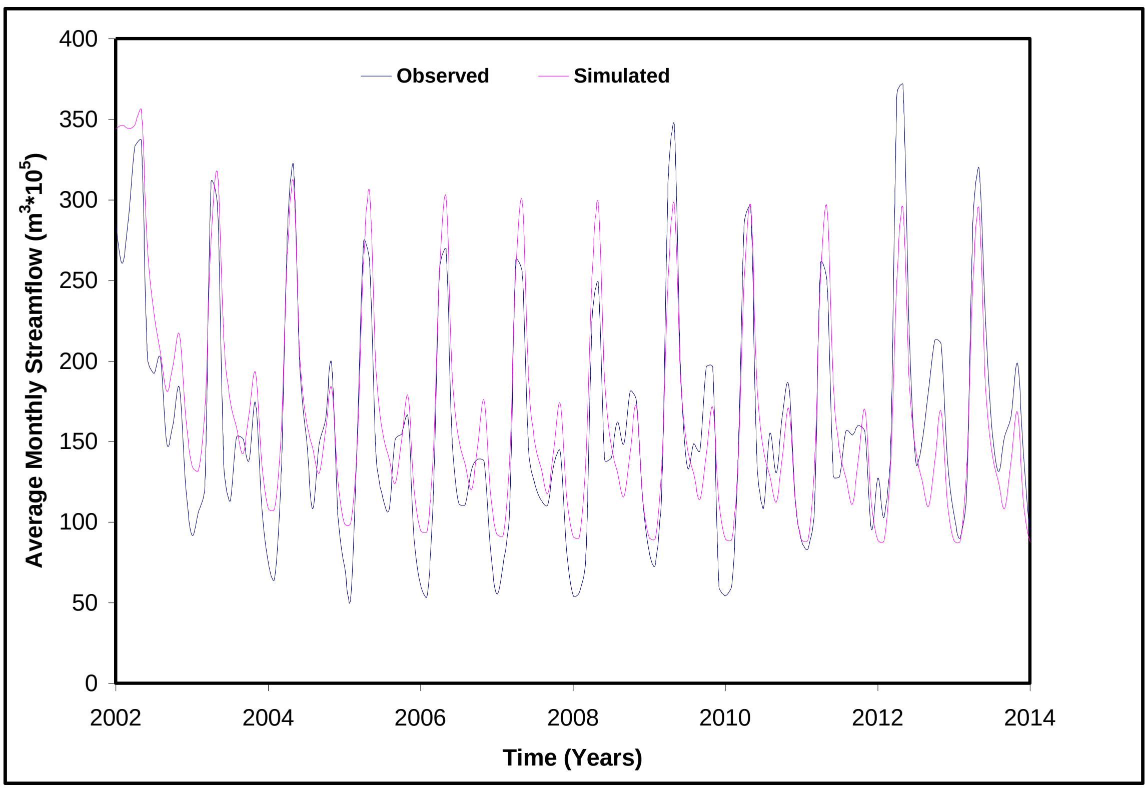

Figure 4.2. Calibration Chart for 1GD03 Stream-gauge.

to be over predicted at the peaks. The general trend shows a regular pattern of monthly peak, medium and low flows.

Figure 4.3 shows the scatter plot of the monthly observed versus modeled flow volumes for 1GD03. The goodness of fit at the final R^2 value of 0.82 shows a good agreement between the observed and simulated flows.

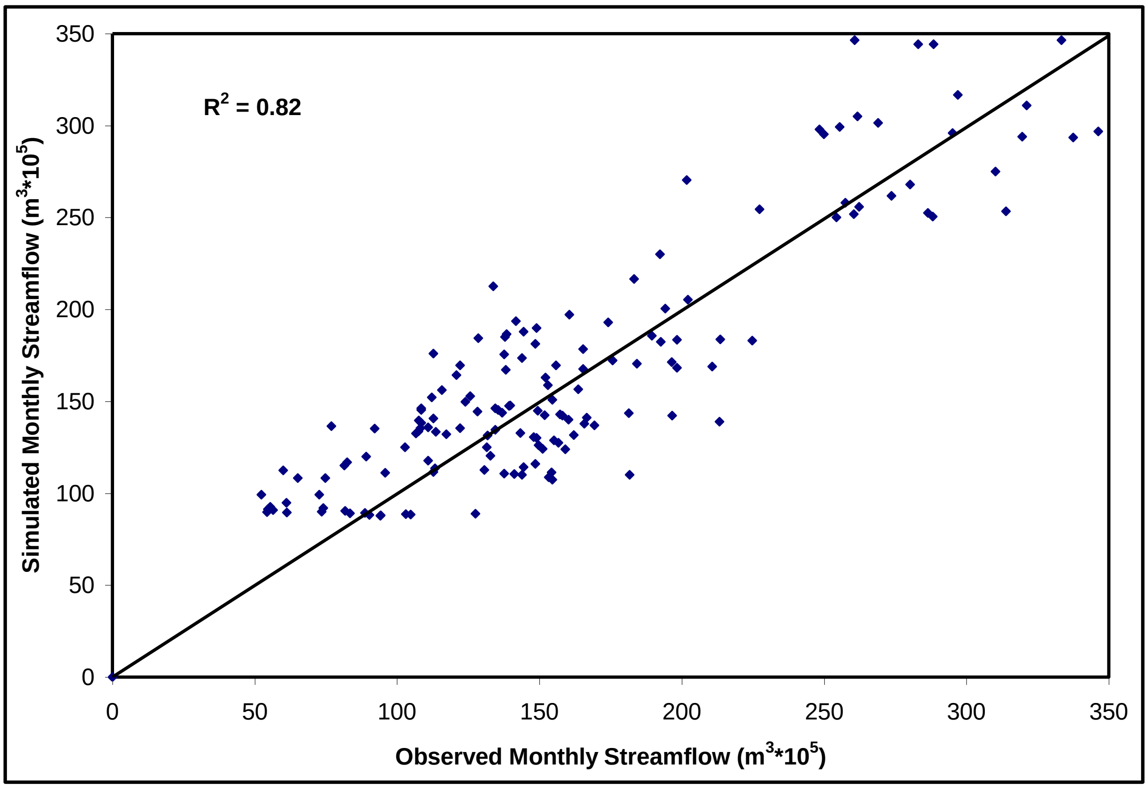

Figure 4.3. Scatter Plot for the 1GD03 Stream-gauge

There was better correlation between the observed and simulated streamflow at 1GB03 than at 1GD03 (Table 4.3). The model performed much better in simulating the low flows (Figure 4.4). However the model over-predicted the lowest flows of about $65 * 10^5$ m^3

while it under-predicted the medium flows of about 100 * 10^5 m^3. The peak flows were largely over-predicted. However, the model accurately predicted the mean flows probably since mean values of parameters like root zone water capacity and deep water capacity were used in calibration.

The relatively accurate low flow prediction would result in reliable simulation of ecological in-stream flow requirement which was fixed based on minimum flow levels. Table 4.3 shows a comparison of the observed and simulated mean flows, R^2 and RMSE at the two stations during calibration.

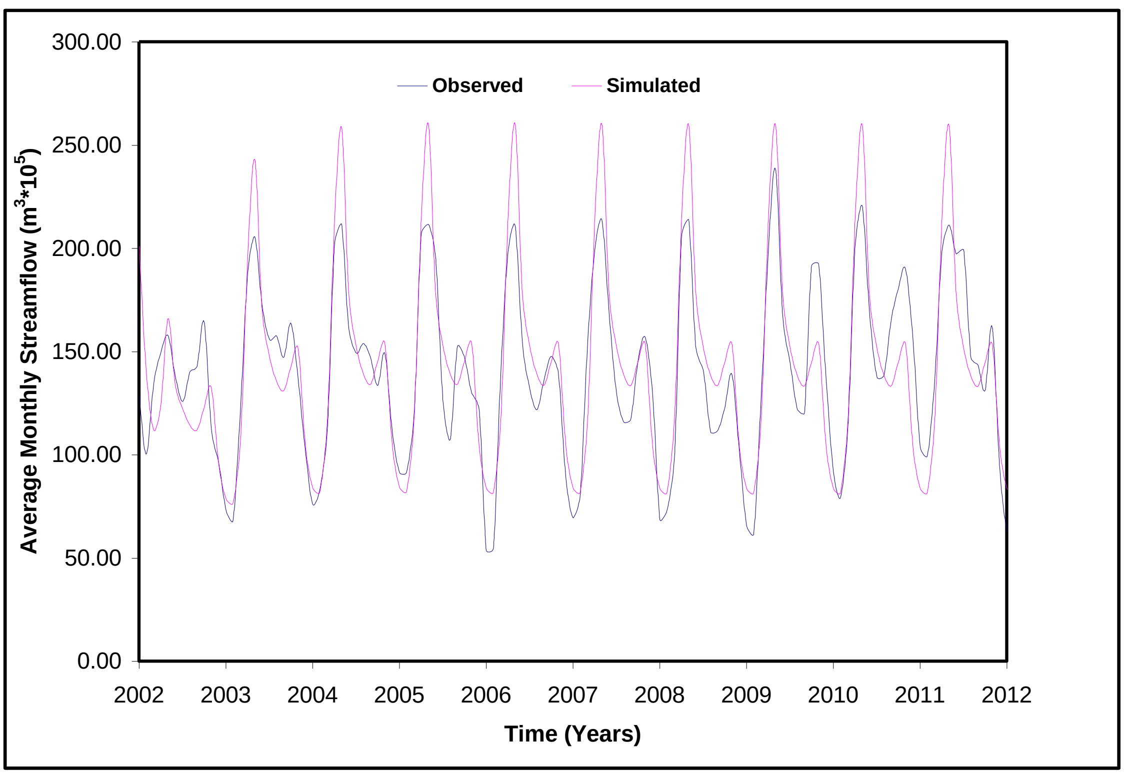

Figure 4.4. Calibration Chart for the 1GB03 Stream-gauging Station.

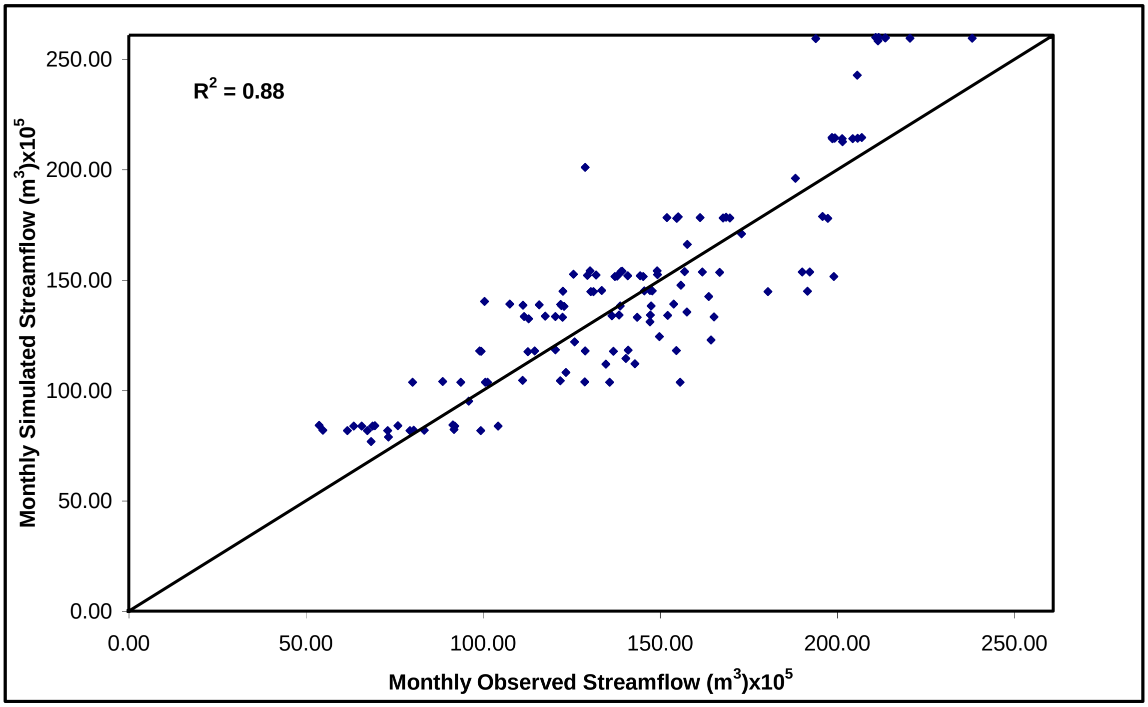

Figure 4.5: Scatter Plot for 1GB03 Stream-gauging Station

Table 4.3: Comparison of the observed and simulated mean monthly flows.

River Gauging Station	Mean monthly flow (m^3)		Correlation Coefficient (R^2)	Root Mean Square Error (*10^6) (RMSE)
	Observed	Simulated		
1GB03	13.9	14.6	0.88	0.7
1GD03	16.4	17.1	0.82	0.6

4.1.3. Validation of the WEAP model

For the 1GD03 gauging station, data for the period 1965-1972 was used for validation while 1981-1990 data were used to validate flow at 1GB03. Figure 4.6 presents a comparison of the observed and predicted average monthly flows at 1GD03. The WEAP model predicted peak flows of about 300 * 10^5 m^3 fairly accurately. Lower peaks of about 230 * 10^5 m^3 were however grossly under-predicted. Extreme low flows of below 100 *10^5 m^3 were also generally over-predicted during the validation. In general however the model performed well in simulating streamflow giving a correlation coefficient (R^2) value of 0.80 (Figure 4.7) and a root mean square value of 0.7 * 10^6. For the 1GB03 gauging station it was observed that the model reproduced low flows better than peak flows. Median flows were not accurately predicted since the calibration data were generally of extreme type as opposed to mean frequency type.

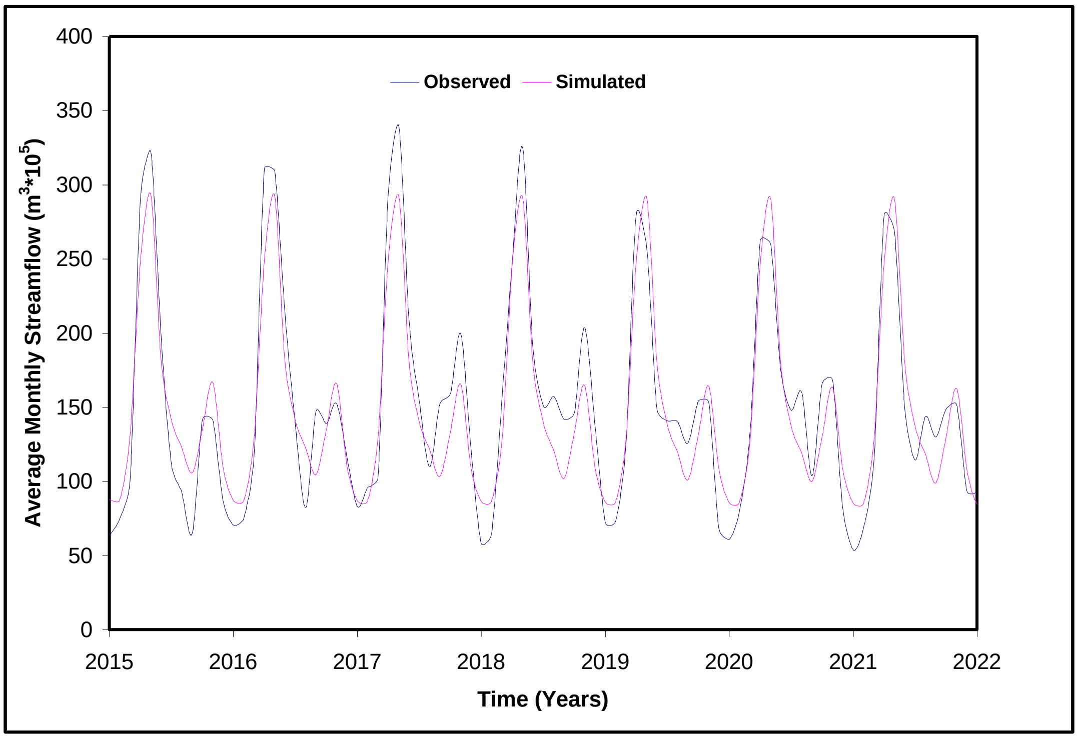

Figure 4.6. Validation Chart for the 1GD03 Stream-gauging Station

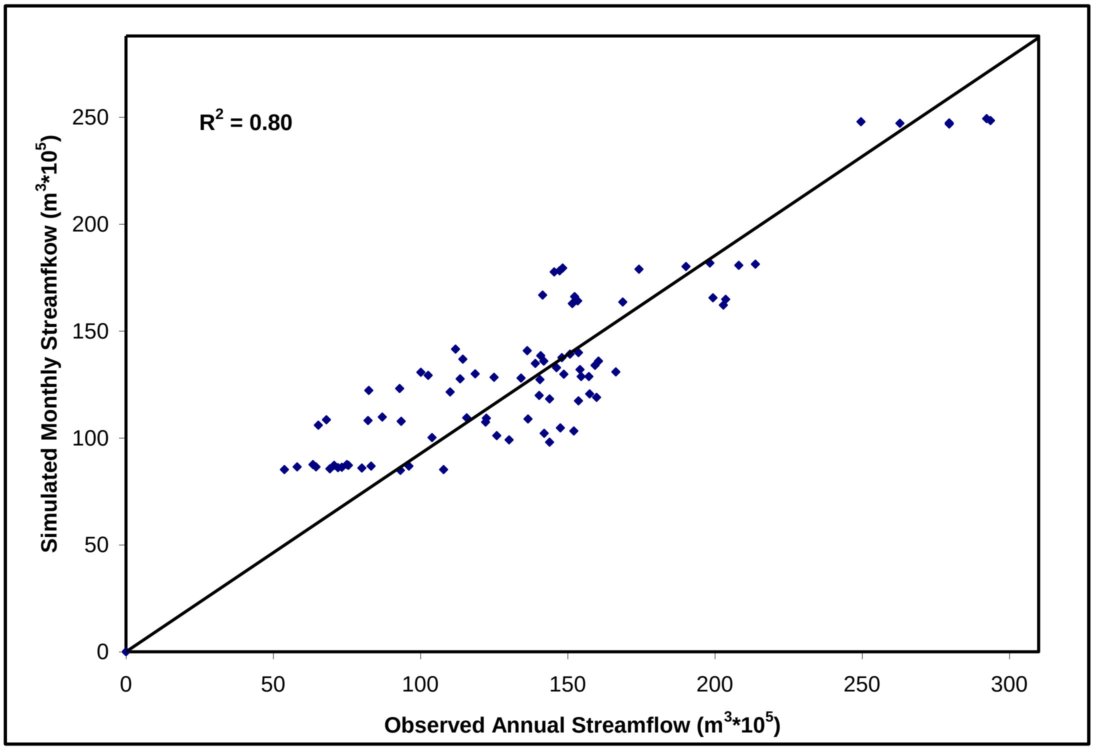

Figure 4.7: Validation Scatter plot for 1GD03 Stream-gauging Station

The low flows were predicted fairly accurately unlike the medium flows which were largely poorly predicted. The scatter-plot for the simulated versus observed flow for 1GB03 gauging station gave a correlation coefficient (R^2) value of 0.80 (Figure 4.9).

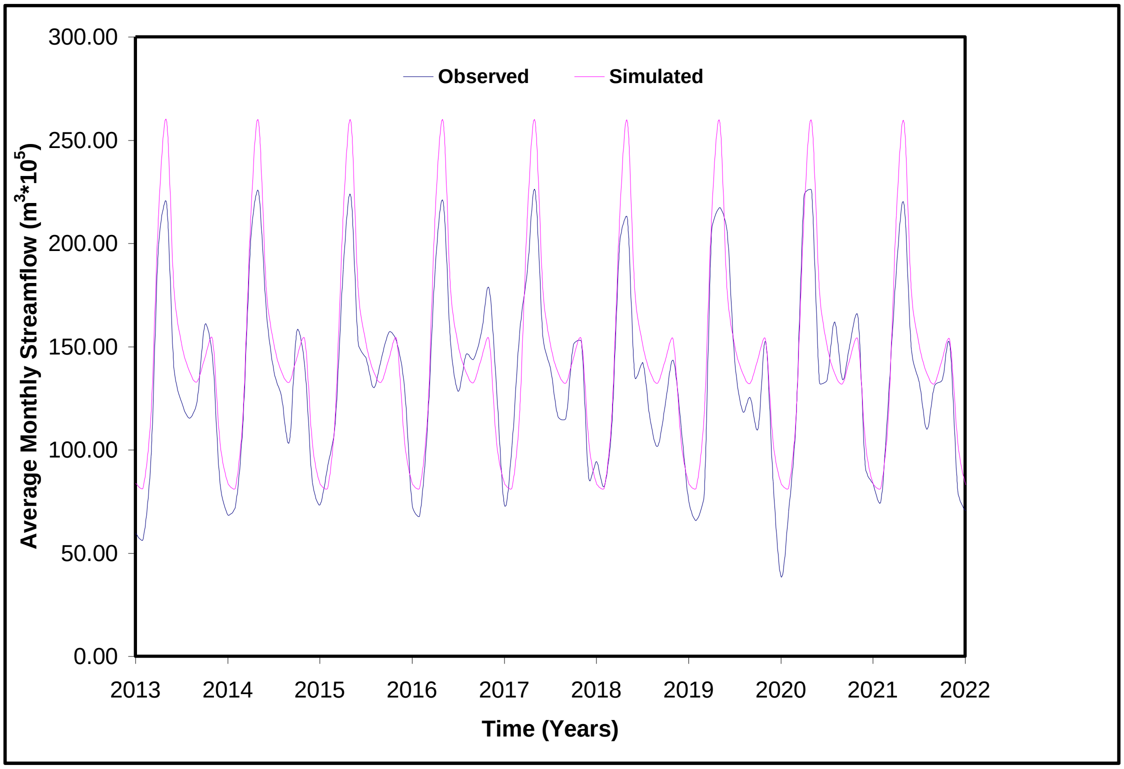

Figure 4.8: Validation Chart for the 1GB03 Stream-gauging Station

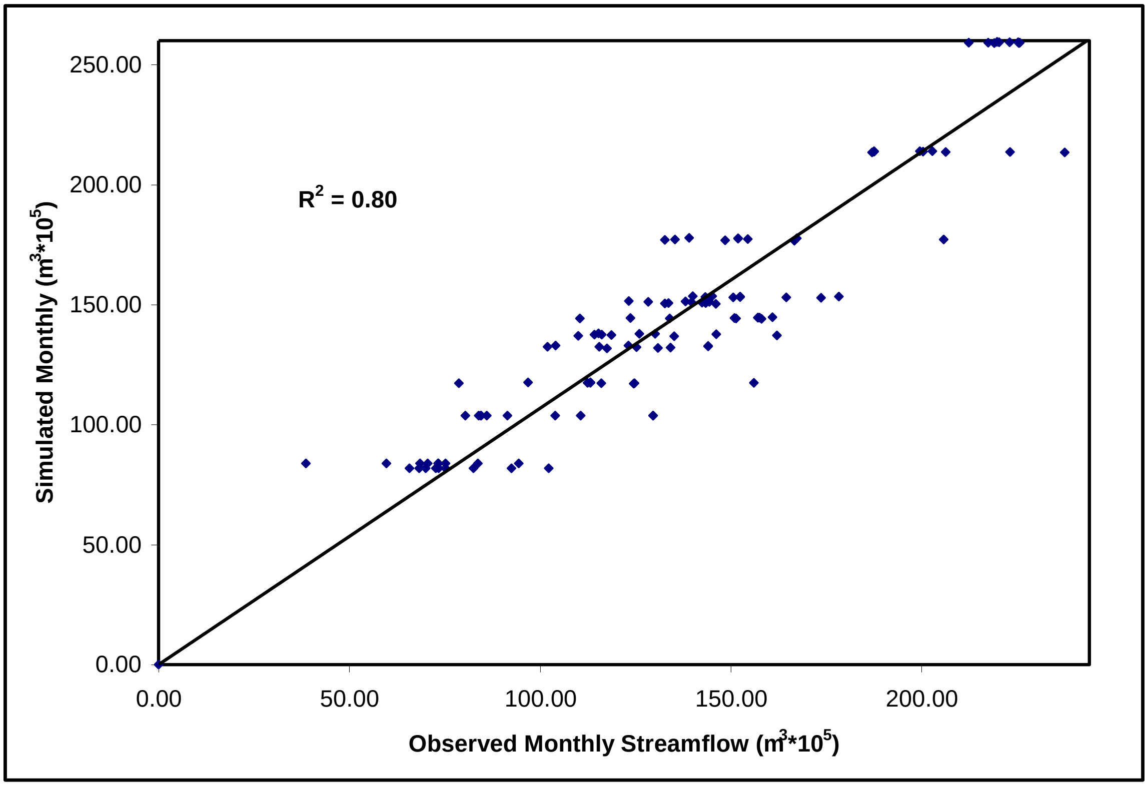

Figure 4.9: Validation Scatter-plot for 1GB03 gauging station.

Despite the inability of the model to capture some of the low streamflows, it was able to reproduce most of the cyclic variability and the low, medium and peak flow characteristics of the watershed. The capability of the model to simulate streamflow for the Nyando basin can therefore be relied on since it was capable of capturing the most important hydrologic processes that dominate the watershed.

4.2. Spatial and temporal distribution of river water resources

4.2.1. Ecological Flow Requirement

The in-stream or ecological flow requirement is a minimum flow requirement that is set at a point on the river to meet ecological and other downstream flow requirements. The in-stream flow requirement at 1GB03 was set at the mean flow level of 13.9 MCM (5.2 m^3/s).The Result of the Unmet in-stream Flow Requirement downstream of 1GB03 along the Nyando-Ainabngetuny River is then as shown in Figure 4.10.

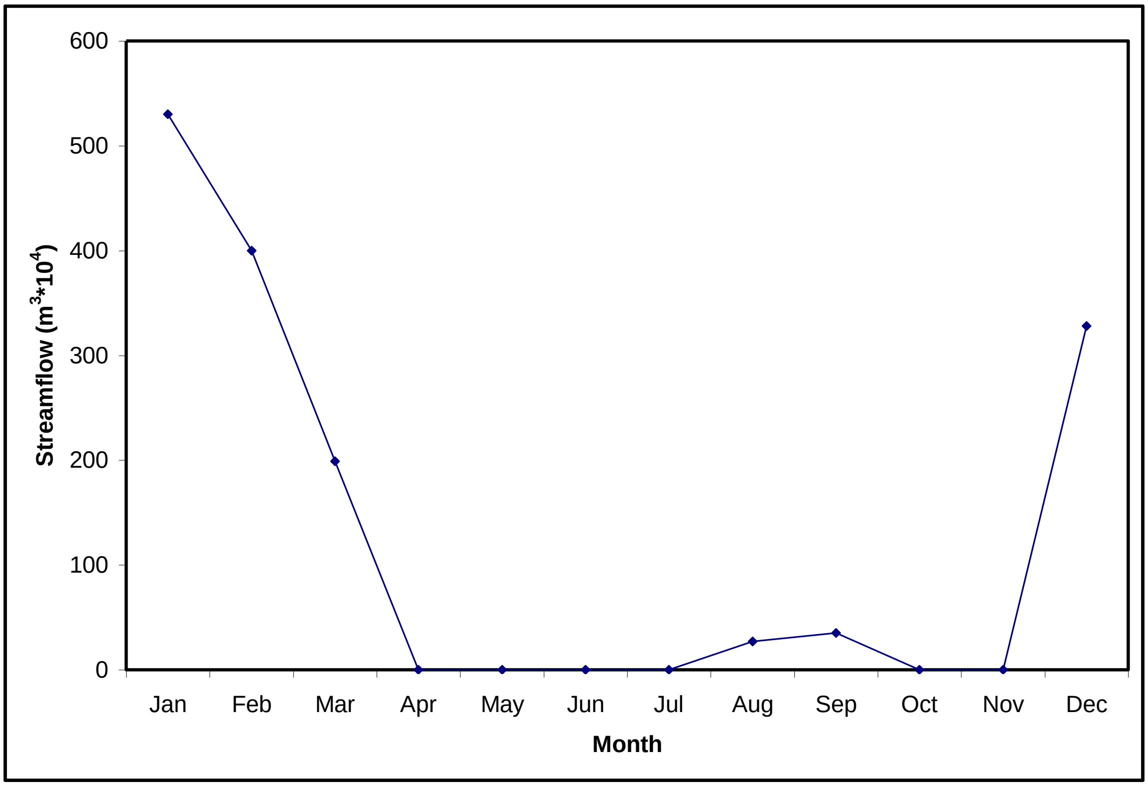

Figure 4.10. Unmet Flow Requirement downstream of 1GB03.

The Unmet in-stream flow requirement is highest in January and February during extreme low flow situation in the river. It reduces in March before the onset of the long rains in April. The requirement is adequately met till August and September during peak irrigation water requirement at Ahero Irrigation Scheme. It is fully satisfied again in October and November during the short rains before rising again in December when low flow conditions commence. A similar trend was observed for the unmet ecological flow requirement at 1GD03 as at 1GB03 (Figure 4.11).

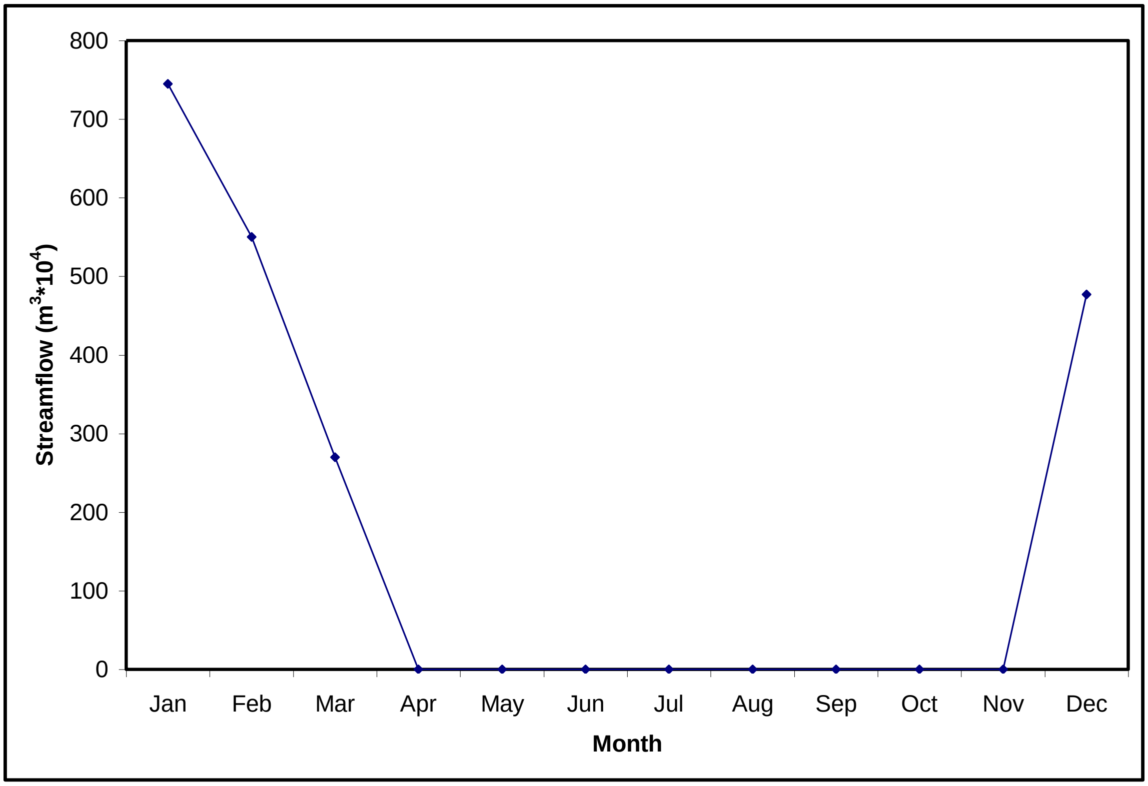

Figure 4.11: Unmet Flow Requirement downstream of 1GD03

The ecological flow requirement for 1GD03 was set at 16.1MCM (Fig. 3.4, sub-section 3.2.1.). However the flow requirements for the rest of the months were fully met apart from the months of January, February, March and December. Ecological Flow Requirement for 1GC05 was set at 2.8 MCM. It was largely unmet (Figure 4.12) most likely due to the extreme low flows in the upper reaches of the Nyando-Kipchorian River, industrial withdrawal from Muhoroni, Chemelil and Agro-chemical Companies and the introduction of *D20* for irrigation and water supply in the Kano Plains. The requirement was only fully met in October through November during low irrigation activities in Ahero and S.W. Kano Irrigation Schemes, coupled with the short rains.

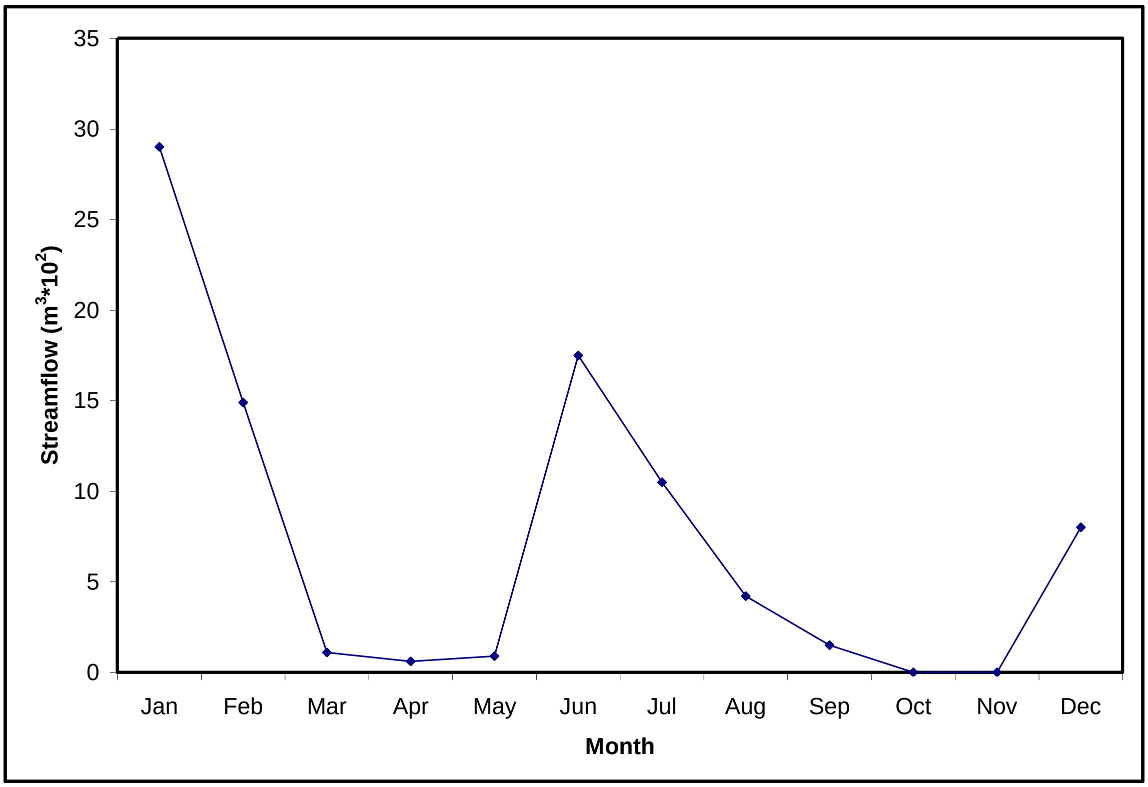

Figure 4.12. Unmet Flow Requirement for 1GC05

4.2.2. Reference Scenario

Reference Scenario represents the changes that are likely to occur in the future without intervention or new policy measures. It is also known as business-as-usual scenario. Finally "what-if" scenarios can be created to alter the Reference Scenario and evaluate the effects of changes in policies and/or technologies (SEI, 2005).

4.2.3. Water demand

Table 4.4 shows the forecast future water demand for the basin starting from the current accounts year (2002) to the final study year (2022). The GrowthFrom function was used to calculate the water demands and a common population growth rate of 3.4% based on

Table 4.4:Forecast Domestic, Industrial and Livestock Water Demand for major sites in selected years (MCM)

D/S	2002	2004	2007	2012	2015	2019	2022
Chemamul	1.57	1.63	1.73	1.88	2.04	2.23	2.39
Chemelil	2.53	2.60	2.73	2.91	3.11	3.34	3.54
Kibigori	3.45	3.61	3.86	4.24	4.67	5.15	5.55
Kipkelion	3.90	4.06	4.33	4.72	5.16	5.66	6.07
Londiani	4.05	4.22	4.51	4.93	5.40	5.93	6.37
Maso	1.47	1.54	1.66	1.84	2.05	2.28	2.48
Muhoroni	2.84	2.99	3.23	3.59	3.99	4.44	4.81
Nandi Tea	1.03	1.07	1.14	1.25	1.37	1.51	1.62
Taachasis	1.01	1.05	1.12	1.21	1.32	1.45	1.56
Others	9.0	9.3	5.18	5.63	6.11	6.68	7.16
Sum	**30.85**	**32.07**	**33.91**	**36.77**	**39.71**	**43.19**	**45.99**

the National population growth rate (Republic of Kenya, 1999c) was assumed. The water demands at the various demand sites consisted of urban, rural, livestock and industrial requirements. Irrigation water demands at Ahero and South West Kano Irrigation Schemes were worked out separately using the soil-moisture model. The estimate for the current total water demand was 33.91 MCM, excluding irrigation water demand. The Report on the National Water Master Plan by JICA (1992b) estimated it at about 30 MCM in 1996 using the 20l/h/d per capita water demand. The JICA estimate was lower since livestock water demand was not included. The other sites include, Muhoroni Factory, Chemelil Factory, and Agrochemical and Food Company. Water supply for the model input has been considered solely from the three major tributaries of the Nyando River, namely, Ainabng'etuny, Kipchorian and the main Nyando River. In order to capture the actual current water demand, single existing off-take points have been considered to cover wide areas in each Division according to the basin boundary. For example, Maso water supply covers part of Kapsoit, Kenegut and Kapsaos in Ainamoi Division. It also covers part of Soin and Chilchila Divisions in Kericho District. The areas covered by Kipkelion water supply include, Kipchorian, Kamasian, Barsiele, Kimugul and Kipsegi also in Kericho District. Appendix B1.1 shows the water supply coverage by each off-take point for the entire basin. Other water supplies within the basin have been documented in appendices B1.2 – B1.4.

4.2.4. Sectoral Water Demand

Table 4.5 shows the breakdown of the various Nyando Basin demand sectors. Irrigation water demand has been dealt with solely in section 4.5. The water demand sectors are rural domestic, urban domestic, industrial and livestock water demands. Only major demand sites have been considered. Rural domestic water demand is the highest since a large percentage of the population stays in the rural areas. Industrial water demand is concentrated mainly at the sugar processing factories of Chemelil and Muhoroni and at the Agro-chemical and Food Company and is generally lower than the other sectoral water demands.

Figure 4.6 shows a pie-chart representation of the sectoral water demands. The main urban centres in the basin such as Londiani, Kipkelion, Ahero and Awasi lack major industries with high water demand. At 8% livestock water demand has some impact and is greater in the upper region than in the lower region. Sectoral water demand was developed by entering human and livestock population data for the various demand sites and the per-capita water use rate. Industrial water demand data was entered as production

Table 4.5. Nyando Basin Water Demand by Sectors (Units: MCM)

Demand Sites	Rural	Urban	Industrial	Livestock	Total
Agro-chemical Co.	-	-	0.74	-	0.74
Chemamul	1.40	0.03	-	0.30	1.73
Chemelil	0.92	1.9	-	0.21	3.03
Chemelil Fact.	-	-	0.87	-	0.87
Kibigori	2.40	1.36	-	0.10	3.86
Kipkelion	1.73	2.10	-	0.50	4.33
Londiani	1.41	2.60	-	0.50	4.51
Maso	1.32	0.20	-	0.40	1.92
Muhoroni	0.99	2.00	-	0.22	3.21
Muhoroni Fact	-	-	0.81	-	0.81
Nandi Tea	1.02	-	0.30	0.10	1.42
Taachasis	1.92	0.10	-	0.30	2.32
Other sites	4.96	-	-	0.20	5.16
Total	18.07		2.72	2.83	33.91

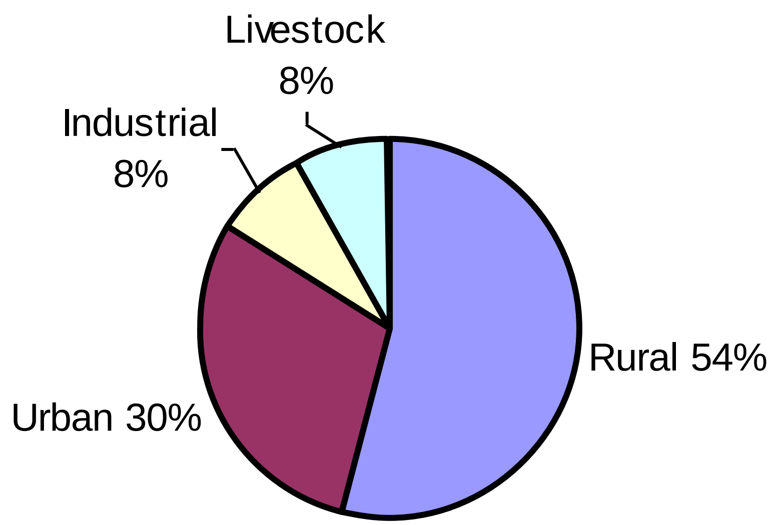

Figure 4.13. Nyando Basin Sectoral Water Demand

units. The major production units for the sugar industries were, processing and cooling units.

4.2.5. Basin Unmet Water Demand

Even though the per capita water demand was taken as low as 20l/h/d for people without individual connections, 60l/h/d for those with individual connections and 150l/h/d for urban centres (MWI, 2006), the total basin unmet water demand was still high at approximately 15.23 MCM (Table 4.6). The total contribution from other water sources has been estimated at approximately 2.19 MCM, leaving the total basin unmet water demand of 13.04 MCM. The other water sources indicated in Table 4.6 are boreholes, springs and roof catchment.

Table 4.6. Unmet Domestic, Livestock and Industrial Water Demand (MCM)

Demand Site	Unmet demand	Other Sources	Net Unmet
Agrochemical	0.38	-	0.38
Chemamul	0.31	0.08	0.23
Chemelil	1.68	0.09	1.59
Kibigori	2.08	1.15	0.93
Kipkelion	2.81	0.05	2.76
Londiani	2.93	0.1	2.83
Maso	0.94	0.23	0.71
Muhoroni	2.14	0.14	2.00
Muhoroni Fact	0.25	-	0.25
Nandi Tea	0.90	0.27	0.63
Taachasis	0.81	0.08	0.73
Total	**15.23**	**2.19**	**13.04**

4.2.6. Water Year Simulation Results

The calculated average annual inflow for each of the years 1965-1985 in quintiles are presented in Table 4.7.

Table 4.7. Water Year Definition and Average Annual Streamflow

Water Year Definition	Average annual flow (MCM)	Coefficient
Very Wet	3.12– 7.23	2.93
Wet	2.09 – 3.11	1.37
Normal	1.36 – 2.08	1
Dry	1.19 – 1.35	0.73
Very Dry	0.45 – 1.18	0.49

The water year definition then depended on the relationship between the flows in that year to the normal using the coefficient or definition factor. The coefficient determines how much water flows into the system in a particular year relative to the normal year. The streamflows at 1GC05 were offset by 37 years for the simulation years 2002 to 2022.

Figure 4.14 shows the results of the definitions of the water year types, i.e. Very Dry, Dry, Normal, Wet, Very Wet, the average flow and the water year. The bar-chart shows that Dry, Normal, Wet and Very Wet years appear four times each while Very Dry years appear five times. Very Dry and Dry years appear a total of nine times out of twenty years, which is 45% of twenty years. The basin is likely to experience water scarcity during that period.

The defined sequence has been assumed to be a reasonable approximation of the climatic pattern of the basin. The method assumes hydrological homogeneity across the basin and permits the exploration of future water patterns that deviate from historical patterns due for example to climatic alterations. Table 4.8 presents the annual average water demand coverage – the ratio of supply available to demand – at the major demand sites in selected future years.

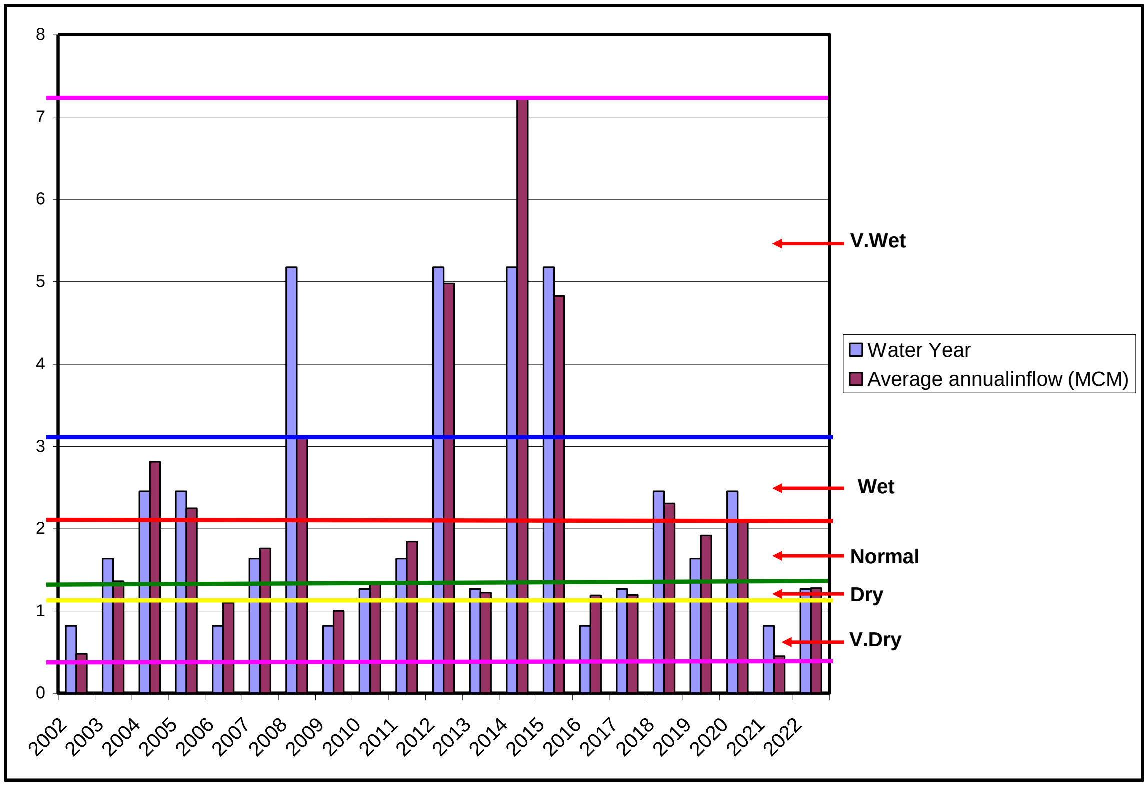

Figure 4.14. Graphical Representation of Water Year Definition Frequencies.

When the coverage value is one, the demand is fully met; otherwise only the indicated portion of the demand is supplied. Coverage is less than or equal to one, since supplies are driven by demands in the model and redundant water is not sent from supply sources to distribution system. The representative years in Table 4.8 have been selected in order to depict every water year definition such as Wet, Very Wet, Normal, Dry and Very Dry.

Table 4.8. Projected Demand Coverage in Selected Years.

D/S	2002	2004	2007	2012	2015	2017	2021
	Very dry	**Wet**	**Normal**	**V. Wet**	**V. Wet**	**Dry**	**V. Dry**
Chemamul	0.88	1.00	1.00	1.00	1.00	0.87	0.70
Chemelil	0.85	1.00	0.95	1.00	1.00	0.67	0.52
Kibigori	0.52	0.70	0.62	1.00	0.96	0.56	0.48
Kipkelion	0. 45	0.71	0.68	0.97	0.92	0.41	0.34
Londiani	0.42	0.69	0.65	0.95	0.90	0.40	0.33
Maso	0.60	1.00	0.94	1.00	1.00	0.75	0.62
Muhoroni	0.79	1.00	0.98	1.00	1.00	0.63	0.58
Nandi Tea	0.81	1.00	0.99	1.00	1.00	0.72	0.60
Taachasis	0.84	1.00	0.97	1.00	1.00	0.78	0.65

Demand Sites along the Ainabng'etuny tributary and the main Nyando River would be mostly satisfied in the selected years while Demand Sites along the Nyando-Kipchorian tributary would mostly face water shortages especially in the future dry and very dry years. In Londiani and Kipkelion, water users will only receive 40% and 41% respectively in the dry years and 34% and 33% respectively in the very dry years (Table 4.8). In the Dry and Very Dry years water shortages will be experienced in all the Demand Sites. Kibigori which supplies those in Nyando Division and Miwani will experience more shortages than the upstream Demand Sites especially during normal and dry years receiving only 62% during the normal year of 2007. The situation will get worse in the dry and very dry years of 2017 and 2021 when the Demand Site will obtain only 56% and 48% respectively of the supply coverage. The use of reservoirs in the future may alleviate water supply shortages in the lower basin.

4.3. Evaluation of future water demands in the basin

4.3.1. Future Development Scenarios

A number of key scenarios describing possible future irrigation situation in the lower Nyando Basin have been defined. The starting point for the scenarios was an assumption that in line with the new Water Resources Management Strategy as contained in the Water Act 2002, the overriding policy is to prioritize the development of irrigated areas to their full potential. Working from this assumption, both the existing and potential future irrigation development in the lower Nyando Basin have been considered. Three of the many proposed dams in the basin have been selected for simulation of irrigation water supply in Ahero and South West Kano Irrigation Schemes (Figure 4.13). According to simulation results, Reservoir DS2 and DS5 both have a capacity of 18.6 MCM and are located at Twin's Bridge and Songhor respectively. Reservoir DS20 has a capacity of 23 MCM and is located upstream of Awasi town.

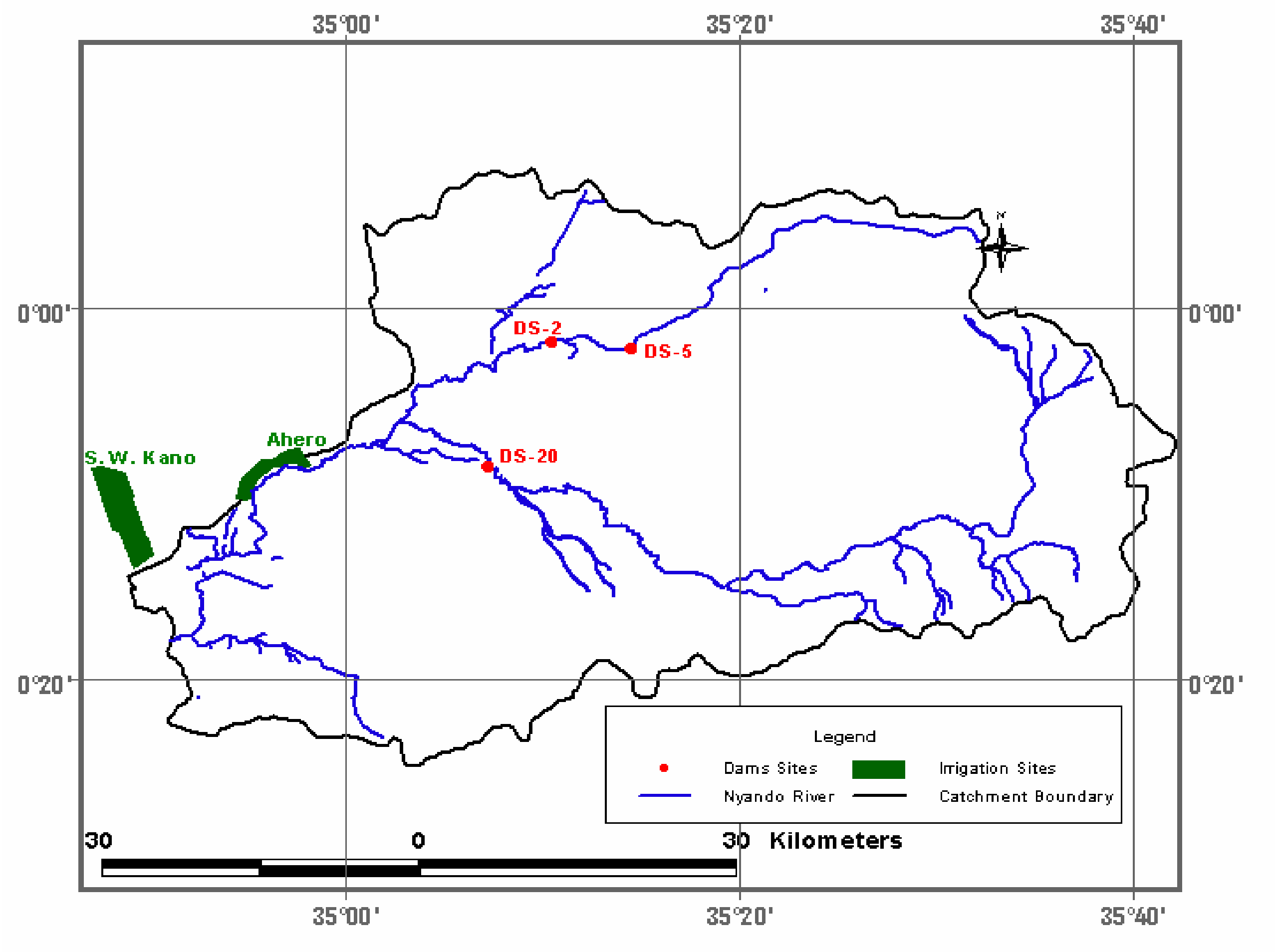

Figure 4.13: Proposed dam sites

The present rice irrigation coverage for Ahero Irrigation Scheme and South West Kano is 830 ha and 800 ha respectively. The forecast full potential irrigation area is 11000 ha for Ahero and 14000 ha for South West Kano, giving a total irrigable potential of 25000 ha (Samez Consultants, 2005). Six scenarios have been simulated. Scenario one shows the current unmet water demand for Ahero and S.W.Kano Irrigation Schemes without the use of dams. Scenario two shows the unmet water demand at the two schemes when half the irrigation development potential is exploited without dams. Scenario three shows the exploitation of the full irrigation potential without dams. Scenario four shows the exploitation of the half irrigation potential for the two schemes when dam DS2 is used. Scenario five shows the exploitation of the full irrigation development potential with the use of two dams, DS2 and DS5. Scenario six shows the exploitation of the full irrigation potential with the use of three dams, DS2, DS5 and DS20.

4.3.2. Reservoir Storage volume "rules"

During high demand periods for the half and full potential irrigation demands the surface storages of the reservoirs are drastically drawn down to meet water requirements. The reservoirs are also set to capture flood flows (Yates et al., 2005b). To reflect these operational objectives, reservoir operating rules are expressed as monthly average reservoir volume thresholds (Figure 4.14). These include a conservation volume above which water is immediately passed downstream and within which water can be fully released to meet downstream demands. The next storage zone is called the buffer zone and defines a portion of the reservoir where demands are restricted and downstream demands can only be met as a percentage of the available storage within the buffer zone by multiplying by the buffer coefficient. Below the buffer zone is the inactive storage that cannot be used to meet demand. Top of inactive was set at zero for all the reservoirs to maximize buffer storage.

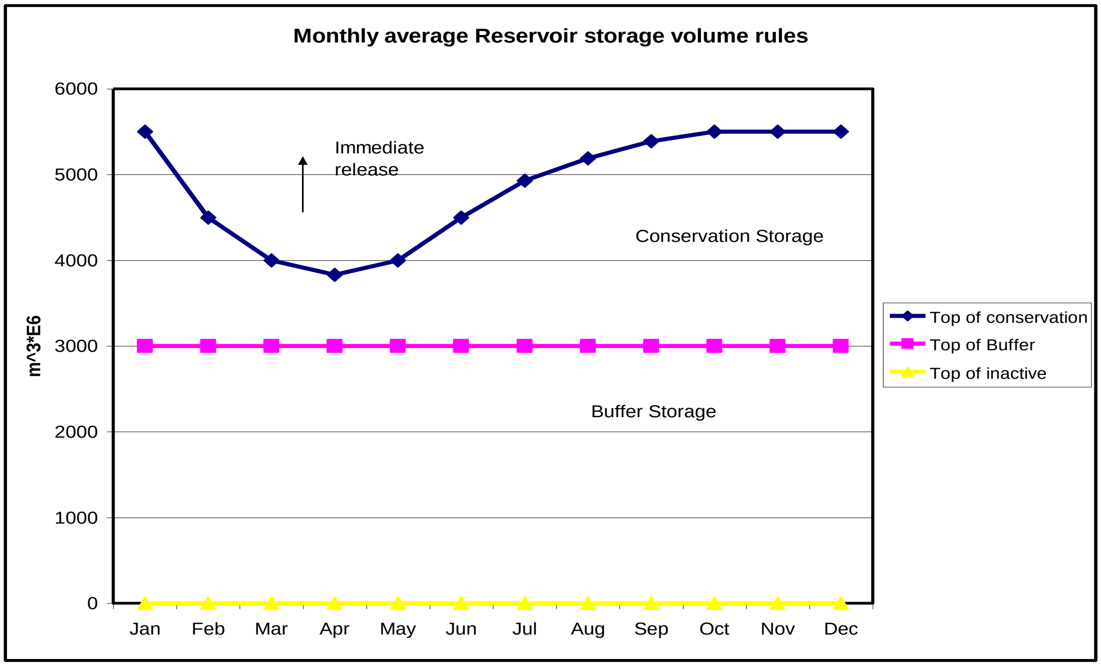

Figure 4.14. Monthly average storage volume "rules" for the DS2, DS5 and DS20 reservoirs.

4.3.3. Irrigation Water Demand

The model results give the annual average water demand for Ahero Irrigation Scheme as 21.3 MCM and that for S.W. Kano as 20.5 MCM (Table 4.9).

Table 4.9. Water Demand Scenario Summary (MCM)

Scenario	Ahero Scheme	S.W. Kano Scheme
Current Status	21.3	20.5
Half Potential	141	180
Full Potential	282	359

According to Njogu (2000), the total annual water demand for the Ahero Irrigation Scheme is 19 MCM and that for the S.W. Kano Schemes is 21 MCM. The two results compare favourably. Figure 4.15 shows the current water demand trends for the two schemes.

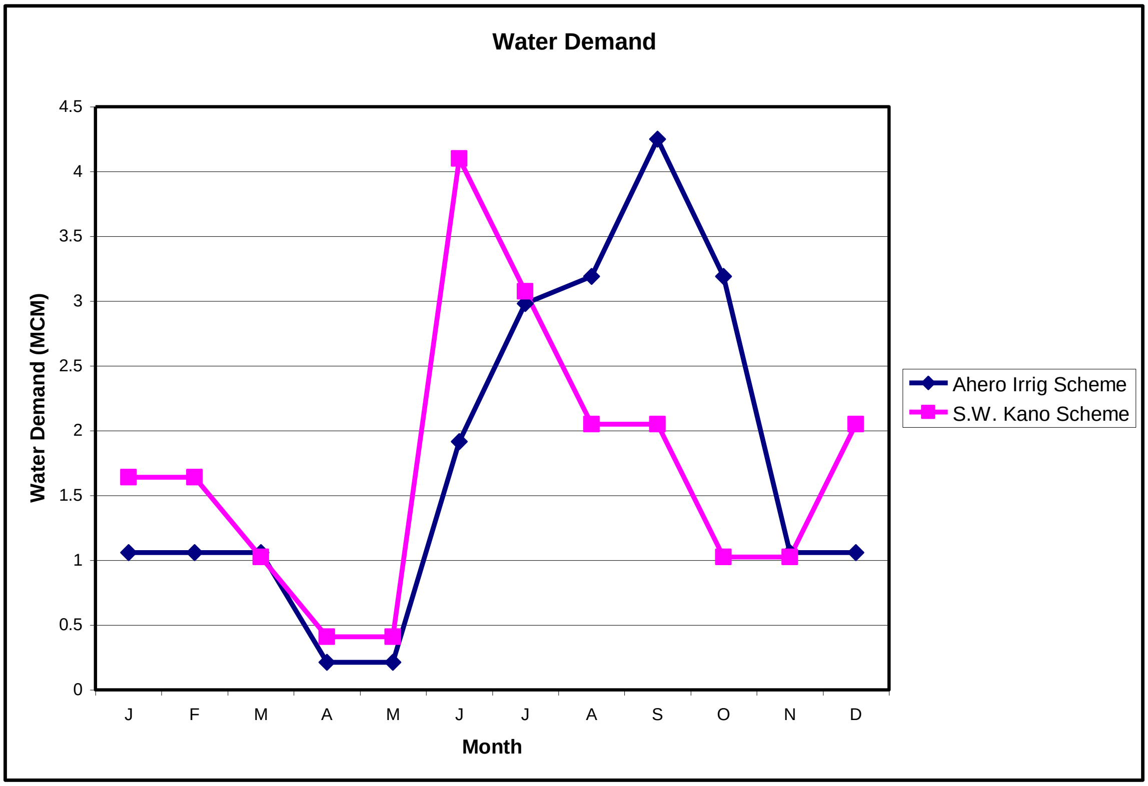

Figure 4.15: Current Water Demand for Ahero and S.W. Kano Irrigation Schemes.

Water demands are low during the dry periods from December to February because these are not peak planting seasons. At the Ahero Scheme, rice cultivation schedule is tighter than at the S.W. Kano Scheme. The rice irrigation schedule at Ahero was defined from June through January (Table 4.10). At Ahero, major field preparation starts in June, while planting starts from July to August. Maximum water use therefore spreads from August, peaks in September and starts declining in October. The crop growth pattern in South West Kano Scheme is more undefined; however peak water use periods occur mostly between May and June during the weeding stage. Water demand is lowest in April and May when the long rains supplement irrigation water from the river Nyando.

Table 4.10. Rice Irrigation Schedule at Ahero Irrigation Scheme (Source: NIB)

Operation	Period	Remarks
Land Preparation and Puddling	June-September	Mechanized Rotavator
Transplanting	July – October	Manual
Water Management	June – December	Manual
Field Maintenance	Mid Aug –January	Manual

Leaf Area Index (LAI) value for rice was set at the high value of 30 (SEI, 2005) resulting in less surface runoff and more percolation from the heavy precipitation from April to May and October to November. There was therefore reduced water demand during these months to meet evapotranspiration. Water demand in S.W. Kano is higher than in Ahero in December, January and February, because the rice cultivation season in S.W. Kano is almost continuous throughout the year. This is because there is no specified irrigation schedule. Maximum water allocation for the two schemes would therefore start from May to October.

The upper (U) and lower irrigation (L) relative storage thresholds are used to estimate seasonal and annual irrigation depths based on established irrigation practices (DWR 2005). The high irrigation demands are due to the fact that rice adopts a flooded-field irrigation strategy. Yates et al (2005b), suggests that, to mimic the flood irrigation process for rice, the upper and lower irrigation thresholds should be set at 0.95 and 0.85 respectively. This forces the model to continually supply water to the irrigated area in order to keep the relative storage near complete saturation during the growing season.

Figure 4.16 shows the characteristic average monthly precipitation pattern for the Nyando Basin (based on Rain Gauging Stations at Kaisugu, Kipkurere and Ahero Irrigation Scheme). The peaks in April and November result into considerable water demand reduction for both demand sites. Conversely, the relatively dry period from June through October show escalating demand patterns as the natural precipitation is not enough to adequately meet the soil moisture demand. The model gives the annual effective precipitation available for evapotranspiration of 1100mm and the respective annual rainfall contribution at Ahero and S.W. Kano Irrigation Schemes of 9.1 MCM and 8.8 MCM.

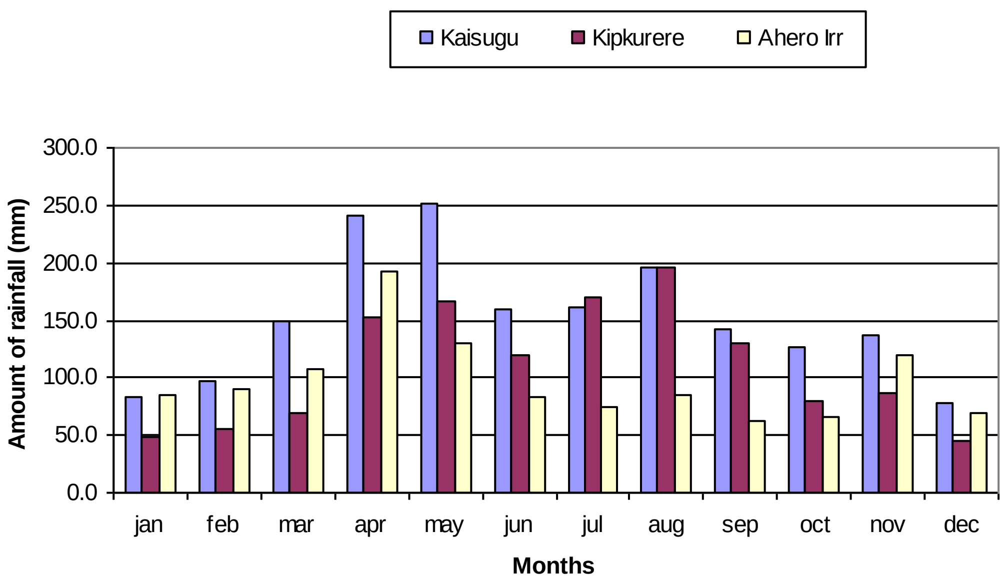

Figure 4.16. Characteristic rainfall patterns for stations in the Nyando Basin. (Source: Samez, 2005).

4.3.4. Scenario 1: Current Status

The current total annual average unmet water demands for the two schemes are quite low at 1.2 MCM and 3.0 MCM at Ahero and South West Kano Schemes respectively. Much of the demand is unmet in the dry months of December, January and February. The demands are however fully met during the rest of the year (Figure 4.17 and Figure 4.18). At both Irrigation Schemes the demand is unmet during these months because of the relatively low baseflow levels occasioned by the high flow direction factor *f* of 0.8 whereby interflow dominates over deep percolation. The model shows that at the moment there should be enough water to meet minimum irrigation requirement for much of the year for the two schemes.

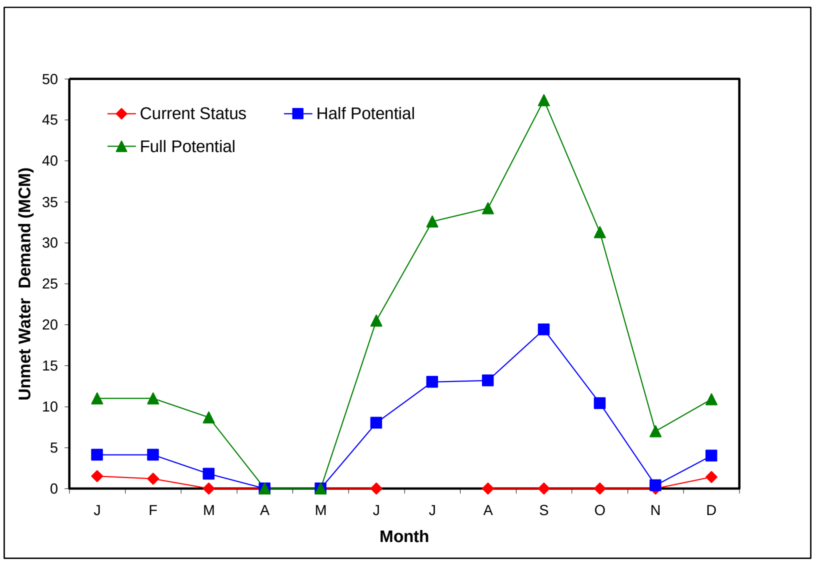

Figure 4.17: Unmet Demand at current, half and full potential at Ahero Irrigation Scheme without dams.

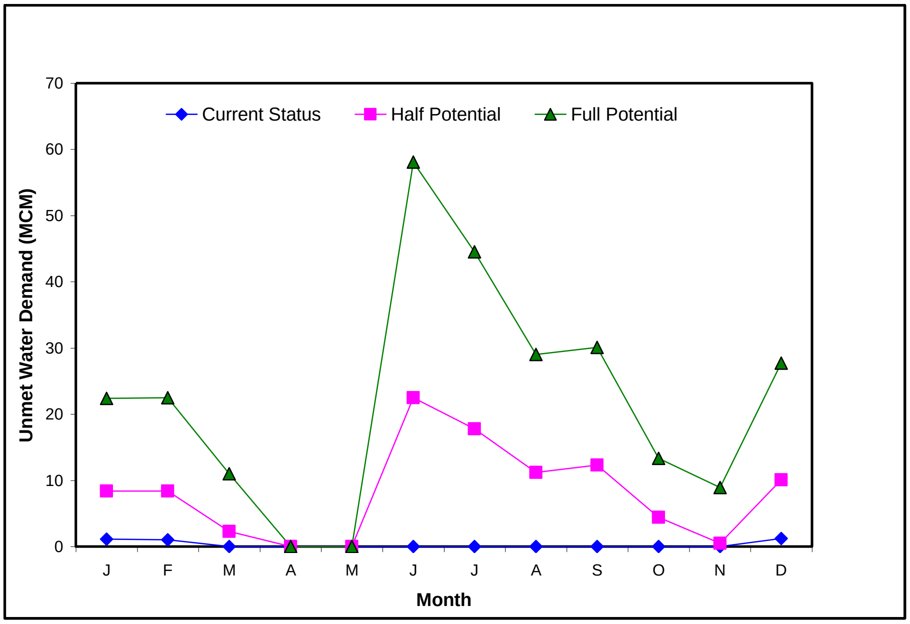

Figure 4.18: Unmet Demand at current, half and full potential at S.W.Kano Scheme without dams.

4.3.5. Scenario 2: Half Potential without dams

If the irrigation areas are increased to half their maximum potential, the trend would follow the same pattern as the water demand (Figure 4.15, sub-section 4.3.3.). The unmet annual water demands would increase to 78.4 MCM and 98 MCM for Ahero and S.W. Kano respectively, the South West Kano unsatisfied demand being higher because of the larger potential area. In both schemes the unmet demand would be lowest in April and May during the long-rainy seasons. At the Ahero Scheme it would peak in September during the maximum water use period. There would be no unmet demand in November during the short-rainy period for both schemes. The S.W. Kano unsatisfied demand would however peak in June. Increasing the irrigation area to half maximum potential would create great water stress especially between May and October, unless an extra water source is tapped. The high streamflows fail to provide adequate water supply to meet the early season irrigation demands for both schemes. In spite of the rising baseflows after the long rainy season from May to September streamflow is insufficient to meet irrigation demand. The model results suggest that an increase in the irrigated area up to the half maximum potential greatly increases the annual average consumptive demand loss of the watershed through evapotranspiration. The mitigation methods suggested include dam construction and water transfers from Yala or Sondu Miriu Basins (Lotti et al, 1985).

4.3.6. Scenario 3: Full Potential without dams

Full exploitation of the maximum irrigation potential without any intervention would tremendously increase the total annual unmet water demand to 214.5 MCM and 267.4 MCM for Ahero and S.W. Kano Schemes respectively (Figures 4.17 and 4.18). The trend follows the pattern as in Figure 4.15; however demand during the short rainy period would also not be met. Water use would be very high since a large area would be under paddy rice. It would require additional water sources to meet the high irrigation demand.

4.3.7. Scenario 4: Half Potential with DS2 Added.

If a reservoir is introduced at dam site 2 (DS2) (Figure 4.13), then there would be totally no unmet water demand at half total irrigation potential (Figures 4.19. and 4.20.) for both schemes. The reservoir of monthly capacity 86 * 10^6 m^3 would be a viable option in the exploitation of the irrigation potential of the basin.

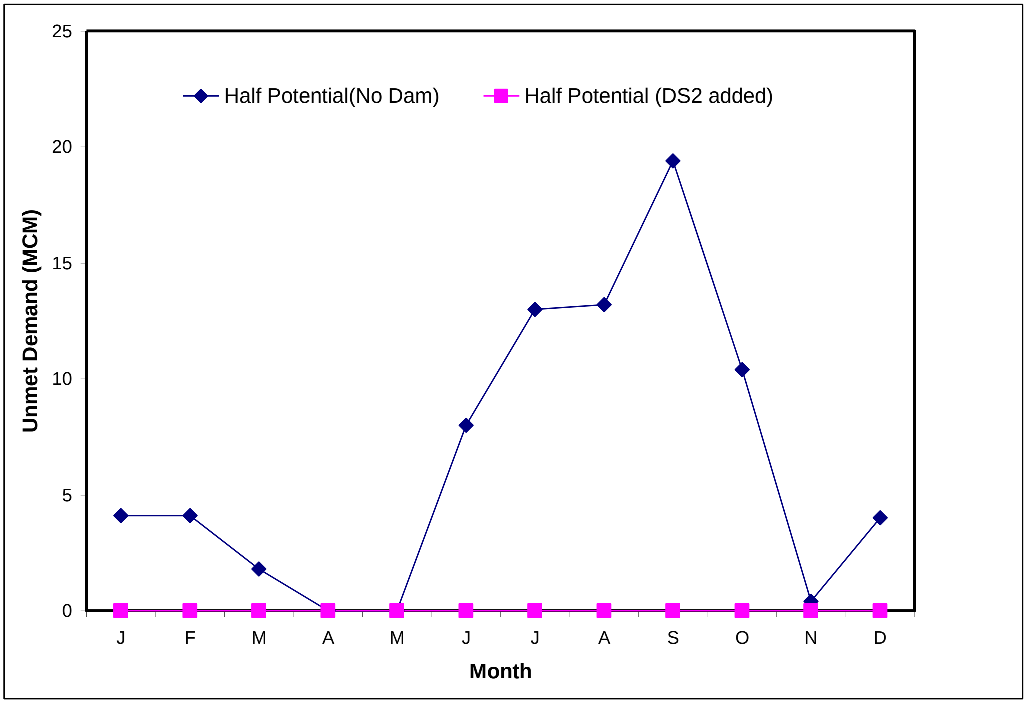

Figure 4.19: Unmet Water Demand at Ahero Irrigation Scheme with the introduction of a dam at site (DS2).

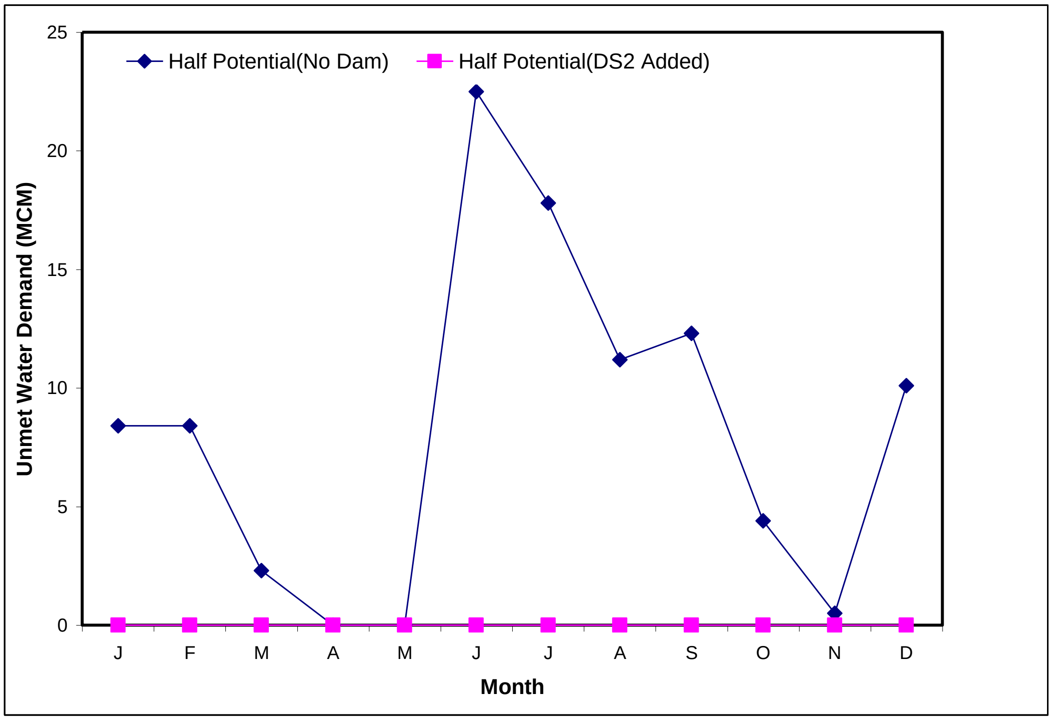

Figure 4.20: Unmet Water Demand at S.W.Kano Irrigation Scheme with the introduction of a dam at site (DS2).

4.3.8. Scenario 5: Full Potential with DS2 and DS5 Added

If the maximum projected irrigation area is utilized, then the average monthly annual Unmet Water Demand for the Ahero Scheme rises to 214.5 MCM while that for S.W. Kano rises to 267.4 MCM. If however the two reservoirs at DS2 and DS5 are used together, the Unmet Demand at Ahero is reduced to 19.22 MCM, while that at S.W. Kano Scheme is reduced to 20.71 (Figure 4.21 and 4.22). This implies that with the use of the two dams, over 90% of the maximum irrigation potential would be adequately supplied with water. That is, by considering the reduced unmet demand following the use of the two reservoirs as a percentage of the initial total unmet demand. It follows then that about

10 % of the irrigable area would still lack adequate water supply. The addition of a third reservoir would take care of the unmet demand.

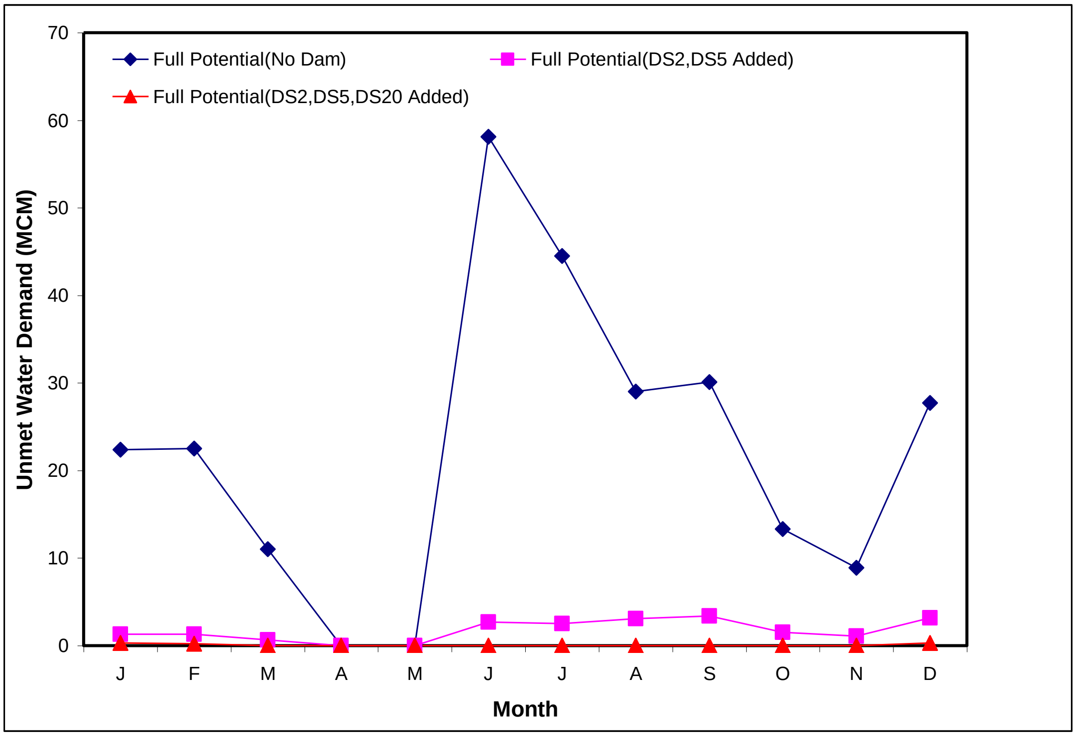

Figure 4.21: Unmet Water Demand with the introduction of three dams at sites DS2, DS5 and DS20 at S.W.Kano Scheme.

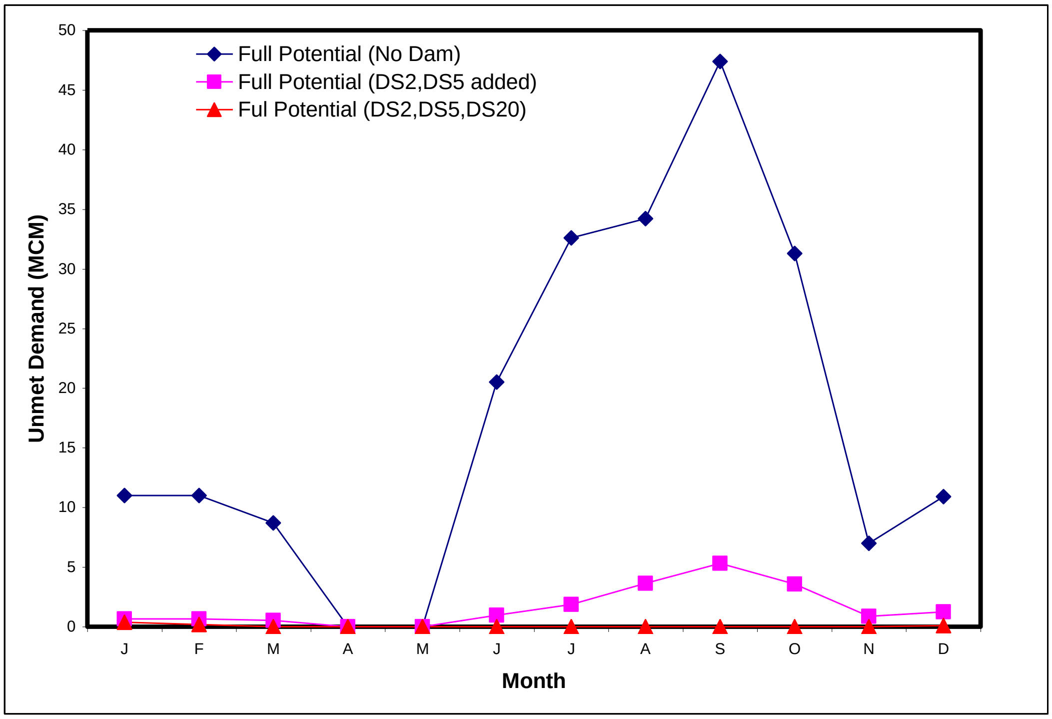

Figure 4.22: Unmet Water Demand with the introduction of three dams at sites DS2, DS3 and DS20 at Ahero Irrigation Scheme.

4.3.9. Scenario 6: Full Potential with DS2, DS5 and DS20 Added.

With the addition of the third reservoir DS20, The total annual average unmet demand is completely eliminated for both the schemes (Figure 4.21 and 4.22). It can therefore be inferred that rice irrigation in the lower catchment of the Nyando Basin can be exploited to its maximum potential with the use of the three proposed dams. This would greatly uplift the economic status of the people in this part of the basin. Rice production at that potential would also augment the total national yield.

4.3.10. Unmet Water Demand

Table 4.11 shows the summary of the annual average Unmet Water Demands for the various scenarios depicted for the Ahero Irrigation Scheme and the South West Kano Irrigation Scheme.

Table 4.11. Summary of Annual Average Unmet Demands (MCM)

Scheme Status	Ahero Scheme	S.W. Kano Scheme
Current Status	1.2	3.0
Half Potential (No Dams)	78.4	98
Half Potential (DS2, Added)	0	0
Full Potential (No Dams)	214.5	267.4
Full Potential (DS2, DS5 Added)	19.22	20.71
Full Potential (DS2, DS5,DS20 Added)	0	0

The results show the level of irrigation development that can be undertaken in the Nyando River Basin when the proposed dams are constructed and used. This would greatly improve income in the downstream region of the basin and augment the National Rice production.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of this study was to use the Water Evaluation and Planning Systems (WEAP) Model for Sustainable Water Resources Management in the Nyando River Basin. The following conclusions were therefore drawn from the analysis.

1. Despite the availability of the Nyando River Water Resource, the domestic, industrial and livestock water demands of the Nyando Basin have not been fully met. This is mainly due to the increasing population pressure and climate variability as indicated by the many forecast dry years.
2. The water demand in the basin will continue to grow and by 2020 the domestic, industrial and livestock water demand shall have increased by 10 MCM. Irrigation water demand shall have increased by 280 MCM at only half the maximum irrigation development potential.
3. The use of the proposed reservoirs will greatly improve irrigation development since they help meet the deficit in irrigation water requirements even at the full development potential.
4. The Water Evaluation and Planning System (WEAP) Model has been found to be useful as an Integrated Water Resources Management tool for balancing water supply and demand for current and future scenarios in a sustainable way.

5.2 Recommendations

1. Since the unmet domestic and irrigation water demand in the Nyando Basin is still high, alternative water supply sources such as springs and boreholes should be further explored.
2. The proposed reservoirs in the basin should be constructed in order to meet current and future irrigation and domestic water demands.
3. The level of water abstraction from the Nyando River should be regulated in line with water demand, streamflow patterns and ecological flow requirements.
4. The use of the Water Evaluation and Planning System (WEAP) Model as an Integrated Water Resources Management (IWRM) tool should be further explored.

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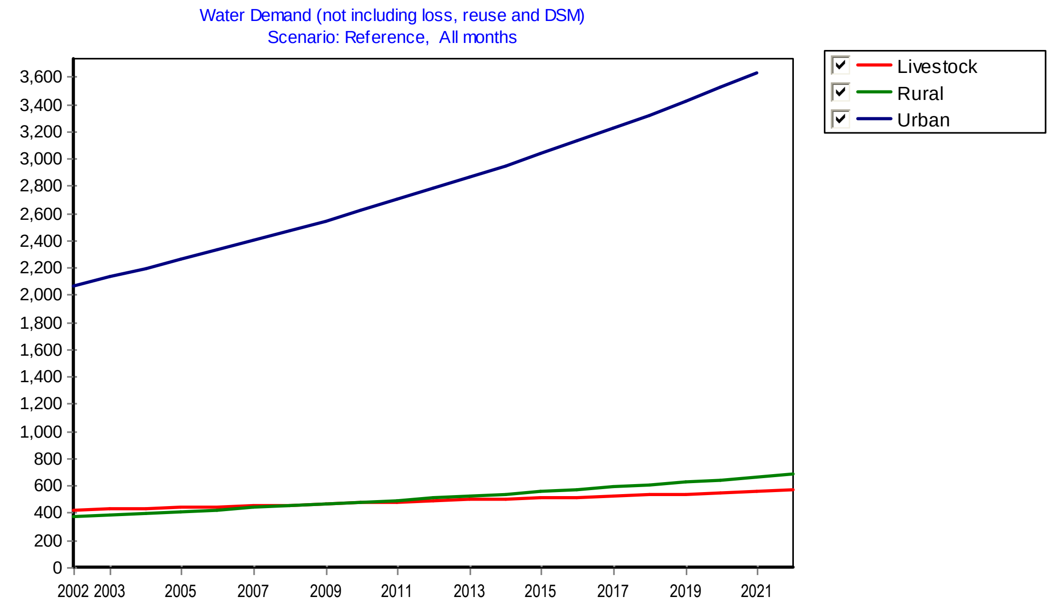
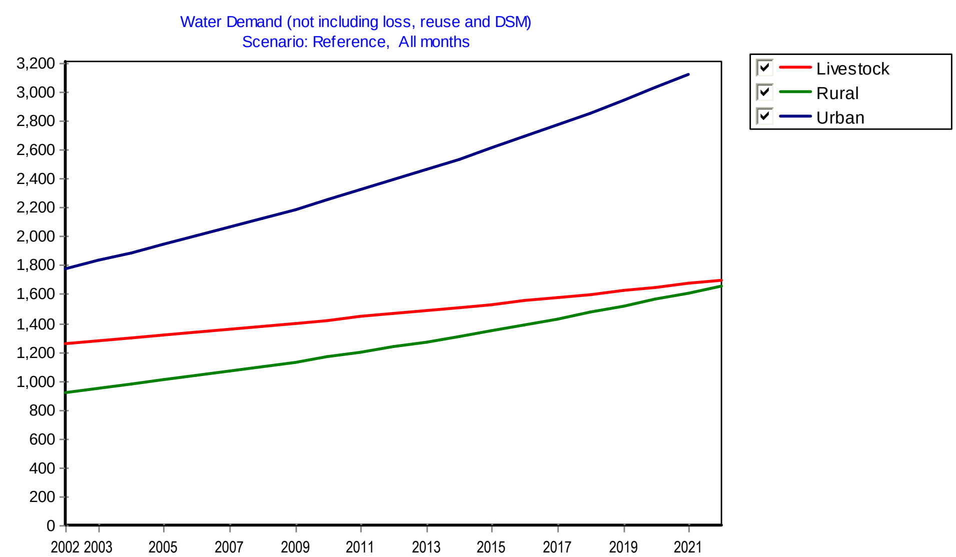
APPENDICES

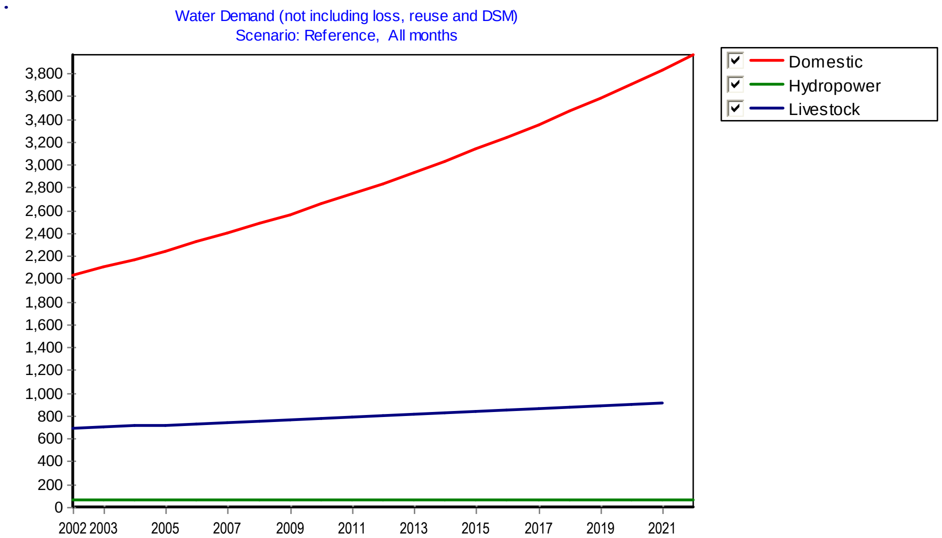
Appendix A1.1: Muhoroni Water Demand Pattern



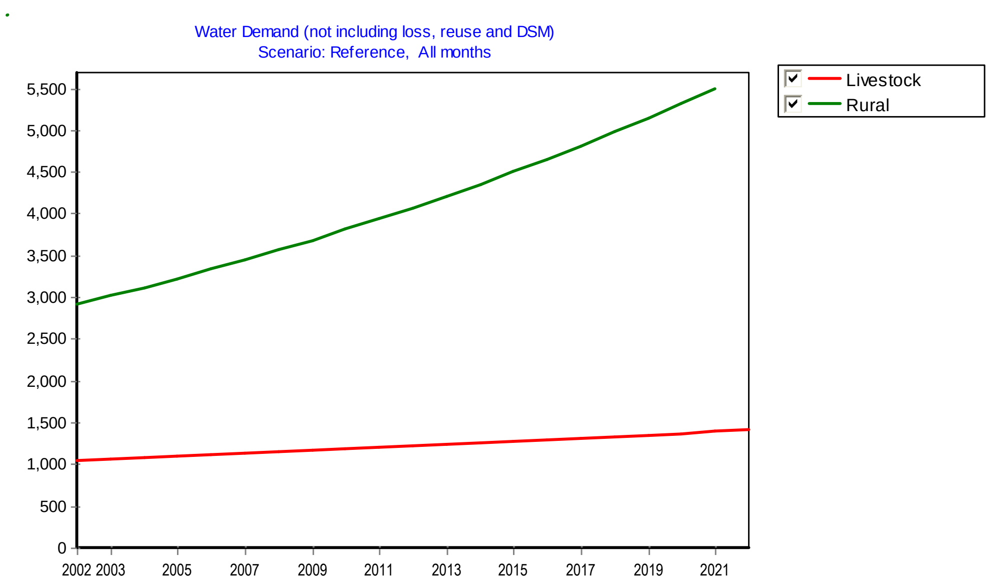
Appendix A1.2: Kipkelion Water Demand Pattern



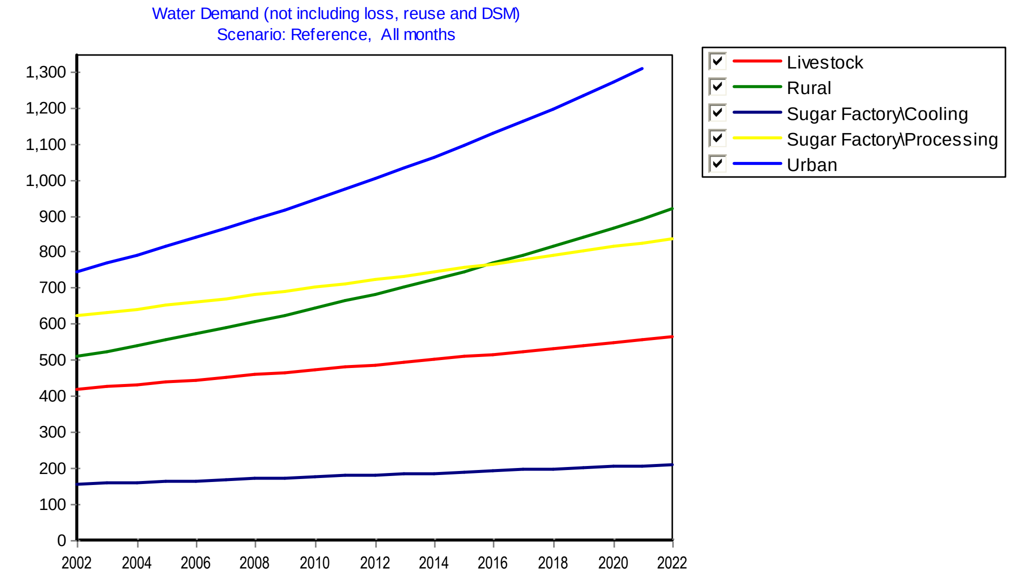
Appendix A1.3: Chemamul Water Demand Pattern



Appendix A 1.4: Maso water demand pattern



Appendix A1.5: Chemelil Water Demand Pattern



Appendix B 1.1: Water Supply Coverage in the Nyando River Basin for input in WEAP model

MASO W/S	KIPKELION W/S	LONDIANI W/S	KIBIGORI W/S	MUHORONI W/S	CHEMELIL W/S	NANDI TEA W/S	CHEMAMUL/ TACHASIS
Div: SOIN	Div:KIPKELION	Div:LONDIANI	Div:MIWANI	Div:MUHORONI	Chemelil	Nandi Hills	Div:Tinderet
Kaitui	Kipchoran	Kedowa	Nyangoma	Fort-Ternan	Nyangore	Mogobich	Kapkitony
Soliat	Kamasian	Masaita	N.E.Kano	God Nyithindo	W.Songhor Chemelil Factory	Kapchorua	Kabuki
Kapsorok	Barsiele	Sorget	Ombeyi	Koru		Chebarus	Songhor
Koitaburot	Kimugul	Lemotit	Div:NYANDO	Tamu		Siret	Kabirer
Kapsegut	Kipsegi	Tendeno	Awasi			Chemomi	Kapkoros
Div:AINAMOI	Lesirwa	Kipsirichet	Kakola			Kipsebwo	Kamelil
Ainamoi	Chepseon		Kikole			Tartar	Meteitei
Kenegut	Kapseger		Kochogo				Chemamul
Kapsaos			Onjiko				Soba
Kapsoit			Wawidhi				Ainapngetuny
Div:CHILCHILA			Div:L. Nyakach				Kamelilo
Chilchila			Asao				Div:Aldai
Kunyak			C. Nyakach				Chemase
Kapkoros			N.E.Nyakach				Ndurio
Kipteris			N.Nyakach				Kemeloi
Kokwet			Nyalunya				Kapkures
			Paponditi				Terik
			Rangul				

Appendix B 1.2: Water Supply Status in Nyando District

Division	Name of Scheme	Status	Source	Operator	Type	Discharge (m^3/month
U. Nyakach	Nyakach W/S	Operational	Sondu/Miriu	LAVICTSWSB	RWS	135000
Miwani	Kabar W. Group	Operational	Borehole	Community	RWS	500
Miwani	Nyakoko Sch.W/S	Operational	Borehole	Public School	IWS	450
Miwani	Ngere Kagoro	Operational	Borehole	Public School	IWS	2160
Miwani	Obaga Pri. School	Operational	Well	Public School	IWS	300
L. Nyakach	Rae Girls Sec.	Operational	Borehole	Public School	IWS	1296
L. Nyakach	Komwono Spring	Operational	Spring	Community	RWS	2160
U. Nyakach	Kotiende Spring	Operational	Spring	Community	RWS	1080
U. Nyakach	Konyango Mainga	Operational	Well	Community	RWS	500
U. Nyakach	Kobongo "B"	Operational	Well	Community	RWS	450
U. Nyakach	Ajaka "B"	Operational	Well	Community	RWS	450
U. Nyakach	Osco Njira	Operational	Well	Community	RWS	450
U. Nyakach	Obanda "A"	Operational	Well	Community	RWS	450
U. Nyakach	Obanda "B"	Operational	Well	Community	RWS	450
U. Nyakach	Mbugra	Operational	Well	Community	RWS	450
U. Nyakach	Ang'ogo Remo "B"	Operational	Spring	Community	RWS	2000
Nyando	DWO	Operational	Well	Community	RWS	450
Nyando	Ahero Cath. Mis.	Operational	Borehole	School/Town	IWS/UWS	3750
Nyando	Boya W/S	Operational	Borehole	Community	RWS	2520
Nyando	Awasi W/S	Operational	Borehole	MW&I	RWS	3600
Nyando	Nyang'oma	Operational	Borehole	Private	RWS	2500
Nyando	Onjiko High Sch.	Operational	Borehole	Public School	IWS	2500
Muhoroni	Koru-Mnara	Operational	Spring	MW&I	RWS	4500
Muhoroni	Tamu W/S	Operational	Borehole	MW&I	RWS	2580
Muhoroni	Koru Mission W/S	Operational	Borehole	Private	IWS	1800
Muhoroni	Homalime W/S	Operational	River	Private	IWS	2880

Appendix B1.3: Nandi Hills and Tinderet Water Supply Status

Division	Name of Scheme	Status	Source	Operator	Type	Discharge (m^3/month)
Nandi Hills	Siret W/S	Operational	Kepchoma Str.	Private Co.	IWS	4500
Nandi Hills	Kepchomo W/S	Operational	Kepchoma Str.	Private Co.	IWS	1240
Nandi Hills	Kibwari W/S	Operational	Chemotindam Str.	Private Co.	IWS	3600
Nandi Hills	Nandi Tea W/S	Operational	Soboiywo Str.	Private Co.	IWS	3000
Nandi Hills	Nandi Tea W/S 2	Operational	Taito Str.	Private Co.	IWS	3000
Nandi Hills	Kipkoimet W/s	Operational	Mokong Str.	Private Co.	RWS	3840
Tinderet	Tinderet W/S	Operational	Kosabei Str	Private Co.	RWS	2280
Tinderet	Tinderet W/S 2	Operational	Kibiriukut Str	Private Co.	RWS	200
Tinderet	Tinderet 3	Operational	Kiptendon Str	Private Co.	RWS	960
Aldai	Serem High Sch.	Operational	Spring	Public Sch.	IWS	900
Aldai	Maraba/Chepkun	Operational	Spring	Public Sch.	IWS	1800
Aldai	Kapkabai Chep.	Operational	Spring	Private Co.	RWS	1080
Aldai	Ndurio High Sch.	Operational	Spring	Public Sch.	IWS	1800
Aldai	Tumoek	Operational	Spring	Private Co.	RWS	3600

Appendix B 1.4: Water Supply Status in Kericho District

Division	Name of Scheme	Status	Source	Operator	Type	Discharge (m^3/month
Londiani	Tegunot Nyakiny.	Operational	Tegunot dam	MW&I	RWS	100
Londiani	Londiani F.Coll.	Operational	Spring	MW&I	IWS	1800
Londiani	Londiani Sec.Sch	Operational	Borehole	Public Sch.	IWS	3600
Londiani	Tapsachei W/S	Operational	Tapsachei Str.	Community	RWS	1500
Londiani	Sugutek W/S	Operational	Sugutek Str.	Community	RWS	900
Londiani	Barotion W/S	Operational	Barotion Dam	MW&I	RWS	200
Kipkelion	Tuyabei W/S	Operational	Kipsirichet Str.	Community	RWS	2000
Kipkelion	Moi Tea W/S	Operational	Stream	Public Sch.	IWS	1800
Ainamoi	Ainamoi W/S	Operational	Ainaptarit Str.	Community	RWS	1500
Ainamoi	Laliat W/S	Operational	Chepngetuny S	Community	RWS	1800
Ainamoi	Cheplil/Chepkoiyo	Operational	Sambula Str.	Community	RWS	1700
Ainamoi	Kenegut W/S	Operational	Kenegut Str.	Community	RWS	2000
Soin	Soliat S. Sch.	Operational	Soliat Str.	Public Sch.	IWS	2500
Soin	Bargeywet	Operational	Kebanywo Str.	MW&I	RWS	1900
Soin	Kaitui/Soliat	Operational	Chepkemei Str	MW&I	RWS	1500
Soin	Kipsitet	Operational	Sewetwet Str.	MW&I	RWS	2100
Soin	Ngecherok	Operational	Koboito Str.	MW&I	RWS	2100
Sigowet	Sigowet W/S	Operational	Spring	MW&I	RWS	900
Chilchila	Chemogoch W/S	Operational	Spring	MW&I	RWS	1000

Appendix C 1.1: Water Year Simulation Data

Year	Average annual flow (m^3)	Water Year Sequence
2002	476085	Very Dry
2003	1360850	Normal
2004	2812767	Wet
2005	2243830	Wet
2006	1098367	Very Dry
2007	1759709	Normal
2008	3107080	Very Wet
2009	998708	Very Dry
2010	1343110	Dry
2011	1841448	Normal
2012	4975352	Very Wet
2013	1220465	Dry
2014	7234323	Very Wet
2015	4825963	Very Wet
2016	1184336	Very Dry
2017	1190318	Dry
2018	2304185	Wet
2019	1915085	Normal
2020	2091116	Wet
2021	446824	Very Dry
2022	1275856	Dry