SIMULATION AND SCENARIO ANALYSIS OF WATER RESOURCES MANAGEMENT IN PERKERRA CATCHMENT USING WEAP MODEL

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS OF THE AWARD OF THE DEGREE OF MASTER OF SCIENCE IN WATER ENGINEERING TO THE DEPARTMENT OF CIVIL AND STRUCTURAL ENGINEERING, SCHOOL OF ENGINEERING OF MOI UNIVERSITY.

DECEMBER, 2010

DECLARATION

STUDENT DECLARATION

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DEDICATION

To the many gifts bestowed on us by the almighty God, including knowledge and intellect.

ABSTRACT

Integrated Water Resources Management (IWRM) approach at the catchment level especially for a water stressed system creates room for conflicts among the upstream and downstream users. Decision Support Systems (DSS) can provide effective tools for water allocation, supply and demand analysis. This research used Water Evaluation and Planning System (WEAP) as a DSS to evaluate the current water management scenario and the effect of proposed water development projects in Perkerra catchment. The main objective was to apply WEAP to the catchment and assess the impact of various proposed water infrastructural developments, policy and regulation under various scenarios in view of the Water Act 2002. Hydrometeorological and water use data were obtained from the Ministry of Water and Irrigation, Water Resources Management Authority (WRMA), Kenya Meteorological Department (KMD) and Perkerra Irrigation Scheme. The collected information was geo-referenced in GIS software (ArcView) to create spatial database. The FAO Rainfall-runoff method was used to simulate runoff. In the simulations using WEAP21, the catchment was divided into three main sub-catchments where the supply (catchment runoff) and demand nodes were spatially located. Two main scenarios were built from the reference scenario; Chemususu dam and water resources development scenarios. Three sub-scenarios were built to analyse current abstraction levels; increased water demands and improved irrigation efficiency at Perkerra irrigation scheme. The results of the reference scenario were validated using observed flows at Marigat Bridge station (2EE7B). Results indicated very sharp peaks of the flow time series downstream and a high vulnerability at the demand nodes, with demand coverage varying between 10% and 100%. The construction of two Dams (Chemususu and Radat) stabilizes the flow and improves the demand coverage to between 60 % and 100 %. However with the implementation of environmental flows downstream of station 2EE7B, and water supply projects, the average demand coverage downstream drops to between 45% and 100 %. Moreover, the improved storage (by two dams) allows supply of 13,000m^3/d of water to neighbouring towns and 90% increase of water available for irrigation at Perkerra Irrigation Scheme. This analysis however, assumes proper regulation of abstraction and reservoir operations.

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ACRONYMS

CAAC – Catchment Area Advisory Committee

CGIAR – Consultative Group on International Agriculture Research

CMS – Catchment Management Strategy

DHI – Danish Hydraulic Institute

FEWS – Flood Early Warning System

DPSIR – Driving Pressure State Impact Response

DSS – Decision Support System

GIS – Geographical Information System

GWP – Global Water Partnership

ILRI – International Livestock Research Institute

IWRM – Integrated Water Resources Management

PAWDP – Partnership for Africa Water Development Programme

RVCA – Rift Valley Catchment Area

UNDP- United Nations Development Programme

WEAP – Water Evaluation and Planning System

WFD – European Water Framework Directive

WRMA – Water Resources Management Authority

ACKNOWLEDGMENTS

This study was made possible by the contributions of many people, whom I may not completely mention. I am sincerely grateful to all my supervisors, Dr. Kipkorir and Prof. Otieno for continual guidance from the inception of the thought to final writing, the contribution of Dr. Kibiiy, in shading more clarity into the study and final write-up. The time spent at Durban University of Technology with Prof Otieno and Dr. Adeyemo was instrumental in finishing this work. The Department of Civil and Structural Engineering and the MUK-VLIR_UOS project for financial support and a chance to undertake my MSc. studies.

The encouragement from my fiancée, family and friends was heartfelt. Finally to the almighty God for in him we live, move and have our being.

CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND OF STUDY

The need for water is universal and without water, life, as we know it, will simply cease to exist. Earth's water is constantly in motion, passing from one state to another, and from one location to another, which makes its rational planning and management a very complex and difficult task under the best of circumstances (Turner et al., 2004). The availability and use of water is therefore mainly constrained by its spatial quantity and quality distribution.

Earth's fresh water is stored in reservoirs such as glaciers and ice caps, surface water, underground, and in the atmosphere. The replenishment rate of this water per annum is used to determine a country's freshwater availability. Kenya's natural endowment of freshwater is limited by an annual renewable freshwater supply of only 647 m^3 per capita, (World Bank, 2000). Globally, a country is categorized as "water-stressed" if its annual renewable freshwater supplies are between 1,000 and 1,700 m^3 per capita and "water-scarce" if its renewable freshwater supplies are less than 1,000 m^3 per capita (World Bank, 2004). Only 8.3% of the countries in the world are classified as water-scarce, Kenya being one of them, while 9.8% of the countries are considered water stressed (Mogaka et al., 2006).

Globally countries are working towards effective water resources management systems. Many countries worldwide through the Global Water Partnership (GWP) and other initiatives like the European Water Framework Directive (WFD) are implementing systems which are anchored on the Dublin principles (http://www.gwpforum.org/servlet/, http://eur-lex.europa.eu/LexUriServ/).

In Africa, the GWP and Partnership for Africa's Water Development Programme (PAWDP) have fostered the development of Integrated Water Resources Management (IWRM) programmes and policies in several African countries (GWP, 2010). Water management in Kenya is undergoing sector reforms occasioned by the Water Act 2002. The implementation of the Water Act 2002 began in 2005. Water management is now done at the catchment level, with the formation of Catchment Area Advisory Committees (CAACs) which are composed of all stakeholders in water sector at the catchment level. The effectiveness of these committees requires scientific tools designed as decision support systems (DSS) to enable discussion and decision making. Among the difficult decisions is the resource allocation and development problem.

Kenya is divided into five major catchments as shown in Figure 1.1. These are Lake Victoria, Rift Valley, Athi River, Tana River and Ewaso Ng'iro basins (CMS-RVCA, 2008). Two (Lake Victoria and Tana River basins) of these basins have surplus water. The Great Rift Valley running north/south of Kenya greatly influences the drainage pattern so that from the flanks of the Rift Valley, water flows westwards to Lake Victoria and Eastwards to the Indian Ocean, while the Rift Valley itself forms an internal drainage system.

Figure 1.1 Location of Rift Valley Catchment Area (Inland drainage basin) in relation to other Regions (source: Catchment Management Strategy, RVCA, draft, 2008)

Kenya has currently developed 15% of its safe water resources, availing $4.3m^3$/person storage (Mogaka et al., 2006). The increasing pressure on land and especially known water catchment zones has a direct bearing on the renewable water resource. The fundamental issue is to develop high productivity and carrying capacity of the catchment whilst achieving acceptable environmental quality and protection of the land and water resources (Saifuka and Ongsomwang, 2003).

Perkerra Catchment is located in the Rift valley catchment. The catchment has a humid upper zone and a semi-arid to arid lower zone. Perkerra River is the only source of water for Perkerra Irrigation Scheme. The irrigation scheme has a potential of 2340ha with a developed irrigated area of 810ha. Due to irrigation water shortages, only 607ha is cropped (irrigated) annually out of the 810ha developed for gravity furrow irrigation system (http://www.nib.or.ke/). The water flow in the river (at the catchment outlet) has been reducing over the years and at times all the water in the river is diverted to the canal at the headwork to Perkerra Irrigation Scheme leaving no environmental flows into Lake Baringo. Critical water shortage in Perkerra irrigation scheme began in 1987 with the launching of greater Nakuru water project, upstream of Perkerra River. Another factor attributed to the flow decrease is destruction of the forests and general watershed degradation especially in the upper catchment (Kipkorir et al., 2002).

The Koibatek district development plans of 1997 to 2001 and 2002 to 2008 have proposed many water projects. The overall objective of the plans is to increase water accessibility through construction of dams, borehole drilling and water supply projects.

Majority of these projects will be in Perkerra catchment (Kabarnet district development plan, 2002). In the lower catchment, water use during the dry season falls to a low value of 5litres per day per capita (Mogaka et al, 2006) as the distances to water sources increase. This presents the challenge of balancing the interests of different users. The report (Mogaka et al, 2006) further asserts that the water deficits in Marigat area are due to the use of water for irrigation in Perkerra Irrigation scheme. The report to the Consultative Group on International Agriculture Research (CGIAR) by Yatich (2003) indicates that on average domestic and livestock water deficits are $40m^3$/day and $50m^3$/day in the lower catchment zones. These locations experience water deficits because of human and livestock population pressure, irrigation and rainfall variability (Yatich, 2004).

The concluding remarks of the Framework for Action exercise of GWP (GWP, FFA, 2000) captures the increasing dilemma facing water sectors across the globe. In part it states, “On the one hand, the fundamental fear of food shortages encourages ever greater use of water resources for agriculture. On the other hand, there is a need to direct water from irrigated food production to other users and to protect the resources and the ecosystems. Many believe this conflict is one of the most critical problems to be tackled in the early 21st century”. Food shortage is a real challenge in Kenya and more so in light of the high rate of population growth, this can be greatly reduced by among other strategies increasing food production through irrigated agriculture.

The water sector reforms are progressive and are bringing about fundamental changes in the way in which water is used and shared among the different users. Its main objective is to ensure a better balance between efficiency, sustainability and equity in all water allocations (Water Act, 2002). Modelling of the current and possible scenarios due to the various water resources developments and changes in supply conditions forms a decision support system for water managers at the catchment level. In such models, hydrological data, water development projects, policy and other metaphysical aspects of catchment hydrology and socio-economic factors are analysed in an interactive computer based system.

1.2 PROBLEM STATEMENT

The Catchment Management Strategy for Rift Valley Catchment Area (CMS-RVCA) (2008) has domesticated the Dublin Principles into 7 functional principles. The first three seek to manage water resource based on sound science, ensure equity and conserve natural resources. River Perkerra is faced with pressure of usage from irrigation, municipal, domestic, livestock and ecological demands. The river flows have been reducing over the years and conflicts often arise between the downstream and upstream users over the resource development upstream. WRMA and CAAC endeavours to follow the principles set out in the CMS-RVCA in Water Resources Management (WRM) of the catchment. To implement these principles, consolidated information showing the interrelationships between biophysical and human factors, policy, water resource development and demands is necessary. There is therefore an apparent need to have a spatial DSS that will assist stakeholders to evaluate various scenarios that integrate most of these information and data thereby analysing the significance of each scenario against aims and objective of CMS-RVCA. Currently the institutions as outlined in Water Act (2002) are in place but there is no water management tool that can enable WRM evaluation of the catchment based on CMS-RVCA principles. This is even more critical for Perkerra River, Lake Baringo and its catchment because of water scarcity experienced in the mid and lower catchment zones.

1.3 JUSTIFICATION OF THE STUDY

Availability of surface water in a catchment for socio-economic and ecological sustenance is primarily influenced by its quantitative and quality distribution in time and space. The water sector reforms as stipulated in the Water Act (2002) advocates for IWRM at catchment level. This research seeks to develop a clear picture through linking demand and supply in a model that can help understand the situation in the area and hence propose water resource management and irrigation management options in Perkerra catchment under the new policy framework that is being implemented (Water Act, 2002). This will make information easily available for discussion and decision making regarding water resources use and development in River Perkerra catchment.

The use of modelling tools to perform scenario analysis is an important approach to developing catchment management strategies and achieving integrated management of catchments (DWAF, 2004). Computer-based Decision Support Systems (DSS) are very useful tools for this because they allow the user to forecast and evaluate the impacts of different possible future trends and management strategies before implementing them.

1.4 STUDY OBJECTIVES

1.4.1 Main Objective

The main objective of the study is to apply Water Evaluation and Planning System (WEAP21) as a DSS tool for the allocation and development of water resources in Perkerra catchment.

1.4.2 Specific Objectives

i. To develop a conceptual framework of water management cycle for Perkerra catchment.

ii. To use WEAP to assess the impact of suggested water development projects in Perkerra Catchment.

1.5 STUDY AREA

1.5.1 Location

Perkerra catchment is in Kabarnet sub-region, Rift Valley Catchment Area (RVCA) of WRMA under the new policy framework (Figure 1.1). Under administrative and political boundaries however, Perkerra River catchment and Perkerra irrigation scheme are located in Koibatek and Baringo Districts of Kenya (Figure 1.2). The river has its tributaries from Koibatek district and flows to Lake Baringo in Baringo district. River Perkerra drains a catchment area of 1207 km^2.

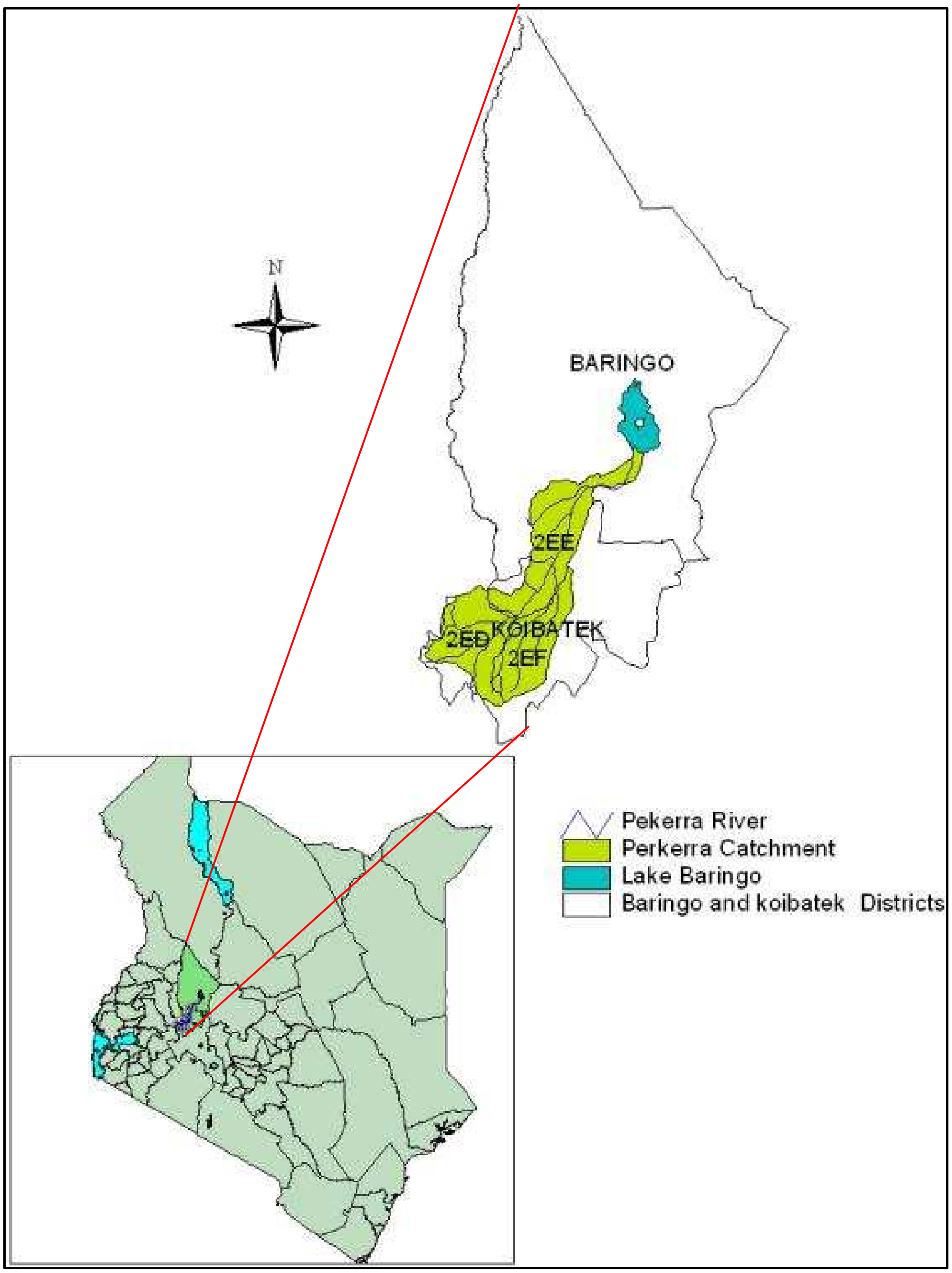

Figure 1.2-Location of Study Area

This is one of the rivers flowing into Lake Baringo whose catchment area is 6820 km^2. The lake is in a semi-arid area of Kenya. Its depth has reduced from 8 m in 1972 to 2.5 m in 2003 due to siltation resulting from high erosion rates in the catchment and high water abstractions (Onyando et al., 2005). The catchment is characterised by very steep slopes on the hillsides and gentle slopes in the middle and lower reaches where the surface is bare with very little vegetative cover. A union of several streams from the Lembus forest highland forms Perkerra River. The river has several tributaries; Tigeri (chepkungur), Lelgal, Eldama Ravine, Narosura and Esageri.

1.5.2 Climate

In general rainfall in the Koibatek and Baringo districts is seasonal and fairly reliable, with long rains coming between March and July with maxims occurring in May and the short rains occurring between September and November with the maxims in October. Minimum rain occurs in January. The average total rainfall per annum ranges between 800mm in the lowlands to 1200mm in the highlands. The mean average temperature is 30^{o}C in the lowlands and 24^{o}C in the highlands. The major vegetation types in the catchment are forest 26%, evergreen and semi-deciduous bushland 37%, and deciduous and semi-deciduous bushland 37% (Onyando et al., 2005).

1.5.3 Soils and Geology

Koibatek and Baringo districts lie within the East African Rift Valley which is bounded physiographically by the Elgeyo Escarpment to the west and Laikipia Escarpment to the east. The Tugen Hills stand out as a horst in the middle part of the main rift graben. The oldest rocks found in the area belong to the basement system. Fluvial sediments are deposited in the depressions of the basement (Kabarnet District Development Plan, 1997).

In summary, the main rock formations can be divided into three groups; metamorphic rocks of the basement system, tertiary sediments and volcanic and quaternary volcanic and sediments. The soils are mainly of clay type. The landscape is characterised by steep slopes from the Tugen hills and Eldama Ravine highlands to the Perkerra River, grading in to gentle slopes and finally to the floodplains of Marigat and Lake Baringo (Odada et al., 2005).

1.5.4 Population and Landuse

River Perkerra is a heterogeneous catchment with a fragile ecosystem. Its soils are mainly clay, loam and sand in texture. The vegetative cover range from thickly forested cover to scattered shrubs in low lands. Deforestation is evident, charcoal burning, bee keeping, and small to large scale irrigation form the main activities. The inhabitants of the semi-arid lower reaches of the catchment are nomadic pastoralists. They keep traditional cattle under communal grazing. In the upper reaches of the catchment, agriculture is practiced by the local communities, but mainly for subsistence purposes where wheat, maize and flowers are main crops grown. According to the census report released by the Central Bureau of Statistics (1999), Koibatek and Baringo districts have a population of 138,163 and 264,978 respectively. Eldama Ravine town is the most populous market centre within the catchment with a population of 10,518. (http://www.citypopulation.de./kenya.html)

1.6 PREVIEW OF WATER SECTOR REFORMS IN KENYA.

The water sector reforms in Kenya began in the mid 1980's with the reports generated from the water resources assessment programme (WRAP) and the National Water Master Plan of 1992 (NWMP, 1992). The challenges which were noted during these studies lead to the formation of a water policy to address the challenges of the then Water Act cap 372 (1972). The water policy was finalised (NWP, 1999) in 1999 and it culminated into the Water Act (2002) which was enacted and became effective on March, 18, 2003. This has led to radical reforms in the water sector, where water management and water service provision is handled by two separate institutions, (WRMA and Water Service Regulatory Board respectively, as shown in Figure 1.3.). Summary of institutional roles and responsibilities is shown in Table A1.

The Water Act (2002) also provides for the change of water resources management from political boundary based concept to catchment management approach. Based on this approach and the drainage network in Kenya, six catchment areas were created each drained by one river system or several rivers and their tributaries. These are Lake Victoria North, Lake Victoria South, Rift Valley, Tana, Athi and Ewaso Nyiro North. The catchment areas are shown in Figure 1.1. The national WRMA office located in Nairobi regulates the activities of the regional offices. Stakeholder participation is institutionalised at the region through the CAACs and Water Resources Users Associations (WRUAs).

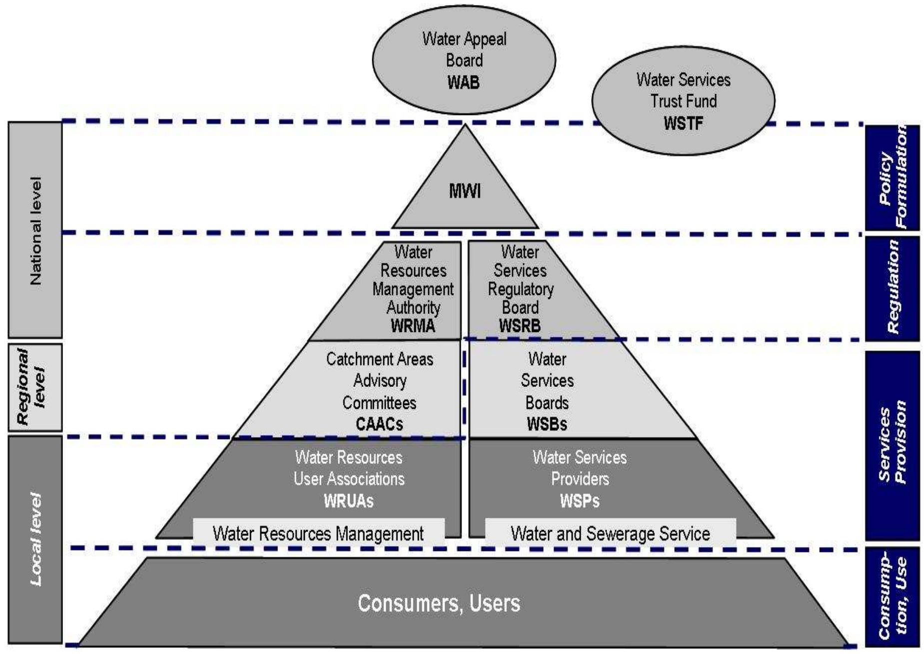

Figure 1.3 Institutional Framework of the Water Sector in Kenya (Source: NWRMS, 2007)

There are eight water service boards in the country; Tana, Rift Valley, TanaAthi, Athi, Coastal, Northern, Lake Victoria North and Lake Victoria South services boards. Each of these boards is in areas with unique challenges of water quality and quantity as they strive to increase potable water accessibility and sanitation services. The challenges are even more unique from sub-catchment to another; some of these include scarcity of water, low storage, saline ground water, salt water intrusion and flooding.

The service boards issue licences to water service providers and regulate the use of the licences. The water use permits on the other hand are issued by WRMA regional and sub-regional offices after evaluation by the CAACs. This in turn is introducing water markets for the various sub-catchments; however functional water markets in rural areas are still a challenge (Yatich, 2003).

The water resources institutional management structures are in place, though some sub-catchments are in the process of forming WRUAs. There is ongoing infrastructural development that will assist in management and regulation of the resources. Among these is the rehabilitation and installation of river flow gauging stations, construction of intake works and weirs and construction of dams. The non structural measures include campaigns on water conservation and management, formation of WRUAs at the grassroots, training and workshops (http://www.water.go.ke).

The water management regions are able to attract investment for water resources development and management, a good example is the Western Kenya Community Driven Development and Flood Mitigation Project (WKCDD&FMP), which is collaborating with WRMA to install flow gauging stations, soil conservation initiatives and real time hydrometric stations (http://www.wrma.or.ke/). The water service boards are also attracting individual investment in water resources development and construction of water supply schemes.

WRMA has developed a national water resources management strategy that give guidelines on how water resources are managed, protected, used, developed, conserved and controlled. The catchment areas in turn have developed catchment management strategies that are at various levels of implementation. The shift of policy is improving water management at all levels and it is hoped that with the current pace of the sector reforms, full implementation of the Water Act is within reach and the benefits are realizable.

CHAPTER TWO: LITERATURE REVIEW

2.1 INTRODUCTION

Water resources planning, once an exercise based primarily on engineering considerations, increasingly occurs as part of a complex, multi-disciplinary investigation that bring together a wide array of individuals and organizations with varied interests, technical expertise, and priorities. In this multi-disciplinary setting, successful planning requires effective IWRM models that can clarify the complex issues that can arise (Loucks, 1995). IWRM is viewed as a systematic process for the sustainable development, allocation and monitoring of water resources use in the context of social, economic and environmental objective (Cap-Net, 2005). The decision problems regarding water resources such as water use and allocation, development, conservation, sustainability and sustenance of fragile ecosystems can be confusing and a DSS tool may bring about clarity.

2.2 INTEGRATED WATER RESOURCES MANAGEMENT

IWRM is a process which promotes the coordinated development and management of water, land and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP, 2000). This definition adopted by the global water partnership initiative applies to two major areas of concern; the natural system with its critical importance for resource quality and availability and the human systems which fundamentally determine the resource use, pollution and which must also set the development priorities. This definition captures a holistic view of IWRM; however critics view it as highly hypothetical, dismissing it as an amorphous definition. This is seen as having problems in concept and implementation, especially for meso to macro- scale projects (Biswas, 2004).

There are documented reports from around the globe by the Global Water Partnership (GWP) of projects which have been successfully implemented under IWRM concepts and principles. Moreover, many countries are changing the water policies to reflect the IWRM principles, a good example being the WFD (http://eur-lex.europa.eu/LexUriServ/) being implemented by European countries.

Kenya is in the process of implementing water sector reforms which are based on IWRM. The new policy framework in Kenya, seeks to bring about integration of key sectors and stakeholders in water allocation and catchment management. This idea even though very plausible, but when information on the resource and metaphysical interactions are not clear to a management team or committee, the IWRM process is delayed and characterised with misunderstanding. The use of scientific means to enhance understanding through modelling of the current and possible scenarios due to the various water resources development and changes in supply conditions forms a decision support for water managers at the catchment level. Such modelling can be achieved through; water balance models, ground water flow models and economic water use models (Alfarra, 2004).

2.3 THE FRAMEWORK FOR INTEGRATED WATER RESOURCES PLANNING AND MANAGEMENT

There is a general consensus about integrated water management at catchment level as the approach to use for sustainable water resources management (GWP-TEC, 2009). It is important therefore to look at the overall basin and include all the elements in the basin that can effect and be affected by water. Figure 2.1 provides a schematic view of these elements, which can be stored in the form of GIS database sets.

Among the major aims of managing water resources is to safeguard human health whilst maintaining sustainable aquatic and associated terrestrial ecosystems. It is therefore important to quantify and identify the current state of, and impacts on, water environment and how these are changing with time (Kristensen, 2004). The elements in Figure 2.1 can be evaluated analytically using a conceptual framework for water management based on the Driving forces, Pressure, State, Impact and Responses (DPSIR) framework.

This allows a comprehensive assessment of the issues through examination of the relevant **D**riving forces and **P**ressures on the environment, the consequent **S**tate of the environment and its **I**mpacts, and the **R**esponses undertaken, and of the inter-linkages between each of these elements. A generic DPSIR framework for water management is shown in Figure 2.2.

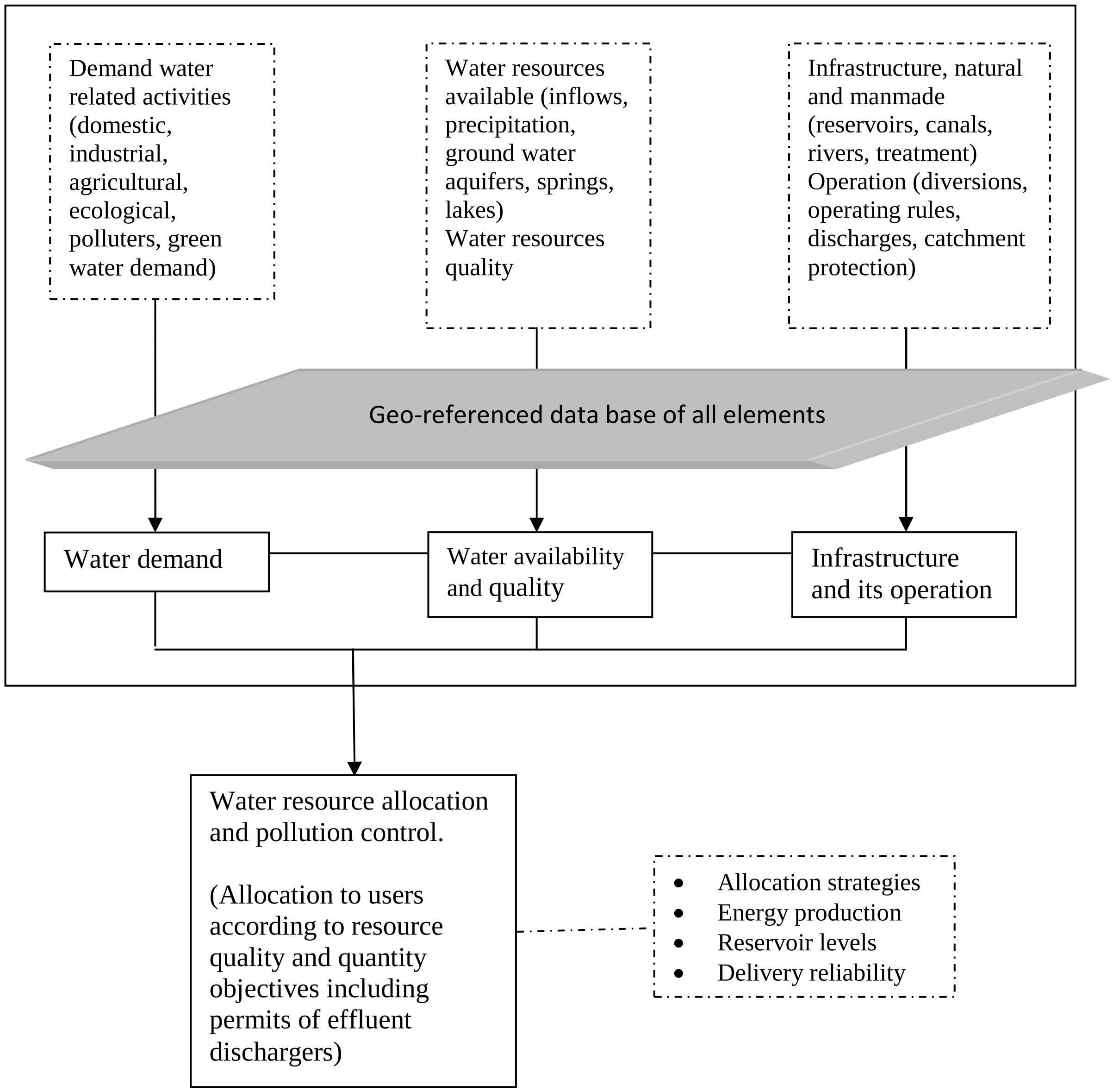

Figure 2.1 Schematic Elements of Water Management

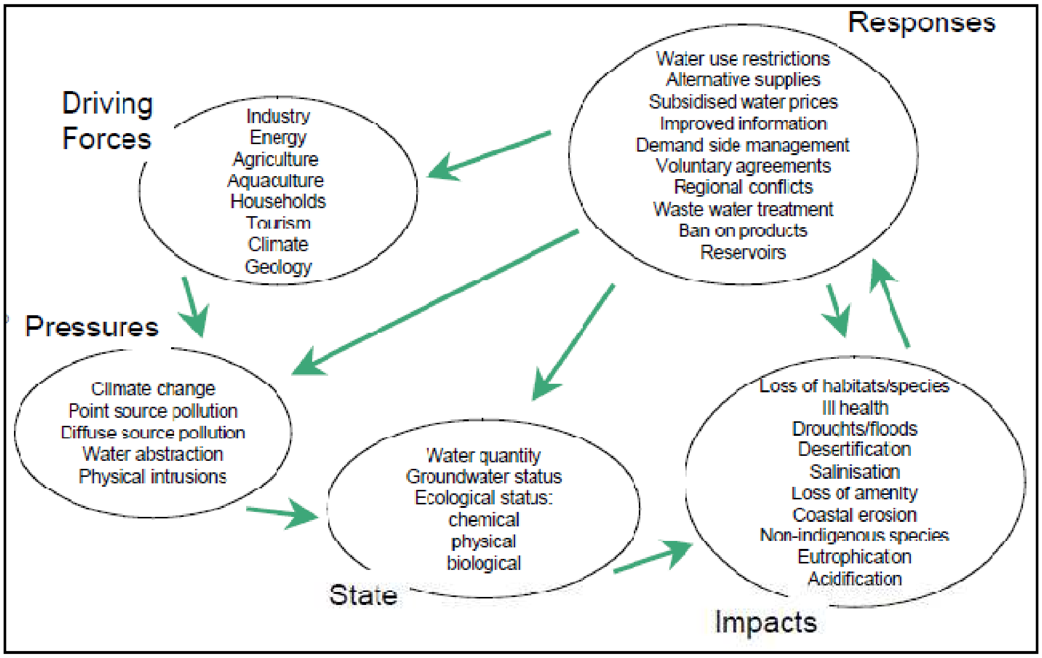

Figure 2.2 Generic Water DPSIR Framework (source: Kristensen, 2004)

In any catchment, water availability problems occur when the demand for water exceeds the amount available during a certain period. Freshwater shortages occur frequently in areas with low rainfall and high population density and in areas with intensive agricultural or industrial activity. Perkerra catchment has large spatial and temporal differences in the amount of fresh water available *(state)*. These are felt more because of rainfall variability in the catchment and the differences are expected to change due to climate changes. Other pressures on water quantity arise from the main sectoral users of water *(Driving Forces)* such as agriculture, livestock, households, vital ecosystems (Lake Baringo, Ng'ambo Swamp) tourism and industry. The impacts of over-abstraction of available water include decreases in groundwater levels and surface water flows that in turn can lead to impacts on associated aquatic and terrestrial ecosystems such as wetlands (Lake Baringo, Ng'ambo Swamp). In addition, over-abstraction of groundwater and lack of sufficient recharge can lead to the intrusion of saltwater at the lowland aquifers in the catchment.

Measures *(responses)* to increase the amount of available water include the construction of storage reservoirs to safeguard supplies when other sources are stressed. Other measures are aimed at reducing or controlling the demand for water including water pricing, water-saving devices and reduction of water leakage in distribution systems. This framework is shown in Figure 2.3.

This study used WEAP21 to perform the analysis of the water quantity management in the Perkerra catchment. The responses are modelled as the various scenarios (increased water storage by building of dams upstream, improved irrigation efficiency). The irrigation scheme at Marigat, which is located at the catchment outlet, forms a very important component of the driving forces in the system.

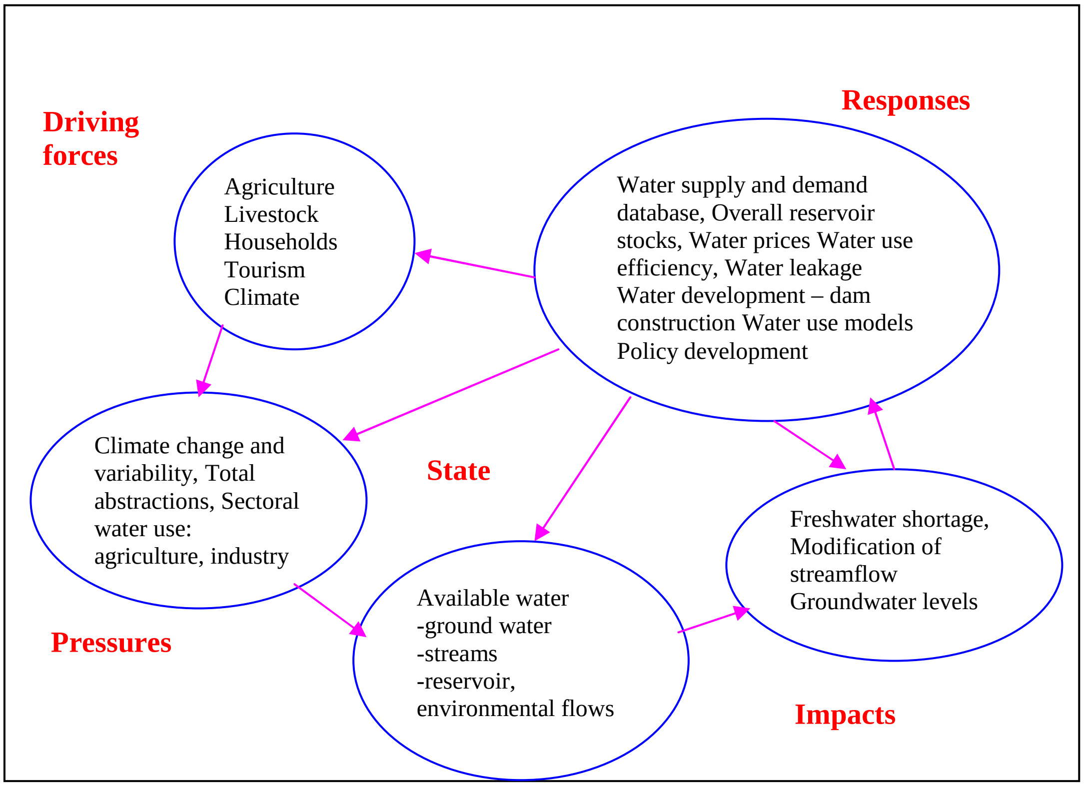

Figure 2.3 DPSIR Framework for Assessing Water Quantity in Perkerra Catchment

2.4 DECISION SUPPORT SYSTEMS FOR RIVER BASIN SIMULATION

Effective IWRM models must address the two distinct systems that shape the water management landscape namely bio-physical and socio-economic (Yates et al., 2005). Factors related to the bio-physical system include; climate, topography, land cover, surface water hydrology, groundwater hydrology, soils, water quality, and ecosystems, which shape the availability of water and its movement through a watershed. Factors related to the socio-economic management system, driven largely by human demand for water, shape how available water is stored, allocated, and delivered within or across catchment boundaries.

There are several programs which are designed to simulate water development and management policies in river basins. The generic programs that are designed to be applicable to a wide variety of specific river basin, water resource system configurations, institutional conditions, and management issues are briefly discussed. Each of these example programs is based on a node-link network representation of the water resource system being simulated. Some of the programs include optimization that replaces a more detailed representation of operating policies. All contain menu-driven graphics-based interfaces that facilitate user interaction. These programs are appropriate for use in shared vision exercises involving stakeholder involvement in model building and simulations.

The models include:

i. River Basin Simulation Model RIBASIM
ii. MIKE Basin
iii. Water Balance Model (WBalMo)
iv. MULti-sectoral, Integrated and Operational Decision Support System (MULINO – DSS)
v. Water Evaluation and Planning System (WEAP)

These programs are reviewed briefly to discuss their topology, data requirements and their limitations if any. They are among the few DSS that are commercially available and have been applied on various catchments for studies or catchment management.

2.4.1 River Basin Simulation Model (RIBASIM)

RIBASIM is a generic model package for analyzing the behaviour of river basins under various hydrological conditions. The model package is a comprehensive and flexible tool which links the hydrological water inputs at various locations with the specific water-users in the basin. RIBASIM is developed and maintained by Delft Hydraulics in the Netherlands. The model is based on an integrated framework with a user-friendly, graphically, GIS-oriented interface, enabling the user to evaluate a variety of measures related to infrastructure, operational and demand management and the results in terms of water quantity and water quality. RIBASIM generates water distribution patterns and provides a basis for more detailed water quality and sedimentation analyses in river reaches and reservoirs. It provides a source analysis, giving insight into the water's origin at any location of the basin. The flow routing is executed on daily basis starting at any selected day for any number of days ahead, this utilizes various hydrologic routing methods; Manning formula, Flow-level relation, 2-layered multi segmented Muskingum formula, Puls method and Laurenson non-linear “lag and route” method (http://www.wldelft.nl/soft/ribasim/int/index.html). The model uses the Case Analysis Tool (CAT) to compare and evaluate the simulation cases. RIBASIM has been applied for river basin planning and management in a great number of countries in a variety of projects (http://www.wldelft.nl/soft/ribasim/cases/index.html). A recent application of

RIBASIM is in the description of the water distribution in the upper Nile coupled to a hydrological model to form the Nile Hydrological simulation Model (Martijn et al, 2010).

2.4.2 MIKE BASIN

MIKE BASIN is designed to address water allocation, conjunctive use, reservoir operation and water quality issues. It couples ArcGIS with hydrologic modelling to provide basin-scale solutions, where the emphasis is on both simulation and visualization in both space and time, making it appropriate for building understanding and consensus. MIKE BASIN was developed by Danish Hydraulic Institute (DHI) in Denmark. For hydrologic simulations it builds on a network model in which branches represent individual stream sections and the nodes represent confluences, diversions, reservoirs, or water users. This is a quasi-steady-state mass balance model, allowing for routed river flows. The water quality solution assumes purely advective transport and the groundwater is described by the linear reservoir equation (http://www.dhisoftware.com/mikebasin/).

In Denmark, MIKE BASIN has been linked with MIKE SHE to form an integrated catchment management system (Christensen, 2006). WRMA is in the process of applying MIKE BASIN to various water catchments in Kenya. However, success is yet to be reported because of model data requirement constraints. These include availability of complete discharge time series, accuracy of data available and human capacity and inaccurate spatial water abstraction data. The model also requires naturalised flow time series; this is modelled and calibrated using a separate hydrological model like NAM, or MIKE SHE of DHI.

2.4.3 Water Balance Model (WBalMo)

WBalMo was developed by WASY Ltd in Germany and it is an interactive simulation system for river-basin management. It models the natural processes of runoff and precipitation stochastically (Monte-Carlo simulation) and the respective time series are balanced with monthly water use requirements and reservoir storage changes. WaBalMo has been used to identify management guidelines for river basins, design reservoir systems and their operating policies, and perform environmental-impact studies for development projects. Using an ArcView user interface, a representation of the river basin (”system sketch”) is constructed or derived from an existing digital stream network. Model data can subsequently be modified in various scenarios. By recording of relevant system characteristics during the simulation, probability estimates can be provided for water deficits, maintaining minimum runoff levels, or reservoir levels. Simulations can be performed both for stationary and transient (e.g., changes in climate) conditions. By comparing various plausible scenarios an approximately optimal water resources management can be obtained (http://www.wasy.de/english/produkte/wbalmo/index.html).

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

MULINO-DSS is the result of a European Union RTD project for sustainable use of water resources at the catchment scale which was commissioned in 2001 aiming to develop a DSS to assist water authorities in the management of water resources. Specific aims of the MULINO-DSS were improving the quality of decision making and seeking to achieve a truly integrated approach to river basin management. Through integration of socio-economic and environmental modelling techniques with GIS functions and multi-criteria decision aids, where decision problems are structured on the Drivers-Pressures-States-Impacts-Responses conceptual framework (DPSIR), the tool was used for implementing or adopting new European water policy and objectives together with local regulations (Giupponi and Cogan, 2002, 2003).

2.4.5 Water Evaluation and Planning System (WEAP21)

The Water Evaluation and Planning System Version 21 (WEAP21) is an IWRM model that seamlessly integrates water supplies generated through watershed-scale hydrologic processes with a water management model driven by water demands and environmental requirements. WEAP21 considers demand priorities and supply preferences, which are used in a linear programming heuristic to solve the water allocation problem as an alternative to multi-criteria weighting or rule-based logic approaches. It introduces a transparent set of model objects and procedures that can be used to analyze a full range of issues faced by water planners through a scenario-based approach. These issues include climate variability and change, watershed condition, anticipated demands, ecosystem needs, the regulatory environment, operational objectives, and available infrastructure (Yates, 2005). WEAP21 was developed by the Stockholm Environment Institute's Boston Centre at the Tellus Institute. The model is designed to assist rather than substitute the skilled planner.

2.4.6 Summary of Models.

The models described above can be used for catchment project planning, water allocation, river flow routing, reservoir routing, demand analysis, hydrological analysis, catchment water balance, water quality and sedimentation analysis and general catchment management support applications. However, some models are better in the spatial water quality analysis, supply and demand management in the catchment like MIKE BASIN and MULINO, whereas others are good analysis of projects where river and reservoir routing is done like the RIBASIM. WaBalMo works well for specific types of resources management, to implement a flood control, or when addressing water-quality issues. It also has the advantage of modelling the natural processes of rainfall-runoff, which is not possible with most of the models described that use hydrological data inputs at various locations.

The models described above with the exception of WEAP21 and WaBalMo, work as integrated water resources management tools when coupled or linked to an extra management model or hydrological model. WalBalMo is a modle used mainly for design projects in a catchment and requires detailed data for design purposes. WEAP21 seamlessly integrate both the hydrological and management model to provide a better platform for IWRM analysis. However, ‘specialized’ models; that simulate water resource management and those simulating hydrological process are able to perform detailed simulation if sufficient data of good quality are available.

This study applied WEAP21 in the Perkerra catchment, in Kenya. The model was preferred to others because of its robustness and ease of use depending on data availability. The model can perform both lumped to distributed catchment hydrological simulation. The model can handle aggregated to disaggregated water management demands of various sectors. The system is therefore appropriate for studying catchments with minimum to moderate data availability. Given the cost implication and data availability in the catchment, the model was selected for the purposes of this study.

The Water Evaluation and Planning Version 21 (WEAP21) IWRM model attempts to address the gap between water management and watershed hydrology and the requirements that an effective IWMR be useful, easy to-use, affordable, and readily available to the broad water resource community (Yates, 2005).

This model was used in Ghana to simulate the impact of small reservoirs in the Upper Volta (Hagan, 2007). The model performed well. Arranz and McCartney (2007) have also applied the model to the Olifants catchment in South Africa. In their analysis, the model performed well in doing quick analysis of current and future water demands. Other investigators (Amani, 2004, Levite et al, 2003, and the WatManSup Project), have applied the model to various catchments around the Globe with success.

2.5 RAINFALL RUNOFF SIMULATION

Rainfall-runoff simulation is very significant in catchment management. Simulation of the catchment hydrology gives an indication of resource capacity. For the purpose of water resource assessment, it is necessary to have an understanding of flow conditions unaffected by human-induced land cover and water use changes, ‘naturalised flow’. Flow naturalization adjustments consist primarily of removing the effects of historical reservoir storage and evaporation, water supply diversions, and return flows from surface and groundwater supplies and in some cases other considerations (Wurbs, 2006).

The sectoral report (B) of the National Water Master Plan of 1992 provides naturalized mean monthly flows of sub-catchments in Kenya. The study report was synthesised from 30 years data (1960 to 1990). In generating naturalized stream flows for the catchment, the study used TAMS rainfall/runoff model. The model consisted of two major components; storm runoff due to excess rainfall, and base flow consisting ground water flow and delayed subsurface runoff. The curve number procedure was adopted for the study. The model was calibrated and validated using well instrumented catchments of $0.16km^2$ to $7km^2$. The model was then applied to sub-drainage areas in Kenya taking their soil classification and vegetation index into considerations to generate naturalised flows.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 INTRODUCTION

This chapter discusses the methods which were used in this research project. It focuses on hydrological analysis and water management simulation in the WEAP21 system. Figure 3.1 illustrates the conceptual model of analysis.

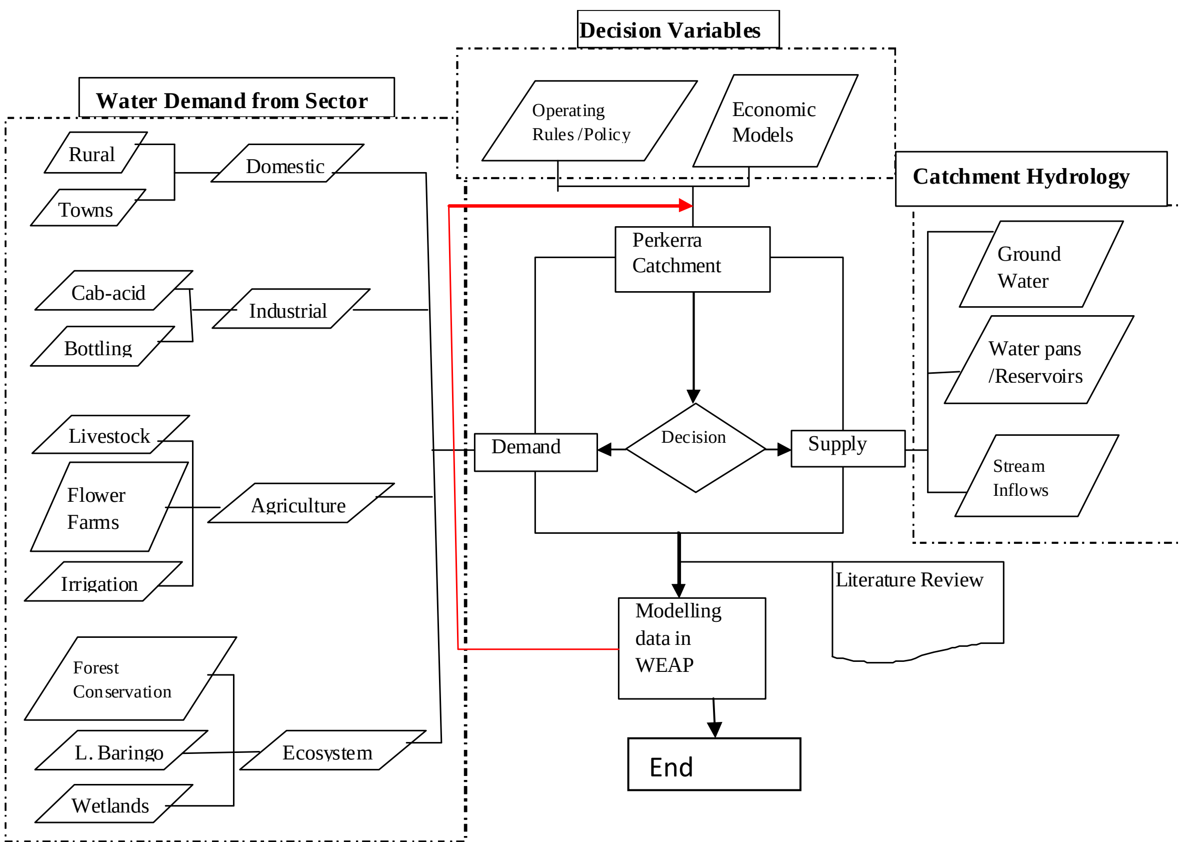

Figure 3.1 Conceptual Modelling Framework

The demands in the catchment are the driving forces in the system. The pressure on the water resources comes from among other things, the quantity of abstraction, soil erosion and discharge of waste water. This in turn affects the state of water in quantity and quality. In the conceptual model, the decision variables which are in form of policies, dam operating rules, water market tariffs, discharge permits are used to impose control and regulation of water usage. The decision made from the various constraints will affect both the state of water resources and the demands in the catchment. This is revisited through a cyclic loop from the modelling results until a specific objective is met.

3.2 MODELLING PROCESS OF WEAP21

WEAP21 is structured as a set of five different "views" onto the working Area: Schematic, Data, Results, Overview and Notes. These views are listed as graphical icons on the View Bar, located on the left of the screen. The Current Accounts represent the basic definition of the water system as it currently exists, and forms the foundation of all scenarios 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. The comparison of these alternative scenarios proves to be a useful guide to development policy for water systems from local to regional scales (Vogel et al., 2007).

The main screen of the WEAP21 system consists of the View Bar on the left of the screen and a main menu at the top providing access to the most important functions of the program. WEAP21 calculates a water quantity and pollution 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.

The modeling of a watershed using the WEAP21 consists of the following steps (Levite et al., 2003):

i. Definition of the study area and time frame. The setting up of the time frame includes the last year of scenario creation (last year of analysis) and the initial year of application.

ii. Creation of the Current Account which is more or less the existing water resources situation of the study area. Under the current account available water resources and various existing demand nodes are specified. This is very important since it forms the basis of the whole modeling process. This can be used for calibration of the model to adapt it to the existing situation of the study area.

iii. Creation of scenarios based on future assumptions and expected increases in the various indicators. This forms the core or the heart of the WEAP model since this allows for possible water resources management processes to be adopted from the results generated from running the model. The scenarios are used to address a lot of "what if situations", like what if reservoirs operating rules are altered, what if groundwater supplies are fully exploited, what if there is a population increase. Scenarios creation can take into consideration factors that change with time.

iv. Evaluation of the scenarios with regards to the availability of the water resources for the study area. Results generated from the creation of scenarios can help the water resources planner in decision making, which is the core of this study.

3.2.1 Algorithm Structure

WEAP uses a hierarchical structure to disaggregate water demand data. One can easily adapt this structure to the nature of the problem and data availability. The first level corresponds to the demand sites (sector demands for example, domestic, agriculture, municipal). One can create as many levels necessary to explicitly disaggregate demand. A demand site's (DS) is needed for water and it is calculated as the sum of the consumptions for all the demand site's bottom-level branches (Br). A bottom-level branch is one that has no branches below it (disaggregated from the sectoral demands).

Annual Demand DS = (Total Activity Level Br x Water Use Rate Br).

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

Total Activity Level Br = Activity Level Br x Activity Level Br' x Activity Level Br'' x...

Monthly demand: To specify the demand for each month, typically using the ReadFromFile function, or by entering direct in WEAP using the monthly time series wizard.

Monthly Supply Requirement: the supply requirement is the actual amount needed from the supply sources. The supply requirement takes the demand and adjusts it to account for internal reuse, demand side management strategies (DSMS) for reducing demand, and internal losses.

Monthly Supply Requirement DS,m = (Monthly Demand DS,m x (1 – Reuse Rate DS) x (1 – DSM Savings DS))/ (1 – Loss Rate DS).

Inflows and Outflows of Water: this step computes water inflows to and outflows from every node and link in the system in monthly time steps. This includes calculating withdrawals from supply sources to meet demand.

Hydrologic analysis is done through the Food and Agriculture Organization (FAO) and soil moisture rainfall-runoff models. The Software allows three methods to define the projection of the surface water hydrology over the study period.

i. The Water Year Method: It is an in-built model in WEAP that allows the predictions of hydrological variables based on the analysis of historical inflow data. It uses the statistical analysis to identify the coefficients, which is used to replace the real data for future projection.

ii. ReadFromFile Method: If monthly data on inflows to some or all of the rivers and local supplies are available, then the ReadFromFile Method allows the system to be modelled using this sequence of real inflows data. The required file format for these data files is ASCII Data File Format for Monthly Inflows.

iii. Expressions: This method allows any equation that explains the physical or evolutionary problem required in WEAP analysis to be used.

3.3 CATCHMENT HYDROLOGY

3.3.1 Rainfall Runoff Simulation in WEAP21

There are three methods presented in WEAP21 for simulating catchment processes. These are (1) Irrigation Demands Only versions of the FAO Crop Requirements Approach, (2) the Rainfall Runoff and (3) the Soil Moisture Method.

Irrigation Demands Only uses crop coefficients to calculate the potential evapotranspiration in the catchment, then determines any irrigation demand that may be required to fulfil that portion of the evapotranspiration requirement that rainfall cannot meet. It does not simulate runoff or infiltration processes.

The Rainfall Runoff method also determines evapotranspiration for irrigated and ‘rainfed’ crops using crop coefficients. The remainder of rainfall not consumed by evapotranspiration is simulated as runoff to a river, or can be proportioned among runoff to a river and flow to groundwater via catchment links.

The Soil Moisture Model is the most complex of the three methods, representing the catchment with two soil layers, as well as the potential for snow accumulation. In the upper soil layer, it simulates evapotranspiration considering rainfall and irrigation on agricultural and non-agricultural land, runoff and shallow interflow, and changes in soil moisture. This method allows for the characterization of land use and/or soil type impacts to these processes. Baseflow routing to the river and soil moisture changes are simulated in the lower soil layer. Correspondingly, the Soil Moisture Method requires more extensive soil and climate parameterization to simulate these processes. These kinds of data were not available.

The rainfall runoff method was used to simulate river flows in this study; this was constrained by the type of data available (Rainfall, Evaporation and crop data). The following type of data is required to perform rainfall-runoff simulation using this method;

i. Land use (Area, Kc, Effective precipitation)

ii. Climate (precipitation and ETo)

Where Kc- crop coefficients and ETo is the reference crop evapotranspiration

Rainfall data was obtained from the Kenya Meteorological Department and WRMA Kabarnet sub-region. The catchment is divided into three major sub-catchments, following WRMA delineation (2ED, 2EF and 2EE) as shown in Figure 3.2. There is a fair distribution of rainfall stations in the catchment. Monthly rainfall data was obtained for the period of study, 2000 to 2009. Data for some of the stations had gaps. By use of correlation analysis with neighbouring stations, the gaps were filled to give a complete rainfall time series.

The simulated flows represent naturalised flows. These flows represent the available surface water resource in the catchment. This is then linked to demand/withdrawal nodes, the flows are modified by these activities at the demand nodes resulting in simulated stream flows at gauging stations.

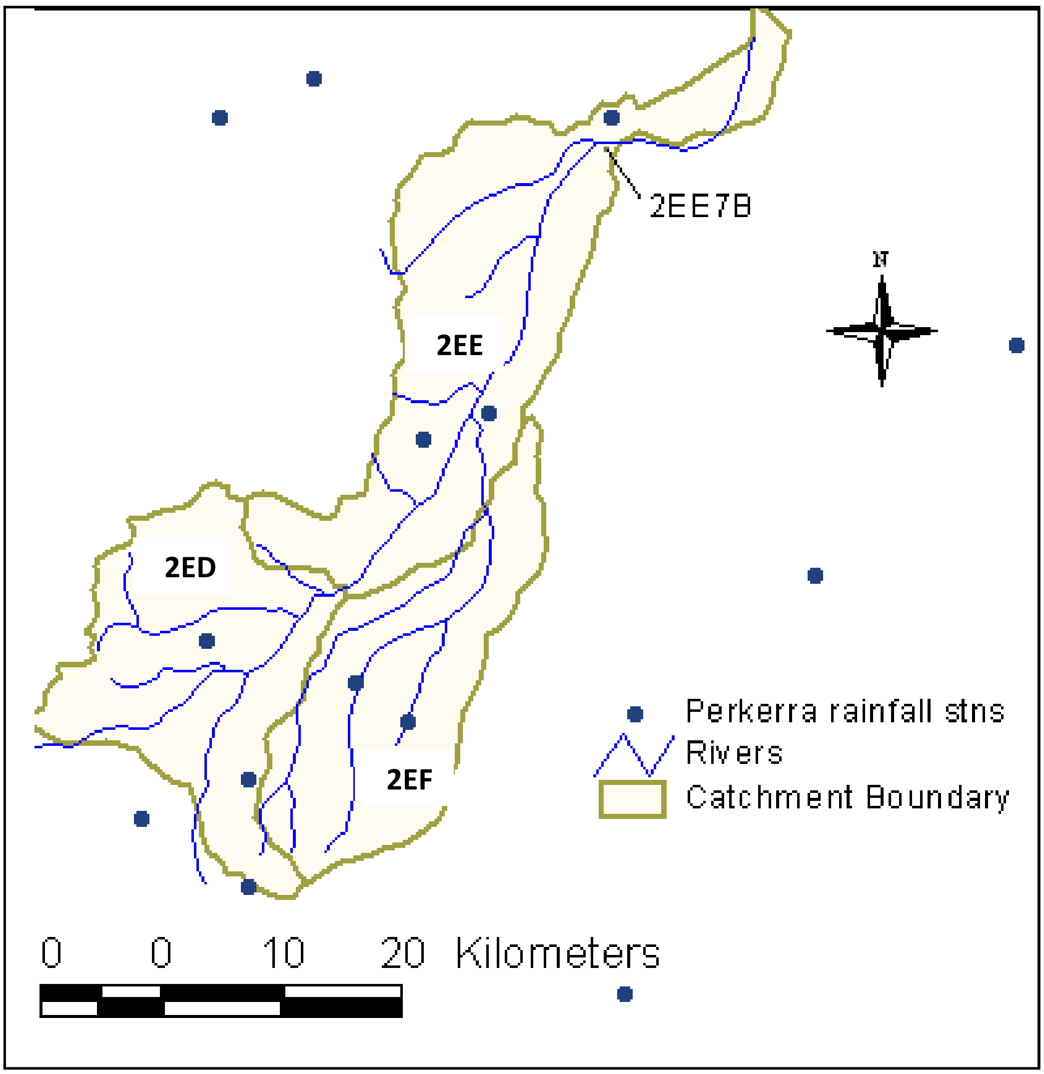

Figure 3.2 Perkerra sub-catchments and Rainfall station distribution

Observed river flow data was obtained from WRMA regional offices at Nakuru. The data for some stations were available as gauge height readings and for one station (2EE7B-Marigat Bridge station) had most of the data as discharge values. The observed flows were used to calibrate and validate the model.

There are several water pans in the catchment; these were simulated as small reservoirs within the streams. The water pans storage capacity is between 10,000 and 25,000m^3. The pans were lumped and modeled as one reservoir per sub-catchment. The reservoirs served as water withdrawal points for livestock and rural domestic use. The small reservoirs have no constraints or operating rules. The average depth of each reservoir was assumed to be 3m and a linear stage-volume relationship was assumed following studies done by Hagan (2007) on small reservoirs. The net evaporation from the reservoirs was estimated from the data contained in NWMP (1992) and WRAP, Baringo district (1993).

It is estimated that there are close to 35 operational boreholes in the Perkerra catchment. WRAP report (1993) of Baringo district has classified the ground water potential in the catchment using maps. However, the size of the aquifer was not estimated, thus groundwater was not simulated in this study. Groundwater simulation would have allowed this study to investigate the conjunctive use of surface and ground water, and to establish the interactions of surface and ground water in terms of storage. This is because groundwater aquifers act as storage which contributes to baseflows during the dry season; however this is overcome by calibrating the model using observed flows at the catchment monitoring stations. In the upper catchment, groundwater potential is high and hand dug wells provide water for domestic purposes in some households. This therefore implies that the model will not comprehensively illustrate the demand coverage upstream of station 2EE7B.

3.3.2 Stream flow Analysis

The stream flow data obtained was in the form of gauge height readings for some stations. The rating curves for some stations were missing, but the data used to construct the rating curves were available (current meter readings).

The most common formula for describing the stage-discharge relationship at a gauging station is the power-law stage-discharge rating curve.

$$Q=ph^{a} \qquad \text{(eqn. 3.1)}$$

Where Q is discharge, h the depth of flow and **(p, a)** parameters

Experience has shown that Eq. (3.1) is appropriate in most cases, given that the stage-discharge relationship is not significantly affected by unsteadiness and/or backwater effects. (Morten and Svein, 2005).

This method was used to fit the rating curves for stations which did not have them. Using spreadsheets to fit the curve, the power type of trendline uses equation 3.2 to calculate the least squares fit through points:

$$y = cx^{b},\qquad \text{(eqn. 3.2)}$$

Where c and b are constants; where $R^2 > 0.7$, y is the depth and x is the discharge.

Perkerra catchment monitoring station, 2EE7B is located at the Marigat Bridge. Three rating curves for the period 1964 to 1989 and 1990 to 1999, and 2000 to 2009 were used for this station; this is because of morphological changes that have occurred over the years at this station. The channel geometry changes due to siltation, erosion and other factors cause the flow regime to be altered. This in turn affects the discharge measurement at the gauging station and the rating curve needs to be updated from time to time for accurate measurements of the discharge.

3.3.3 Modelling the Reservoir

The catchment does not have big reservoirs, however, two major dam projects have been proposed to be undertaken by the year 2014 to boost storage and regulate stream flows especially for Perkerra irrigation scheme (Vision 2030). The dams have been designed to have big reservoirs of 13 and 9 million m^3 of water. These reservoirs were modelled in scenario analyses as illustrated in Figure 3.3.

The flood control storage (Sf) defines the zone that can temporarily hold water but must be released before the end of the time step. Thus storages above the flood control storage are spilled. The conservation storage (Sc) is the storage available for downstream demands at full capacity. The buffer storage (Sb) is a storage that can be controlled to meet water demands during shortages. When reservoir storage falls within the buffer storage, water withdrawals are effectively conserved via the buffer coefficient, bc, which determines the fraction of storage available for release; the inactive storage (Si) is the dead storage that cannot be utilized.

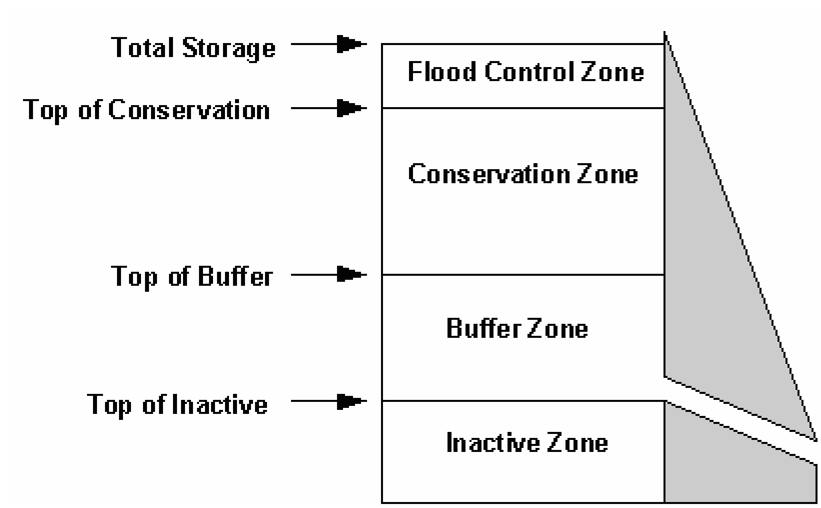

Figure 3.3 Reservoir Storage Zones used to describe operating rules

The amount available to be released from the reservoir, Sr (Eqn 3.3) is the full amount in the conservation and flood control zones and a fraction (given by bc) of the amount in the buffer zone (Yates et al., 2005).

$$S_r = S_c + S_f + (b_c * S_b) \qquad \text{(eqn. 3.3)}$$

Where S_r is total amount for release from reservoir storage, S_c is conservation storage, S_f is flood control storage, S_b is buffer storage and b_c is buffer coefficient

3.4 WATER DEMAND

WRMA, Kabarnet sub-region keeps a database of water use permits for each sub-catchment. In the current study, this database was used to estimate the demands within the catchment for the reference scenario and provided the basis for modifying demands for scenario analysis. Because of the nature of settlement and water use patterns within the catchment where majority of the population is not supplied with piped water, the village population estimates based on the 1999 census and cattle population estimates from International Livestock Research Institute (ILRI) database (1999) were used to approximate the overall total demand within the catchment.

Four main water use sectors were simulated in the WEAP21 model. These were the water permit holders (irrigation, domestic, public and other uses), Perkerra irrigation scheme, rural (domestic and livestock), and conservation flows (forests, tourism).

The rural domestic demands; it was estimated that 80lit/cap per day is the water use rate (Mogaka et al, 2006). Livestock water use rate was estimated at 70lit/head per day (Neijens, 2001). Demand sites simulated in this study were based on this information. The data on demand was summed up for each sub-catchment and assumed to be abstracted at the catchment outlets of the sub-catchments; this was so especially for the rural demands which can be viewed ‘as non point abstractions’.

The irrigation demands under permit holders in the upper catchment are mainly from flower farms, since this is done mainly under green houses, it was assumed that this is a constant demand. Perkerra irrigation scheme downstream of the catchment monitoring station formed a very important abstractor. The irrigation demand for the year 2000 was adopted from the study conducted in 2000 on irrigation efficiency of the scheme (Neijens, 2001). The subsequent demands are based on the information obtained by administering questionnaires and interviews to farmers and the irrigation scheme management.

3.5 WATER ALLOCATION

WEAP21 uses a linear programming technique to solve the water allocation model; priorities (1 to 99) are used to classify demands. 1 represents high priority demand node and 99 represents the lowest priority demand node. A Demand-Priority- and Preference driven Approach used presents a robust solution algorithm to solve the water allocation problem.

A standard linear program is used to solve the water allocation problem whose objective is to maximize satisfaction of demand, subject to supply priorities, demand site preferences, mass balances and other constraints.

The types of competing uses are classified by WRMA as commercial, livelihood and environmental. These use demand water of varied quantity and quality expressed in terms of Reserve and the Resource Quality Objectives in consideration of resource class. Each type of demand is divided into three classes of importance – high (1), medium (2) and low (3). This results in nine classes as shown in Figure 3.4.

This classification was used to give priorities to the demand sectors in the simulation of demand preferences and priorities.

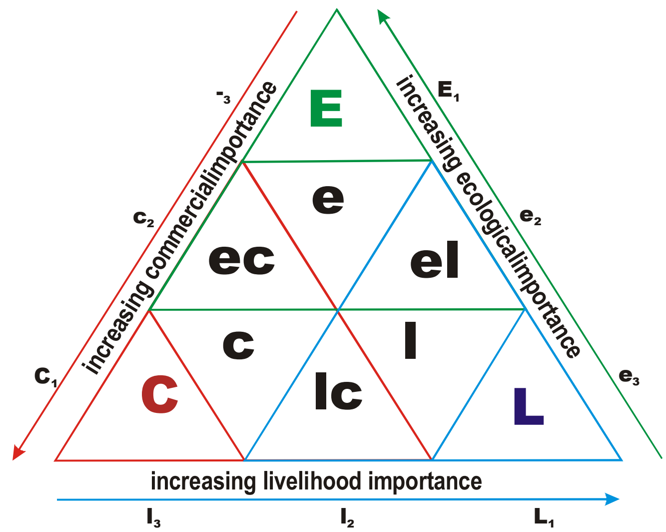

Figure 3.4 Water Resource Classification (source, WRMA/RVCA, 2008)

3.6 MODEL CALIBRATION AND VALIDATION

The complexity of water allocation models and the fact that they are required to simulate human behaviour (to reflect changes in demand) in addition to physical processes means that model calibration and validation is extremely difficult and has often been neglected in the past (McCartney and Arranz, 2007). To calibrate the model, observed stream flow data at gauging station 2EE7B (at Marigat Bridge) of 2000 to 2005 were used. These flows present an integrated time series of climate, changes in demand, water resource development and land use within the catchment.

Calibration included changing the model parameters to better simulate historic patterns. WEAP21 has no automatic calibration routine; therefore the changes implemented were tested manually by comparing the simulated and observed time series. WRMA has given a permit for forest conservation for sub-catchments 2ED and 2EF; however, the abstraction limit is not specified. Studies indicate that environmental flows vary from year to year, depending on rainfall, where it ranges from between 15.7% to 33.5% of the annual flow, in dry seasons going up to 78% of the natural river flow (MacCartney and Arranz, 2007). In estimating the in stream losses, 0.68m3/s per 100km reach was assumed (NWMP, 1992).

3.7 CREATION OF SCENARIOS

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. Scenarios are built and then compared to assess their water requirements, costs and environmental impacts. All scenarios inherit data from the Current Accounts year.

The scenarios can address a broad range of "what if" questions, such as: What if population growth and economic development patterns change? What if reservoir operating rules are altered? What if groundwater is more fully exploited? What if water conservation is introduced? What if ecosystem requirements are tightened? What if new sources of water pollution are added? What if a water recycling program is implemented? What if climate change alters the hydrology?

In creating scenarios, the reference scenario was used to evaluate the impact of development of two dam projects (NWMP, 1992 and Vision 2030, 2007) upstream of the irrigation scheme at Perkerra and environmental flows downstream. What if scenario analyses were built and done for 2009 to 2015. The scenarios are built on the data of the preceding scenario. Therefore, level 1 scenario is built on level 0 scenario. The following scenarios were therefore created based on the reference scenario and are tabulated in order of their data inheritance in Table 3.1. which is illustrated by Figure 3.5.

Table 3.1 Summary of Scenarios Created for Analysis

Level of scenario analysis	**Scenario**	**Remarks**	**Scenario**	**Remarks**
0	Reference	Simulations of catchment with no changes to system		
1	Chemususu Dam only	One reservoir in catchment for storage and flow regulation only	Water resources development	Two reservoirs in catchment for flow storage and flow regulation only.
2	Chemususu dam water supply project.	Water supply project to Nakuru and other towns and implementation of	Increased water demand	Water supply project to Nakuru and other towns and implementation of

		reserve flows to Lake Baringo		reserve flows to Lake Baringo
3	Increased irrigation efficiency 1	Improved irrigation efficiency at Perkerra irrigation scheme.	Increased irrigation efficiency 2	Improved irrigation efficiency at Perkerra irrigation scheme.

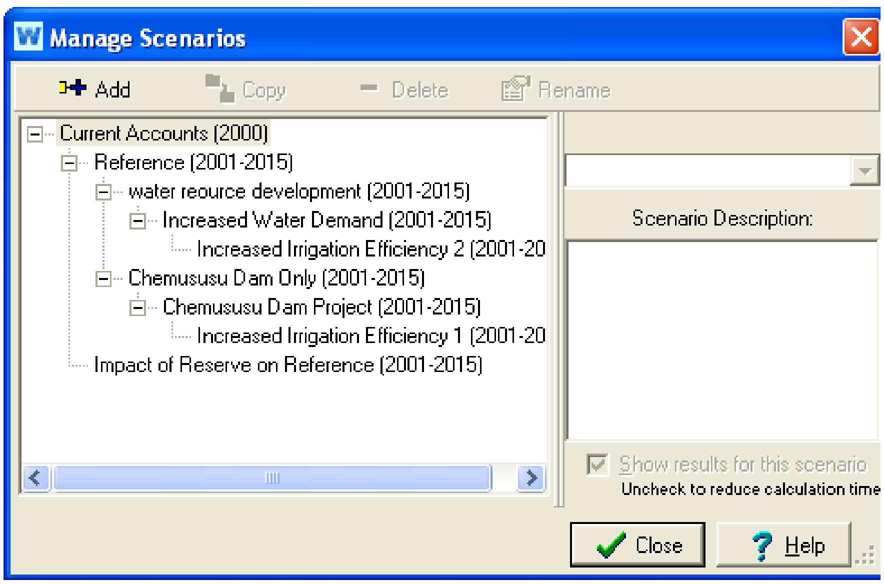

Figure 3.5 Scenarios in WEAP

Figure 3.5 illustrates a window showing how scenarios are arranged in WEAP21. The Current Accounts represent the basic definition of the water system as it currently exists. The reference scenario or "business as usual projection" forms the base from which other scenarios are evaluated.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter presents the results of the analysis of the application of WEAP21 to Perkerra catchment. Two main scenarios that are based on the reference scenario were analysed. These are the 'Chemususu dam only' scenario and the 'water resource development' scenario. From these two scenarios, the effect of implementing the reserve as suggested in the Water Act (2002) and water supply project to Nakuru town are analysed at the second level. After which the impact of improved irrigation efficiency at Perkerra irrigation scheme is analysed and compared to the other scenarios.

4.2 CATCHMENT HYDROLOGY

Hydrological events and processes in the catchment were defined in order to simulate some aspects of its hydrology. These include; precipitation, evapotranspiration, observed streamflow data, catchment size, the vegetation and dominant crops grown within the catchments. Groundwater analysis was not considered in this study, this is because the available information was not sufficient to estimate the aquifer storage capacity and the recharge rates to the various aquifers. This therefore does not enable the investigation of conjunctive use of water resources. However, an assumption of $0.68m^3/100km$ (NWMP, 1992) of seepage along the river channel is used to account for losses to groundwater. This represents the net losses which is the difference between infiltration and groundwater outflows as baseflows.

4.2.0 Stream Flow Data

The data used in this analysis were obtained from WRMA databases. The catchment monitoring station at Marigat Bridge (Station Number, 2EE7B) was used for streamflow analysis and model calibration and validation. The observed streamflow data at this point is also more comprehensive than most of the streamflow gauging stations in the catchment. The rating curves (Appendix D) were used to generate flows using available gauge height data resulting in daily discharges at station 2EE7B. The flows were averaged monthly generating a monthly average time series from January 1962 to February 2009.

Rainfall-runoff and consequently river discharges are the result of a large number of interacting and spatially variable hydrological catchment processes. When evaluated based on river flow gauging data, thus in a lumped macroscopic way, the rainfall-runoff subflow components can be broadly grouped in classes based on the different orders of magnitude of the subflow responses to rainfall (Willems, 2009). The flows at gauging station 2EE7B were analysed using the Water Engineering Time Series PROcessing tool (WETSPRO) of Willems (2009). The flows are separated into baseflows, interflows and overland flows. The tool uses the recursive digital filter technique with an exponential recession constant k and a parameter w, adjusting these two by trial and error and visual inspection of the time series leads to an average value of the recession constant and parameter w. The recession constant k equals the time in which the flow is reduced during dry weather flow periods to a fraction exp (-1) =0.37 of its original discharge. Given the big difference in order of magnitude of the recession constant of the three subflows, separation is carried stepwise. In a first step, the slow flow component is split from the total flow, and in a second step the interflow split from the remaining flow (total flow minus filtered slow flow). The rest fraction then represents the quickest flow component (Willems, 2009).

The result showed that baseflows in the catchment reduced drastically from the late 1980's to present. This result is shown by sharp hydrograph peaks and a reduction of the baseflows as shown in Figure. 4.1.

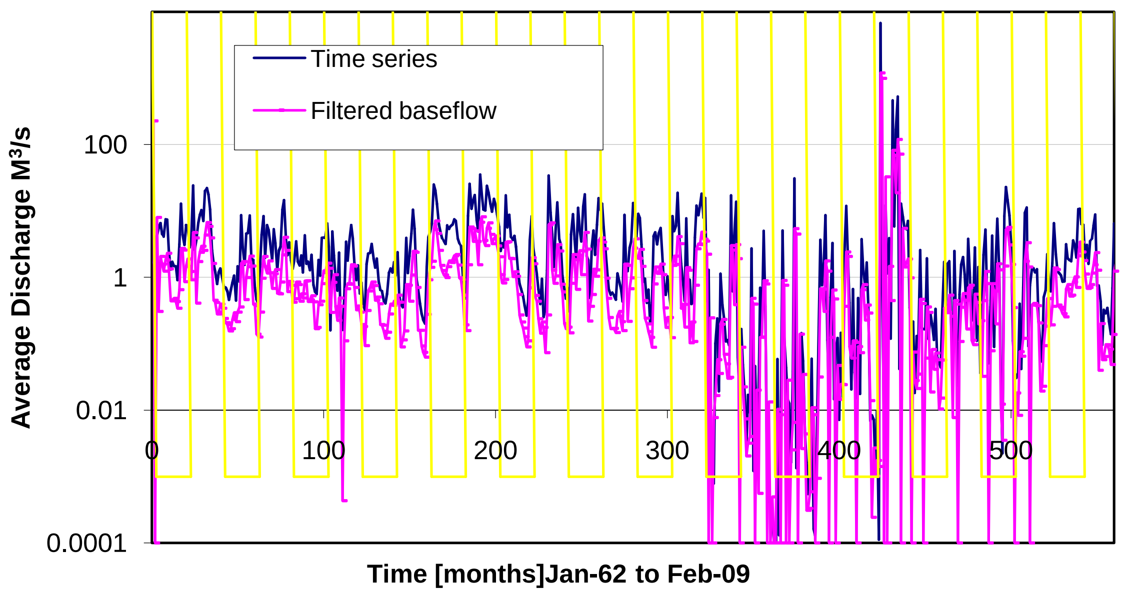

Figure 4.1 Time Series of Monthly Average Discharge at Station 2EE7b, (Perkerra Catchment Monitoring Station) from Jan 1962 to Feb. 2009

This indicates that for the last two decades, the catchment response to precipitation events has been quick showing tendencies of urban drainage system. This trend indicates possible catchment degradation resulting to reduced infiltration/percolation. The sharp peak of hydrographs indicates that little water is stored in the catchment.

4.2.1 Rainfall-Runoff Modelling Results.

The rainfall runoff method was used to simulate river flows; this was constrained by the type of data available (Rainfall, Evaporation and crop data). The following types of data are required to perform rainfall-runoff simulation using this method;

i. Land use (Area, Kc, Effective precipitation)

ii. Climate (precipitation and ETo)

Where Kc- crop coefficients and ETo is the reference crop evapotranspiration

4.2.1.1 Catchment

In setting up the WEAP21 model, 7 catchment sites generated the input for the 5 main tributaries of River Perkerra (Figure 4.2). Two catchment sites (Perkerra and Kimose) represent the contribution of the mid catchment streams. Using the FAO rainfall runoff method, the land use and climate of a catchment site were defined. The other input options of the catchment sites: ‘Loss and reuse’, ‘Yield’, ‘Water quality’ and ‘Costs’ were not taken into consideration in this project.

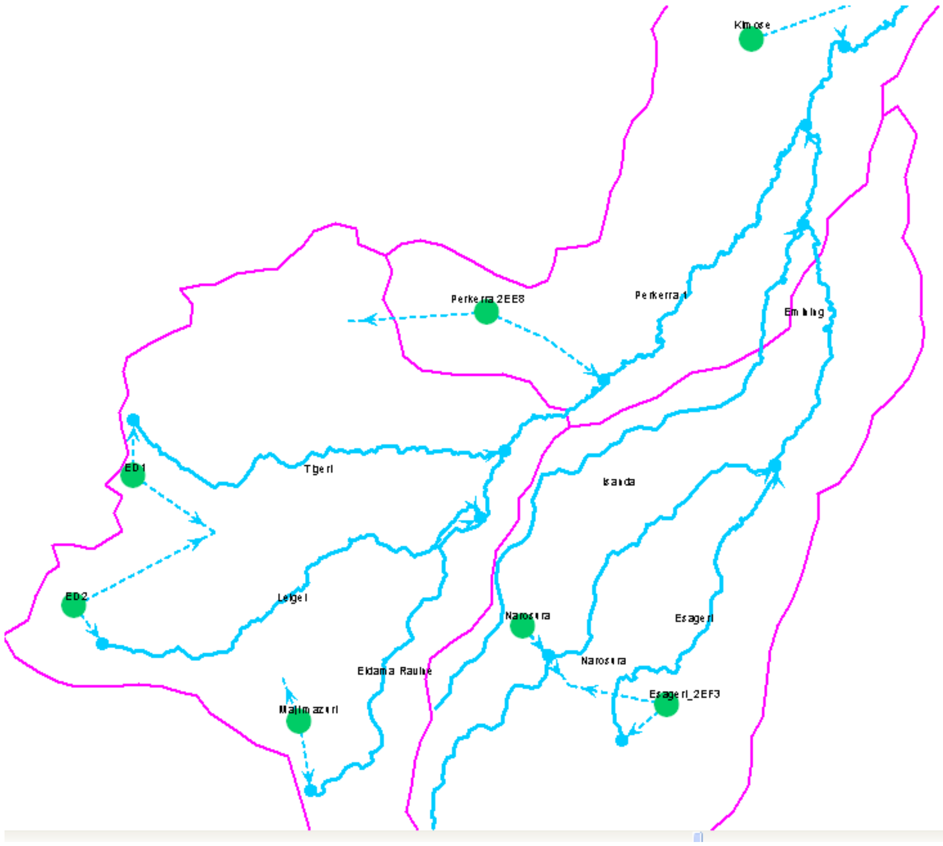

Figure 4.2 Catchment sites (nodes) in part of study area

4.2.1.2 Climate

Rainfall data for the period 2000 to 2009 were obtained from the Kenya Meteorological Department (KMD). The data available were converted to GIS platform (ArcView), and then using GIS software (ArcView) Thiessen polygons were developed for aerial rainfall. The rainfall station distribution and Thiessen polygons are shown in Figure 4.3.

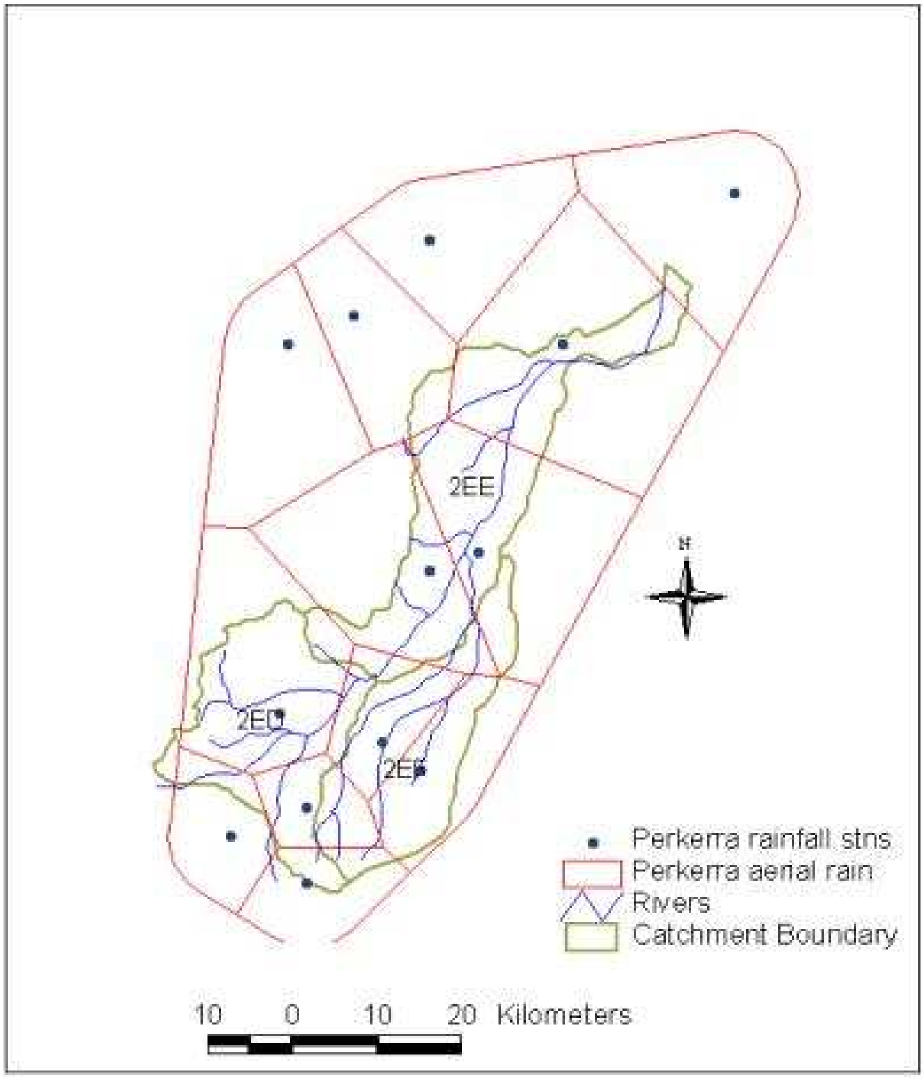

Figure 4.3 Thiessen polygons for estimating areal rainfall over the catchment

There was no reliable data for potential evapotranspiration. Estimation of climatic data for calculating ETo was done using LocClim V1.10 database, developed by FAO. The new LocClim program uses a statistical analysis based on data from about 30,000 meteorological stations around the world to estimate climate data for any location. The weather parameters obtained were used to estimate ETo using the ETo calculator which is based on the Penman-Monteith method. Both precipitation and reference evapotranspiration are given in Appendix E, and included in WEAP21 as a key-assumption. Monthly average ETo values derived from LocClim V1.10 are summarised in Table 4.1.

Table 4.1 Monthly Average ETo Values

Station Name and coordinates	ETo											
	J	F	M	A	M	J	J	A	S	O	N	D
Londiani Makutano, 35.62° E, 0.04° S.	136.4	134.4	145.7	114.0	102.3	90.0	77.5	83.7	105.0	117.8	111.0	117.8
Kiptunget Forest, 35.71°E, 0.09°S.	124.0	117.6	127.1	102.0	99.2	90.0	83.7	86.7	102.0	111.6	96.0	108.5
Maji Mazuri, 35.71°E, 0.02°S.	136.4	134.4	145.7	111.0	102.3	87.0	77.5	80.6	102.0	117.8	108.0	114.7
Chemususu, 35.67°E, 0.08°N	136.4	134.4	145.7	111.0	102.3	87.0	77.5	86.8	105.0	114.7	111.0	114.7
Esageri, 35.81°E, 0.03°N	133.3	128.8	139.5	105.0	99.2	90.0	83.7	89.9	102.0	114.7	102.0	114.7
Baringo FTC, 35.77°E, 0.05°N	136.4	134.4	145.7	111.0	102.3	87.0	77.5	80.6	102.0	117.8	108.0	114.7
Cheberen Market, 35.83°E, 0.23°N	167.4	165.2	179.8	150.0	151.9	141.0	136.4	148.8	156.0	164.3	147.0	151.9
Kimose Agric. Holding Ground, 35.88°E, 0.25°N	167.4	162.4	164.3	132.0	108.5	105.0	102.0	117.8	132.0	139.5	126.0	145.7
Perkerra Agricultural Stn., 35.97°E, 0.48°N	167.4	165.2	179.8	150.0	151.9	141.0	136.4	148.8	156.0	164.3	147.0	151.9

4.2.1.3 Land use

Crop coefficient (Kc coefficient) incorporates crop characteristics and averaged effects of evaporation from the soil. For most hydrologic water balance studies, average crop coefficients are relevant and more convenient than the Kc computed on a daily time step using a separate crop and soil coefficient (http://www.fao.org/docrep/x0490e/).

The land use of the lower catchment is mainly characterised as range-bushland, however in the upper catchment in Koibatek district, maize is the main crop cultivated. For the WEAP21 model a 40% cover with (rainfed) maize and 70% other vegetation, such as fruit trees, grass and natural trees was assumed. Perkerra Irrigation scheme is not considered as it is at the catchment outlet. Maize is chosen as the representative crop for the area, because it is the principal crop in Koibatek district. The crop coefficient (Kc) for the “Other vegetation” is set to 1.0. Almost all the maize in Koibatek district (upper catchment) is not irrigated so the data for dry maize are used. Combination of the length of the stages and the growing season and the Kc-factor Table E10 results in the monthly variation in Table E1, (Appendix E).

Effective precipitation is that precipitation that is neither retained on the land surface nor infiltrated in the soil (Chow et al, 1988). In the months with peak rainfall the precipitation rate exceeds the infiltration rate of the soil. Therefore, part of the precipitation is surface runoff to streams and not available for evaporation. The data for the effective precipitation are based on data of Neijens (2001) and are included as a key-assumption in WEAP21 (Table E11).

The catchment has three main sub-catchments; 2ED, 2EF and 2EE. These have been further subdivided into 7 as shown in Table 4.2 and used in the reference scenario. The subdivisions were done along the Thiessen polygons constructed over the catchment (Figure 4.3) for estimating aerial rainfall.

Table 4.2 Catchment Size and Receiving Tributary

Catchment	**Size (km^2)**	**Tributary**	**Rainfall station/polygon**
ED1	135	Tigeri	Chemususu
ED2	108	Lelgel	Makutano-Londiani
Maji Mazuri	117	Eldama Ravine	Maji mazuri
Esageri_2EF3	60	Esageri	Esageri
Narosura_2EF4	115	Narosura	Baringo FTC
Perkerra	157	Perkerra	Cheberan Market
Kimose	128	Perkerra	Kimose Agric. Stn.

4.2.2 Modelling demand

Every catchment has at least four demand sites: domestic, agriculture, livestock, dams/reservoirs and other uses. Domestic water use is the most important, it has the highest priority. Second important use is livestock, third is agriculture and the dams/reservoirs have least priority. This classification was derived from the general classification in the CMS-RVCA (2008).

4.2.2.1 Domestic water demand

The estimates of the water use of one household range from 35 to 140 l/day as shown in Table 4.4. For the WEAP model an intermediate value of 80lit household per day was used (MoWI, 2005). This means 29.2 m^3 per capita per year. No considerable monthly variation was imposed. The various rural populations were considered (Table E15) based on 1999 census report, a population growth rate of 2.85% and 3% for rural and urban centres respectively was used to estimate the population for the study period (http://www.cbs.go.ke, Kenya facts and figures, 2007, 2009). The rural population of catchment 2ED and 2EF can access water from boreholes and hand dug wells, however the consumption from these catchments was assumed as 100% from surface water because no credible data was available to use to determine the per capita usage of groundwater. This implies that the model allocated more water than is actually needed to demands in these catchments.

Table 4.3 Priority Demand Sites

Demand	**Priority**
Domestic	1
Livestock	2
Agriculture	3
Other uses	4
Dams/ reservoirs	10

Table 4.4 Rural Water Uses per Household According to Different Sources

Source	**Water use (l/d)**	**Country**
Free University Amsterdam	35-70 l/d	Global estimates
Neijens (2001)	40-100l/d	Global estimates
Louis Berger International Inc. (1983)	140 l/d	Global estimates
De Bruijn and Rhebergen (2006)	90 l/d	Kenya
MoWI (2005)	40 to 80 l/d	Kenya

WRMA issues water permits to various bulk users of water. The demand points due to permit allocations were aggregated per catchment and per category of use. Water permits were classified under the various categories (Table E12 to Table E14). Monthly variation data were not available; in this study monthly variation was not imposed. However, random checks during the study period revealed that some abstractors exceed permit allocations by double. This makes it difficult to perform accurate analysis of demand management. It therefore implies that the abstraction limits used from the permit information is just an average estimate of the actual abstractions by permit.

4.2.2.2 Agricultural water demand

The permit water demand for irrigation and livestock were considered in this category. However, to cater for the rural households, Livestock water demand was modelled separately. Livestock population data were obtained from online database ILRI (1999). ILRI has classified the data per division in Kenya, where latest data available were used (for year 1999). The data is available as maps in ArcView format. The water use rate per head of cattle per annum was estimated as 21.9m^3 (Loon and Droogers, 2006).

There were some small industrial uses at Eldama Ravine and Emining towns; Cabacid, and bottling companies. Other uses under permits were municipal uses; water supply to schools, hospitals, government offices. It is important to note that at the time of data collection, WRMA Kabarnet sub-region was in the process of auditing all the permits and installing weirs at the various abstraction points for monitoring purposes. There are also other ‘illegal’ water users (bulk users who don’t have WRMA permit) of whom it was not possible to account for in this study. This will make the calibration of the reference scenario difficult because such uses modify the observed stream flow at the catchment observation station 2EE7B.

The catchment has 38 small reservoirs and water pans (Table E17), with an average storage volume of 15,000m^3 and 2m depth. The pans and reservoirs were lumped together into 3 big reservoirs in the three major sub-catchments. A linear depth volume relationship was assumed following the studies by Hagan (2007). No operating regulations were imposed on them because the water pans did not have any regulation structures.

The schematic presentation of the whole catchment is shown in Figure 4.4. The figure shows all the elements simulated and their spatial relationship.

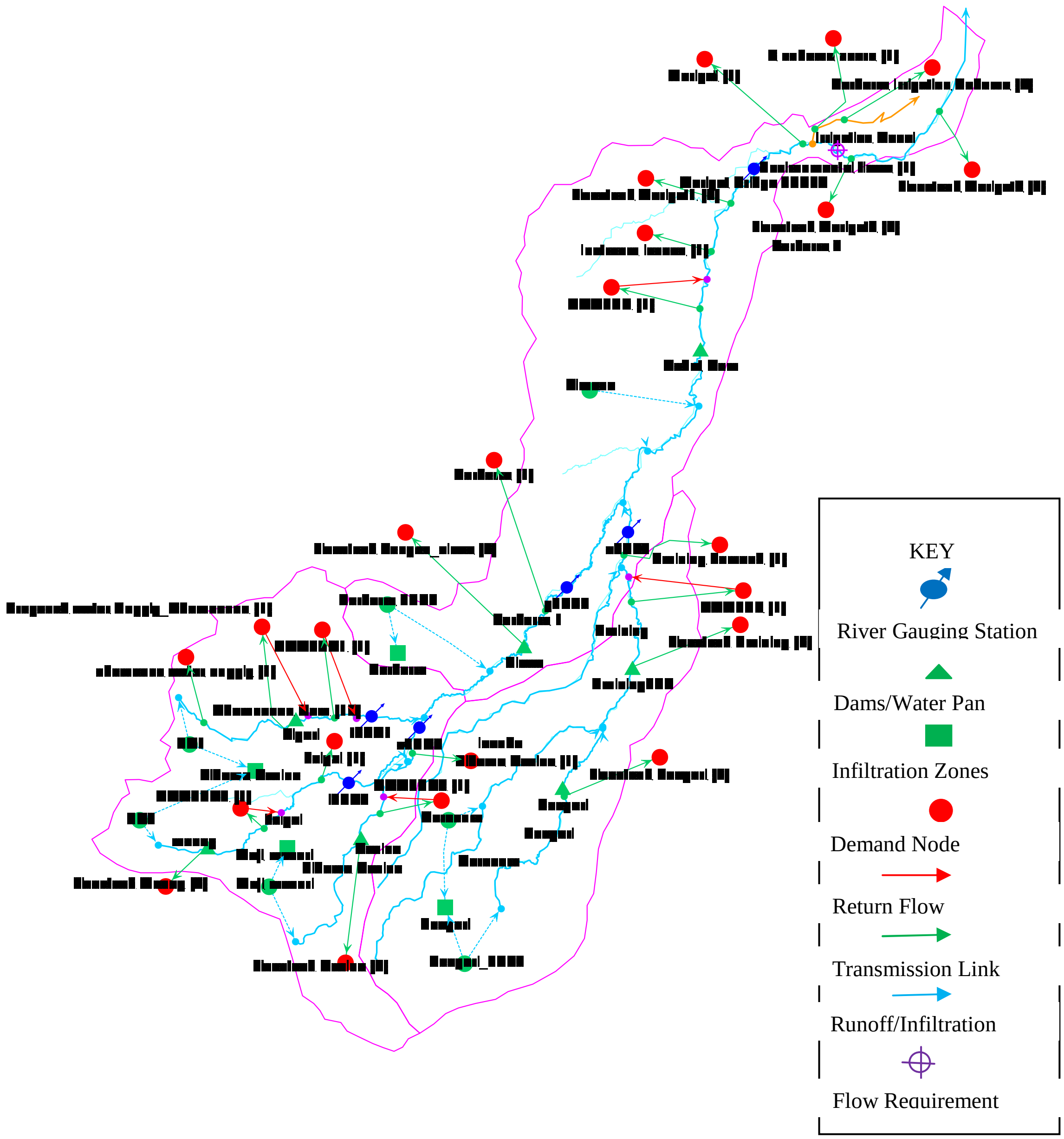

Figure 4.4 Catchment Demand Nodes

The canal diversion from River Perkerra about 1 km downstream of Marigat Bridge river gauging station, to Perkerra irrigation scheme serves various purposes; irrigation, domestic and livestock. Interviews with Perkerra Irrigation Scheme management indicated that during peak water supply (when water is at canal capacity), they only irrigate up to 90 acres per day. This is because of low irrigation efficiency, which is as low as 27% (Neijens, 2001) and the other competing uses in the irrigation scheme. There has been an extension of irrigation field canals by farmers to 'Extension plots'. The extension plots are as a result of the increased pressure on land, this is because most of the plot owners are second and third generation from their parents. Therefore, the other family members who fail to get a share in the formal irrigation scheme have been allowed to make extensions with the assistance of Perkerra Irrigation Scheme Board. Given this huge demand, the irrigation canal capacity is inadequate.

Perkerra irrigation scheme demand is therefore modelled through the canal, with supply constraint as $0.94m^3/s$. (canal capacity). The other demands sites are points of abstraction along the canal which drains back to Perkerra River. The other uses are also prioritised according to Table 4.3.

Perkerra irrigation scheme management approximates that 200 m^3 of water is used to irrigate one acre of maize crop, this figure is comparable with the findings of Neijens (2001). Questionnaires and interview analyses indicated that an irrigation cycle takes an average of 17 days (two and half weeks). This means an acre is irrigated at least twice a month. 1500 acres of seed maize are cultivated each year (1200 acres of irrigation scheme and 300 acres of extensions). In WEAP, 1700 acres were modelled to be under irrigation each year and an irrigation cycle of 14 days was adopted according to the findings of Neijens (2001), (Perkerra Irrigation Scheme demand node). Figure 4.5 is the data view of WEAP21. The consumption by demand sites on the irrigation canal was 100%, this is because there is hardly any return flows that leave the scheme after the creation of the 'Extension' farms.

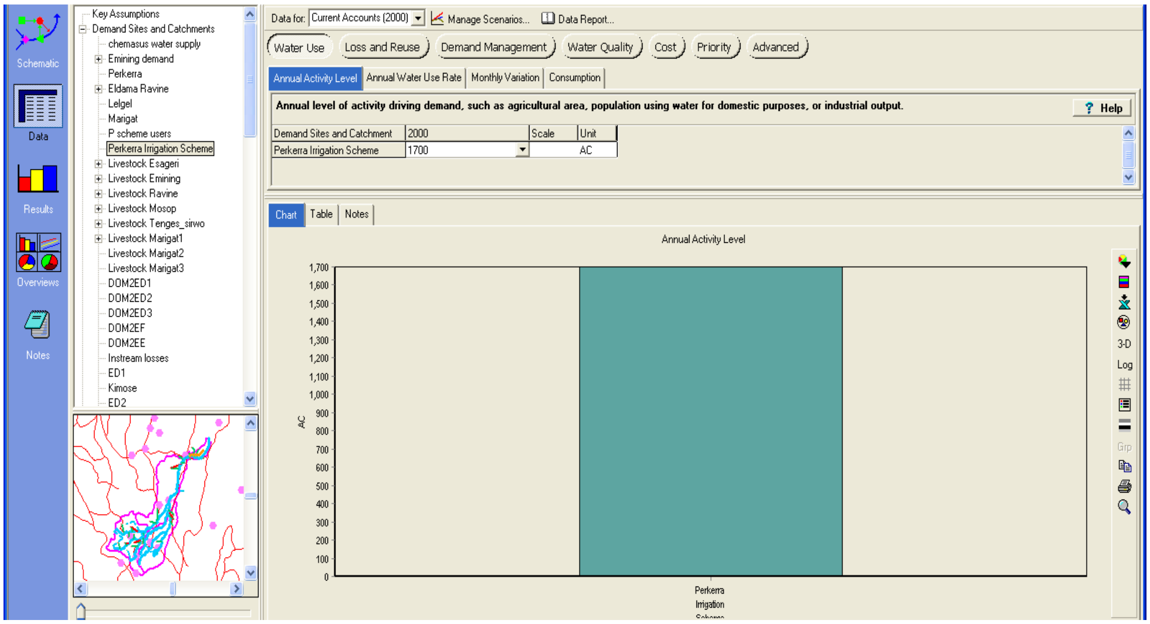

Figure 4.5 Data View of WEAP Model

Figure 4.5 shows an example of data entry view where Perkerra Irrigation Scheme is considered, and the displayed data in the view is its annual activity level.

4.3 SCENARIO ANALYSIS

Scenario analysis enables the answering of 'what if' questions in a water system. The reference or business as usual scenario is the base scenario that uses the actual data, to help in understanding the best estimates about the studied period. The objective of a reference scenario is to bring an understanding of the current trend. Other scenarios are built on this reference scenario with variations on the demand or supply side.

4.3.0 Reference Scenario

The Reference scenario is the scenario in which the current situation, current account year as 2000 is extended to the ‘future’ (2001-2009). No major changes are imposed in this scenario. A linear population increase was assumed based on the Central Bureau of Statistics reports (Facts and Figures 2007 and 2009). The model mimics reality over the period 2000 to 2009, given the constraints of simplification of the model and data limitations.

4.3.1. Model Calibration Results

The observed stream flows for the period 2000 to 2005 were used to calibrate the model, and 2006 to 2008 for validation. The results presented in Figure 4.6 indicate that the model is able to predict the general trend of the catchment processes. However, this result was obtained after variation of land use factors. The model performance is evaluated using standard statistics; mean error (ME), mean square error (MSE) and model coefficient of efficiency (EF) as described by the equations below.

$$E_Q = Q_m - Q_o \qquad \text{(Model residual)} \qquad (4.1)$$

$$ME = \overline{E}_Q = \sum_{i=1}^{n} \frac{Q_m(i) - Q_o(i)}{n} = \sum_{i=1}^{n} \frac{E_Q(i)}{n} \qquad (4.2)$$

$$MSE = \sum_{i=1}^{n} \frac{(Q_m(i) - Q_o(i))^2}{n} = \sum_{i=1}^{n} \frac{(E_Q(i))^2}{n} \qquad (4.3)$$

$$EF = \left[1 - \frac{\sum_{i=1}^{n} \left(Q_m(i) - Q_o(i) \right)^2}{\sum_{i=1}^{n} \left(Q_o(i) - \overline{Q_o} \right)^2} \right] = \left[1 - \frac{MSE}{S_{Q_o}^2} \right] \qquad (4.4)$$

Where

Q_o *- observed flow*

Q_m *– simulated flow*

ME - Mean Error

MSE - Mean Squared Error

EF- Model Efficiency Coefficient

n- The number of data points

s- Variance (squared standard deviation)

The *ME* and *MSE* reflects the bias or systematic deviation in the model results and the random error after correction. They have the disadvantage that their magnitudes highly depend on the flow magnitude, and thus on the river under study. The model efficiency coefficient *EF* of Nash and Sutcliffe (1970), which is a dimensionless and scaled version of the *MSE* for which the values range between 0 and 1 (0 or 1 for a perfect model) gives a much clearer evaluation of the model results and performance. The analysis was done as shown in Table F1 where the ME is 1.7E6 m^3, the MSE is 6.63233251E5m^3 and the EF was found as 0.999. Though the magnitudes of the ME and MSE are high, the EF indicates that the model is good. R-Squared is another statistical measure of how well a regression line approximates real data points; an r-squared of 1.0 (100%) indicates a perfect fit. The formula for r-squared is:

r(x,y) = [Cov(x,y)] / [StdDev(x) x StdDev(y)]

The model results had an r-squared value of 0.885 or 88.5%.

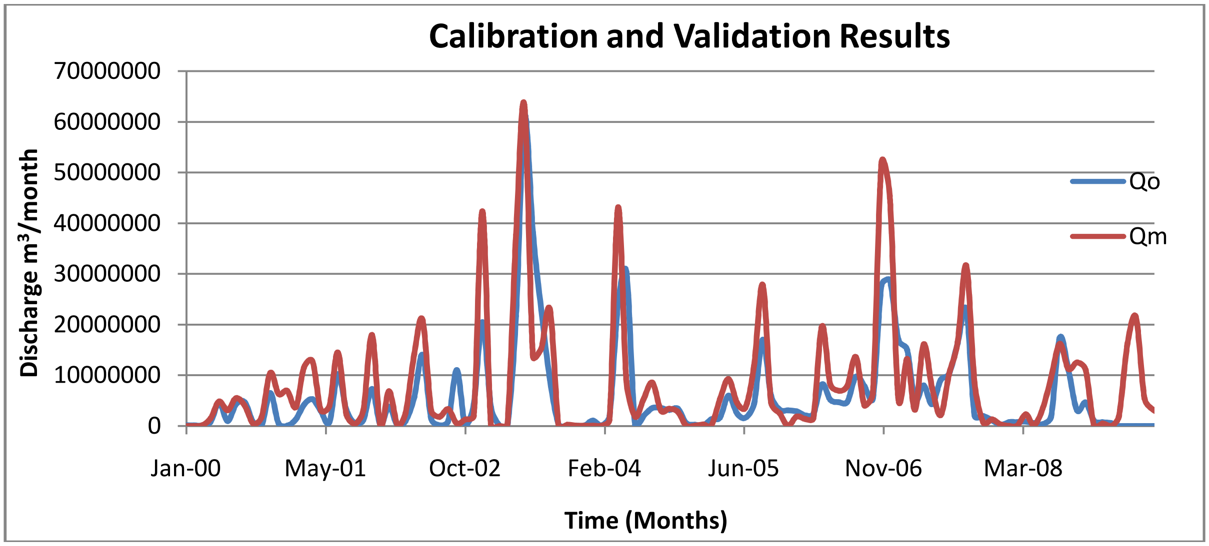

Figure 4.6 Calibration and Validation Results

In calibration, the land use factors (effective precipitation and Kc-factors) were modified, where the average Kc values between maize and other vegetation was used, in place of having Kc values for Maize applying to 40 percent of land cover. Effective precipitation was reduced by between 10 to 20 %, by trial and error. Seepage along the river channels was estimated to be $0.68m^3/s$ per 100km as it was used in the National Water Master Plan report (NWMP, 1992).

In Figure 4.6, the time series, Qo is the observed stream flows and Qm is the simulated stream flows of the reference scenario. The graph shows that the simulated flows follow the trend of the observed flows, however it shows some peaks of Qm to be much higher than Qo, this may be due to excess water being attributed to runoff, whereas it forms groundwater recharge. On the other hand it may be an indication of other abstractions which have not been fully accounted for. The model is based on equitable allocation of water which may not be the case leading to certain peak discharges which are quite abnormal. Finally certain peaks are due to high storms from rainfall events, leading to high effective rainfall. The EF of 0.99 and r-squared of 88.5% indicates that the model performance is not perfect but provides a good estimate.

4.3.2 Unmet Demand and Demand Coverage

The reference scenario is overshadowed by the Perkerra irrigation scheme unmet demand (Figure 4.7). Water shortages occur often between November to March of most years (Figures 4.8 and 4.9). Water allocation to demand sites in WEAP is done through linear programming solution of the water allocation problem. Therefore demand site satisfaction is maximized subject to the mass balance, supply preferences, demand priority and other constraints. In the result of Figure 4.7, all domestic demands are met except for rural upper catchment domestic demands (DOM2EF, DOM2ED). However, the average monthly demand site coverage is more than 60% except for the month of February. There is therefore no acute domestic and livestock water shortage in the catchment upstream and downstream of Marigat Bridge (gauging station 2EE7B), if such a policy of regulation is adopted.

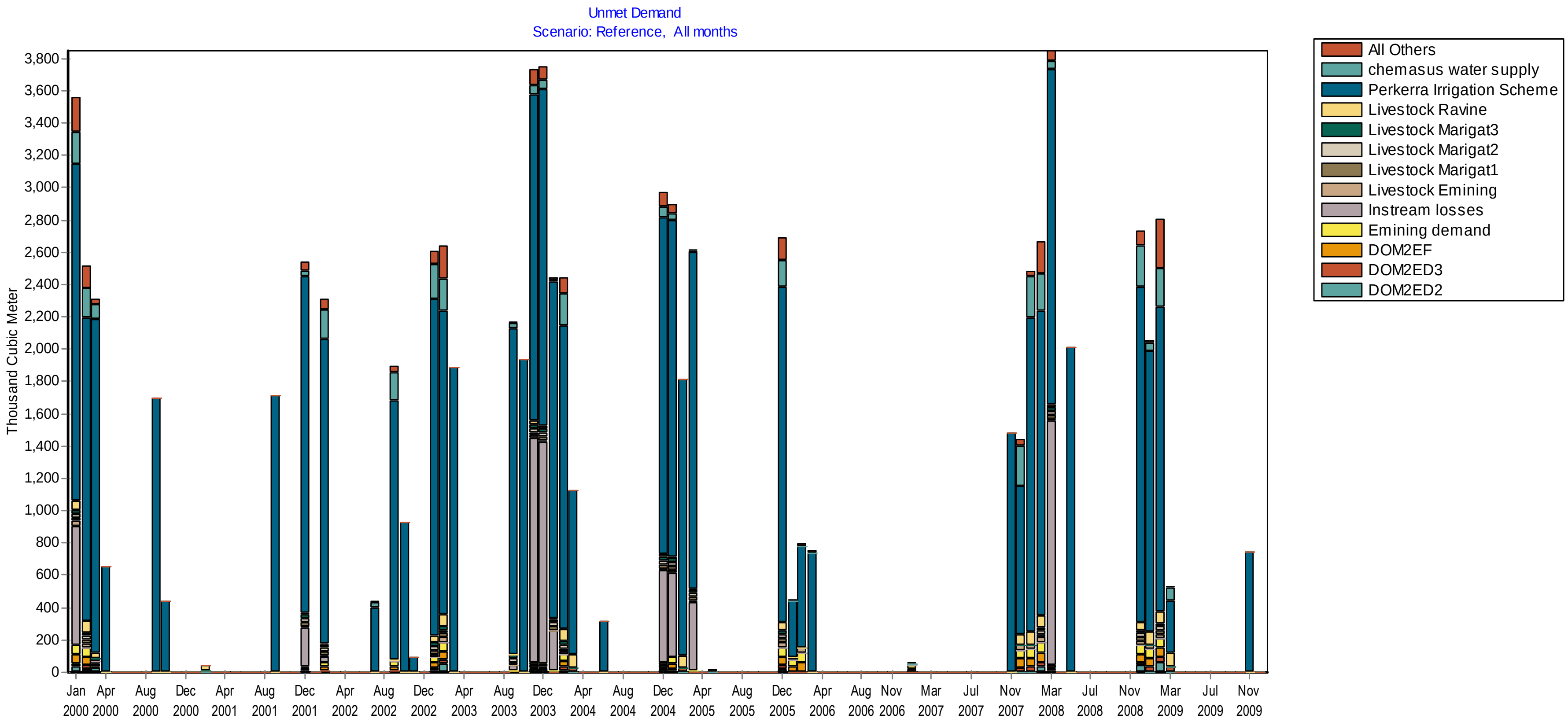

Figure 4.7 Reference Scenario: Monthly Unmet Water Demands

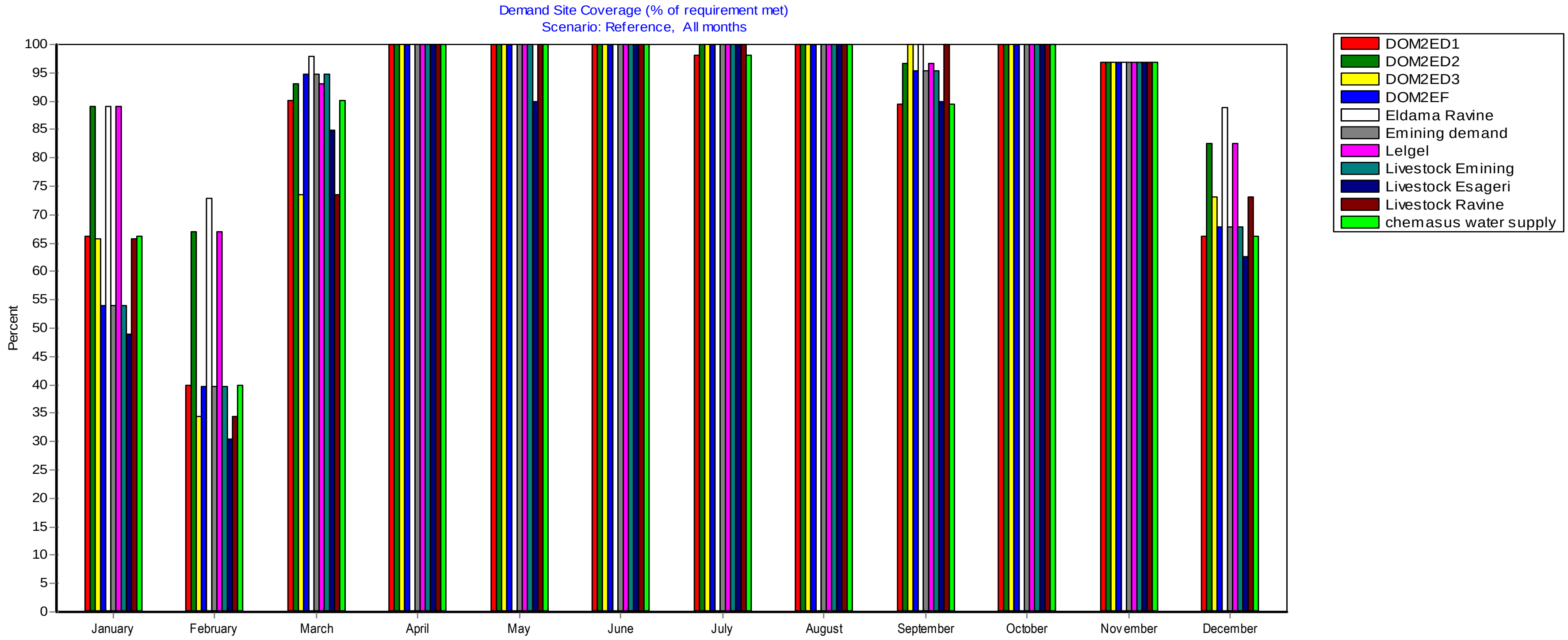

Figure 4.8 Reference Scenario: Mean Monthly Water Demand Coverage of Upper Catchment

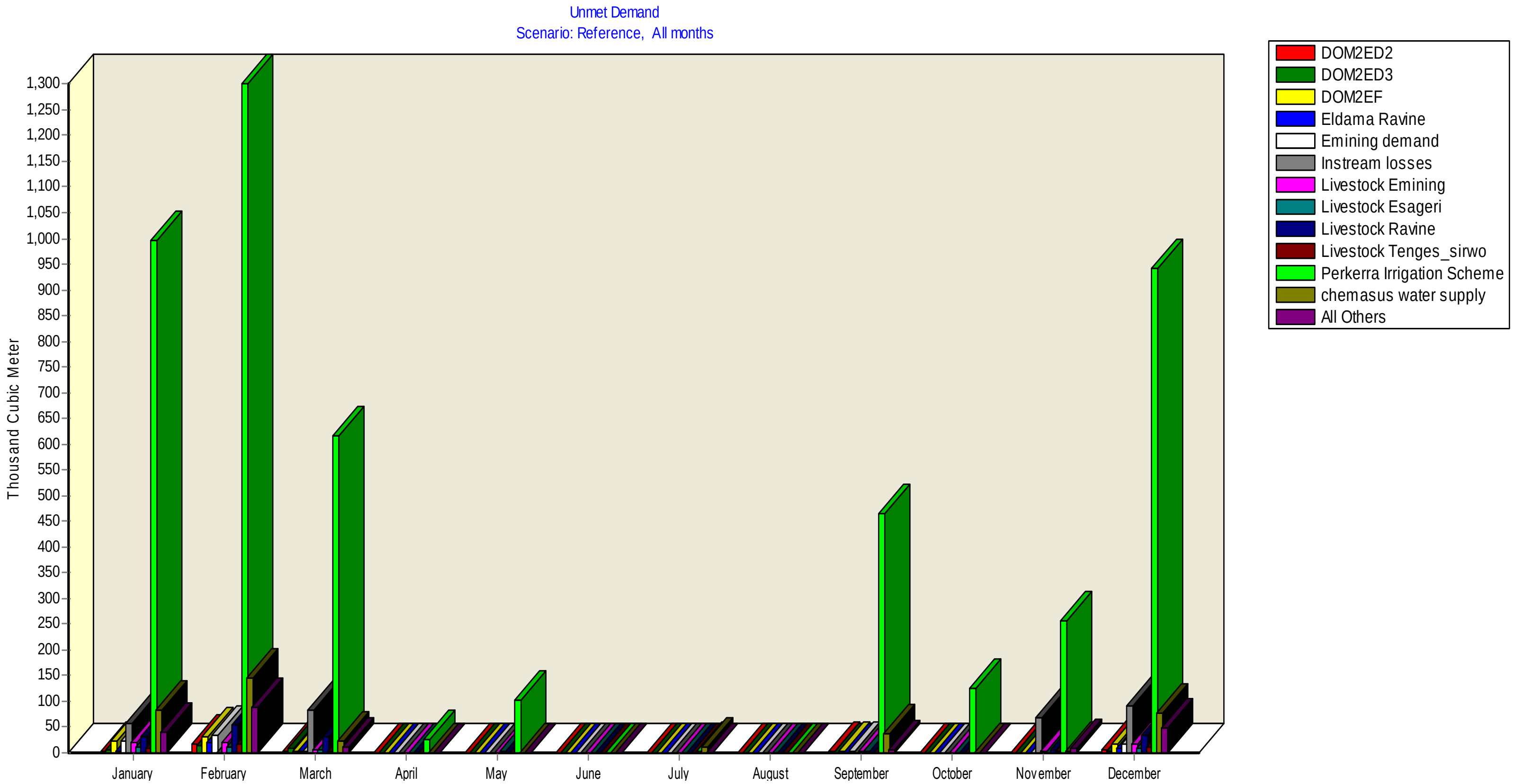

Figure 4.9 Reference Scenario: Mean Monthly Unmet Water Demands

On an average the demand coverage is more than 50% for all demand sites for at least 11 months. The WRAP report (1987) indicates that there is high groundwater potential in the highlands as compared to the lower and mid catchment where most of the groundwater is saline. The upper catchment has a number of hand dug wells as compared to the mid and lower catchment where ground water is accessible only through boreholes. It is interesting to note that the upper catchment has slightly less demand site coverage compared to the lower catchment. The WRAP report (1990) indicates that there is shallow ground water in parts of the upper catchment. The low demand coverage in this zone can be attributed to the dependence on shallow wells by the residents to meet domestic and livestock water demands.

On an average, the mean monthly unmet demand of February is the highest at 1.9 million m^3. The months of April and August have all the supply requirements in the catchment met, (Figure 4.9). In Figure 4.7, 2008 March recorded the highest supply deficit of 3.8 million m^3 for the whole catchment, followed by December 2003 and January 2000 at 3.7 and 3.5 million m^3 respectively. April of 2006 to November 2007 is the longest period in the series where supply was adequate.

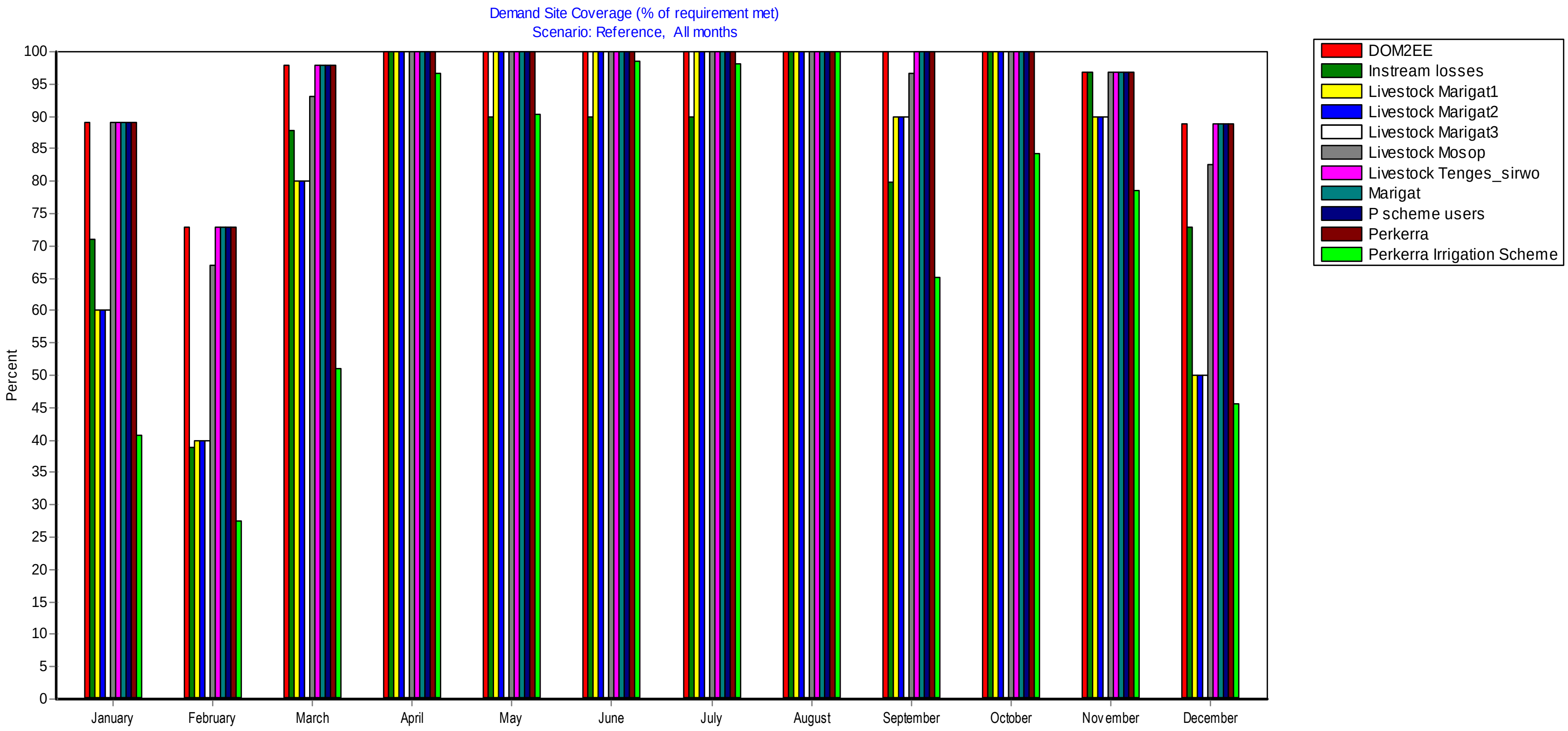

Figure 4.10 Reference Scenario: Mean Monthly Water Demand Coverage of Lower Catchment

4.4 SCENARIO ONE: ONE DAM IN THE CATCHMENT

4.4.0 Chemususu Dam Scenario

The government is planning to construct two dams on river Perkerra for water supply and for stabilizing flows downstream for Perkerra Irrigation Scheme (NWMP, JICA, 1992). The first one being Chemususu dam with an estimated reservoir volume of 14 million m^3 and Radat dam with an estimated reservoir volume of 9 million m^3. This scenario looks at the effect of having only Chemususu dam at its presently proposed location. The demand sites and hydrology remains as in the reference scenario.

The dam and reservoir is modelled as shown earlier in Figure 3.3. It is represented as a demand node on the river with the least supply priority as shown in Table 4.3. Simple operating rules were imposed in the management of the dams as shown in Table 4.5. The depth volume area curve was adopted from Chemususu dam final design report (NWC&PC, 1989).

Table 4.5 Operating Rules for Dams

Storage Limit	**Chemususu Dam** (vol. in million m^3)	**Radat Dam** (vol. in million m^3)
Top of conservation	13.0	9.0
Top of buffer	7.0	6.0
Top of inactive zone	1.5	1.0
Buffer coefficient	0.7	0.5

The mean monthly evaporation of the dam is obtained from the same report. The design under seepage is in the order of 500 to 1000 m^3/day. The dam is designed to have a yield of 13,000m^3/d. The simulation is extended to 2015 where catchment hydrology is assumed not to change.

The dam was assumed to have been commissioned in January 2002. Figure 4.11 shows that the reservoir takes only one season (about 9 months) to fill. Chemususu dam design report (1989) and Environment Impact Assessment report (2006) indicate that the dam will fill in one year. This indicates that the catchment has high peaks of runoff, thus the available storage quickly fills. The storage volume curve indicates that in the first 6 years of simulation, the storage fell to the inactive zone three times (March 2004, March 2005 and May 2008), after which the storage stabilizes. Initially, there is great strain on the dam to meet demands. This is without including the supply requirement of 13,000m^3/day proposed when the dam is constructed. Perkerra Irrigation Scheme demand site coverage increases to 75% in February from 20% (Figure 4.10 and Figure 4.13) in the reference scenario. Figure 4.12 show that in this scenario, downstream of the dam, Perkerra Irrigation Scheme is the demand site that is lowest covered by supply.

The construction of dam in this scenario will impact significantly on the downstream users. Thus Perkerra irrigation scheme will be able to have crop all year round with the lowest average water supply being experienced in February at 75% of the irrigation demand.

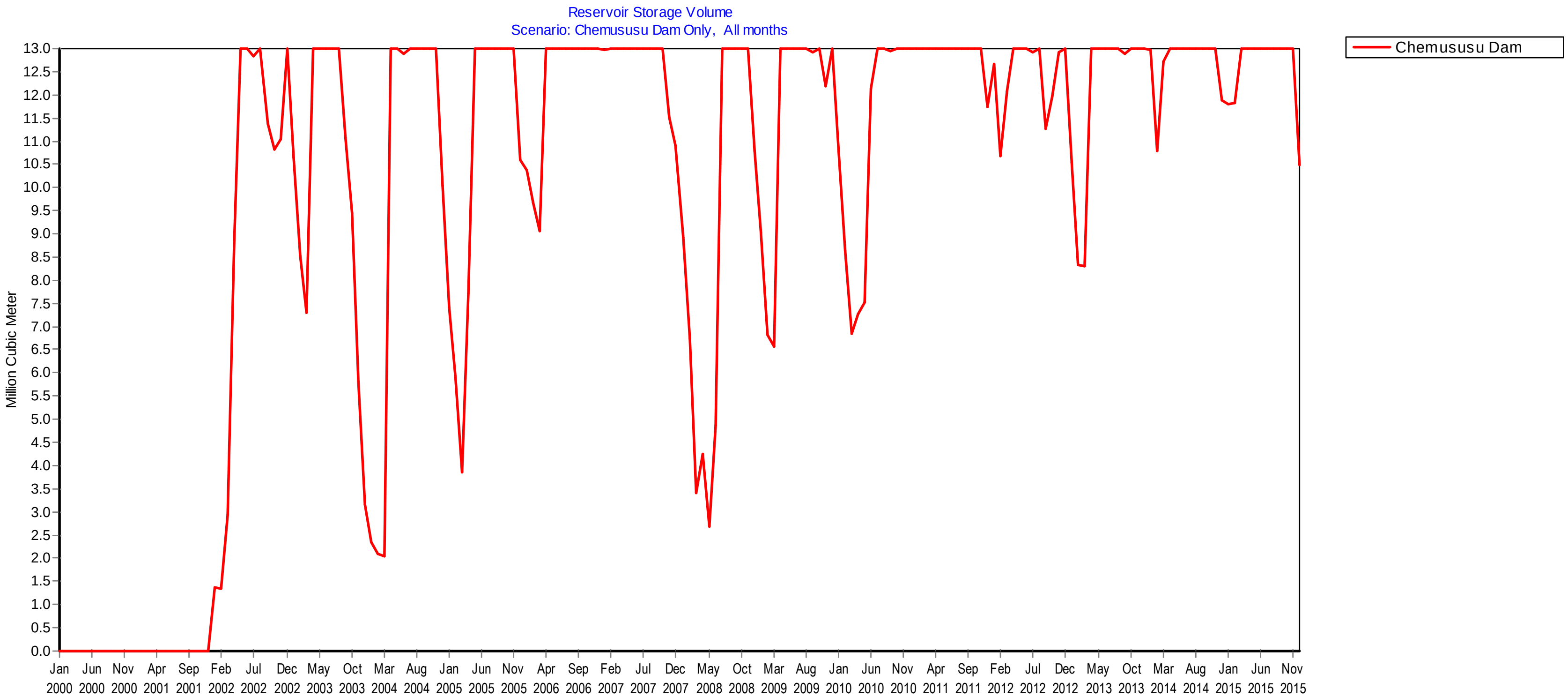

Figure 4.11 Chemususu Dam Scenario: Reservoir Storage Volume Curve

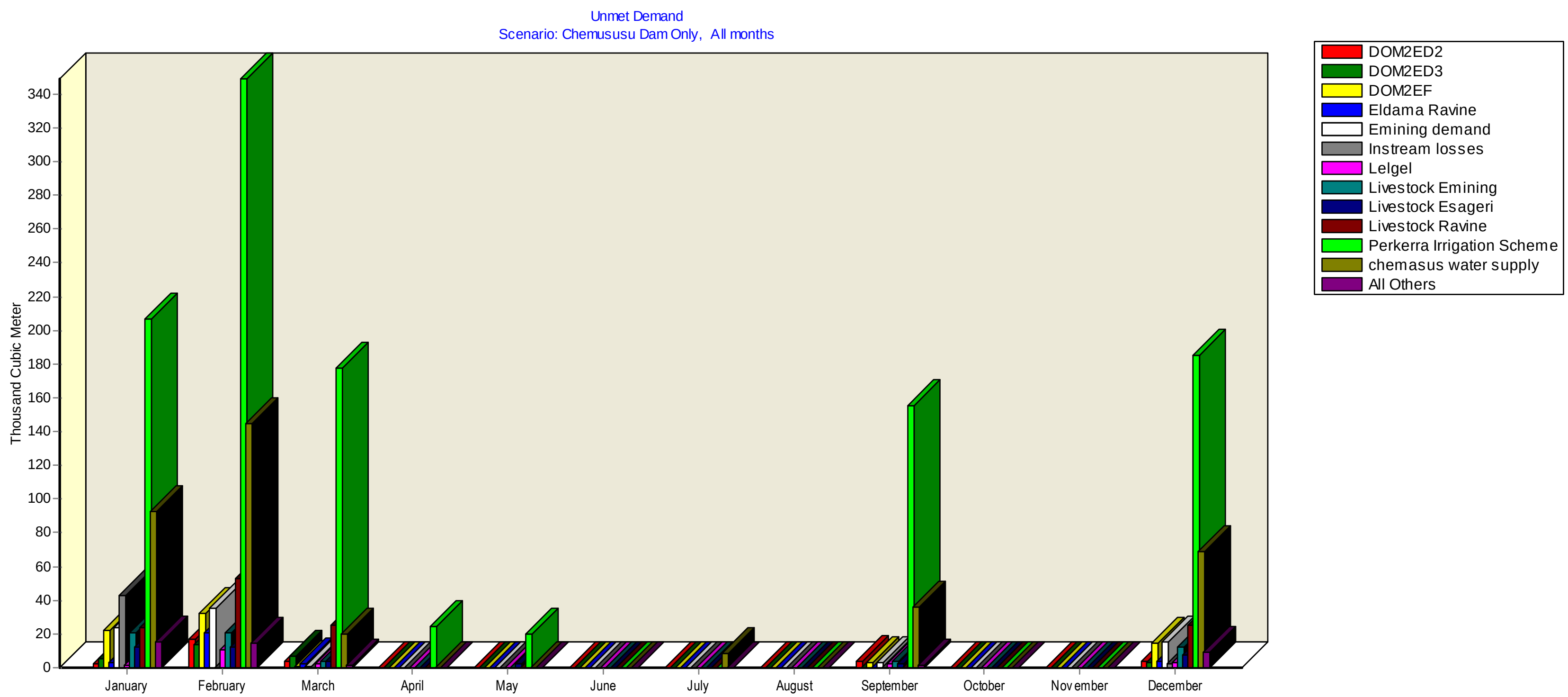

Figure 4.12 Chemususu Dam Scenario: Mean Monthly Unmet Water Demands

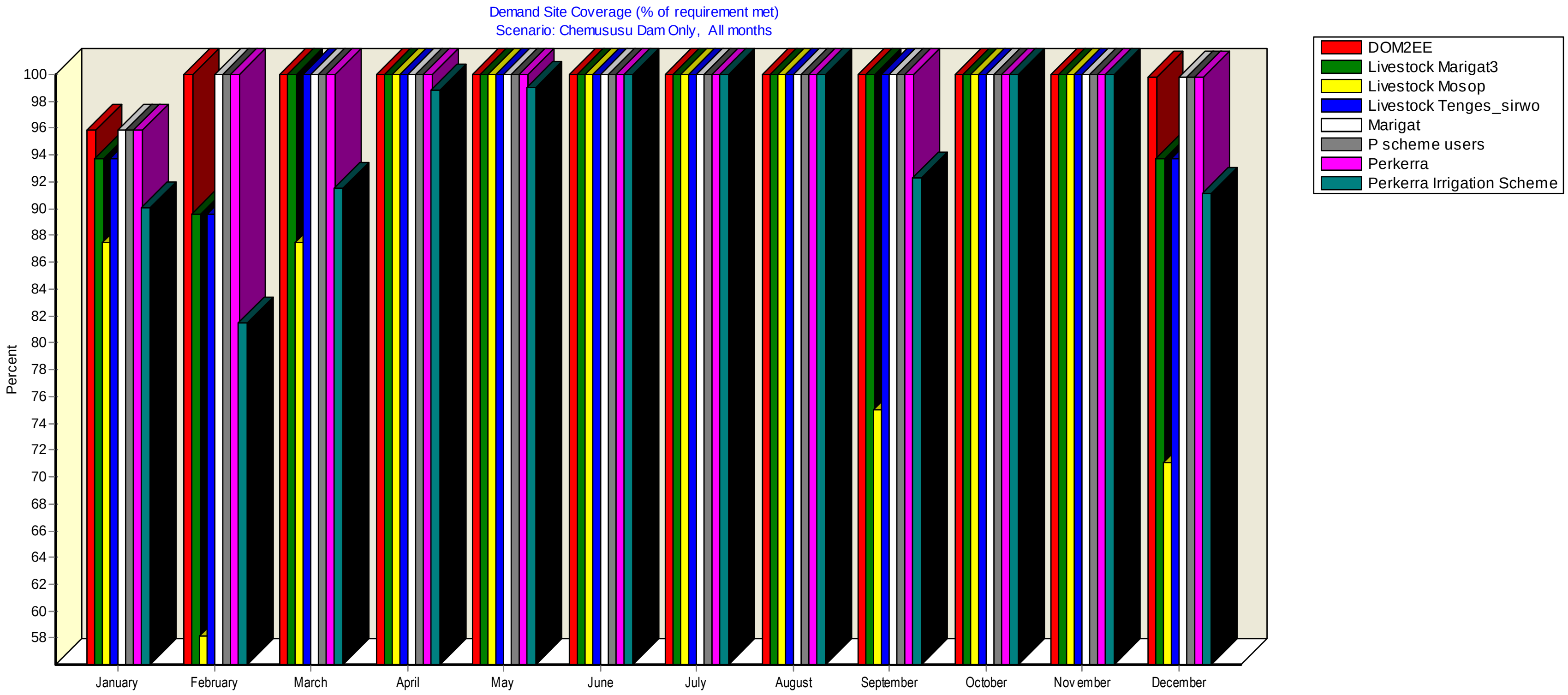

Figure 4.13 Chemususu Dam Scenario: Mean Monthly Water Demand Coverage

On average, there is a great reduction in monthly average unmet demand in the catchment for the simulated period as compared to the results obtained from the reference scenario Figure 4.9. The highest amount of unmet demand dropped more than 50% (Figure 4.9 and Figure 4.12); 1.3 million m^3 to 340,000 m^3 in this scenario, which is experienced in February. This indicates that the construction of this dam will reduce water scarcity situations downstream of the catchment assuming that the proposed water supply project is not implemented.

4.4.1 Chemususu Dam Water Supply Project Scenario

This scenario is built on Chemususu dam scenario to assess the significance of abstraction of 13,000m^3/day, as proposed in project designs. Instream flow requirement node was placed just after the diversion canal to Perkerra Irrigation Scheme. This is to serve users downstream and flows to Lake Baringo through Ngambo swamp. Reserve flows are intended to protect the ecological processes and services indicated by the presence of the species present, such as degradation of contaminants, breakdown of organic matter and erosion control. These processes are critical not only to the health of the river, but primarily to the health of the human communities that depend on it, many of whom rely on it as their primary source for drinking water (LVBC & WWF-ESARPO, 2010).

Resource quality objectives (RQO) and environmental flows have not been established for Perkerra catchment. Studies indicate that environmental flows vary from year to year, depending on rainfall, where it ranges from between 15.7% to 33.5% of the annual flow, in dry seasons going up to 78% of the natural river flow (MacCartney and Arranz, 2007).

The National Water Master Plan, (1990), estimated the naturalised flow for River Perkerra as shown in Table 4.6. An intermediate value of 35% of mean monthly naturalised flows based on Tennant method (Tennant, 1976 and Mann, 2006) was used to estimate the instream flow requirement node, Table 4.6.

Table 4.6 Mean Monthly Naturalized flows and Estimated Environmental Flow Requirements

Months	**Estimated Naturalized flows m^3/s**	**Estimated Environmental flows m^3/s**
January	1.702	0.596
February	1.886	0.660
March	2.079	0.728
April	3.276	1.147
May	3.782	1.324
June	2.487	0.870
July	2.988	1.046
August	4.749	1.662
September	3.484	1.219
October	1.886	0.660
November	3.782	1.324
December	4.148	1.452

The EIA report on Chemususu dam (2006), suggests that the construction of the dam will regulate flows downstream, environmental flow requirement node was included in this simulation to assess the impact of having a policy regulation which requires some minimum flows to reach Lake Baringo.

The reservoir volume storage curve for Chemususu dam in this scenario Figure 4.14, gives results showing that the dam will be drained to the inactive storage in every dry season. The storage volume fell 12 times to the inactive storage in the 13 years of simulation.

Perkerra Irrigation Scheme has the highest mean monthly unmet demand of 1.2 million m^3 in the month of February (Figure 4.16) which compares to 1.3 million m^3 unmet demand in the reference scenario (Figure 4.9). This is followed by the proposed water supply-Chemususu project Figure 4.15 and Figure 4.16. On average, five months have more than 95% demand site coverage in any given year. The proposed water supply project Chemususu dam is supplied by 37% of its demand during the lowest supply month (February) Figure 4.17. This is not the case for the irrigation scheme where 35% of the demand is met in February. The irrigation scheme has priority three while the water supply project has priority one in terms of allocation. However, on average the irrigation demand is covered at 90% between April and December, which coincides with the cropping season. The environmental flows demand (Figure 4.15) is supplied at 70% during the lowest supply month (February).

The analysis of this scenario indicates that implementing the water supply project and the reserve may solve one problem of water supply to towns including Nakuru and guarantee flows to Lake Baringo. However, the water scarcity situation in the catchment will not change.

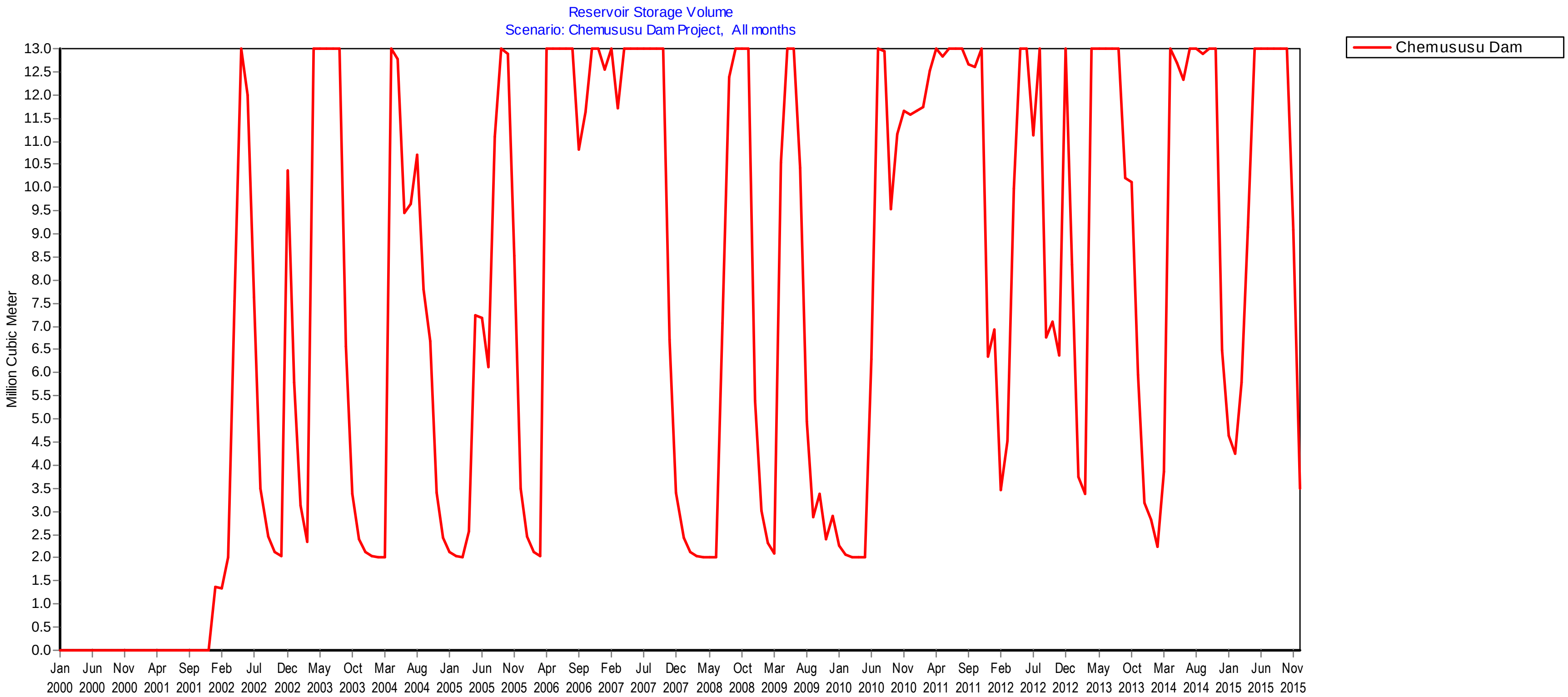

Figure 4.14 Chemususu Dam Water Supply Project: Storage Volume Curve

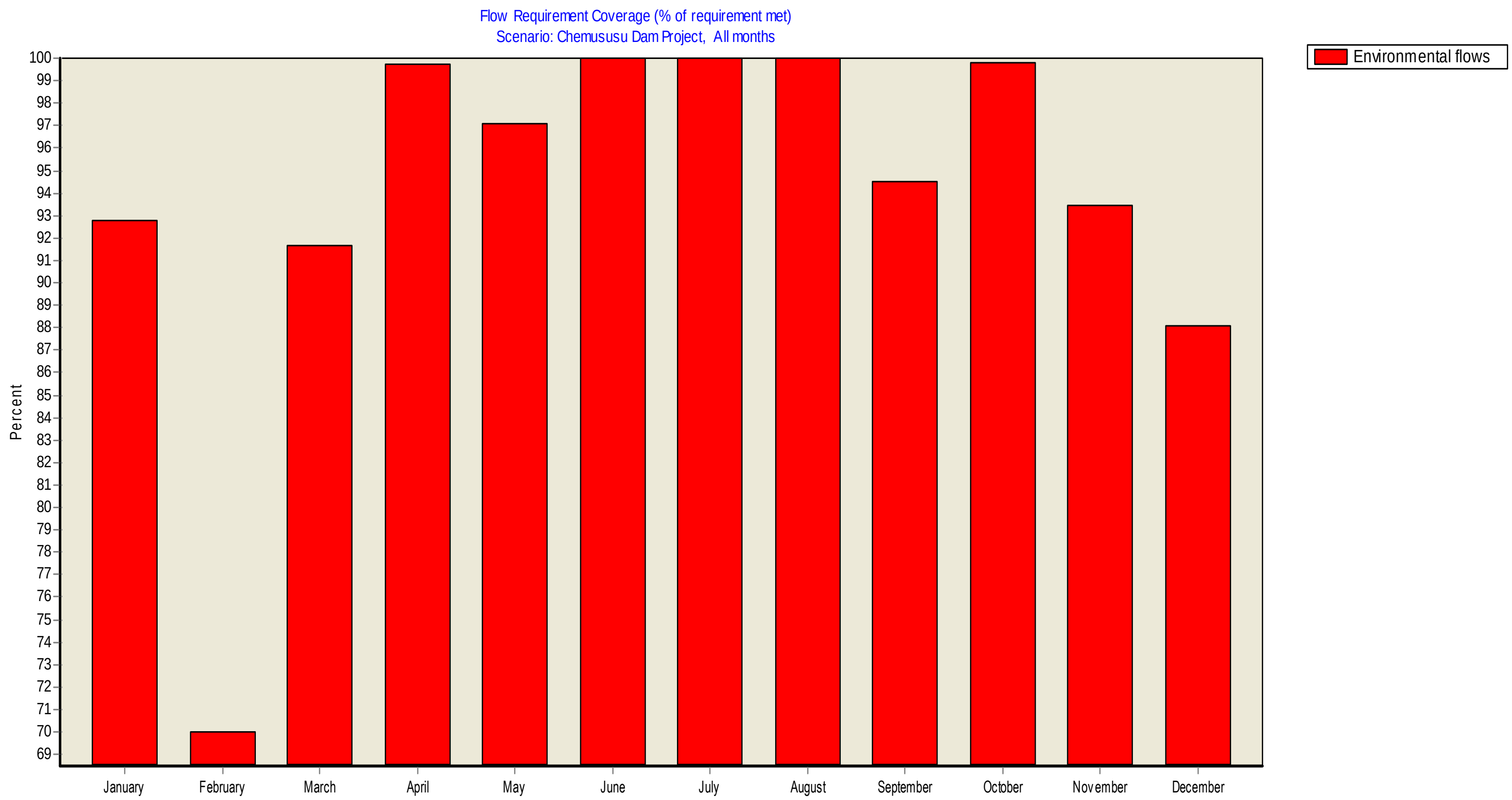

Figure 4.15 Chemususu Dam Project Scenario; Environmental Flow Coverage

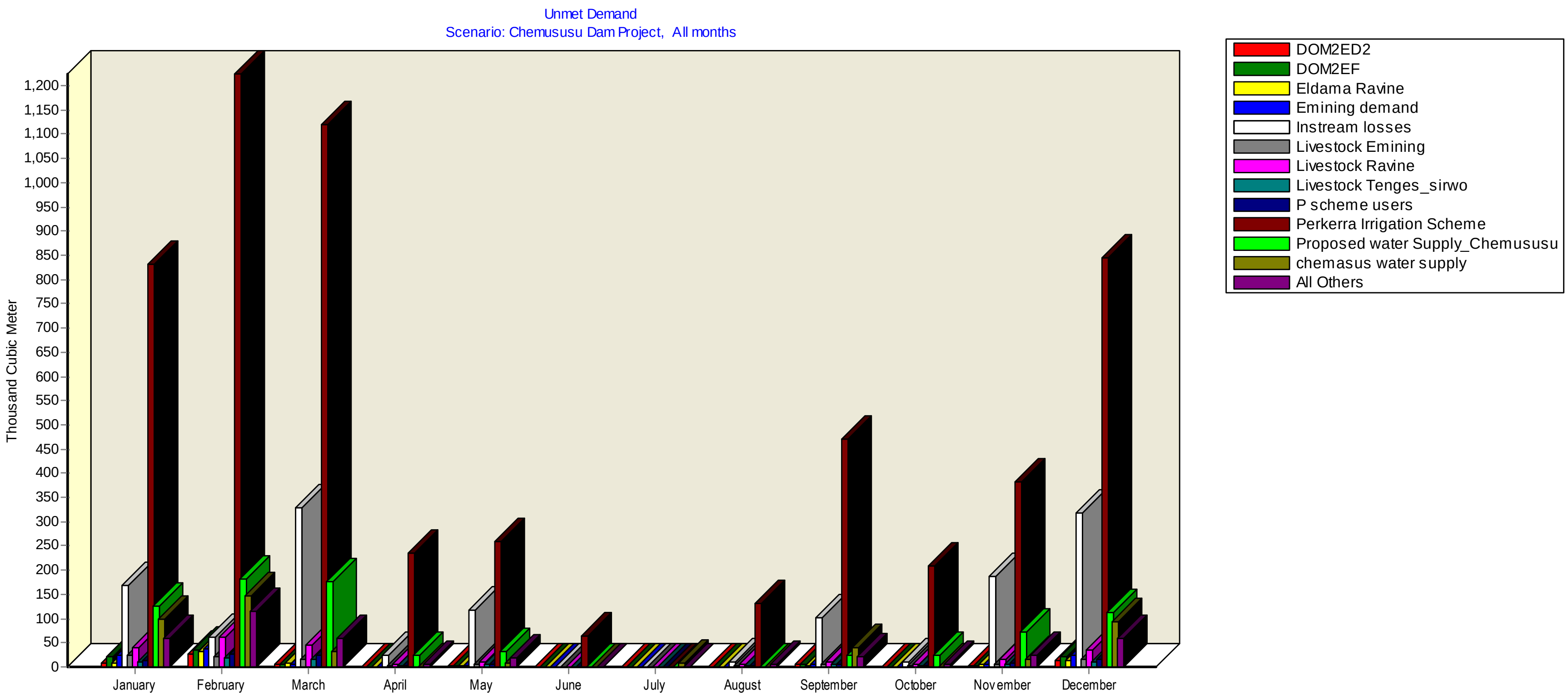

Figure 4.16 Chemususu Dam Water Supply Project: Mean Monthly Unmet Water Demands

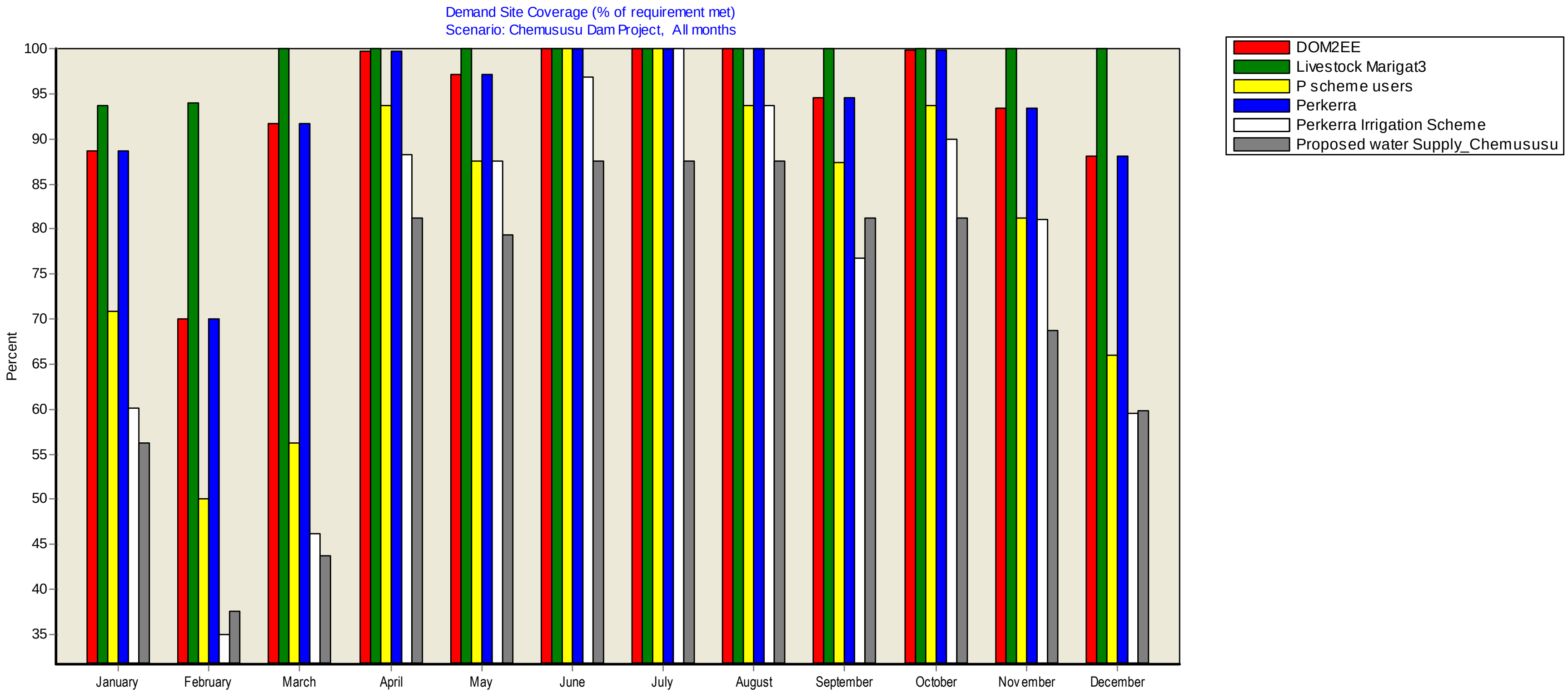

Figure 4.17 Chemususu Dam Water Supply Project: Water Demand Coverage

4.4.2 Improved Irrigation Efficiency 1

It is proposed that for well managed surface irrigation methods, an overall irrigation scheme efficiency of 60% can be attained (http://www.fao.org/docrep/t7202e/). This scenario based on section 4.4.1 scenario was built to simulate irrigation efficiency of 50% at Perkerra Irrigation scheme. The current scheme efficiency is about 27% (Neijens, 2001).

By improving the irrigation efficiency, averagely the months with the highest unmet demand changes from February to March. The highest amount of unmet demand for the irrigation scheme drops drastically from 1.2 million m^3 to 380 000 m^3 (Figure 4.16 and Figure 4.16). The demand coverage improves by an average of 14% (from 34% to 48%) in the month of February (Figure 4.20 and Figure 4.17).

The storage volume curve of the reservoir (Figure 4.19) improves from the previous scenario (Figure 4.14). Critical reduction in storage volume occurs 9 times compared to 12 times during the same simulation period of 2002 to 2015. Environmental flow coverage improves from 70% to 78% (Figure 21) in the month of February when it is least covered. This scenario indicates that savings in irrigation water will significantly reduce water stress in all the other sectors in the catchment. It can also be argued that if certain apportionments or entitlements are given to users, then the water saved becomes extra amount of water available for irrigation. This is about 0.82 million m^3, which can irrigate about 500 acres.

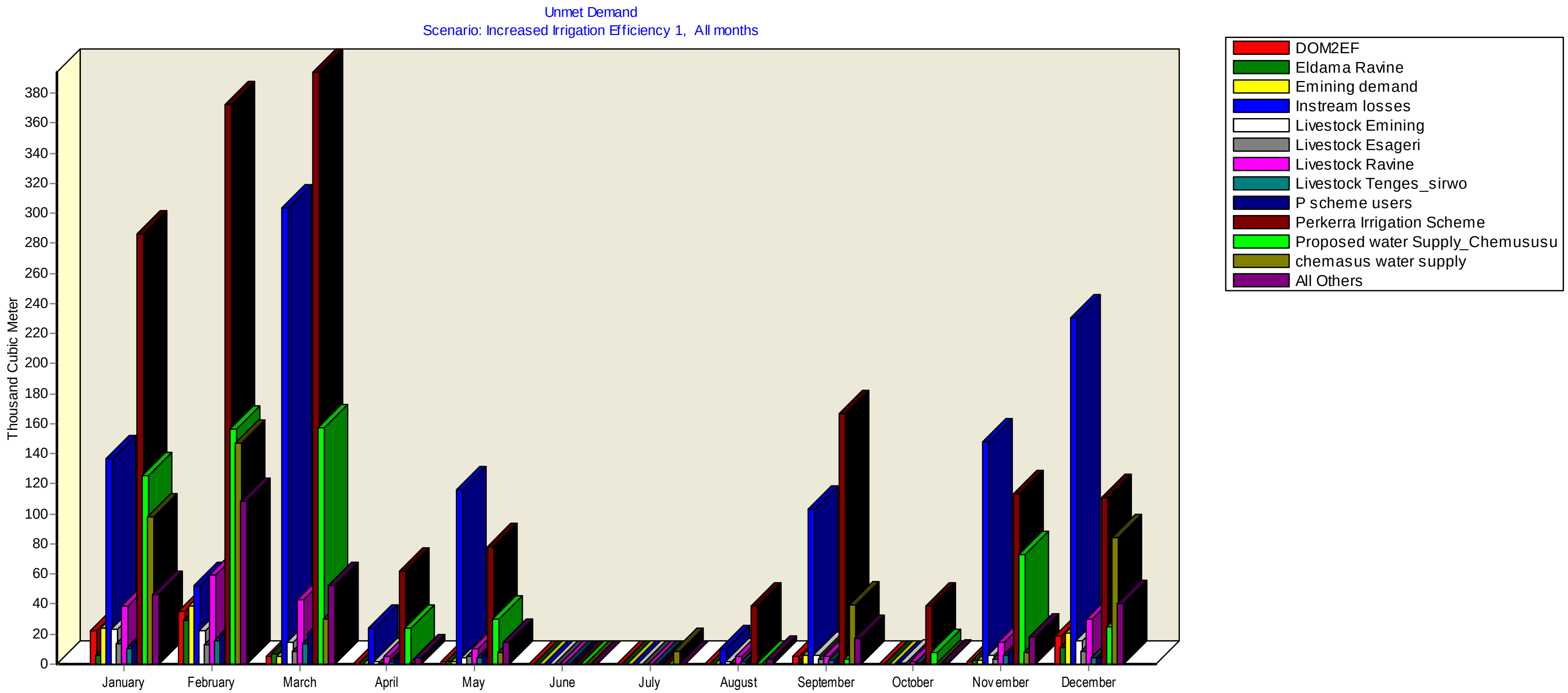

Figure 4.18 Improved Irrigation Efficiency 1: Mean Monthly Unmet Water Demands

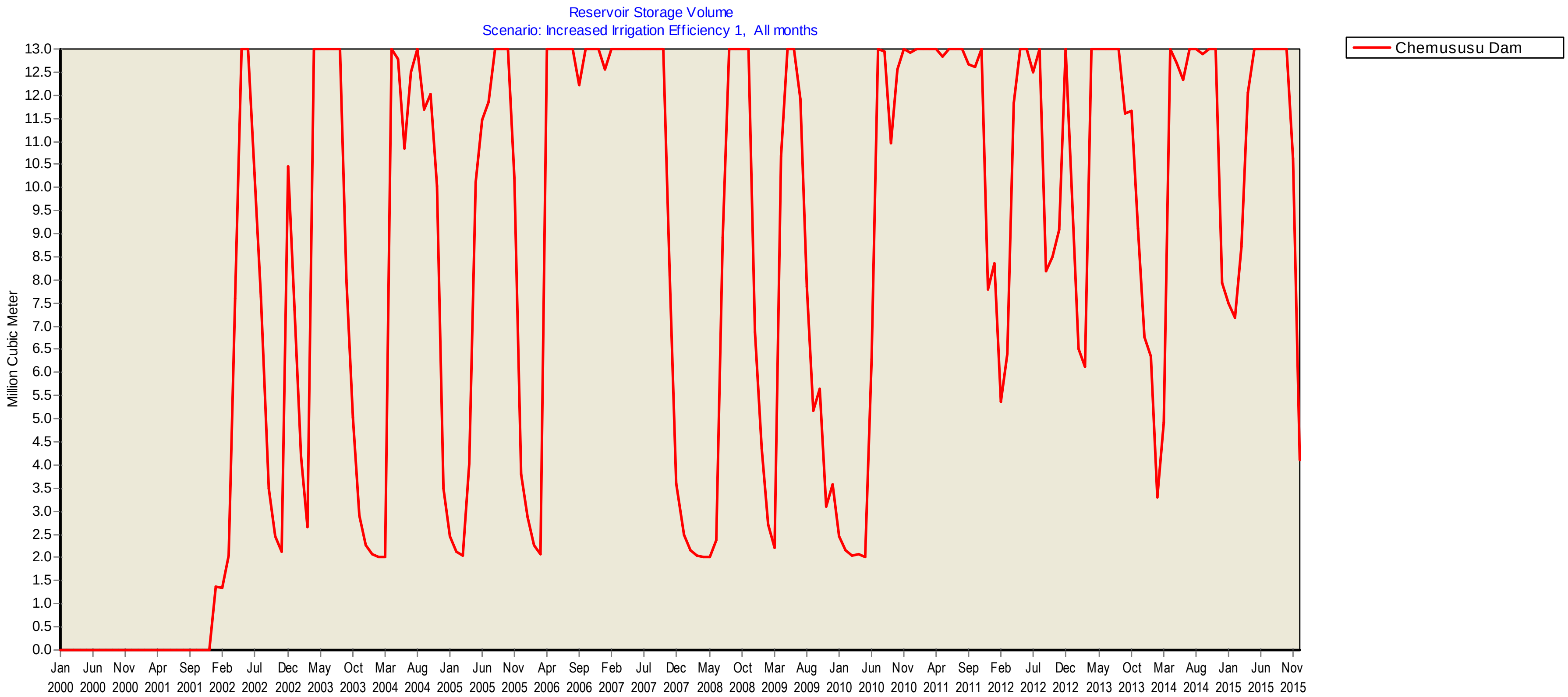

Figure 4.19 Improved Irrigation Efficiency 1: Reservoir Storage Volume Curve

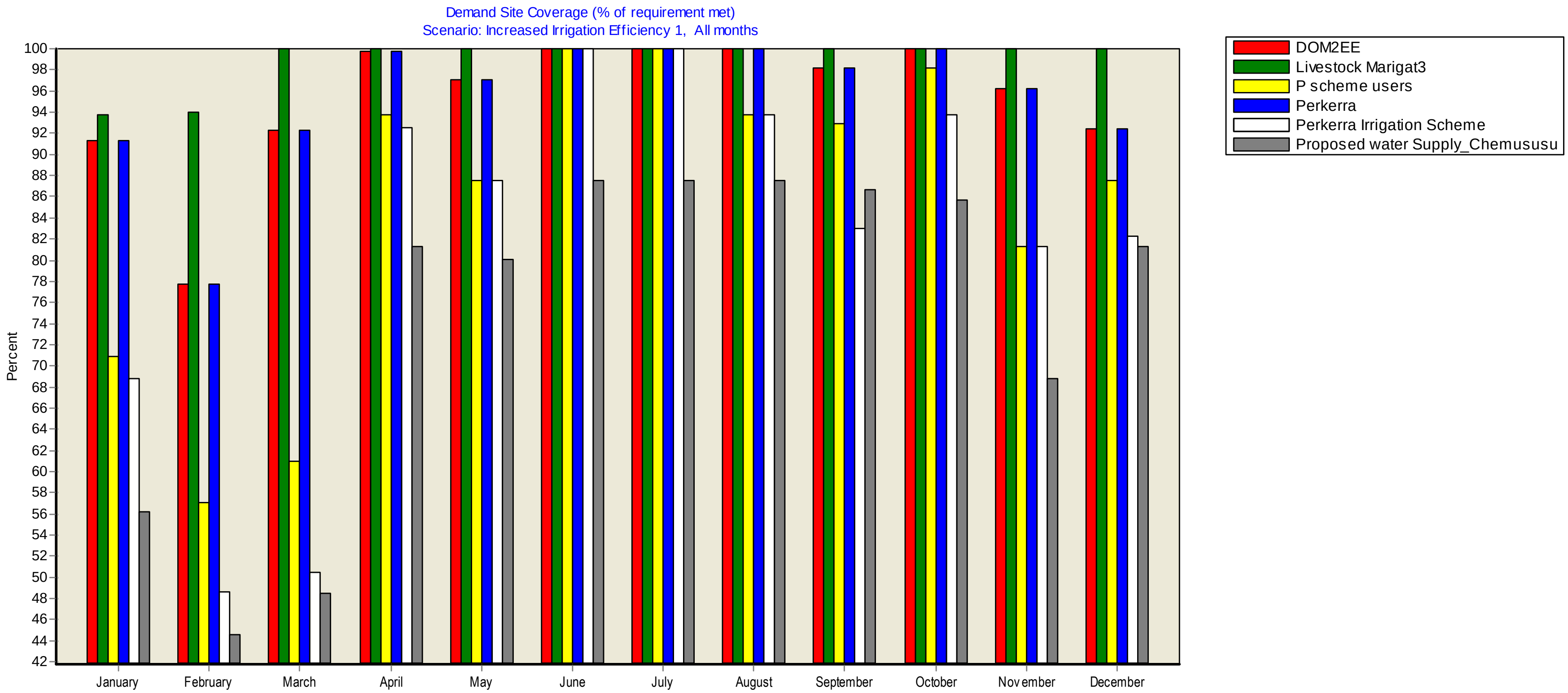

Figure 4.20 Improved Irrigation Efficiency 1: Water Demand Coverage

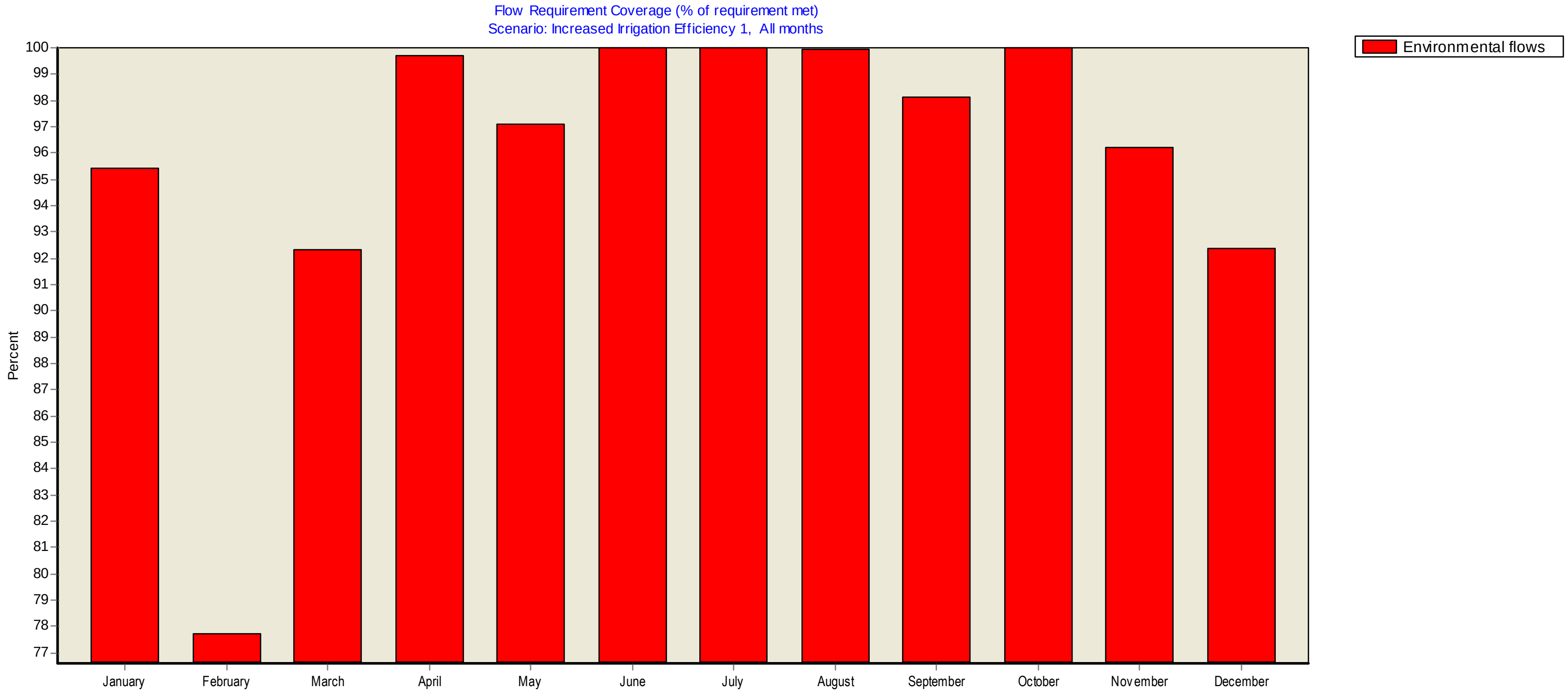

Figure 4.21 Improved Irrigation Efficiency 1: Environmental Flow Coverage

4.5 SCENARIO TWO: TWO DAMS IN THE CATCHMENT

4.5.0 Water Resources Development Scenario.

This scenario simulated the impact of two reservoirs on the reference scenario. In this scenario, it is assumed that the dams were commissioned in January 2002. The water demand remains as in the reference scenario. Simple operating rules were imposed (Table 4.5) to ensure that the reservoirs do not run dry and allow for allocation of reservoir volume.

In the simulation period 2002 to 2015, Radat dam reservoir storage volume never dropped to the inactive zone. Chemususu dam reservoir storage dropped to the inactive zone only twice (Figure 4.22). The monthly average unmet demand for the 13 years of simulation assuming operation of the two dams (Chemususu and Radat) is shown in Figure 4.23. Chemususu water supply has the highest unmet demand of 150, 000 m^3 in February, and it also has the highest frequency of its demand not being met. Chemususu water supply project is upstream of the proposed location of Chemususu dam with an intake weir constructed across the river to dam water for supply. Notably, there is no demand downstream of the dams that is not met. All the unmet demands are upstream of the dam or in a different sub-catchment.

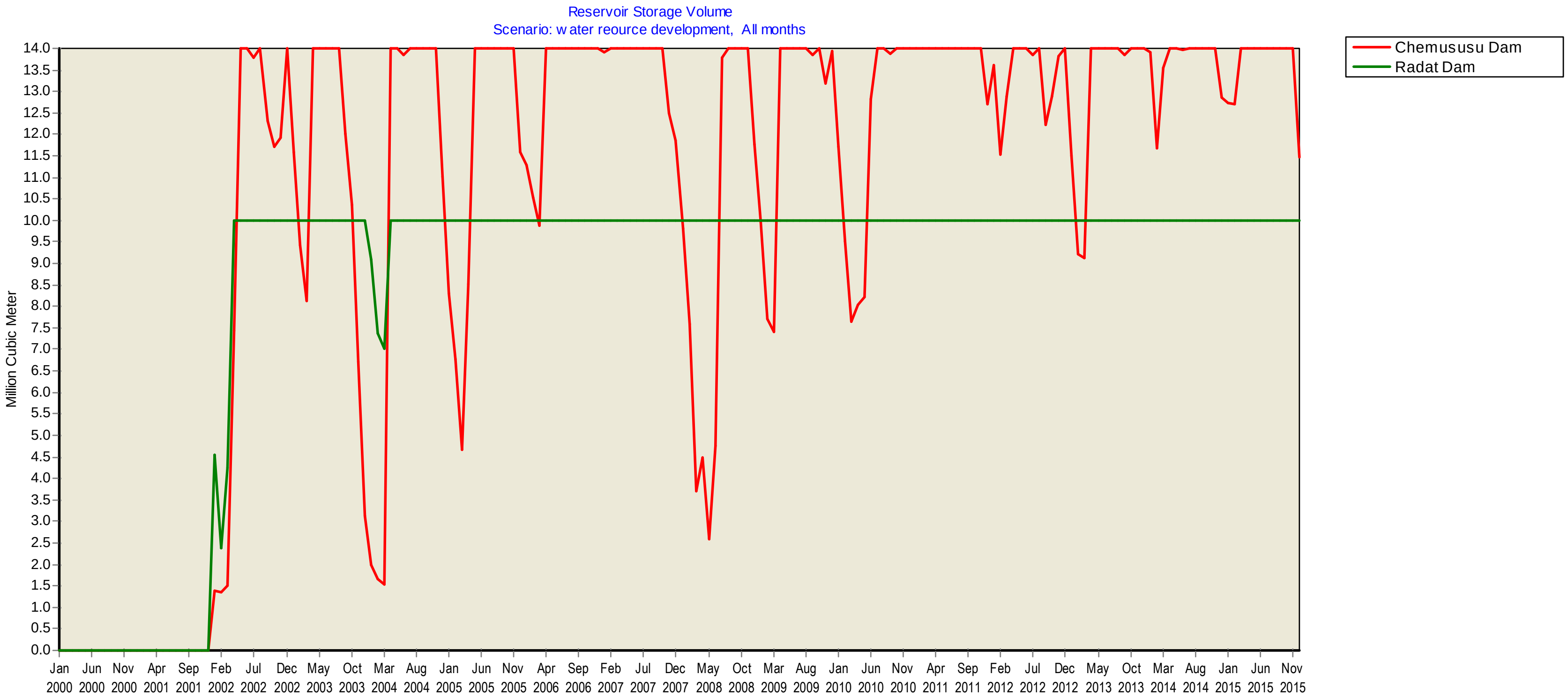

Figure 4.22 Water Resource Development: Reservoir Storage Volume Curve

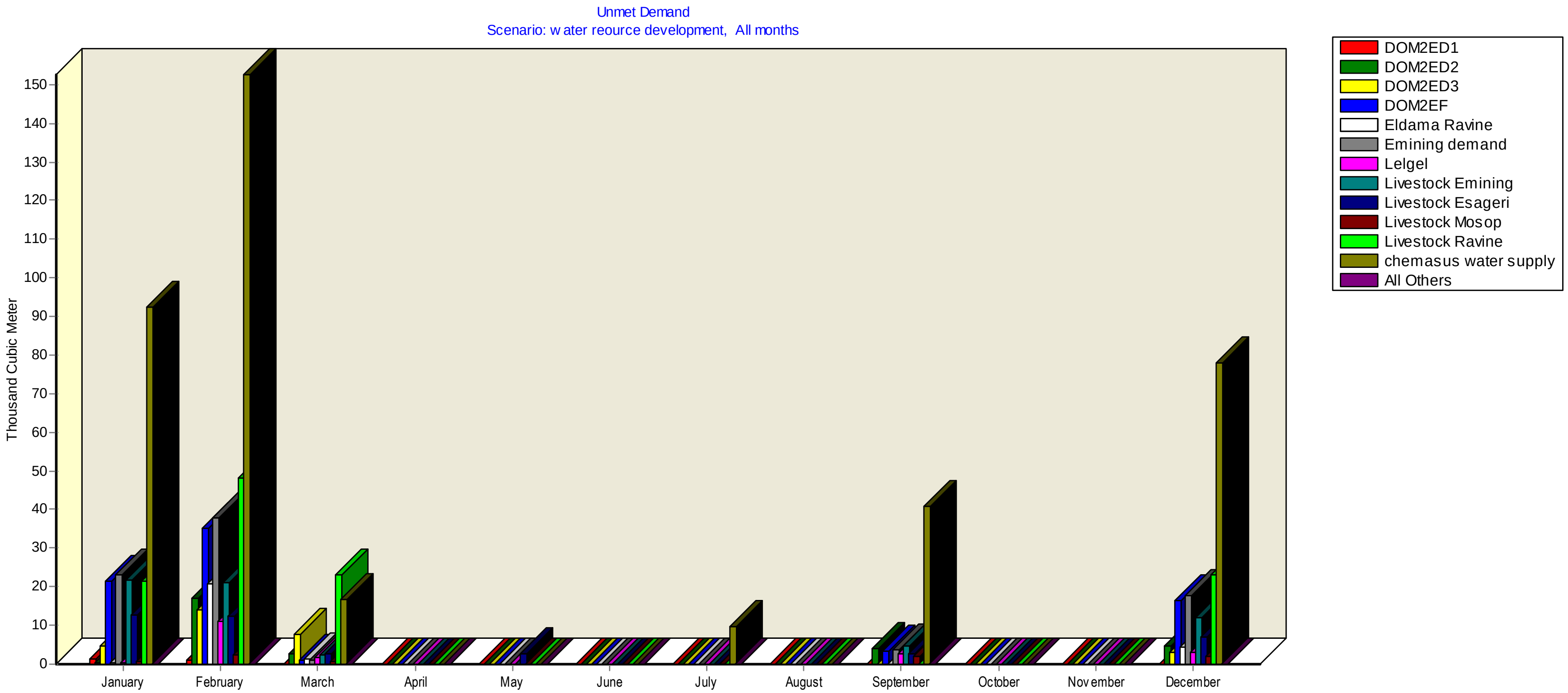

Figure 4.23 Water Resources Development: Mean Monthly Unmet Water Demands

The lowest demand site coverage for this scenario is at 75% for some of the demand sites. Downstream of the dams (Figures F2 and F3), the demand site coverage is 100%. This indicates that increase of storage will benefit downstream users assuming that the two dams are not used for water supply to upstream environs and Nakuru town as proposed and environmental flows to Lake Baringo. If operating rules for the two dams are linked and assuming minimum instream losses, it is possible to fully supply downstream requirements including irrigation at Perkerra Irrigation Scheme. The demands upstream of the dam are not impacted significantly with the commissioning of the dams in this scenario.

4.5.1 Increased Water Demand Scenario

This scenario is adopted from the water resources development scenario in section 4.5.0. The environmental flow requirement of section 4.4.1 and the proposed water supply project at Chemususu dam are added to this scenario.

Reservoirs raise the storage of water in a catchment, thus with increased storage, water shortages during low flow seasons can be reduced. The reservoir storage (Figure 4.24) is used mainly during low flow seasons which occur from December to March in a normal year. In a drought year (2005), Chemususu reservoir hardly gets filled, but Radat reservoir is full for at least three months (August, September and October). In such a year the management of flows from the reservoir is critical. This scenario shows that water in the reservoirs is utilised and the storage stabilizes after 2011, then reservoirs are not completely drained at any one point.

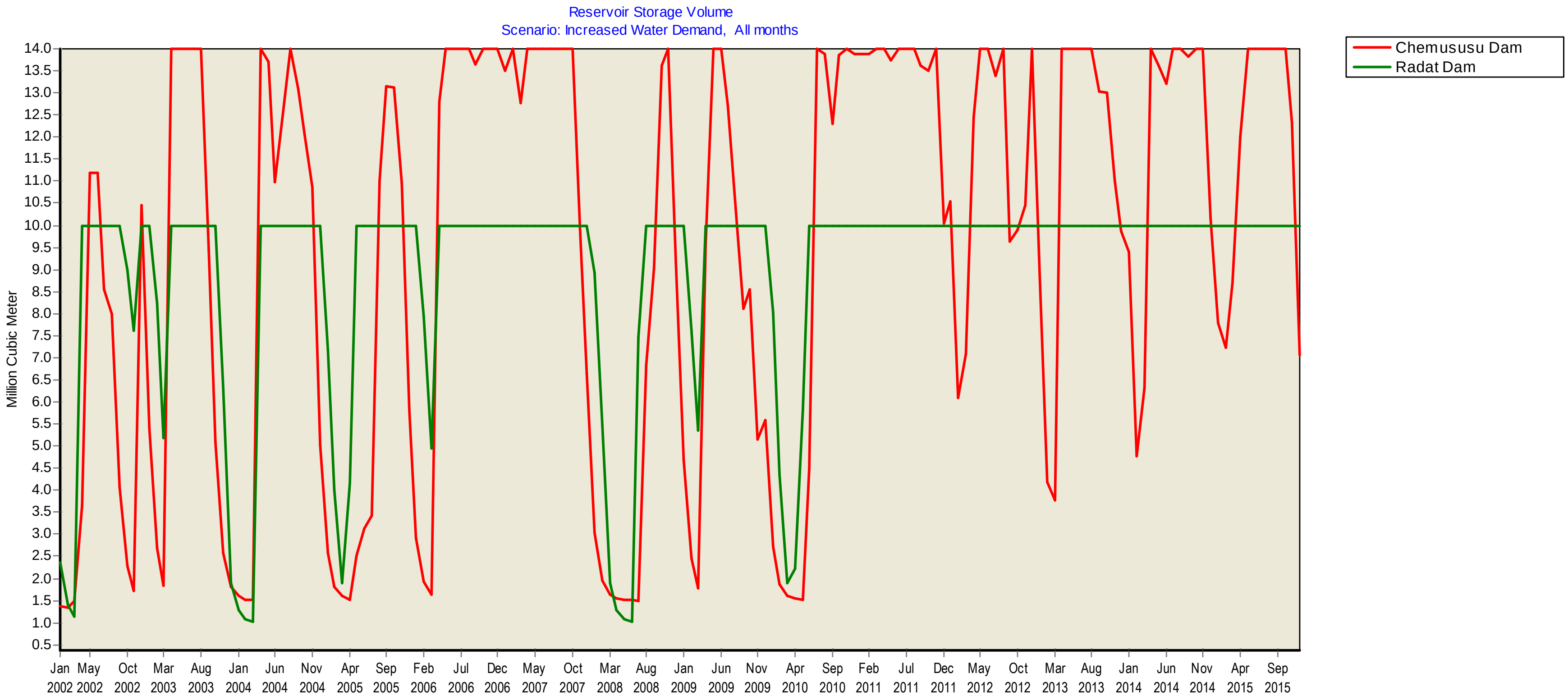

Figure 4.24 Increased Water Demands: Reservoir Storage Volume Curve.

In this scenario, Perkerra Irrigation Scheme has the highest quantity of unmet demand at 540,000 m^3 in March (Figure 4.25). It is the only downstream demand point that has deficit in supply. However, the lowest demand coverage is 73% which is a great improvement from all the scenarios simulated.

Instream losses are flow losses estimated in the reference scenario as seepage in the channel and other ecological uses along the mid catchment where the river flows through bush land and semi arid thickets. The losses were modelled as a demand point with priority 1 and not as an instream flow requirement. This was to allow the losses to vary with demand and seasons. These are fully met in this scenario. The proposed water supply is covered more than 80% for most of the year, thus the reservoir will on an average supply 10,400 m^3 per day (Figure 4.26) instead of the proposed 13,000m^3 per day. The irrigation scheme, will have on average more than 75% of its water demand met. In the driest months, the average monthly demand coverage is 74%. The irrigation scheme is operating with very low efficiency 27% (Neijens, 2001). Therefore the last scenario is modelled with the irrigation efficiency improved to about 50%.

The introduction of environmental flow requirement downstream of Perkerra Irrigation Scheme intake works and instream losses demand node indicates that environmental flows are a major driving force in the system. These flows are not guaranteed in the reference scenario (the present situation). However, it is possible to guarantee these flows with the construction of reservoirs coupled with proper policy and regulation. Agriculture (especially Perkerra Irrigation Scheme) and domestic demands are the key driving forces in this catchment.

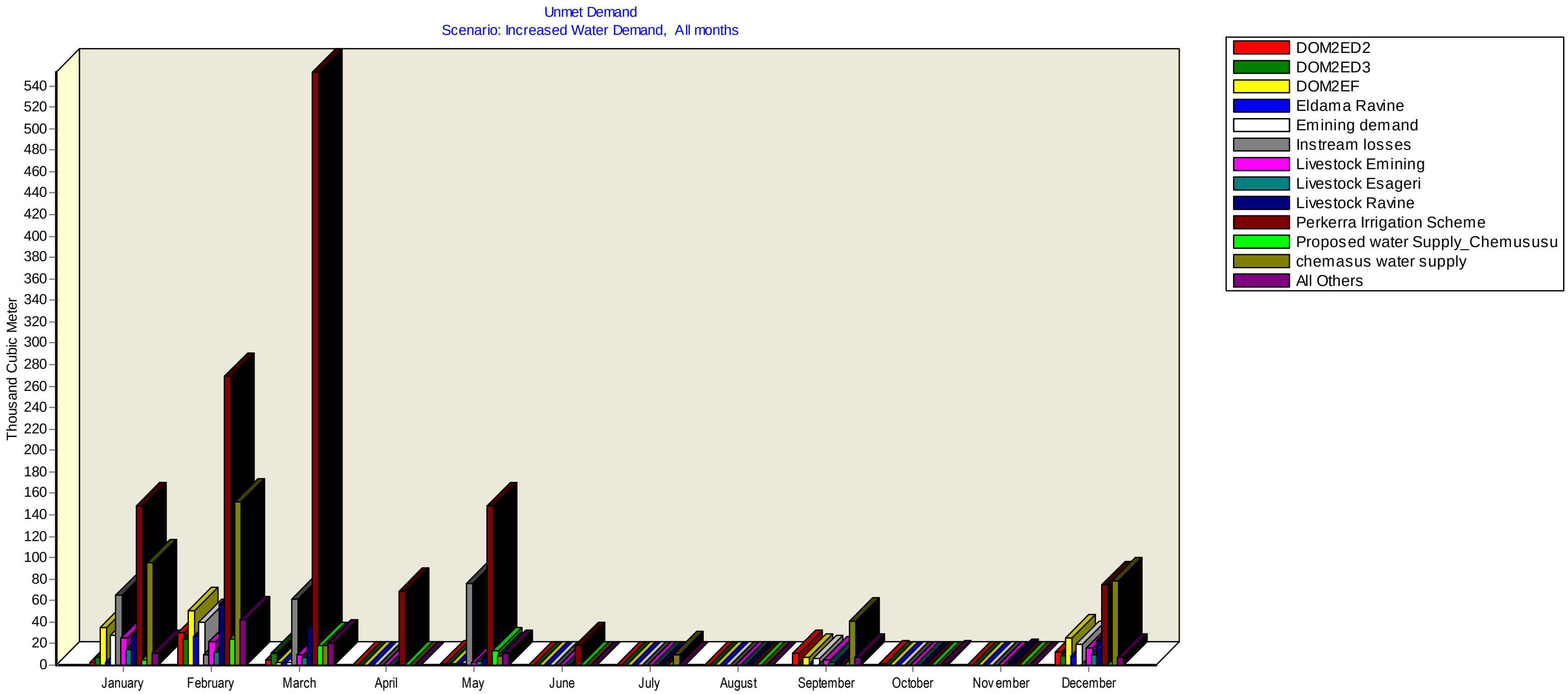

Figure 4.25 Increased Water Demands: Mean Monthly Unmet Water Demand

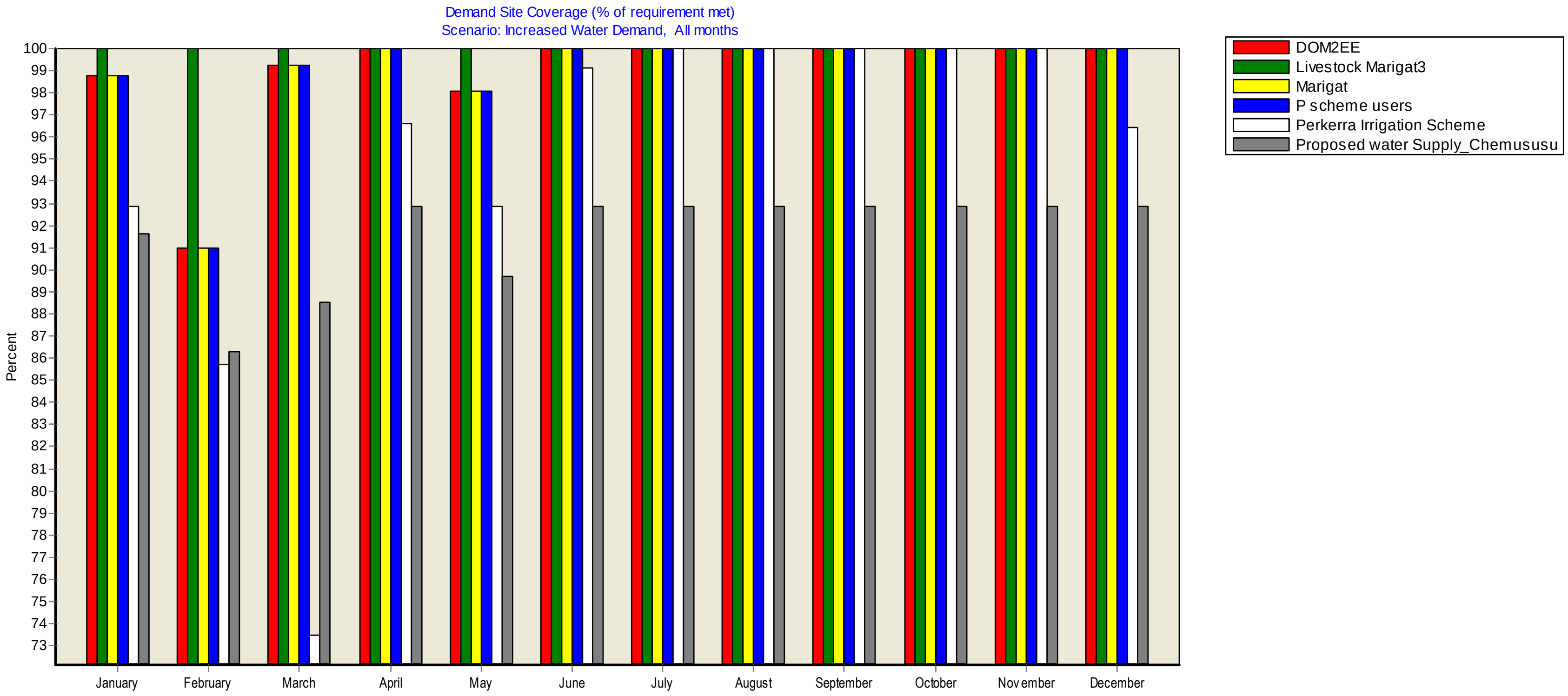

Figure 4.26 Increased Water Demands: Water Demand Coverage

4.5.2 Improved Irrigation Efficiency 2

This scenario was modelled to assess the impact of improved irrigation efficiency when the two dams are in operation in the catchment. It was adopted from the increased water demand scenario, where the conditions of section 4.4.2 were imposed.

Demand coverage at Perkerra Irrigation Scheme increased on average by 10%, as shown in Figure 4.28. In the reference scenario, the month of February had the least demand coverage at only 15%. In this scenario, the lowest demand coverage is 85% in February and 93% in March. Irrigation demand is fully supplied in the other months. In the previous scenario (Figure 4.27 and Figure 4.28), the irrigation efficiency was at 27%. In Perkerra Irrigation Scheme, average unmet water demand dropped from 540,000m^3 to 45,000m^3 in March which had the highest supply deficit. The 'saved' water is equitably redistributed to other demand points downstream of the dams hence an average increase of 10% in demand coverage on all the demand points (Figure 4.29).

This implies that even with the commissioning of Chemususu and Radat dam projects, it is still imperative to improve irrigation scheme efficiency so as to assure farmers of a minimum of 80% irrigation demand coverage. The improved efficiency under IWRM means that more water is available not only for irrigation uses but for more priority demands. Figure 21 shows that on average demand coverage for environmental flow requirements downstream of Perkerra irrigation scheme improved by 10% compared to the scenario in section 4.5.1. In such a scenario, incentives for the irrigation scheme farmers and other measures may need to be put in place so that farmers do not feel cheated of their water entitlements when it is redistributed.

The supply of water for instream flow requirements downstream of the irrigation scheme in this scenario improved to above 94% (Figure F7) compared to above 86% (Figure F6) in section 4.5.1. It is clear from these two scenarios that improved efficiency is imperative. In the context of IWRM and equitable allocation of water resources in Perkerra catchment, improved efficiency affects directly the availability of water for domestic and environmental flows.

The combined effect of irrigation efficiency and construction of two dams on the reference scenario is immense. The storage volume curve (Figure 4.29) shows that Radat dam is not really utilised and more release from the reservoir can be used to expand irrigation downstream.

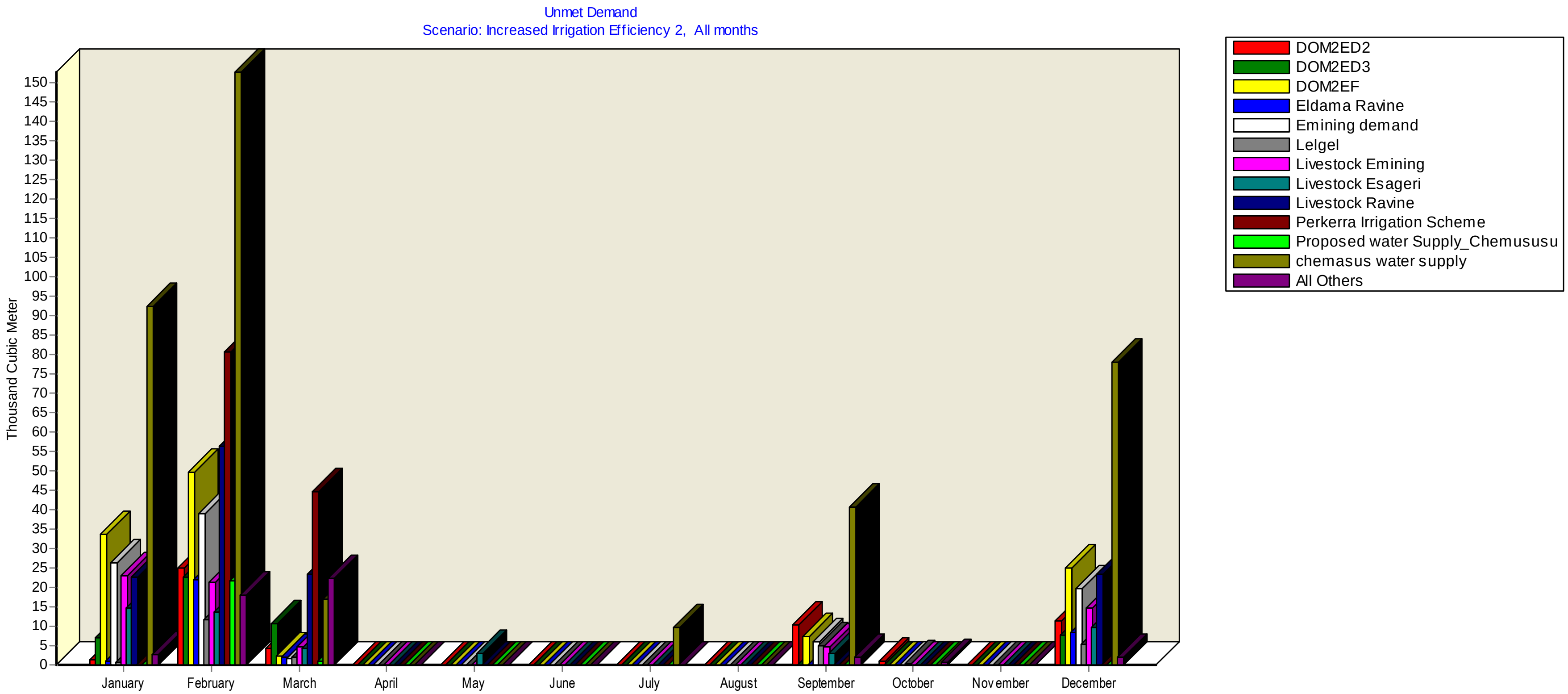

Figure 4.27 Improved Irrigation Efficiency 2: Mean Monthly Unmet Water Demands

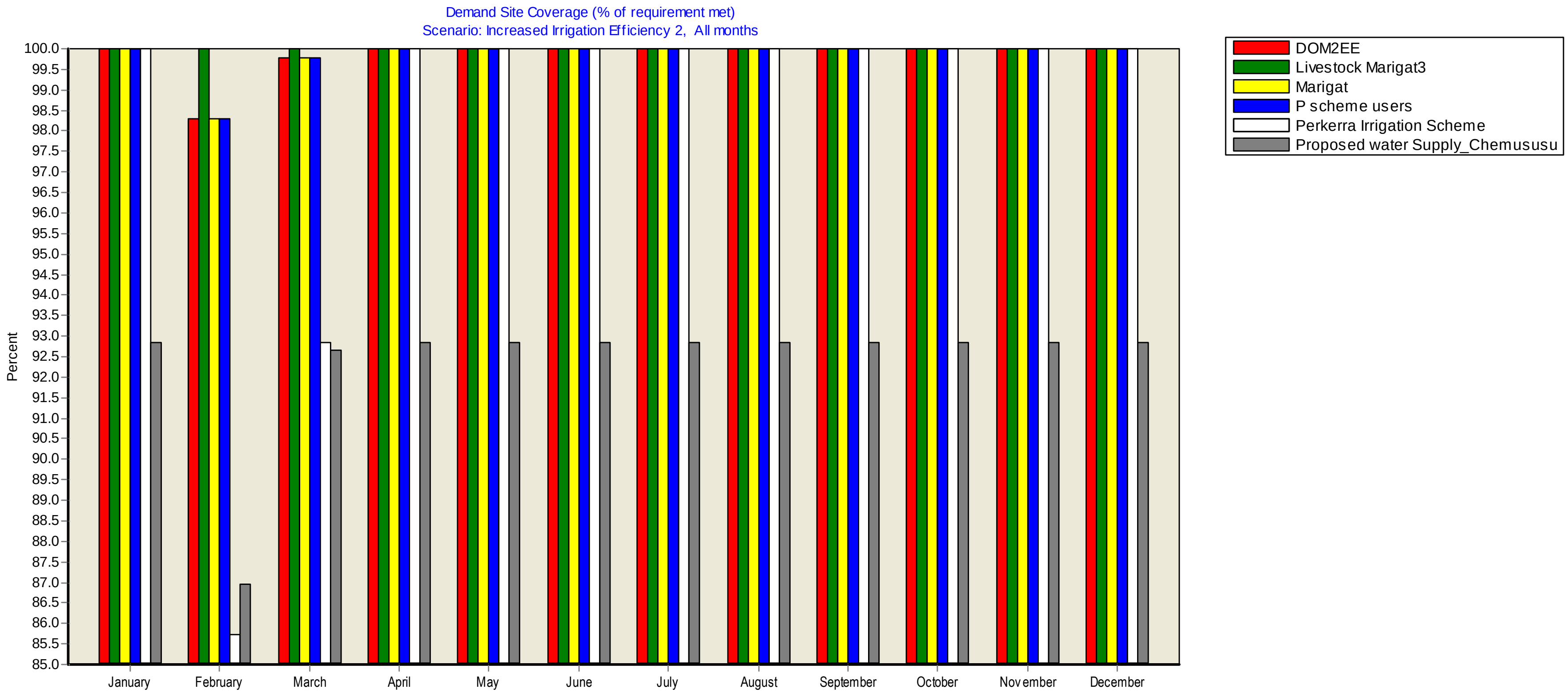

Figure 4.28 Improved Irrigation Efficiency 2: Water Demand Coverage

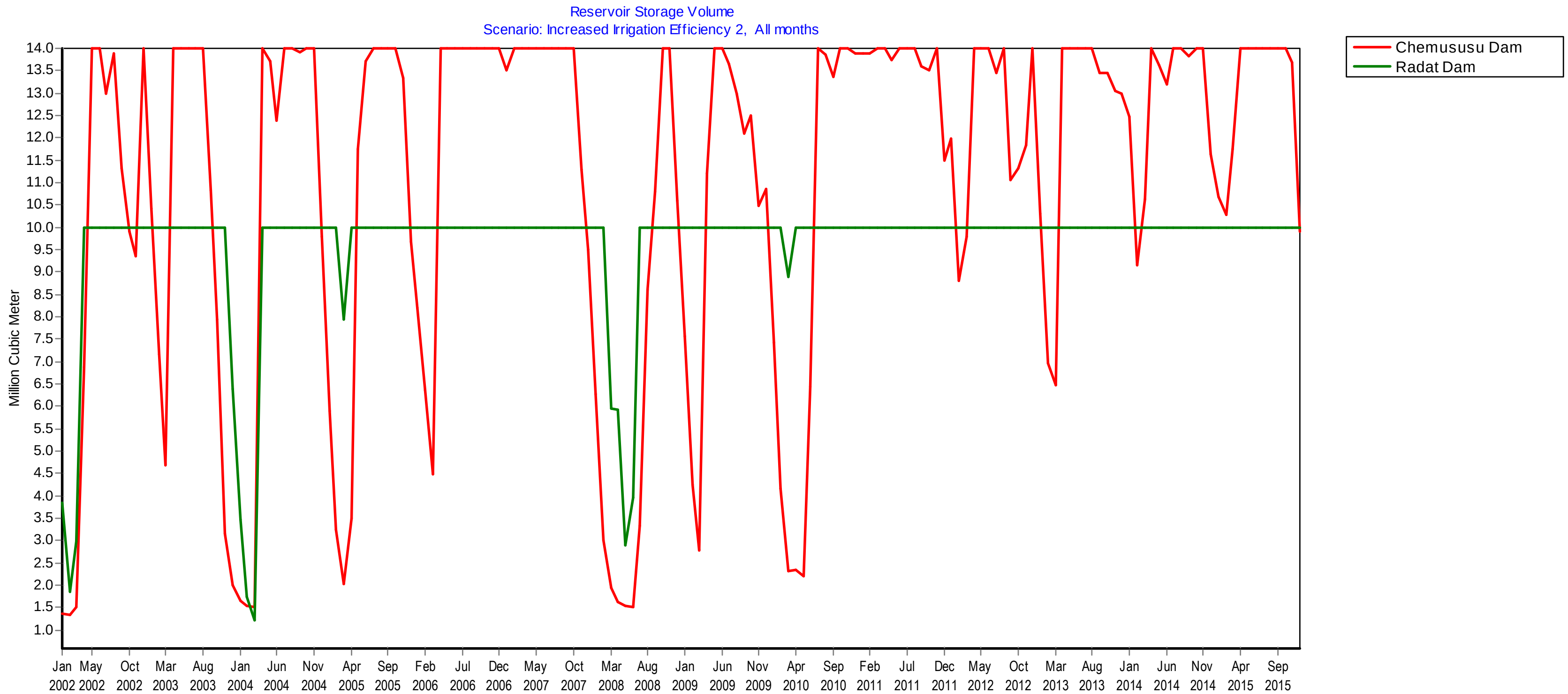

Figure 4.29 Improved Irrigation Efficiency 2: Storage Volume Curve

Following the conceptual model of driving forces pressure state impact response, the building of dams will significantly affect the state of the available resource. The added storage serves to meet the environmental pressure downstream of the catchment. However, the management in this conceptual framework faces a setback of infrastructural development. The Water Act (2002) sets up a good policy that guarantees equitable distribution of water resources and gives the water reserve (for basic human use and environmental sustenance) the first and highest priority over other demands. The various scenarios developed indicate that it is possible through regulation to implement a fairly successful water management strategy.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The aim of this study was to apply or adopt WEAP to Perkerra catchment and hence perform scenario analysis of the surface water quantity management and development in the catchment. To perform such an analysis, accurate data is required to model the hydrology and water management more precisely.

1. The model was able to simulate the catchment water management scenario. The calibration and validation results EF indicated that the modelled result were good, thus the model was well adapted to the catchment. However, model can perform much better with availability of more data (both from demand and supply sides). More accurate simulation of water allocation and demand management is possible if more regulation structures are installed with accurate data recording. Unregulated use of scarce water resources is also wasteful and inherently unsustainable.
2. The r-squared values show that the model performs fairly well. However further investigations are needed to check the suitability of the model especially in modelling semi arid hydrology.
3. It was possible to conceptualize the water management scenario in Perkerra catchment given the available information thus making clear the water management issues and allows the modelling of the same in WEAP21.

4. There are two major water development projects expected to be constructed in Perkerra catchment. These are in response to water inaccessibility and shortages. The commissioning of Chemususu dam project will improve water accessibility to upstream users. However demand coverage downstream improves marginally by an average of 5%.
5. The commissioning of a second dam downstream improves the demand coverage downstream by more than 50%. It also regulates flows downstream and allows for the implementation of 35% of naturalized flow for environmental flow requirements downstream of Perkerra irrigation scheme intake works.
6. Given the nature of the catchment, environmental flows, agriculture and domestic demands downstream forms the major driving forces in the system, thus the most sensitive to changes upstream of the catchment. The reference scenario indicates that the current situation is not sustainable especially for agricultural development downstream at Perkerra irrigation scheme and for environmental flows after Perkerra irrigation scheme intake works. The flows in the current scenario cannot sustain the current irrigation demand of Perkerra Irrigation scheme, therefore the scheme needs to embrace more efficient management of the available water resource. Improved irrigation efficiency of the scheme improves overall demand coverage by 10% in all sectors.
7. In conclusion, Perkerra River is among the few perennial rivers flowing to Lake Baringo. Its management is crucial to the survival of the Lake and Irrigation downstream. As observed in earlier studies (Kipkorir et al 2002, Onyando 2005),

catchment degradation is among the main causes of diminishing flows in the river, therefore concerted efforts of catchment management are important.

5.2 RECOMMENDATIONS

The application of WEAP21 to Perkerra catchment in this study has led to various conclusions. Based on these conclusions, the following recommendations are suggested.

1. It is imperative that irrigation efficient strategies should be employed at Perkerra irrigation scheme
2. The scenarios displayed in this study can be used to bring discussion among various stakeholders involved in water management in the catchment; this will enable understanding of the issues facing the catchment.
3. Chemususu dam construction should not be accompanied by the full implementation of the water supply project of 13,000m^3/day. Half of this amount can be adopted first awaiting the construction of the second dam. This will enable stabilization of flows downstream.
4. Catchment management should be intensified with an aim of increasing infiltration and percolation to reduce the high peak hydrographs
5. Storage should be increased in the catchment to safeguard the reserve.
6. The hydrology of the catchment should be modeled using the soil moisture model with availability of more data to confirm the simulations in this study.

7. A study should be conducted to determine water quality objectives and reserve flows for Perkerra River be determined in order to enhance proper management and regulation, especially when the dam projects are completed.
8. More investment is needed to enable flow regulation infrastructure at intake points of the various abstractors in the catchment.
9. It is also clear that the catchment is very vulnerable to drought situations; therefore there is an urgent need to increase storage upstream. Dams and weirs should be constructed along Perkerra River to improve water availability in the lower catchment zones
10. Groundwater potential needs to be investigated and explored further to enable a more holistic investigation into the analysis of water management in this catchment, especially its potential to offset municipal, domestic and livestock water demand upstream so as to guarantee downstream users of sufficient quality and quantity of water supply.

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APPENDICES

Appendix A

Table A1: roles and responsibilities of water sectors institutions

Institution		Roles and responsibilities
1.	Ministry of Water and Irrigation (MWI)	• Development of legislation, policy and strategy formulation, sector coordination and guidance, and monitoring and evaluation • Overall sector investments planning and resource mobilisation
2.	Water Services Regulatory Board (WASREB)	• Regulation and monitoring of service provision (Water Services Boards and Providers) • Issuing of licenses to Water Services Boards • Setting standards for provision of water services • Developing guidelines (water tariffs etc.)
3.	Water Services Boards (WSBs)	• Efficient and economical provision of water services • Developing water and sewer facilities, investment planning and implementation • Rehabilitation and replacement of infrastructure • Applying regulations on water services and tariffs • Procuring and leasing water and sewerage facilities • Contracting Water Service Providers (WSPs)
4.	Water Service Providers (WSPs)	• Provision of water and sanitation services, ensuring good customer relation and sensitization, adequate maintenance of assets and reaching a performance level set by regulation
5.	Water Services Trust Fund (WSTF)	• Financing provision of water and sanitation to disadvantaged groups (pro-poor) as water poverty fund
6.	The Water Appeals Board (WAB)	• Arbitration of water related disputes and conflicts between institutions and organizations
7.	National Water Conservation and Pipeline Corporation (NWCPC)	• Construction of dams and drilling of boreholes
8.	Kenya Water Institute (KEWI)	• Training and research

Appendix B.

MOI UNIVERSITY

DEPARTMENT OF CIVIL AND STRUCTURAL ENGINEERING

Questionnaire to management of Perkerra Irrigation Scheme for the purpose of carrying out Msc. Water Engineering Research Project on Scenario Analysis of Water Resources Management In Perkerra Catchment. Respondents have been randomly selected to participate in this survey and their VOLUNTARY participation in this survey is highly appreciated. Respondents' opinions will be completely CONFIDENTIAL.

Date ….. **Time ………**

Respondent …………………….. **Sign …………**

1. What is the size of irrigated land annually?

2. Does the size vary from year to year?

   YES NO

   2 (a). If yes by what margin in hectares

3. How many farmers does the scheme engage annually?

4. What is the average size of land that is allocated to each farmer?

5. How does the acreage cultivated vary with available flows?

6. Do all the farmers in the scheme cultivate their farms all year round?

YES	NO

7. If NO how is the rotation of irrigation done?

8. What types of crops are grown in the fields?
   i. …
   ii. …
   iii. …
   iv. …
   v. …
   vi. …

9. Do you have an irrigation schedule for all the crops cultivated? YES NO

9(a). If NO what is the seasonal water demand?

9(b). What is the seasonal peak water demand?

9(c). What time (month) in the year do you have the highest water demand?

10. For what other purposes than irrigation is the water in the canals used for?
   i. ..
   ii. ..
   iii. ..
   iv. …

11. Do you have restriction measures for these uses? YES NO

9(a). If yes, what are the restrictions imposed?

12. Does the scheme have supplementary sources of water? YES NO

12(a). If yes what are they and their equivalent yield per month?

i. Rain water harvesting?

ii. Boreholes and/or wells

iii. Others (specify)

13. If NO in 12 are you aware of any studies on these sources? YES NO

14. If yes, by whom were they done and when?

15. What tools do you use for water allocation and management planning for the scheme?

a). irrigation schedule.
b). other

16. Who enforces the management for the schedule/tools used for allocation and water management?

17. What is the current design of irrigation plans what method is used to develop the plans?

18. How reliable is the water supply for a given designed plan? Tick where appropriate

    Highly reliable

    Reliable

    Moderate

    Not Reliable

19. What can you comment about 18?

20. Do you think the construction of dams far upstream will help solve problems associated with 18? YES NO

21. If NO, why?

22. What other suggestions do you have to improve sustainability of the irrigation scheme in terms of water management?

23. Do you collect climatological data and crop data?

    Evapotranpiration YES NO

    Rainfall YES NO

    K_c for crops grown YES NO

24) If yes in 23 can you avail the data to me

Appendix C.

MOI UNIVERSITY

DEPARTMENT OF CIVIL AND STRUCTURAL ENGINEERING

Questionnaire to a Sample of farmers of Perkerra Irrigation Scheme for the purpose of carrying out Msc. Water Engineering research project on scenario analysis of water resources management in Perkerra catchment. Respondents have been randomly selected to participate in this survey and their VOLUNTARY participation in this survey is highly appreciated. Respondents' opinions will be completely CONFIDENTIAL.

Date ……………………….. Time ……………

Enumerator ……………………..

Place of Residence (village)……………………………

Respondent Name [Owner] …………………………………………..[Tenant]…………………………………………

Locat*ion* of farm *(By block number)*……………………

1. What size of land do you cultivate within the irrigation scheme in acres?
2. What crops do you grow?

   i. ..

   ii. ..

   iii. ..

   iv. ..

   v. ..

   vi. ..

3. What is the rotation cycle of the crops you have cultivated from 2001 to date?

	2006
2001	2007
2002	2008
2003	2009
2004	
2005	

4. Please indicate the years you used rainwater to supplement irrigation and how long did it last?

	2006
2001	2007
2002	2008
2003	2009
2004	
2005	

5. Do you have a schedule to follow when applying water to your crops?

YES	NO

6. How often do you apply water to each of the crops listed when grown in the field? (tick the frequency and then indicate the first and last month of application)

   i. Maize - 3days weekly decadal fortnight other

   From (month) To(month)

   ii. Tomatoes- 3days weekly decadal fortnight other

   From (month) To(month)

   iii. Chillies-3days weekly decadal fortnight other

   From (month) To(month)

   iv. ………. 3days weekly decadal fortnight other

   From (month) To(month)

   v. …… 3days weekly decadal fortnight other

   From (month) To(month)

7. How long does it take to apply water to one acre till its sufficient when the flows are optimum?

8. How many livestock do you have?

   Cattle

   Goats

   Sheep

   Others

9. Do you water your livestock from the water in the canal?

   YES NO

10. If YES in 9 is it always or at what times?

11. If NO from which source?

12. How many members are in your household (spouse, children, relatives, workers and other)?

    State how many. ………………………….

13. Do you use water in the canal for domestic purposes?

    YES NO

14. If YES in 13 is it always or at what times?

15. If NO from which source?

Appendix D.

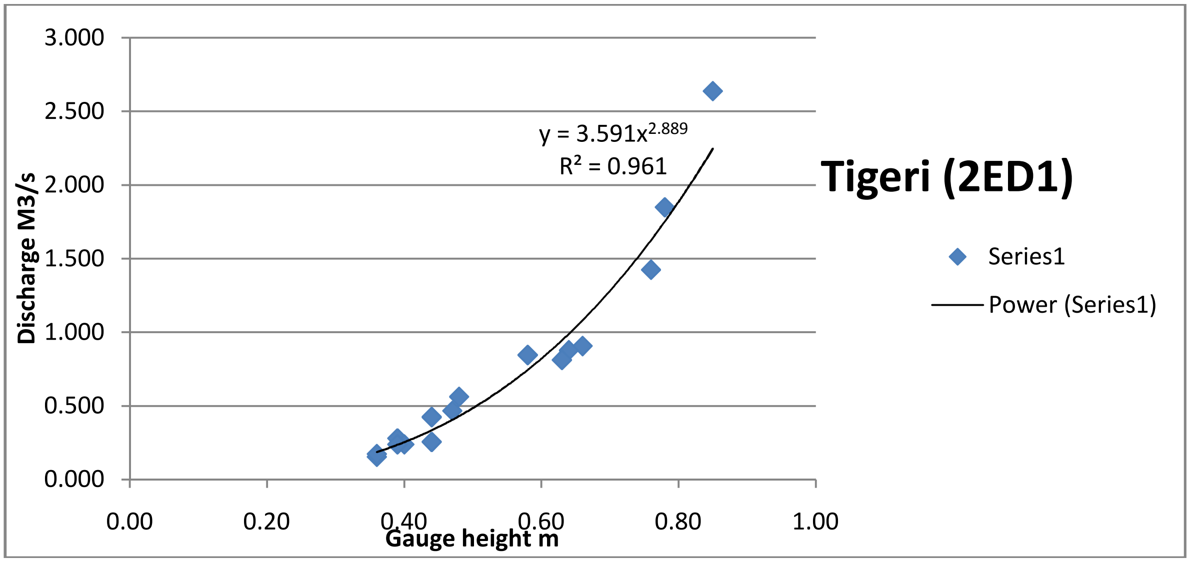

Figure D1 Rating curve for 2ED1

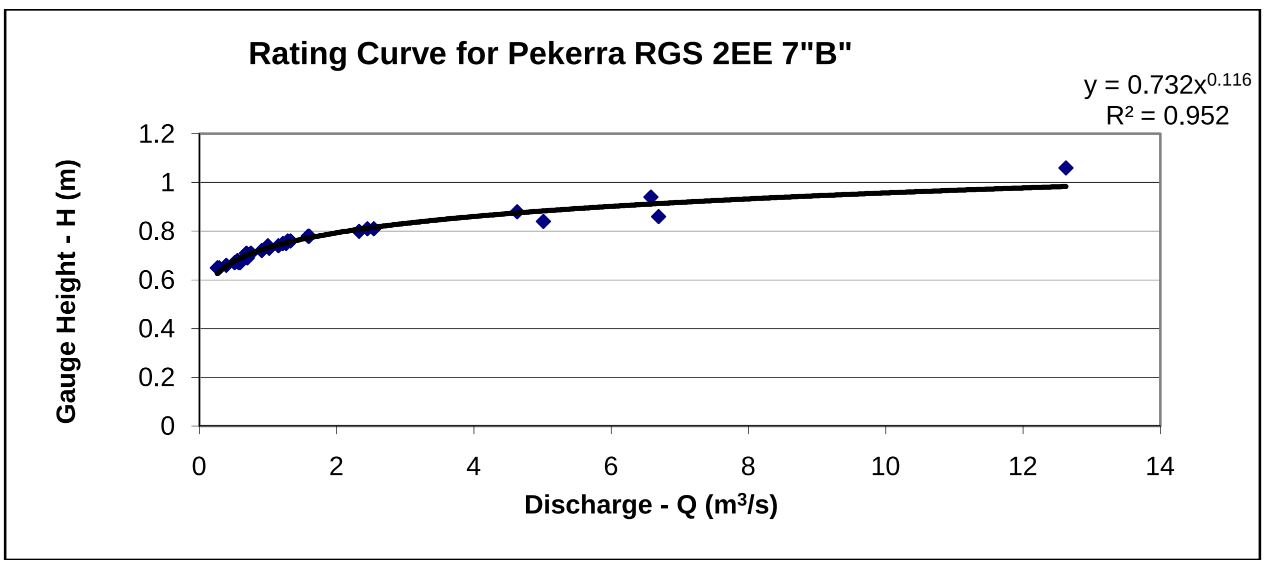

Figure D2 rating curve for 2EE7B for 1962 to 1999

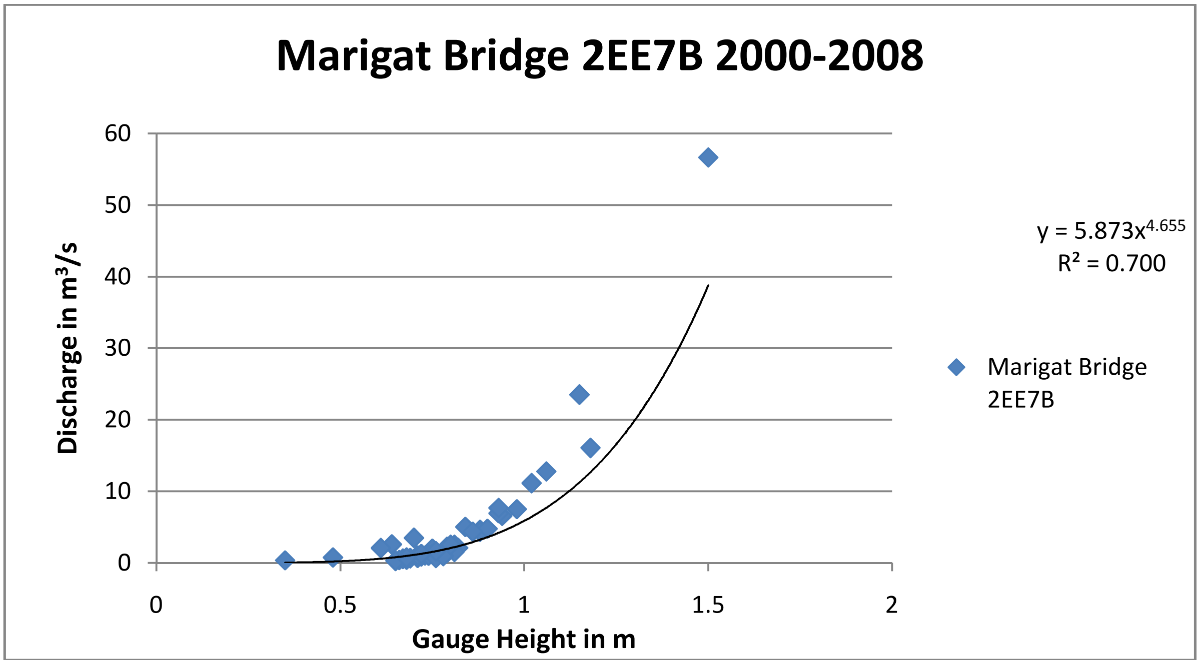

FIGURE D3 rating curve for 2EE7B for 2000 to 2009

Appendix E.

Table E1 Kiptunget forest Precipitation and ETo Values

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Eto mm/d
Jan	12.1	155.4	45.5	150	28.2	52.2	52.3	104.2	80.4	29.1	4
Feb	0	0	0	0	28.5	6.8	19.6	103.6	0	0	4.2
Mar	8.5	133.6	55.7	36.1	87.4	99.7	113	44.3	118.3	0	4.1
Apr	66.9	225.2	108.3	153.5	148.7	160.7	191.3	140.8	65	137.5	3.4
May	153.4	58.3	164	290.7	82.5	204.6	71.4	227.5	53.8	99.9	3.2
Jun	96.7	52.7	103.3	138.3	0	45.7	81.6	145.9	81	25	3
Jul	93.7	192	43.7	147.4	86.8	108.8	71.5	135.5	178.3	21.8	2.7
Aug	151.6	71.5	68.1	177.7	162.6	139.9	249.4	208.3	107.9	34.1	2.8
Sep	70.9	0	20	39.7	74.4	164.1	40.4	175	97	34	3.4
Oct	93.8	54.9	65	39.7	56.8	16.6	35.6	74.1	126.7	50	3.6
Nov	75	148.3	81	70.4	99.3	67.6	263.6	70.2	125.5	47	3.2
Dec	64.2	0	158.6	99.5	26.9	4.9	172	30.5	0	109	3.5

Table E2 Makutano Londiani Precipitation and ETo Values

9035155 MAKUTAN(Precipitation; daily total

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Eto mm/d
Jan	8.4	157.3	83.8	9.6	67.2	99.2	45	87	19.8	34.6	4.4
Feb	3.4	43.4	9.8	0	15.6	59.3	16.2	150	7.8	0	4.8
Mar	6.8	117.2	141.8	66.6	86.8	108.1	129.2	46.5	57.8	30.6	4.7
Apr	37.4	152.6	98.4	288.5	197.5	156.6	180	136.8	68.6	110	3.8
May	97.6	124.8	164.8	133	73.4	231	147.4	220.2	41.4	77.6	3.3
Jun	63	83.4	68.2	105.2	58	100.4	115.2	124.8	80.6	44.8	3
Jul	100.6	163.1	63.4	103.4	66.8	128.5	120.2	186	248.4	42.8	2.5
Aug	123	100.2	106.2	266.2	156.6	145.2	166	142	107.4	83	2.7
Sep	77.6	58	3.4	4.4	61	161.6	51.8	298.6	125.2	50	3.5
Oct	141	79.8	61.4	14.8	54.6	4.8	53.2	64.8	145.4	53.4	3.8
Nov	48.6	123.8	86.8	43.8	105.2	29.9	235.6	46	97.6	48.6	3.7
Dec	49.6	20.6	235.8	105.8	24.4	7.6	159.8	12.8	0	113.4	3.8

Table E3 MajiMazuri Precipitation and ETo Values

9035028 MAJI MAZU Precipitation; daily total

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Eto mm/d
Jan	65	196	65	0	49.4	60.6	35.2	126.1	0	0	4.4
Feb	0	0	15	0	0	0	21.6	112.5	0	0	4.8
Mar	8.7	133.6	189	30.8	0	67.8	35.4	44.3	112	0	4.7
Apr	59.4	123.3	72.1	204	187.1	121.3	217.2	141	74.8	79.7	3.7
May	53.8	43.9	111.2	194.5	128.5	180.7	122.7	90.9	37.9	82.1	3.3
Jun	72.9	118.4	62.5	122.9	118.5	52.2	113.9	132.2	26.4	25.9	2.9
Jul	132.9	113.4	24.2	64.6	24.6	108.8	45.3	146.2	137.2	48.9	2.5
Aug	173.4	121.1	105.6	243.7	100.6	147.4	109	155.1	87	31	2.6
Sep	29.3	30	14.8	122.9	36.6	172.8	62	143.5	83	38	3.4
Oct	62	55.5	39	37.8	39.6	158.9	50.5	38.5	135	71.5	3.8
Nov	82	200	82.3	37.2	120.8	19.9	392.6	55.3	63	46.4	3.6
Dec	35	35.2	170.2	60.8	60.6	4.2	197.9	5.5	0	90	3.7

Table E4 Esageri Precipitation and ETo Values

8935216 ESAGERI W Precipitation; daily total

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Eto mm/d
Jan	0	136	197.8	0	71.4	21.4	26.1	40.7	11.5	15.8	4.3
Feb	0	37.5	0	0	0	12.5	0	91	0	2	4.6
Mar	10.4	102	183.6	35.2	69.8	16.1	0	38.6	120	80	4.5
Apr	33.6	186.6	121	193.3	251.6	126	68.9	142.3	111	75	3.5
May	54.7	44	162.9	152.9	15.6	0	49.5	139.6	22	115.1	3.2
Jun	32.8	120	60.1	86.8	52.3	22.2	32	184.6	35.5	26.4	3
Jul	63.5	76.4	10.2	65.9	49.2	54.5	53.1	160.3	139.8	30.9	2.7
Aug	101.2	107.5	24.9	224.5	43.4	27.8	105.9	96	106.8	10.3	2.9
Sep	14	70.3	0	8.5	23.2	149	42.3	158.5	57.3	45.9	3.4
Oct	93.7	70.3	32.9	62.4	29.7	16	90.3	138	157	87.7	3.7
Nov	151.1	157	54.6	69.1	27.2	45	311.7	17.2	87.9	49.3	3.4
Dec	32	21.1	308.7	16.7	36.9	0	230.7	0	0	200	3.7

Table E5 Kimose Precipitation and ETo Values

8935200 KIMOSE AG Precipitation; daily total

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Eto mm/d
Jan	1.1	96	53.9	0	46.2	0	27	52	0	10.2	5.4
Feb	0.5	16.7	2.3	0	0	52.6	19.5	59.2	0	0	5.8
Mar	7.4	154.2	189.4	79.6	78.1	131.6	19.1	13.5	65	0	5.3
Apr	16.2	60.7	62.3	150.3	130.6	81.4	64.9	169	64.5	26	4.4
May	45.8	65.6	83.7	187.8	45	276.8	5.4	141.8	36	55.9	3.5
Jun	48.8	135.3	67	23.7	13	82.8	84.6	373	12.9	20.7	3.5
Jul	144.4	90.4	9	95.5	83	117.5	67	215.1	237.7	0	3.3
Aug	124.5	190.1	31.2	128	37.6	95.2	101.2	270	302	1.5	3.8
Sep	27.9	42.8	1.1	14.1	60.6	149.8	27.5	189	80.3	26.6	4.4
Oct	57.6	162.2	31	27.2	9.5	49.5	66.1	80	128.7	62.5	4.5
Nov	139.8	100.6	34.8	24.9	62.5	42.1	100.7	13	50.5	3	4.2
Dec	127.5	1.2	162.1	35.6	19	1.4	167.9	56	0	97.5	4.7

Table E6 Baringo FTC Precipitation and ETo Values

8935193 BARINGO F Precipitation; daily total

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Eto mm/d
Jan	3	82.8	174.8	17.1	68.2	28.3	29.4	26.1	13.5	15.4	4.4
Feb	0	18.8	3.5	0	5.9	42.5	0	112.9	0	0	4.8
Mar	7	98	129	42.2	107.3	47.4	44.3	45	156.8	89	4.7
Apr	59	149.6	192.5	242.8	280	118.8	173.4	190.4	96	87.3	3.7
May	103.7	44.7	153.5	225.9	37.9	264.3	59.7	137.3	36.4	80.6	3.3
Jun	74	134.3	63.1	79.8	81.6	56.3	102.8	127.5	52.1	30.4	2.9
Jul	87.2	82.8	22.4	65.9	76.7	54.6	44.1	54.4	175.8	15.8	2.5
Aug	120	107.4	42.4	163	60.9	45.7	115.9	97.1	9.6	45.3	2.6
Sep	15	59.1	2.8	24.5	58.5	154.6	57.2	118.4	42.4	20.9	3.4
Oct	91.7	65.5	43.7	63.6	32	16.8	86.4	144.1	164.8	100.2	3.8
Nov	71.5	133.4	83.2	52.4	114	30.5	312.3	31.6	180.7	40.2	3.6
Dec	30	9.6	256.5	33.5	17.1	0	222.5	6.4	0.4	245.7	3.7

Table E7 Chemususu Forest Station Precipitation and ETo Values

8935187 CHEMUSUSU FOREST STATION Precipitation; daily total

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Eto mm/d
Jan	0	80.5	121	0	37	34	32	30.7	0	21	4.4
Feb	0	43.5	0	0	0	24.5	50	83	0	0	4.8
Mar	6	86	97.2	21.4	126.8	125.5	90	51	80.5	10.3	4.7
Apr	40.5	205.3	154.3	282	228.3	132.7	345	126.5	60	185.7	3.7
May	63	65.1	154.4	229	55.2	236.6	151	84	70	210	3.3
Jun	113.6	145.8	76.4	104	46.4	100.2	75	123.2	140	100	2.9
Jul	212.7	126.8	19.6	103.1	124.3	89	150	188.3	195	50	2.5
Aug	73.8	108.3	216.5	372.5	176.6	157.2	158	116.9	133.2	49.4	2.8
Sep	33	47.1	2.4	20	73.5	120	93.5	167	120.5	30	3.5
Oct	127	40.3	59.2	47	99	60.1	82.5	173.5	160.5	65	3.7
Nov	90.3	158.9	95.9	59	157.8	39.1	230.5	57.2	233.7	45	3.7
Dec	51	15	226.9	57.5	15	5.6	145	0	0	85	3.7

Table E8 Perkerra Agricultural Research Station Precipitation and ETo

Precipitation; daily tot: 8935163 PERKERRA AGRICULTURAL RESEARCH STATION

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	ETo
Jan	3.5	45.7	30.7	1.5	14.5	15.1	23.9	47.0	15.9		5.4
Feb	0.0	13.5	0.0	0.0	0.0	3.0	21.5	81.0	31.2		5.8
Mar	6.6	62.0	54.1	32.2	13.0	47.3	40.5	21.0	55.4		5.7
Apr	16.5	50.4	77.9	157.9	58.0	72.2	41.4	117.1	16.7		5.0
May	26.7	24.1	52.0	60.9	45.2	112.4	23.5	182.6	40.1		4.9
Jun	11.0	19.7	47.6	28.9	14.0	59.6	132.7	98.0	6.0		4.7
Jul	57.0	33.3	8.9	64.7	30.1	76.4	128.2	104.8	129.0		4.4
Aug	61.2	103.5	20.0	0.0	7.1	86.6	50.0	120.7	11.4		4.7
Sep	5.0	7.5	0.3	3.5	11.0	116.0	66.5	109.5	14.6		5.2
Oct	33.2	34.6	14.9	2.0	3.5	27.0	41.3	32.7	141.5		5.2
Nov	41.7	79.7	19.5	6.1	75.0	6.0	96.5	12.1	74.2		4.9
Dec	26.7	0.0	78.2	4.2	4.4	5.0	127.7	0.0	0.0		4.9

Table E9 Cheberen Market Precipitation and ETo Values

8935143
CHEBEREN MARKET - KABARNET
Precipitation; daily total

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Eto mm/d
Jan	2.5	5.7	69.2	1	49	27.2	24.4	32.1	8.3	12.4	5.4
Feb	1.9	73.7	1.6	1.8	1	30.8	3.9	121.4	1.5	1	5.9
Mar	8.8	207.5	156.6	81.7	63.6	69.9	22.6	31.5	8.5	20	5.8
Apr	28.5	86.8	91.4	280.4	165.4	135.6	103.4	155.4	80.5	50	5
May	37.4	45.8	88.3	356	67.1	234.6	37.9	123.9	24	48.9	4.9
Jun	43.1	140.6	110.9	58.6	32.5	73.1	125.8	300	57	7.2	4.7
Jul	177.1	157.8	35.1	74.6	73.5	147.8	38.6	200	174.9	16	4.4
Aug	249	258.3	33.5	184.1	54.6	106.5	203.7	264	168	12	4.8
Sep	25.5	53.4	8.9	31.2	63.2	154.9	18.7	210	80.7	15.2	5.2
Oct	89.6	109.1	48.3	43	41.3	10.5	96.6	107	149.2	48.2	5.3
Nov	87.9	149.5	45.2	21	71.4	29.8	118.8	10	90	5	4.9
Dec	90.5	16.8	277	27.5	12.7	0.1	115.4	48	4	80	4.9

Table E10 Kc Factors

Growing season begins in late march to Early April.
Harvest time November to December (dry)

	Initial	Development	Mid	Late	Total
Length days)	30	50	60	40	180
Kc-value	0.68	1.2	1.2	0.60-0.35	

(Adopted from FAO irrigation and drainage papers)

Table E11 Monthly Input Data on Crop Coefficients and Climate

Month	**Kc Factor (Maize)**	**Kc Factor (other vegetation)**	**Effective Precipitation (%)**
Jan	0.20	1.00	98
Feb	0.35	1.00	90
Mar	0.68	1.00	90
Apr	0.68	1.00	80
May	1.20	1.00	75
Jun	1.20	1.00	79
Jul	1.02	1.00	70
Aug	0.88	1.00	80
Sep	0.75	1.00	85
Oct	0.60	1.00	90
Nov	0.40	1.00	95
Dec	0.35	1.00	95

Table E12 Emining Permit Water Demand

Irrigation

APPLICANT	SUB REGION	STATUS	USE	FLOOD FLOW (M3/D)	NORMAL FLOW (M3/D)	IRRIGATION	DATE ISSUED	DATE OF EXP	LOCALITY / RIVER
JOSEPH M. CHPEKONGA	KABARNET	APP	Irrigation	18.174		18.174			EMINING
KIPTANUI CHERUIYOT	KABARNET	Authorization	Irrigation	9.09		9.09	12/6/1996	1/6/1997	EMINING
NAROSURA W/ASS	KABARNET	PERMIT	Irrigation	1135.47		1135.47	29/5/59	31/12/84	NAROSURA
CHARLES C. CHEBII	KABARNET	Authorization	Irrigation	136.36		136.36	18/6/85	26/6/86	NAROSURA

Industrial

SUB REGION	STATUS	USE	FLOOD FLOW (M3/D)	NORMAL FLOW (M3/D)	INDUSTRIAL	DATE ISSUED	DATE OF EXP	LOCALITY / RIVER
KABARNET	Authorization	Bottling		216		9/7/2007	9/7/2008	KACHUKIA SP. NAROSURA
KABARNET	New	Industrial		23.04	23.04			Narosura

Domestic/Municipal

APPLICANT	SUB REGION	STATUS	USE	NORMAL FLOW (M3/D)	DOMESTIC	PUBLIC	OTHERS	CATEGORY	LOCALITY /
DWO KOIBATEK	KABARNET	Authorization	Public	22.5		22.5		B	MUSERECHI
	KABARNET	PERMIT	CONSERVATION OF FLOOD						Narosura
CHEGE MBUTHIA	KABARNET		Dom & Irr	21					SABATIA
KEMTILIL S. H. W/PROJECT	KABARNET	PERMIT	Domestic	78.4	78.4				NAROSURA
Kabiyet/Benonin W/Ass	KABARNET	Authorization	Domestic	100	100				Narosura
Kipngasuo S.H. W/Project	KABARNET	Authorization	Domestic	70	70				Narosura
Kokorwonin W/Project	KABARNET	Pending	Domestic	75.73	75.73				Esageri
DWO KOIBATEK	KABARNET	Authorization	Domestic	22	22			B	EMINING

Table E13 Lelgel Permit Water Demand

APPLICANT	SUB REGION	STATUS	USE	NORMAL FLOW (M3/D)	DOMESTIC	IRRIGATION	LIVESTOCK	CATEGORY	LOCALITY /
D.W.O Baringo	KABARNET	Authorization	Domestic	22	22			B	Chepande
NGORIKA WATER PROJECT	KABARNET	Authorization	Domestic	20				B	LEMBUS
Nelson K. Bett	KABARNET	Authorization	Domestic	10	10				Mumberes/ Koibatek
Nelson K. Bett	KABARNET	Authorization	Domestic	10	10				Mumberes
POROR W/PROJECT	KABARNET	APP	Domestic	225	225				LELGEL
NYALILIGIRUK W/ASS	KABARNET	APP	Domestic	675	675				LELGEL
Subukia kirima w/p	KABARNET	Authorization	Domestic	4.54	4.54				Morkisis trib of Lelgel
Authorization	Domestic & Irrigation			0.3	0.3	12			LELGEL
APPLICATION	DOM POWER			3.27	3.27				Morkisis trib of Lelgel
Authorization	DOMESTIC, LIVESTOCK & POWER			33.62	10.9		22.72		Lelgel

Table E14 Eldama Ravine Permit Water Demand

APPLICANT	SUB REGION	STATUS	USE	FLOOD FLOW (M3/D)	NORMAL FLOW (M3/D)	DOMESTIC	Public	IRRIGATION	CATEGORY	LOCALITY / RIVER
JOHN KIPKOECH TALLAM	KABARNET	PERMIT	Domestic/Irrigation	36.34	3.27	3.27		36.34		Eldama Ravine R
KIPRAISI CHEBUTUK	KABARNET	PERMIT	DOM IRR POWER	468.58	26.86	26.86		18.18		E/RAVINE
Wilson Sumukwo	KABARNET	Authorization	Domestic & Irrigation	18.174	2.2717	2.2717		18.174		ELDAMA RAVINE
JOHN NGETUNY	KABARNET	Application	Dom & Irr		50				D	ELDAMA RAVINE
GIDEON KIBET TOROITICH	KABARNET	NOTICE	Dom & Irr		150				D	RAVINE
TIMBERLAND LTD(SUPPERPLY)	KABARNET	Authorization	Dom & Ind		60				C	MAKUTANO
WILLIAM KIPTUMBA ARGUT BOIT	KABARNET	Authorization	Dom & Irr		22.7				B	E/RAVINE
SILVIAH ENDERE	KABARNET	NEW	Dom & Irr		111.99				D	E/RAVINE
DISTRICT	KABARNET	Applicatio	Public	116			116		D	RAVINE
DISTRICT	KABARNET						20			KOIBATEK
KOIBATEK DISTRICT HOSPITAL	KABARNET						18			RAVINE
MANDINA PRY SCH & COMMUNITY W/P	KABARNET						90			RAVINE
MUSA CHEPKEITANY CHEBURET	KABARNET						101.77			RAVINE
Hellen Stover		Authorization	Domestic	8.8		8.8			A	Koibatek
TOM KIPTOO CHEMJO		APP	Domestic	17.98		Domestic			B	Koibatek
DISTRICT WATER OFFIC		Authorization	Domestic	20		20			B	RAVINE
KAMELILO COMMUNITY W/P			Domestic	40		40			C	RAVINE
KIPTUNO PRIMARY SCH		Applicatio	Domestic	22.7					D	E/Ravine
HENRY KIPTIONY KIPLA		Applicatio	Domestic	20					B	Eldama Ravine
ELDAMA RAVINE DISTR		Authorizat	Domestic	20					B	Koibatek
Karen Roses Limited	KABARNET	Authorization	Irrigation	27.27				27.27	B	ELDAMA RAVINE
MUSA CHEPKEITANY CHEBURET	KABARNET	Authorization	IRRIGATION	45.45				45.45	C	RAVINE
Karen Roses Limited	KABARNET	Authorization	IRRIGATION	22.7				22.7	B	RAVINE
ELDAMA RAVINE ROSES	KABARNET	Authorization	IRRIGATION	300				300	D	RAVINE

Table E15 Population per location (1999 census report)

location	population	sub catchment	Percentage in catchment	Catchment population
Kiserian	2755	2EE	10	276
Ngambo	3997	2EE	60	2398
Marigat	3608	2EE	80	2886
Kimalel	3189	2EE	80	2551
Ngetimoi	2735	2EE	30	821
Kibnjos	1345	2EE	80	1076
Koibos Soi	2361	2EE	30	708
Bekibon	1765	2EE	100	1765
Tenges	3113	2EE	100	3113
Kimose	2243	2EF	50	1122
Emining	5275	2EF	50	2638
Rosoga	2067	2EF	40	827
Kakmor	1449	2EF	100	1449
Cheberen	2031	2EE	100	2031
Kimng'orom	955	2EE	100	955
Sirwa	4075	2EE	40	1630
Kiptuno	2176	2EE	100	2176
Chemorgong	1392	2EE	100	1392
Lembus Tugur	2305	2ED1	100	2305
Koisamo	2041	2ED1	100	2041
Lembus toron	3949	2ED1	50	1975
Lembus centr	9033	2ED2	100	9033
Lembus Moso	8983	2ED2	80	7186
Maji mazuri	5535	2ED3	85	4705
Sabatia	5363	2EF	85	4559
Kiplombe	5861	2EF	50	2931
Eldama Ravin	2435	2ED3	100	2435
Kabiyet	3030	2ED3	100	3030
Lembus Kabin	2491	2EF	100	2491
Lembus Kipto	3388	2EF	50	1694
Saos/ Kibias	3772	2EF	100	3772
Perkerra	3327	2EF	100	3327
Mumberes	8080	2ED2	50	4040
Ravine Town	10518	2ED	100	10518

Table E16 Livestock Population (ILRI database, 1999)

Division	Zebu	Grade	Cachment
Esageri	12,000	2,400	2EF
Mosop Mumberes	1,900	2,600	2ED1
Ravine	5,500	40,000	2ED3
Sirwa&Kipngorong	8,500	4,500	2EE
Tenges	7,020	1,750	2EE
Emining	25,000	1,000	2EF
Marigat	58,300	250	2EE

Table E17. Pans and Small Dams in Koibatek District

	NAME	CAPACITY	LOCATION	DIVISION
1	Emgwen	10,000	Mumberes	Mumberes
2	Takulo	25,000	Torongo	Torongo
3	Sumbeiwet	20,000	Lembus-Katum	E/Ravine
4	Kapkolilei	20,000	Emining	Emining
5	Kapchelogon	15,000	Emining	Emining
6	Nato	50,000	Emining	Emining
7	Chemonoi	10,000	Kimose	Emining
8	Koitoror	12,000	Koibos-Soi	Emining
9	Kaplelwo	15,000	Koibos-Soi	Emining
10	Kesumin	10,000	Sirwo	Sirwo
11	F.T.C.	10,000	Perkerra	E/Ravine
12	Baarin	10,000	Perkerra	E/Ravine
13	Turkupletio	10,000		Mogotio
14	Nakutakwei	10,000	Kiplombe	Esageri
15	Cheptongilo	22,000	Kiplombe	Esageri
16	Olbaat	20,000	Kiplombe	Esageri
17	Daudi Lagat	15,000	Mogotio	MOGOTIO
18	Josphat Kipkiza	15,000	Mogotio	Mogotio
19	Chepkunur	15,000	Mogotio	Mogotio
20	Ngorika	15,000		
21	Koitegan	25,000	Oldebas	Kisanana
22	Kaboskey	10,000	Mogotio	Mogotio
23	Sitet	10,000	Simotwo	Mogotio
24	Pombo	10,000	Kapkechui	Kapkechui
25	Kapkeles	10,000	Kapkechui	Kapkechui
26	Kobokonga	10,000	simotwo	
27	Chelogomoi	20,000	Koibo soi	Mogotio
28	Tabartab	20,000	Koibo soi	Mogotio
29	Tingtingyon	15,000	Kamar	Mogotio
30	Chomiok		Ngenalel	Kisanana
31	Edward Tanui	10,000	Kisanana	Kisanana
32	Kizima	13,000	Kisanana	Kisanana
33	Kitbot	10,000	Kabuswo	Kisanana
34	Tabartabchumo	15,000	Kamar	Mogotio
35	Sosion	12,000	Emining	Emining
36	Borokwo	14,000	Borokwo	Emining
37	Kapyemit	17,000	Kamar	Mogotio
38	Kabarbesi	15,000	Emining	Emining
39	Chebirereibei "B	12,000	Kisanana	Kisanana
40	Kisgis	12,144	Emining	Emining
41	Cheplelu	16,000	Tolmo	E/Ravine

Appendix F: Results

Table F1 Statistical Analysis of Model Calibration and Validation Results

Q_O	Q_M	E_Q	$(E_Q(i))^2$		$(Q_O(i)-\bar{Q}_O)^2$
170694.8257	19084.10556	-151610.7202	2.2986E+10	3.42893E+12	4.48226E+17
127644.6875	31437.57332	-96207.11416	9255808815	3.22682E+12	4.48284E+17
117553.0234	123048.2848	5495.261321	30197897	2.87178E+12	4.48298E+17
765938.2939	1455047.432	689109.1381	4.7487E+11	1.02216E+12	4.4743E+17
4567737.917	4811038.046	243300.1289	5.9195E+10	2.12234E+12	4.42358E+17
970191.235	3031627.432	2061436.197	4.2495E+12	1.30545E+11	4.47157E+17
4301108.603	5337318.046	1036209.444	1.0737E+12	4.40786E+11	4.42713E+17
4716845.094	4016847.246	-699997.8473	4.9E+11	5.7606E+12	4.4216E+17
666637.9523	423502.432	-243135.5203	5.9115E+10	3.77627E+12	4.47563E+17
123524.0047	1425305.046	1301781.042	1.6946E+12	1.58679E+11	4.4829E+17
6495170.499	10053501.93	3558331.433	1.2662E+13	3.45292E+12	4.39798E+17
490656.7602	6301092.203	5810435.443	3.3761E+13	1.68946E+13	4.47798E+17
63025.3929	1370006.939	1306981.546	1.7082E+12	1.54563E+11	4.48371E+17
1342458.564	2379902.069	1037443.504	1.0763E+12	4.39149E+11	4.46659E+17
4162806.076	4172655.359	9849.282767	97008371	2.85704E+12	4.42897E+17
5268495.048	12708258.55	7439763.501	5.535E+13	3.29434E+13	4.41427E+17
2966831.946	2768397.305	-198434.6414	3.9376E+10	3.60454E+12	4.4449E+17
760797.5622	3737409.415	2976611.853	8.8602E+12	1.62941E+12	4.47437E+17
10247366.09	14472967.3	4225601.214	1.7856E+13	6.37802E+12	4.34835E+17
3143730.372	2244293.305	-899437.0674	8.0899E+11	6.75773E+12	4.44254E+17
576090.7116	403272.2152	-172818.4964	2.9866E+10	3.50792E+12	4.47684E+17
1184166.379	3173671.305	1989504.926	3.9581E+12	83739773224	4.4687E+17
7296507.175	17948248.88	10651741.71	1.1346E+14	8.01314E+13	4.38736E+17
297683.0971	55835.0976	-241847.9995	5.849E+10	3.77127E+12	4.48056E+17
3829788.958	6850194.311	3020405.352	9.1228E+12	1.74314E+12	4.4334E+17
87359.87877	57905.40521	-29454.47356	867566012	2.99145E+12	4.48338E+17
991078.6214	2602257.516	1611178.895	2.5959E+12	7911707202	4.47129E+17
5679899.626	14176482.55	8496582.922	7.2192E+13	4.61918E+13	4.4088E+17
14054207.35	20888043.2	6833835.853	4.6701E+13	2.6355E+13	4.29829E+17
1401125.67	3016578.812	1615453.142	2.6097E+12	7169606877	4.4658E+17
136545.1829	1807513.387	1670968.205	2.7921E+12	850216283.4	4.48272E+17
959450.7671	3335051.203	2375600.436	5.6435E+12	4.56265E+11	4.47171E+17
11063478.11	533674.6811	-10529803.43	1.1088E+14	1.49571E+14	4.3376E+17
241499.1386	1277148.203	1035649.065	1.0726E+12	4.4153E+11	4.48132E+17
4326566.374	2041360.712	-2285205.662	5.2222E+12	1.58829E+13	4.42679E+17
20526355.54	42374982.2	21848626.66	4.7736E+14	4.05962E+14	4.21385E+17
3580609.524	62551.15993	-3518058.364	1.2377E+13	2.72295E+13	4.43672E+17
72741.63053	27830.98602	-44910.64451	2016965991	3.04516E+12	4.48358E+17

5955.312586	318817.4138	312862.1012	9.7883E+10	1.9245E+12	4.48447E+17
21694521.4	37696763.51	16002242.11	2.5607E+14	2.04551E+14	4.19869E+17
61152639.12	63373542.8	2220903.679	4.9324E+12	2.71209E+11	3.70291E+17
38155726.49	13654825.11	-24500901.37	6.0029E+14	6.86494E+14	3.98808E+17
22820758.13	15297029.3	-7523728.83	5.6606E+13	8.50795E+13	4.18411E+17
9174644.124	22959777.3	13785133.18	1.9003E+14	1.46047E+14	4.36251E+17
286927.6841	72992.66302	-213935.0211	4.5768E+10	3.66363E+12	4.48071E+17
100051.1633	271214.3029	171163.1397	2.9297E+10	2.33773E+12	4.48321E+17
78996.29587	51054.04505	-27942.25082	780769381	2.98622E+12	4.48349E+17
94161.69112	56811.52107	-37350.17006	1395035203	3.01883E+12	4.48329E+17
1078630.806	76990.06775	-1001640.738	1.0033E+12	7.29955E+12	4.47012E+17
101359.6997	56643.32381	-44716.37585	1999554269	3.04448E+12	4.48319E+17
1892785.203	1196155.822	-696629.381	4.8529E+11	5.74444E+12	4.45924E+17
24193487.27	43146085.69	18952598.42	3.592E+14	2.97648E+14	4.16637E+17
30365963.3	8800607.629	-21565355.67	4.6506E+14	5.41283E+14	4.08707E+17
238000.146	1823884.69	1585884.544	2.515E+12	13051264032	4.48136E+17
2021410.579	5391245.629	3369835.049	1.1356E+13	2.78793E+12	4.45752E+17
3521176.154	8562554.629	5041378.475	2.5415E+13	1.1164E+13	4.43751E+17
3540541.876	3006881.69	-533660.1863	2.8479E+11	4.9898E+12	4.43726E+17
3183087.419	3429809.962	246722.5429	6.0872E+10	2.11238E+12	4.44202E+17
3422326.176	2806794.357	-615531.8195	3.7888E+11	5.36227E+12	4.43883E+17
584070.5216	58114.02308	-525956.4985	2.7663E+11	4.95545E+12	4.47673E+17
256311.7941	71944.50917	-184367.2849	3.3991E+10	3.55132E+12	4.48112E+17
130369.984	289236.0597	158866.0757	2.5238E+10	2.37548E+12	4.4828E+17
1343916.772	82303.10378	-1261613.668	1.5917E+12	8.77191E+12	4.46657E+17
1662723.319	5253206.781	3590483.462	1.2892E+13	3.57345E+12	4.46231E+17
6007519.803	9271177.58	3263657.777	1.0651E+13	2.44463E+12	4.40445E+17
2460442.071	4521947.315	2061505.244	4.2498E+12	1.30594E+11	4.45166E+17
1657657.659	3638698.653	1981040.994	3.9245E+12	78912855636	4.46238E+17
4403372.263	11961192.65	7557820.39	5.7121E+13	3.43126E+13	4.42577E+17
17023134.19	27876714.78	10853580.59	1.178E+14	8.37857E+13	4.25945E+17
6005958.347	4681646.504	-1324311.842	1.7538E+12	9.14723E+12	4.40447E+17
3201206.648	2522139.748	-679066.9003	4.6113E+11	5.66056E+12	4.44178E+17
3076334.736	31307.37519	-3045027.361	9.2722E+12	2.25165E+13	4.44344E+17
2872035.003	1876333.936	-995701.067	9.9142E+11	7.26749E+12	4.44617E+17
2089484.322	1374188.842	-715295.4801	5.1165E+11	5.83426E+12	4.45661E+17
2320910.028	1486748.159	-834161.8694	6.9583E+11	6.42262E+12	4.45352E+17
8203544.423	19664539.27	11460994.85	1.3135E+14	9.52745E+13	4.37535E+17
5193111.783	8231894.276	3038782.493	9.2342E+12	1.792E+12	4.41527E+17
4697072.494	6921233.87	2224161.376	4.9469E+12	2.74612E+11	4.42186E+17
4713801.205	7864100.276	3150299.071	9.9244E+12	2.103E+12	4.42164E+17
9684373.329	13608940.28	3924566.947	1.5402E+13	4.94813E+12	4.35578E+17

7862256.273	3984460.27	-3877796.003	1.5037E+13	3.11132E+13	4.37987E+17
5368873.234	6415074.609	1046201.376	1.0945E+12	4.27618E+11	4.41293E+17
27787166.8	51877275.94	24090109.14	5.8033E+14	5.01311E+14	4.12011E+17
28826385.29	45379431.28	16553045.99	2.74E+14	2.20609E+14	4.10678E+17
17018696.58	5303626.745	-11715069.83	1.3724E+14	1.79967E+14	4.25951E+17
15059125.79	13250077.15	-1809048.639	3.2727E+12	1.23143E+13	4.28513E+17
5152084.362	3210387.933	-1941696.429	3.7702E+12	1.32629E+13	4.41581E+17
7987222.277	16123467.4	8136245.124	6.6198E+13	4.14236E+13	4.37821E+17
4295550.874	7585414.806	3289863.932	1.0823E+13	2.52726E+12	4.4272E+17
9112060.283	2161578.468	-6950481.815	4.8309E+13	7.4833E+13	4.36334E+17
10309699.88	10160607.81	-149092.0692	2.2228E+10	3.41961E+12	4.34753E+17
16282721.37	16612584.81	329863.4367	1.0881E+11	1.87762E+12	4.26912E+17
22935521.69	31657333.07	8721811.38	7.607E+13	4.93041E+13	4.18263E+17
1995938.414	8535575.14	6539636.725	4.2767E+13	2.34209E+13	4.45786E+17
1945562.401	677386.7343	-1268175.666	1.6083E+12	8.81082E+12	4.45853E+17
1154987.064	1311046.225	156059.161	2.4354E+10	2.38414E+12	4.46909E+17
256311.7941	294020.9253	37709.13119	1421978575	2.76363E+12	4.48112E+17
788314.0068	44917.84961	-743396.1572	5.5264E+11	5.9708E+12	4.474E+17
773149.0332	84808.71941	-688340.3137	4.7381E+11	5.70477E+12	4.4742E+17
895452.8201	2294567.496	1399114.675	1.9575E+12	90608222664	4.47257E+17
584919.3735	163919.9432	-420999.4302	1.7724E+11	4.49918E+12	4.47672E+17
362691.8623	3475354.296	3112662.433	9.6887E+12	1.99526E+12	4.47969E+17
1844824.034	9494462.943	7649638.909	5.8517E+13	3.53967E+13	4.45988E+17
17400383.09	16218739.94	-1181643.147	1.3963E+12	8.3046E+12	4.25453E+17
11122348.72	11253793.5	131444.7724	1.7278E+10	2.46076E+12	4.33682E+17
3112734.693	12537169.28	9424434.584	8.882E+13	5.96649E+13	4.44296E+17
4638301.491	11105967.16	6467665.671	4.1831E+13	2.27294E+13	4.42264E+17
1045672.604	97258.23362	-948414.3703	8.9949E+11	7.01477E+12	4.47056E+17
726159.6362	499941.4835	-226218.1527	5.1175E+10	3.7108E+12	4.47483E+17
537889.7398	18126.45462	-519763.2852	2.7015E+11	4.92791E+12	4.47735E+17
669667873.9	856681807.9	187013934	4.8387E+15	4.52071E+15	4.84466E+19
		1700126.673	4.3988E+13	4.14744E+13	4.40423E+17

EF	0.999900124

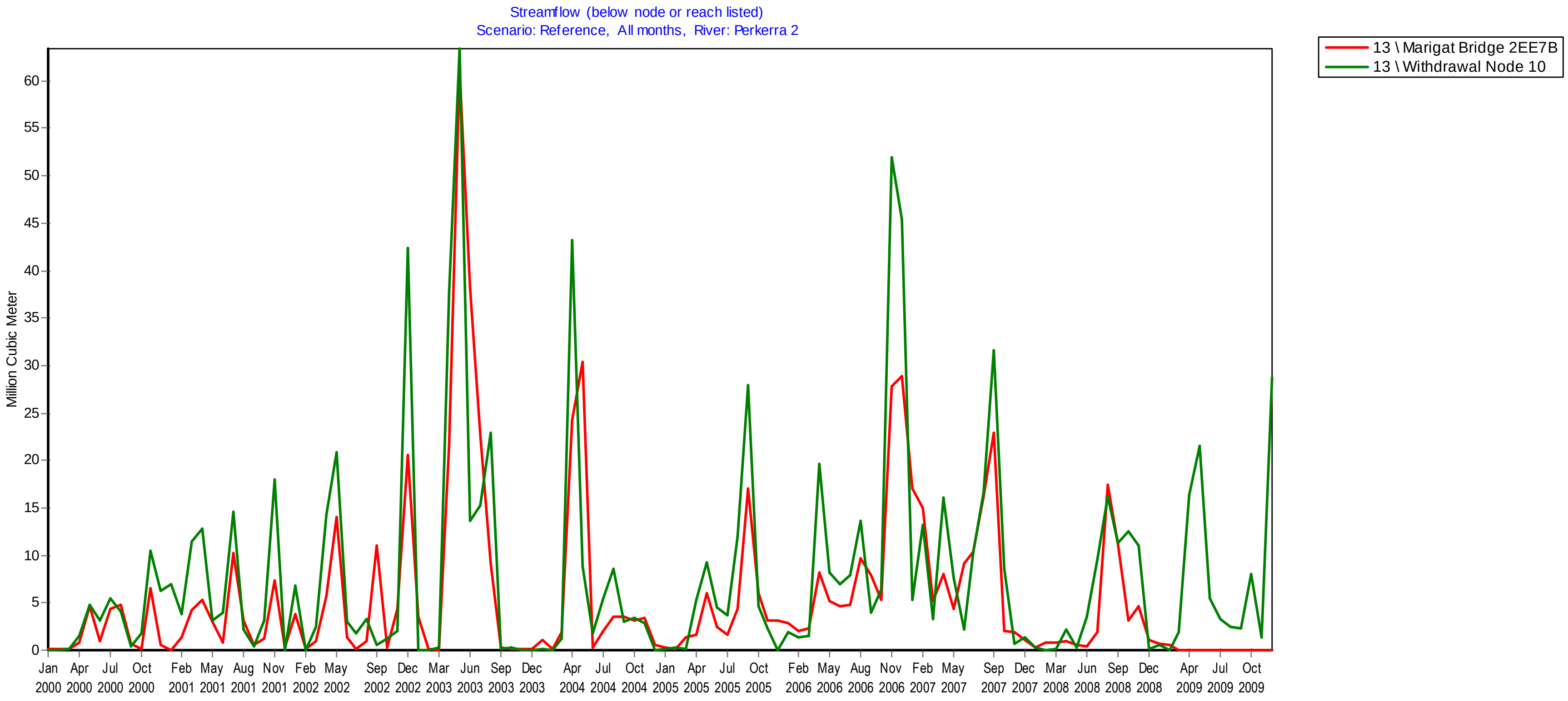

Figure F1. Calibration and Validation Results (WEAP Plot): Reference Scenario

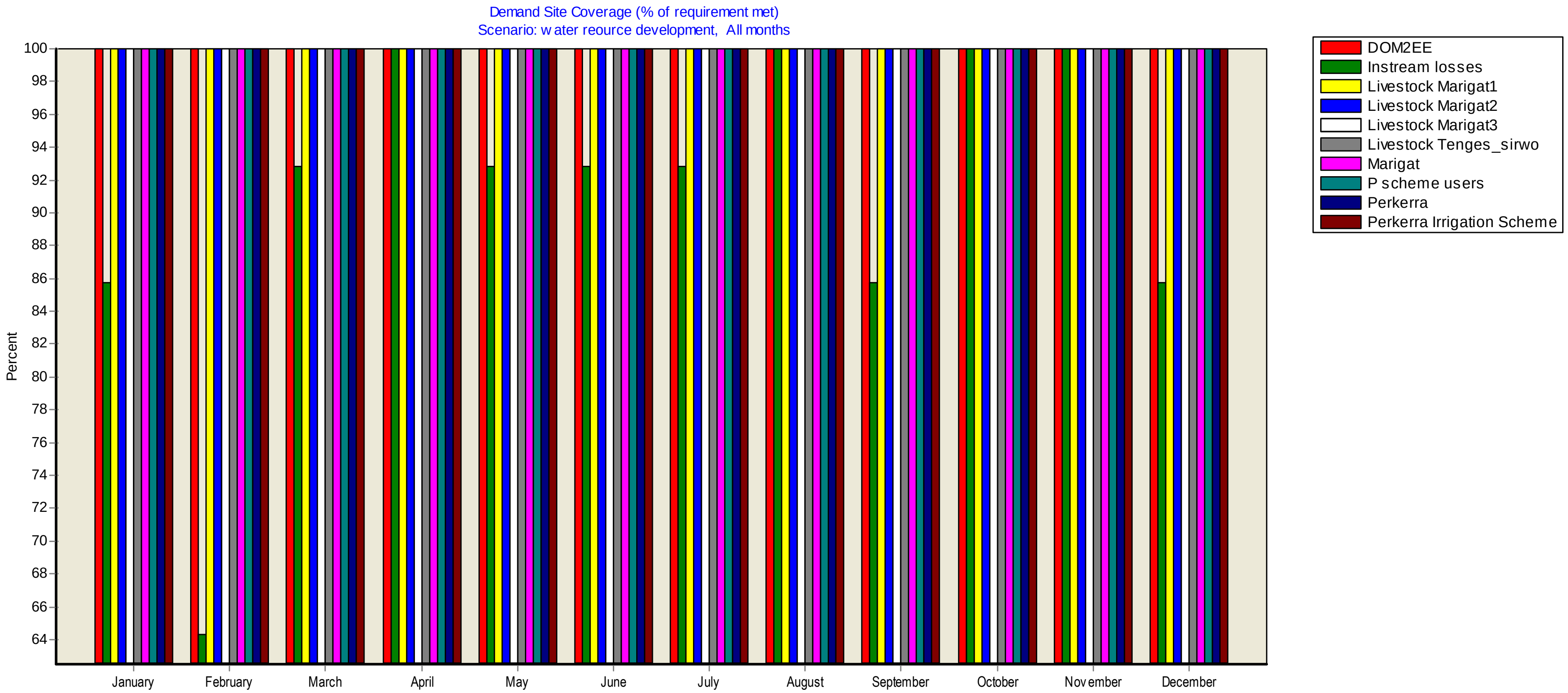

Figure F2. Water Resources Development: Mean Monthly Unmet Water Demands, Downstream Of Dams

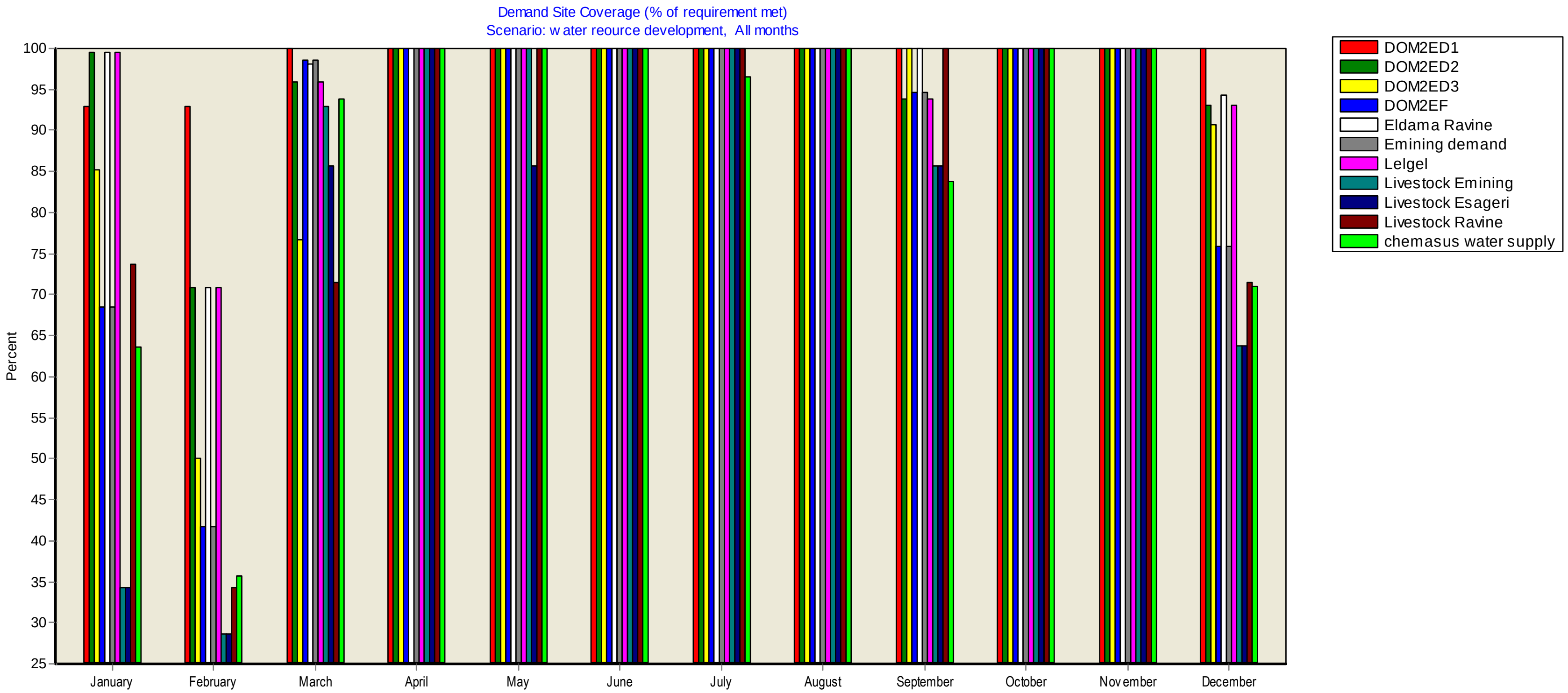

Figure F3. Water Resource Development: Mean Monthly Unmet Water Demands Upstream Of Dams

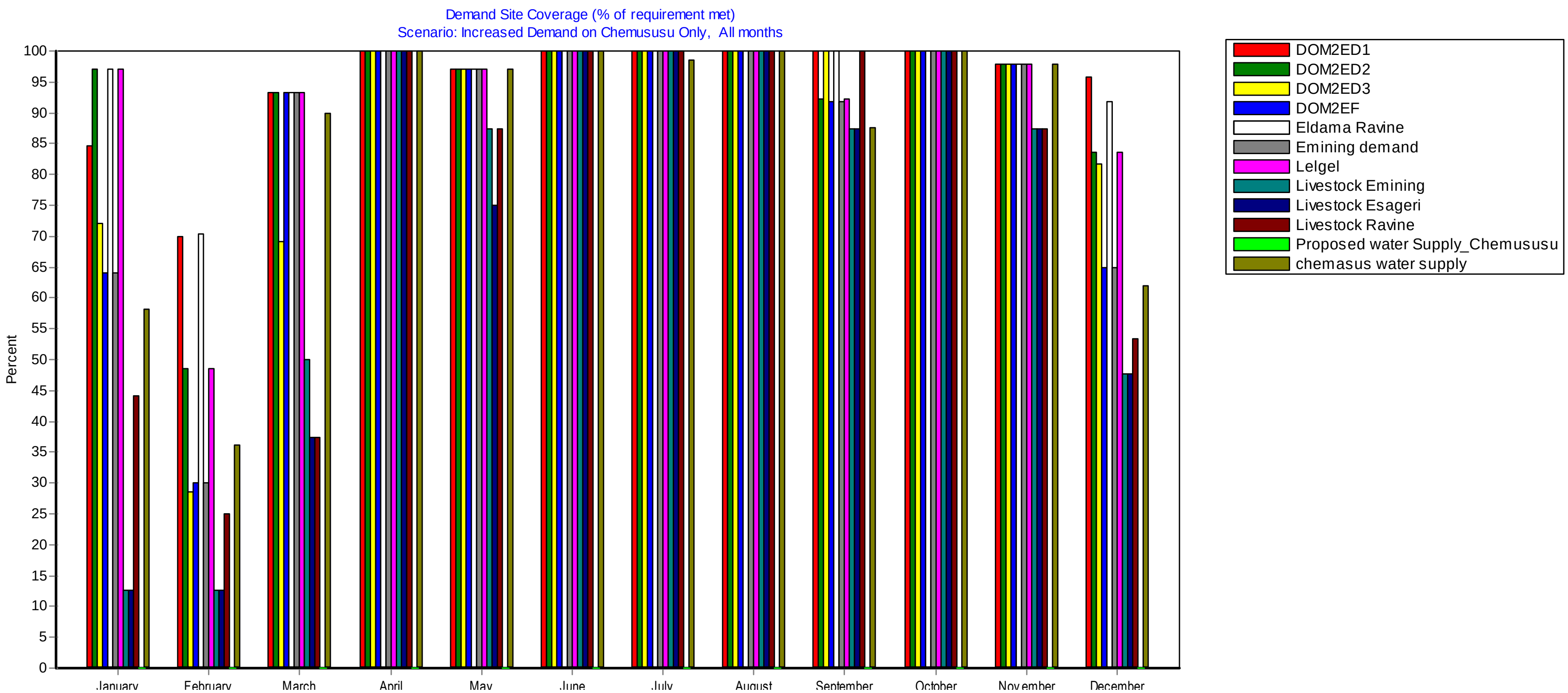

Figure F4. Chemususu Dam Project: Water Demand Coverage Upper Catchment

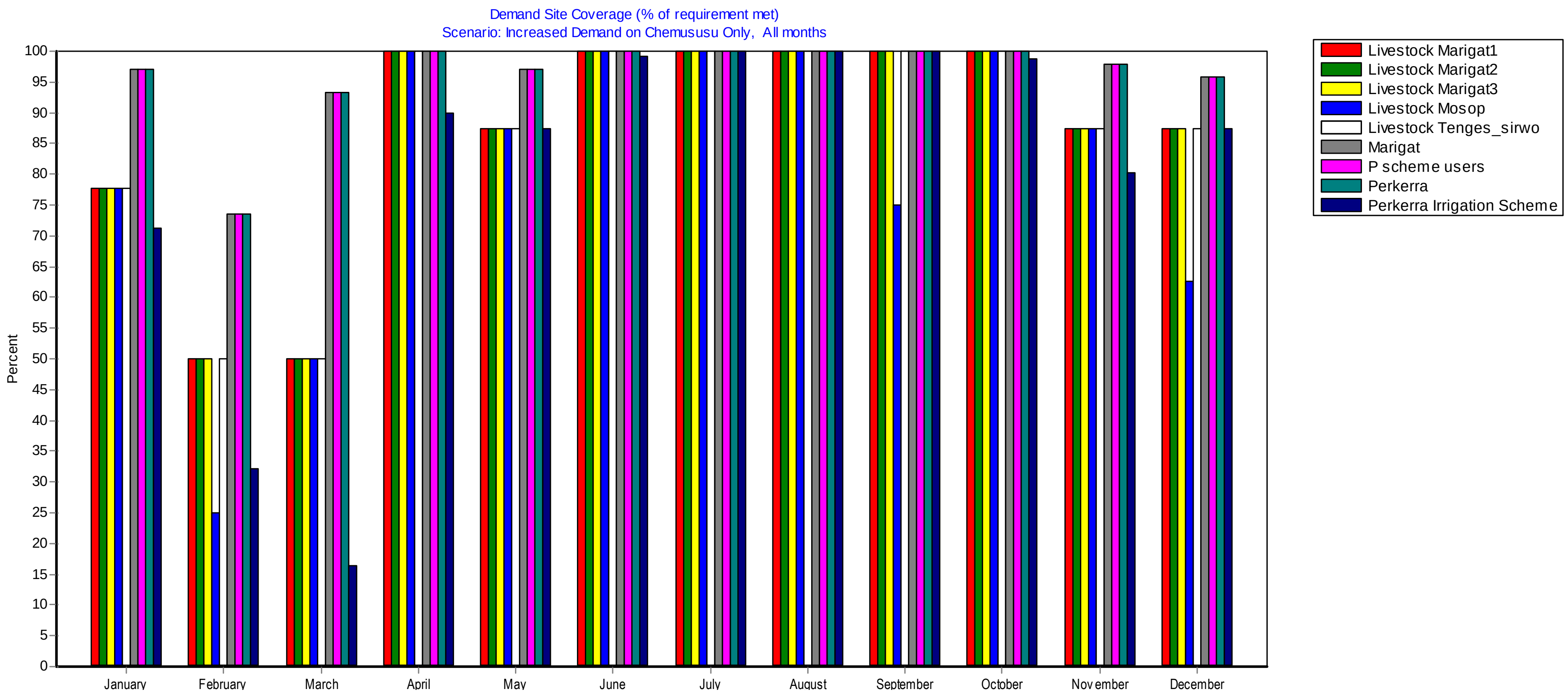

Figure F5. Chemususu Dam Project: Water Demand Coverage Lower Catchment

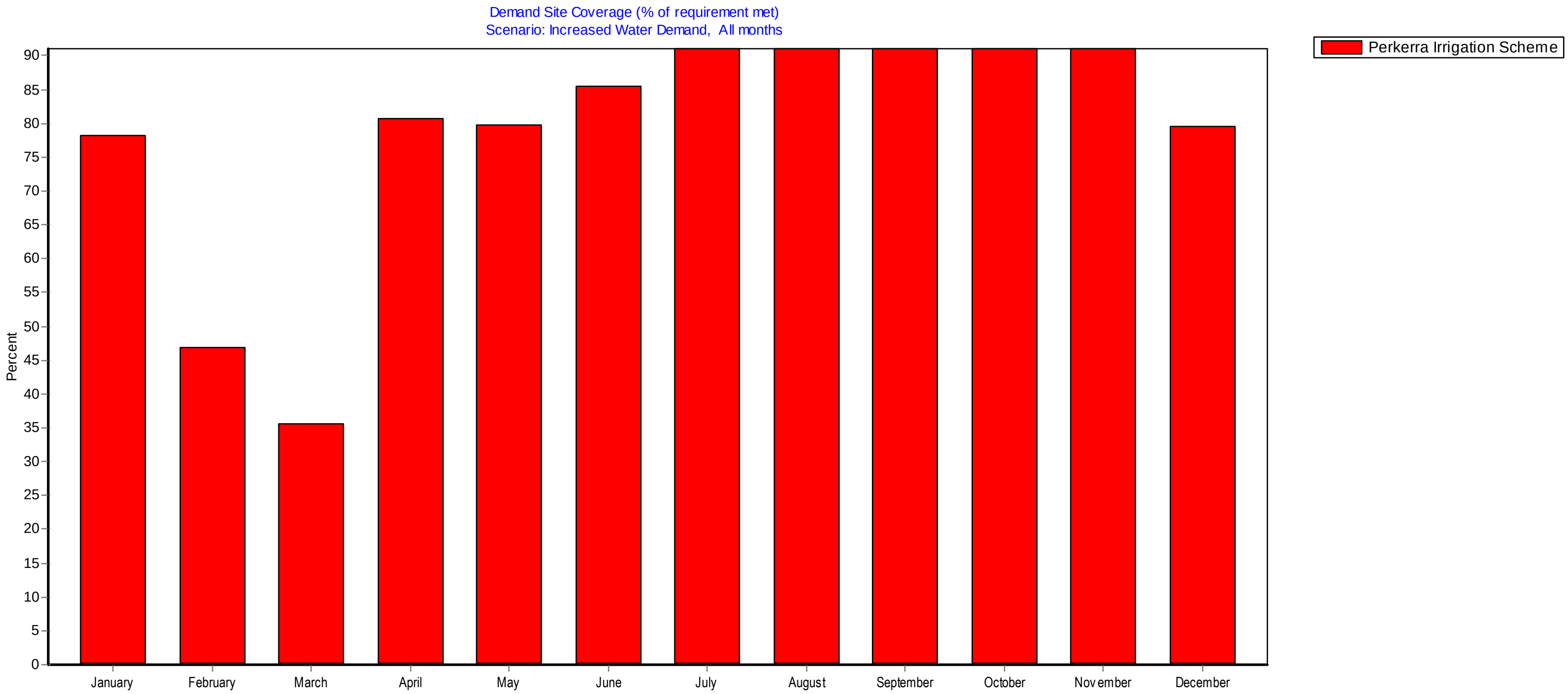

Figure F6 Perkerra Irrigation Scheme Demand Coverage

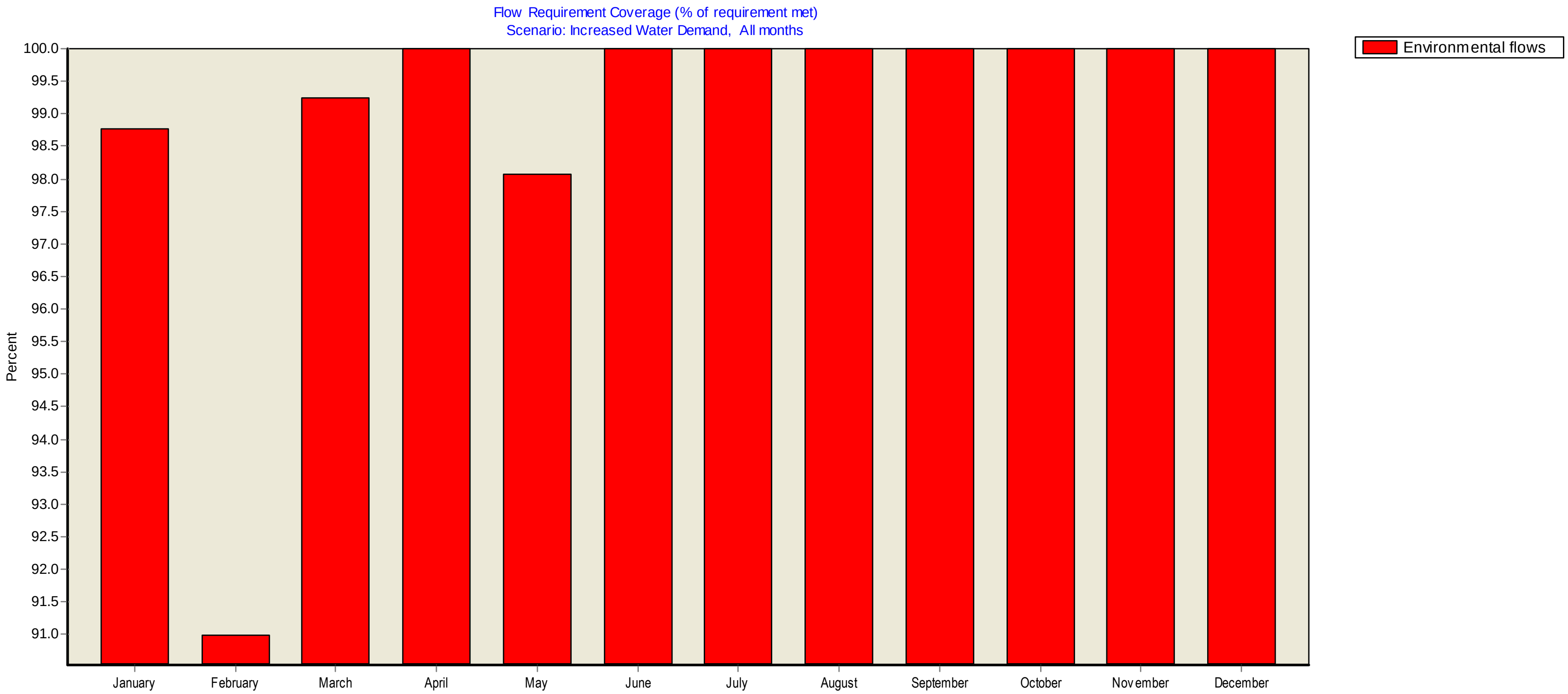

Figure F7 Increased Water Demand: Environmental Flow Coverage

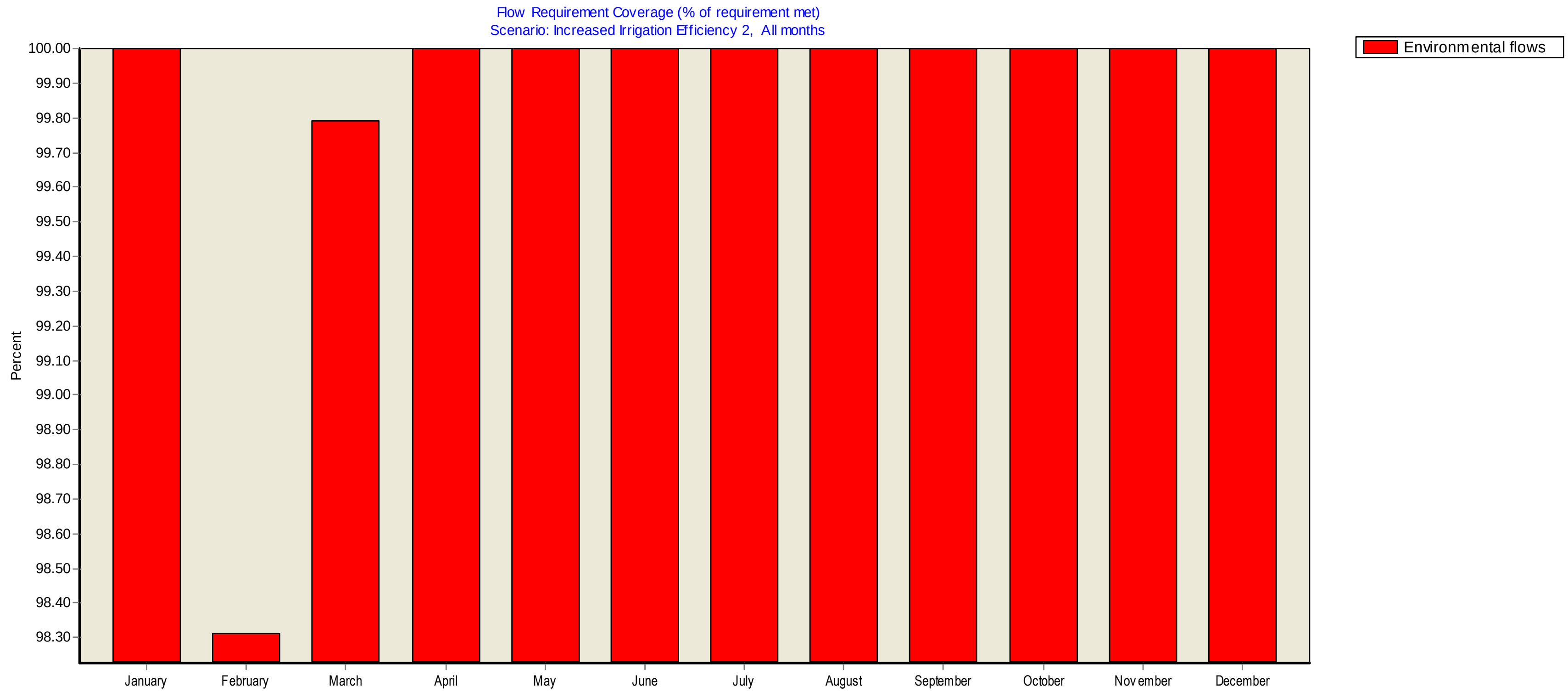

Figure F11. Improved Irrigation Efficiency 2: Environmental Flows Coverage