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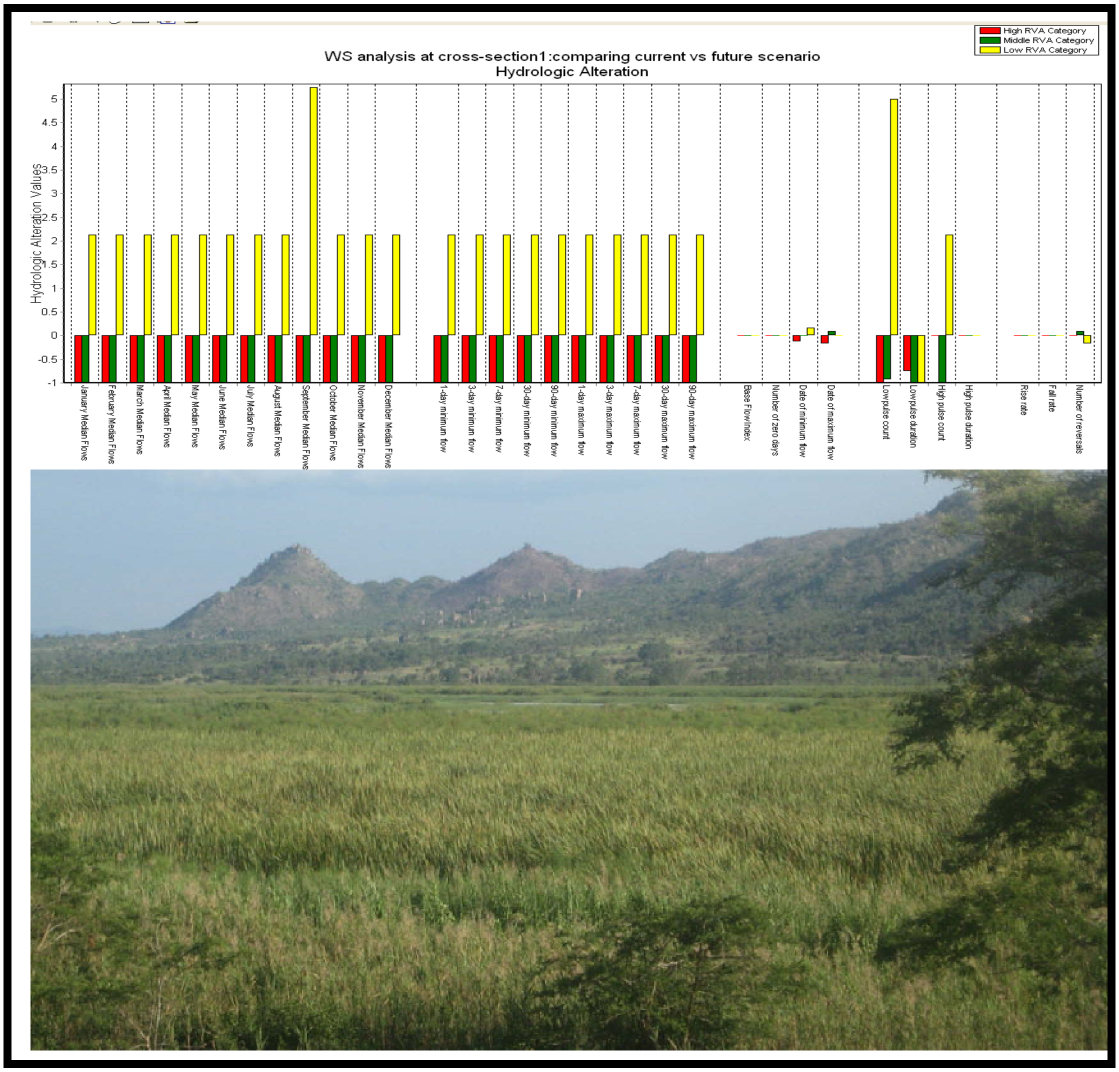

ECOHYDROLOGY STUDY OF KIRUMI WETLAND USING HYDROINFORMATICS TOOLS

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Ecohydrology Study of Kirumi Wetland using Hydroinformatics Tools

Master of Science Thesis
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Dedication

To my family and friends, for their continued support and encouragement.

Abstract

Hydroinformatics tools were used to set environmental water requirements for Kirumi wetland in Mara River catchment shared by Kenya and Tanzania. Mara River flows into lake Victoria in East Africa.

SWAT model was used to simulate the catchment hydrology making use of its ability to make changes in the catchment land use. Rainfall was used as input to the model and flow data from a gauging station at Mara mine was used to calibrate the model. The model calibration did not give good results (Nash-Sutcliffe coefficient of 0.15). A simulation of 25 years was done (1973 -1997) for the current situation and another 25 years for future scenario where land use was changed to reflect the future developments. The results indicated that there was no remarkable change in the water yield for the two scenarios (only 1.4% increase from the present to the future cenarios).

A HEC RAS model used the SWAT simulated flows for the two scenarios as upstream boundary conditions for simulating the Kirumi wetland profiles at 9 cross sections. The first scenario considered the current situation (upstream boundary condition as simulated hydrograph from current SWAT scenario and downstream boundary condition as current lake stage hydrograph). The second, used the upstream boundary condition a flow hydrograph from SWAT model future scenario and the downstream boundary condition, a lake water level hydrograph future scenario with 2 meter drop from the current trend. Manning's n values for the main channel and the overbank/flood plain were taken form literature considering the situation of the river, in the absence of calibration data.

An IHA model used the HEC RAS model results for the two scenarios at the nine cross sections to calculate the hydrologic alterations values. Comparing the pre impact (present scenario) and the post impact (future scenario), results showed no significant change in the parameters of flow in the wetland.

It was thus concluded that, even if the lake water levels goes down to pre sixties levels, and the upstream catchment land use changed (more land converted into farms), the ecosystem functions of the wetland will still be sustained. That is, environmental water requirements would still be met despite the changes. However, the decision as to what level of changes in the wetland and lake levels are acceptable, depend on the management objectives which will be set by the stakeholder.

Keywords: Ecohydrology, Hydroinformatics tools, Wetland.

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GLOWS	Global Water for Sustainability Program
WWF	Global Conservation Organization
NAWAPO	National water Policy 2002-Tanzania
NDSSU	National Decision Support System Unit
EAC	East African Community
mamsl	meters above mean sea level
IHE	Institute for Water Education
TU Delft	Technical University Delft
SWAT	Soil and Water Assessment Tool
HEC-RAS	Hydrologic Engineering Center-River analysis System
GPS	Geographic Positioning System
IHA	Indicators of Hydrologic Alteration
UNESCO	United Nations Education, Science and Culture Organization
AVSWAT	ArcView Soil and Water Assessment Tool
NBI	Nile Basin Initiative
WRPM	Water Resources Planning and Management Project
IUCN	International Union for Conservation of Nature
EFR	Environmental Flow Requirement
PHABSIM	Physical Habitat Simulation Model
IFIM	In-stream Flow Incremental Method
EFA	Environmental Flow Assessment
HRU	Hydrologic Response Unit
DEM	Digital Elevation Model
NASA	National Aeronautics and Space Administration
SRTM	Shuttle Radar Topographic Mission
ASCII	American Standard Code for Information Interchange
FAO	Food and Agriculture Organisation
USGS	United States Geological Survey
LH-OAT	Latin Hypercube-One factor At a Time
PARASOL	Parameter Solutions method
SCE-UA	Shuffled Complex Evolution Algorithm
SSQ	Sum of Squares of Residuals
MSE	Mean Square Error
SSQR	Sum of Squares of Residuals after Ranking
HEC DDSvue	Hydrologic Engineering Center Data Storage System visual utility engine
RVA	Range of Variability Aprroach
FRIEND	Flow Regime from International Experimental and Network Data
NBCBN	Nile Basin Capacity Building Network

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1. Introduction

1.1 Background

1.1.1 Definitions

Ecohydrology is a discipline in the interface of ecology and hydrology which is concerned with the interactions between the two fields of science (Hannah *et al.*, 2004). It tries to explain the effect of hydrological processes on the distribution, structure and functions of ecosystems, and on the effects of biotic processes on elements of the water cycle (Nuttle, 2002).

A wetland is a generic term used to define the universe of wet habits including marshes, swamps, bogs, fens and similar areas. Wetlands are environments subject to permanent or periodic inundation or prolonged soil saturation sufficient for establishment of hydrophytes and/or development of hydric soils or substrates (Tiner, 1999). The Ramsar convention, defines wetlands as areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6m. Five major types are distinguished as marine, estuarine, lacustrine, riverine and palustrine (Ramsar, 1998).

Hydroinformatics is a technology which uses information and communication advancement to solve problems related with the aquatic environment. It originates from simulation modelling, data driven modelling and artificial intelligence fields (Abbott, 1991).

Ecohydrology study of the Kirumi wetland aimed at using hydroinformatics tools in explaining the relationships that exist between the hydrology and the ecology in the wetland with respect to upstream catchment processes and lake level.

1.1.2 Mara catchment description

Mara catchment is a trans-boundary river catchment shared between Kenya and Tanzania. It also falls in the larger Nile river catchment. The Mara River catchment is about 13,750 km^2, of which about 65% is located in Kenya and 35% in Tanzania (figure 1).The catchment can be divided into four distinct physical and/or land-use sections, mainly on the basis of location along the river. The upper catchment comprises two of these sections: first, the forested Mau Escarpment and second, a section characterized by large-scale agricultural farms. Some of the large-scale agricultural farms are irrigated using water from the Mara River. The Mara River then runs through the third section, which is open savannah grassland protected by the Masai Mara Reserve on the Kenyan side and the Serengeti National Park on the Tanzanian side, two important and renowned protected areas in the region. The flood plains and wetlands comprise the fourth section and are located in Tanzania where the Mara River discharges into Lake Victoria (GLOWS, 2007; Mturi, 2007; WWF, 2007).

Main competing interests for water resources in the Mara River include the large scale irrigation plantations on the Kenyan side, the Masai Mara and Serengeti Wildlife protected areas, small scale farmers and pastoralists on both sides of the basin, the mining industry in Tanzania, small scale fishing activities and urban and rural domestic water supplies.

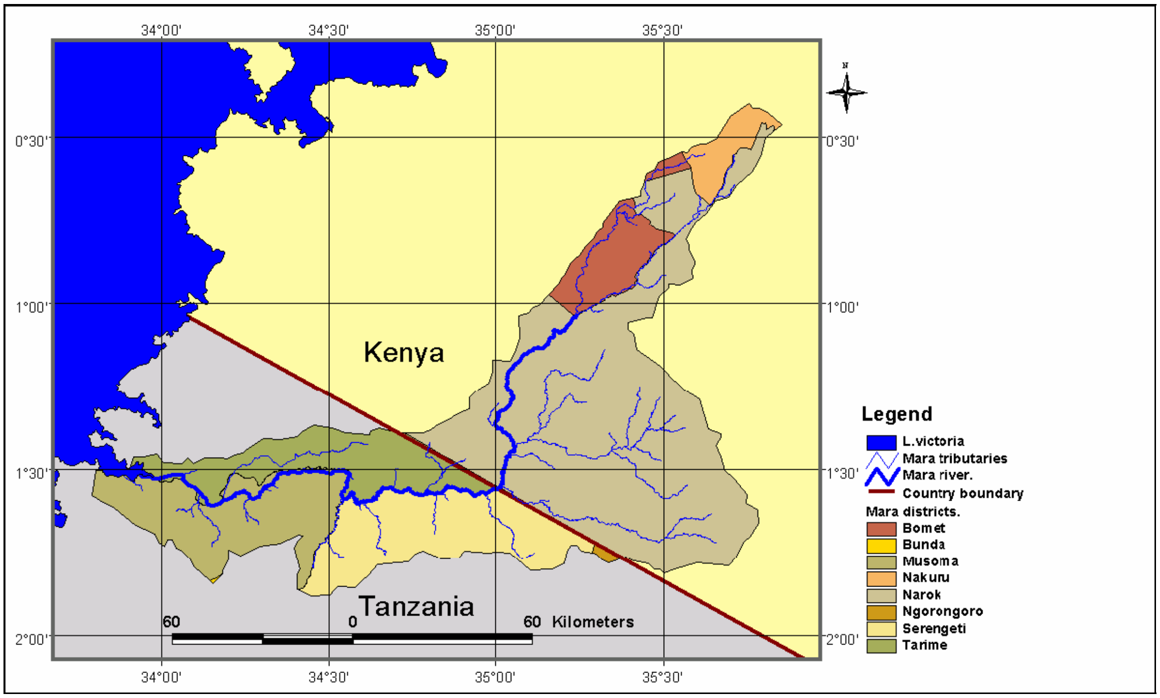

Figure 1: Location of Mara river catchment in Kenya and Tanzania.
Source:(Mutie *et al.*, 2006).

The Mara River faces problems of overuse and pollution of the water. This is due to different economic activities ongoing in the catchment (GLOWS, 2007; Mturi, 2007; Mutie *et al.*, 2006; Ngendahayo, 2007; WWF, 2007). The overuse of water alters the hydrologic regime of the river. This affects the riverine aquatic ecosystems' processes, functioning and components (Bunn and Arthington, 2002; Dyson *et al.*, 2003; Tharme, 2003; Tharme *et al.*, 2007). Communities living along the river depend on the services accrued from the riverine and riparian ecosystems like food, water supply in quality and quantity, timber, firewood and fibbers. These services' sustainability is underpinned by a healthy ecosystem functioning. The communities are impacted by the changes in quality and quantity of river flows in terms of health, income, food security and natural resources (GLOWS, 2007). Further problems are caused by the loss of forest cover in the upper catchments and along rivers, unsustainable agricultural practices (including irrigation), pollution threats from urban settlements, and mining (WWF, 2007). Masai Mara and Serengeti parks contain the most diverse combination of grazing mammals in the world, holding about 400,000 wildlife and livestock (Mutie *et al.*, 2006).

In addressing these problems, different efforts are being done at various levels. At Policy and Legal level, the respective countries sharing the river catchment have adopted and enacted good policies and laws. Tanzania has a new National Water Policy 2002 (NAWAPO) and Kenya has enacted Water Act 2002. All these are based on the rationale of integrated water resources management (Lugomela and Sanga, 2007; NAWAPO, 2002; NDSSU-Kenya, 2007).

At catchment level, efforts are being done to address these issues including the current assessment of environmental flows. This assessment, though done for the whole catchment, is more focused on the upper side of the catchment (Kenyan side) where most problems originate. However, the environmental flows which will be recommended have to take care of the Kirumi wetland which is at the downstream of the catchment. Environmental flows ensures quantity, quality and distribution of water to maintain components, functions and processes of riverine ecosystems on which people depend (O'Keeffe, 2007). In order to recommend flows for Kirumi wetland, studies have to be conducted to establish the hydrological relationship between Lake Victoria, Kirumi wetland and the Mara River catchment.

Mturi (2007) studied Kirumi wetland with regard to the linkage of flow patterns, wetland size and functions. He used GIS to analyse satellite images to assess the changes in size of the wetland over about 30 years. The study found that the wetland water level is largely governed by Lake Victoria water levels. The Mara river flows had little effects to the wetland water level. The local rainfall has no effect on the wetland water level. However, some important issues were not addressed by the study. These include effects of the catchment hydrology on the wetland, spatial variation of the water levels in the wetland and the effects of Lake Victoria and catchment management scenarios on the wetland. Also the method used could not address the study objectives thoroughly.

This research continues the work by Mturi (2007) to provide insight of how the hydrology of the catchment/river, lake and the wetland are related. It aimed at providing some insight as to how the wetland might be affected by different catchment management scenarios or changes to the lake water levels. The result of the research would be used as an input in the ongoing environmental flows assessment process in the catchment. SWAT tool has been used to simulate the hydrology of the catchment. HEC-RAS and IHA were used to simulate water levels in the wetland and effects of management scenarios of the lake and the catchment respectively.

1.1.3 Description of the research area

Kirumi wetland is situated at the lower end of Mara River before entering lake Victoria. The wetland covers an area of about 20 square kilometers, 9 kilometers East of the lake. It is surrounded by Kirumi, Ryamisanga, Marasibora, Kukona and Kwibuse villages (figure 2) (Mturi, 2007).

Figure 2: Location of Kirumi wetland.
Source:Microsoft Encarta Premium Suite 2003

Kirumi wetland (figure 3) has been increasing in size notably since 1980s (Mturi, 2007). Mtalo et al., (2005) attributed the increase by 1.31 of the wetland size to the sedimentation in the river as a result of the land use changes in the Mara river upper catchment (Mtalo *et al.*, 2005).

Others argue that Lake Victoria has backwater flow which affects the Kirumi wetland (Mturi, 2007).

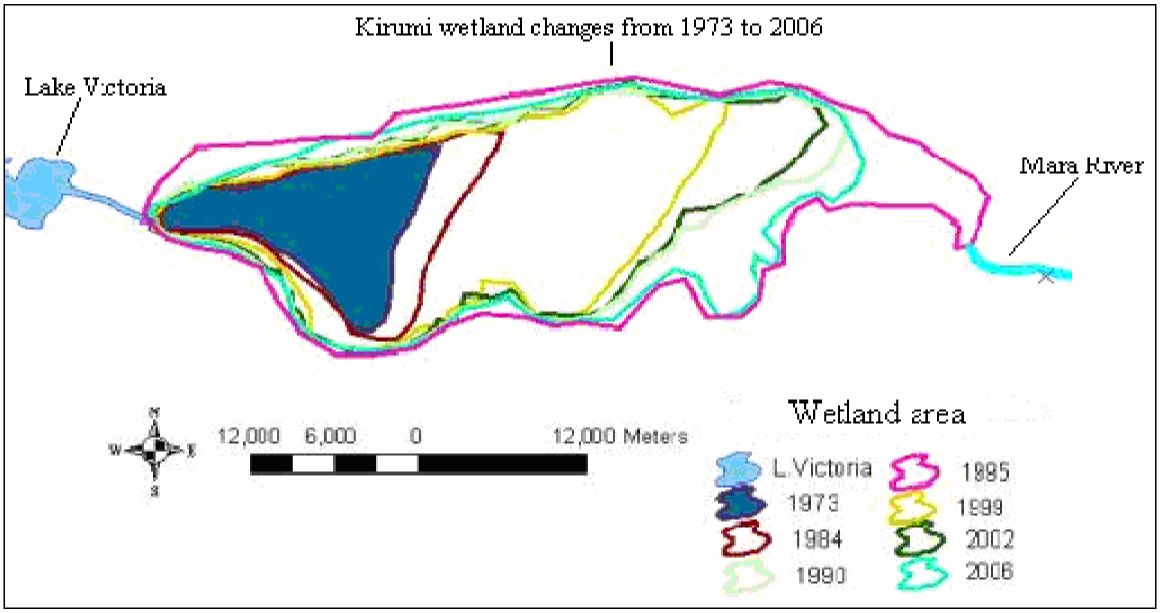

Figure 3: Size change of Kirumi wetland since 1973.

Source: Mturi (2007).

As the wetland provides food, timber, firewood and fibbers to about 6000 people ((Mturi, 2007)), it is important to understand the causes of these changes with regard to the lake water levels, the wetland water level and the river hydrology. It is not known yet as to why the wetland size has increased so fast since 1984 and how different management scenarios of the catchment and the lake may affect the wetland.

Mturi (2007) found out that the lake water levels have a strong correlation with the water levels in the Kirumi wetland. Also the wetland water levels have a weak correlation with the river flows especially during the river high flows.

Water levels in Lake Victoria have been declining recently (EAC-Secretariat, 2006; Mwanuzi *et al.*, 2006). Studies show that while inflows into the lake and precipitation have decreased by 22% and 7% respectively, the outflow has increased by 15% (EAC-Secretariat, 2006). Figure 4 shows the trend of the lake levels from 1900 to 2004. With the current trend of lake level worries exist that the Kirumi wetland might be endangered. It is therefore important to understand the hydrology of the lake, the river and the wetland and how they relate in order to have a proper recommendation of the environmental flows. If the lake levels will drop to pre 1960 levels, there may be a possibility of the wetland reducing in size. In this case, the sustainability of services of the wetland to the 6000 people will solely depend of the quantity, quality and distribution of flow which will be recommended in the ongoing environmental flow assessment for the Mara River.

This study sought to find out the hydrologic relationships between Lake Victoria, Kirumi wetland and the Mara River through looking at the effects of lake and catchment management scenarios. The results may be used in the ongoing study of recommending environmental flows for the Mara River.

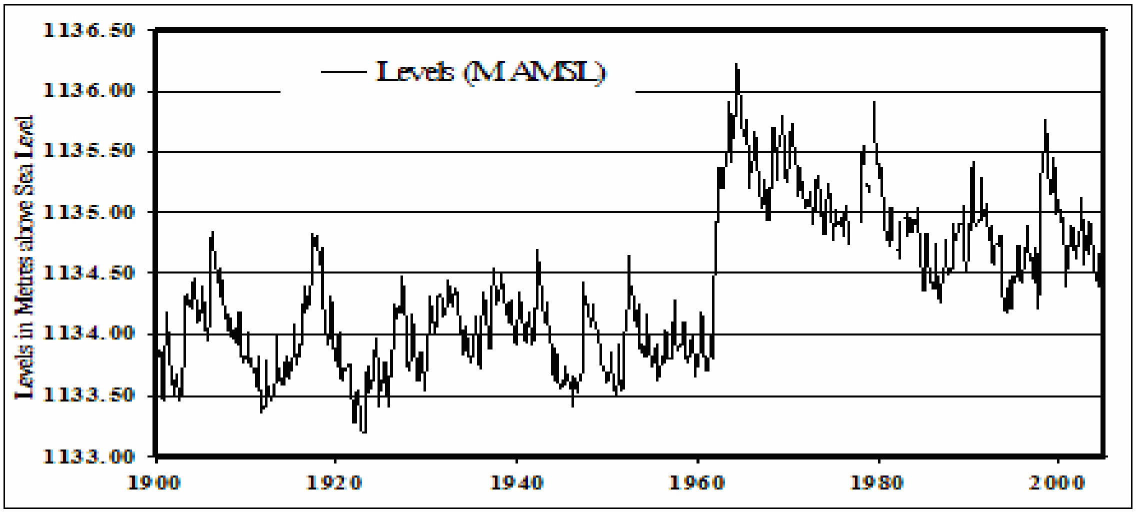

Figure 4: Variation in Lake Victoria levels from 1900 to 2004. Source: (EAC-Secretariat, 2006)

1.2 Objective of the research

The objective of the study is to asses environmental flows required to sustain the functions of Kirumi wetland. Specific objectives include:

- Simulate the catchment hydrology using SWAT model
- Simulate Kirumi wetlands hydraulics using HEC-RAS model.
- Finding the effects of the lake and river water levels on the wetland water levels

The following research questions were sought to be answered by doing the study:

- How has Kirumi wetland been affected by the Mara catchment and Lake Victoria hydrology?
- What are the spatial characteristics of Kirumi wetland water levels?
- How may the wetland respond to Lake Victoria and Mara catchment management scenarios?

The result may contribute to the ongoing environmental flow assessment of the Mara River. The following hypothesis were tested:

- Mara catchment hydrology has no effect on the Kirumi wetland hydrology
- If Lake Victoria water levels continues to fall beyond 1960 levels of 1134 mamsl, Kirumi wetland will disappear

The study outcome is the current wetland levels status, the projections of the future levels and the indications of the alteration of the wetland hydrology by comparing the present and the future situations.

1.3 Thesis outline

Chapter one of the thesis gives the background information about the problems facing the project area, study area description and objectives of the study. Chapter two describes literature reviewed in the process of carrying the research and the methodology adopted in carrying out the study. Report on data collection is explained in chapter three while chapter four describes the models building. Chapters five through six presents and discusses the results of the work while chapter seven gives the conclusion and recommendations of the study.

2. Literature Review and methodology

2.1 Environmental Flow Assessment Models

2.1.1 Introduction

In many parts of the world there is growing awareness of the pivotal role of the flow regime (hydrology) as a key 'driver' of the ecology of rivers and their associated floodplains. Every river system has an individual or 'signature' flow regime with particular characteristics relating to flow quantity and temporal attributes such as seasonal pattern of flows, the timing, requency, predictability and duration of extreme events (e.g. floods and droughts), rates of change and other aspects of flow variability. Each of these hydrological characteristics has individual as well as interactive regulatory influences on the biophysical structure and functioning of river and floodplain ecosystems, including the physical nature of river channels, sediment regime and water quality, biological diversity/riverine biota and key ecological processes sustaining the aquatic ecosystem. These processes in turn govern the ecosystem goods and services that rivers provide to humans like flood attenuation, water purification, production of fish and other foods and marketable goods (Tharme *et al.*, 2007) . When these hydrological regime changes due to reasons ranging from anthropogenic to natural, the ecosystems are in the aquatic environment are bound to respond to these changes.

Recognition of the escalating hydrological alteration of rivers on a global scale and the resultant environmental degradation has led to the gradual establishment of a field of scientific research termed environmental flow assessment (Tharme, 2003). IUCN (Dyson *et al.*, 2003) defines an environmental flow as the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. This flow maintains the ecosystem in a less than pristine condition. The process of determining the quantity of water to be left in the river for this ecological function is called environmental flow assessment or environmental water allocation. Different models have been developed to accomplish this task. The focus of these models has always been two fold, the hydrology and the ecosystem.

2.1.2 Environmental flow assessment methods

Although many methods have been developed and used in different places in the world, four main groups can be distinguished among the methods. These are hydrological methods, hydraulic rating methods, habitat simulation methods and holistic approach methods.

Hydrological Methodologies

These represent the simplest set of techniques where, at a desktop level, hydrological data, as naturalised, historical monthly or average daily flow records, are analysed to derive standard flow indices which then become the recommended environmental flows. Commonly, the EFR is represented as a proportion of flow (often termed the 'minimum flow', e.g. Q95 – the flow equaled or exceeded 95 percent of the time) intended to maintain river health, fisheries or other highlighted ecological features at some acceptable level, usually on an annual, seasonal or monthly basis. In a few instances, secondary criteria in the form of catchment variables, hydraulic, biological or geomorphological parameters are also incorporated. As a result of the rapid and non-resource intensive provision of low resolution flow estimates, hydrological methodologies are generally used mainly at the planning stage of water resource developments, or in situations where preliminary flow targets and exploratory water allocation trade-offs are required.

Hydraulic Rating Methodologies

Hydraulic rating methodologies use changes in simple hydraulic variables, such as wetted perimeter or maximum depth, usually measured across single, flow limited river cross-sections (commonly riffles), as a surrogate for habitat factors known or assumed to be limiting to target biota. Environmental flows are determined from a plot of the hydraulic variable(s) against discharge, commonly by identifying curve breakpoints where significant percentage reductions in habitat quality occur with decreasing discharge. It is assumed that ensuring some threshold value of the selected hydraulic parameter at a particular level of altered flow will maintain aquatic biota and thus, ecosystem integrity. These relatively low-resolution hydraulic techniques have been superseded by more advanced habitat modelling tools, or assimilated into holistic methodologies (Tharme, 2003). However, select approaches continue to be applied and evaluated, notably the Wetted Perimeter Method (Tharme *et al.*, 2007).

Habitat Simulation or Microhabitat Modelling Methodologies

Habitat simulation methodologies also make use of hydraulic habitat-discharge relationships, but provide more detailed, modelled analyses of both the quantity and suitability of the physical river habitat for the target biota. Thus, environmental flow recommendations are based on the integration of hydrological, hydraulic and biological response data. Flow-related changes in physical microhabitat are modelled in various hydraulic programs, typically using data on depth, velocity, substratum composition and cover; and more recently, complex hydraulic indices (e.g. benthic shear stress), collected at multiple cross-sections within each representative river reach. Simulated information on available habitat is linked with seasonal information on the range of habitat conditions used by target fish or invertebrate species (or life-history stages, assemblages and/or activities), commonly using habitat suitability index curves. The resultant outputs, in the form of habitat-discharge curves for specific biota, or extended as habitat time and exceedence series, are used to derive optimum environmental flows. The habitat simulation-modelling package PHABSIM housed within the Instream Flow Incremental Methodology (IFIM), is the pre-eminent modeling platform of this type. The relative strengths and limitations of such methodologies are described in Tharme (2007).

Holistic Methodologies

Over the past decade, river ecologists have increasingly made the case for a broader approach to the definition of environmental flows to sustain and conserve river ecosystems, rather than focusing on just a few target fish species (Richter *et al.*, 2006). From the conceptual foundations of a holistic ecosystem approach, a wide range of holistic methodologies has been developed and applied, initially in Australia and South Africa and more recently in the United Kingdom. This type of approach reasons that if certain features of the natural hydrological regime can be identified and adequately incorporated into a modified flow regime, then, all other things being equal, the extant biota and functional integrity of the ecosystem should be maintained (Tharme, 2003). Likewise, Sparks (Sparks, 1995) suggested that rather than optimizing water regimes for one or a few species, a better approach is to try to approximate the natural flow regime that maintained the “entire panoply of species”. Importantly, holistic methodologies aim to address the water requirements of the entire “riverine ecosystem” rather than the needs of only a few taxa (usually fish or invertebrates). These methodologies are underpinned by the concept of the “natural flows paradigm” (Poff *et al.*, 1997) and basic principles guiding river corridor restoration (Ward *et al.*, 2001). They share a common objective - to maintain or restore the flow related biophysical components and ecological processes of in-stream and groundwater systems, floodplains and downstream receiving waters (e.g. terminal lakes and wetlands, estuaries and near-shore marine ecosystems). Ecosystem components that are commonly considered in holistic assessments include geomorphology, hydraulic habitat, water quality, riparian and aquatic vegetation, macroinvertebrates, fish and other vertebrates with some dependency upon the river/riparian ecosystem (i.e. amphibians, reptiles, birds, mammals). Each of these components can be evaluated using a range of field and desktop techniques (see (Arthington and Zalucki, 1998); for reviews) and their flow requirements are then incorporated into EFA recommendations, using various systematic approaches as discussed in more detail below. Holistic environmental flow assessments may include evaluation of a range of other mitigation measures, for example, how to restore longitudinal and lateral connectivity by providing fish passes or altering the configuration of levee banks on a floodplain. Management of storage water levels may also be examined and recommendations made on the benefits of more, or less, stable water levels. Some holistic methodologies also take into consideration the influence of threatening processes and disturbances unrelated (or less directly related) to flow regulation and advise on possible mitigation measures such as riparian and habitat restoration, or the management of invasive vegetation and fish.

2.1.3 Conclusion

Considering the aforegoing methods of the assessing environmental flows, it is evident that the issue of environmental flows tries to link hydrology, hydraulics and ecological processes in the aquatic environment and riparian vegetation. Hydrological and hydraulic methods deal with only the provision of flows to resemble the natural flows assuming that it is the hydrology which drives the ecosystem dynamics. Habitat modeling and holistic methods incorporates, in addition to hydrology and hydraulics, the ecosystem data in modeling the aquatic ecosystem processes. These methods, how ever, require a heavy investment in funds and time.

In this research, use was made of indicators of hydrologic alteration model (IHA) (Richter *et al.*, 1996) which is based upon an analysis of hydrologic data available either from existing measurement points within an ecosystem (such as at stream gauges or wells) or model-generated data. This method falls in the first two groups of methods which do not use ecosystem data.

2.2 SWAT model

2.2.1 SWAT model theory

SWAT is an abbreviation for Soil and Water Assessment Tool, which is a river basin scale tool developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds. It is a physically based model as it requires specific information on weather, soil properties, topography, vegetation and land management practices occurring in the watershed. The physical processes associate with water movement, sediment movement, crop growth cycling, etc are directly modelled using these data(Arnold *et al.*, 2002). The model is computationally efficient to enable simulations of very large basins without investing much in time or money. The model has modules which represent these processes in the catchment.

SWAT model is capable of modeling different processes from, sediment movement, pesticides to nutrients. Water balance is used as a driving force for modeling all other processes where the hydrology of the catchment is separated into two divisions, land phase (figure 6) and the routing phase (figure 8). The model simulation must conform to what is happening in the watershed.

2.2.1.1 Land phase of the hydrological cycle

The simulation by SWAT of the hydrological cycle is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

Where

SW_t is the final soil water content (mmH_2O),
SW_o is the initial soil water content on day *i* (mm H_2O),
R_{day} is the amount of precipitation on day *i,*
Q_{surf} is the amount of surface runoff on day *i* (mm H_2O),
E_a is the amount of evapotranspiration on day *i* (mm H_2O),
w_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm H2O),
Q_{gw} is the amount of return flow on day *i* (mm H2O).

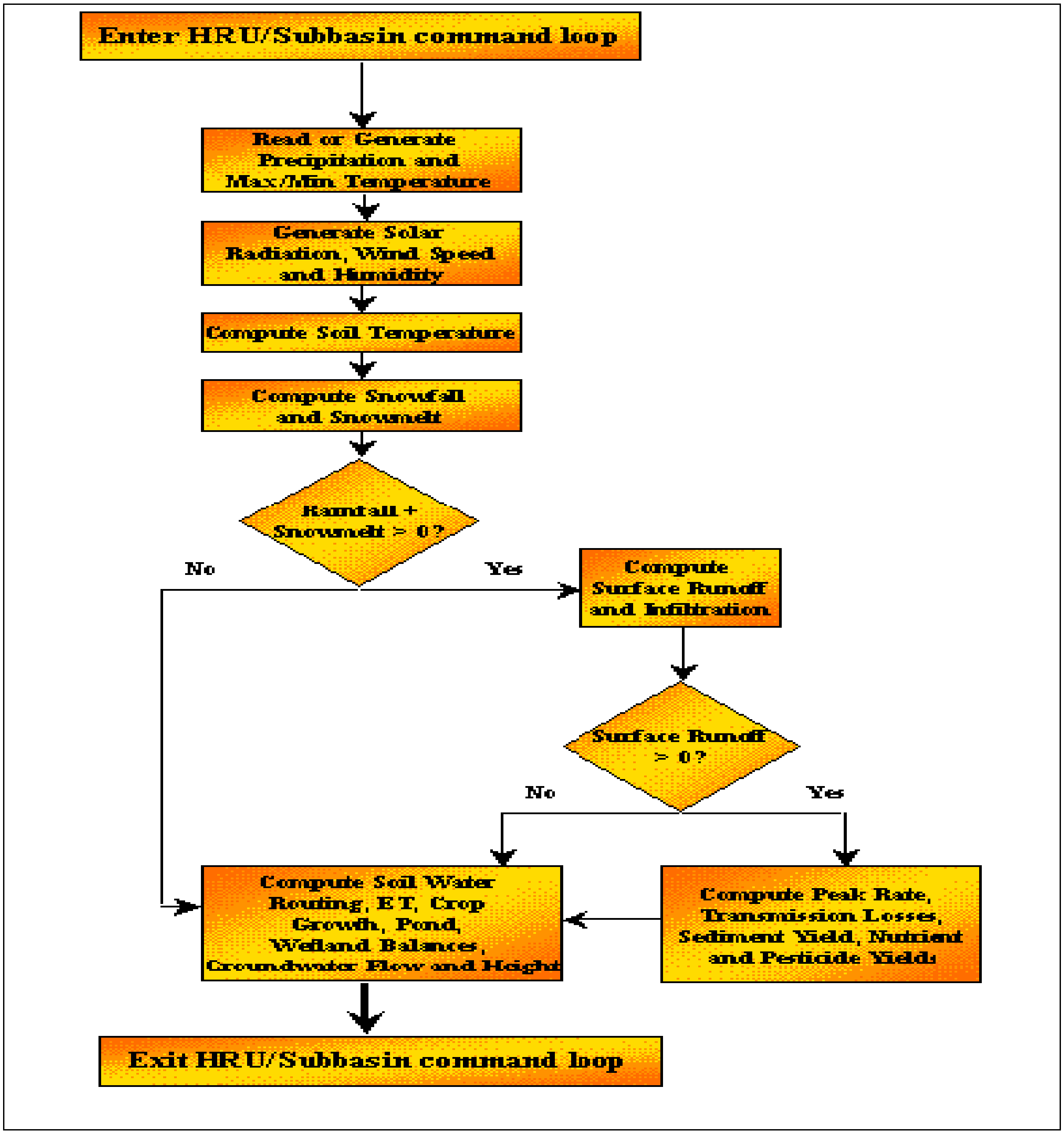

Figure 5. The general sequence of processes used by SWAT to model the land phase of the hydrologic cycle. Source (Neitsch *et al.*, 2002).

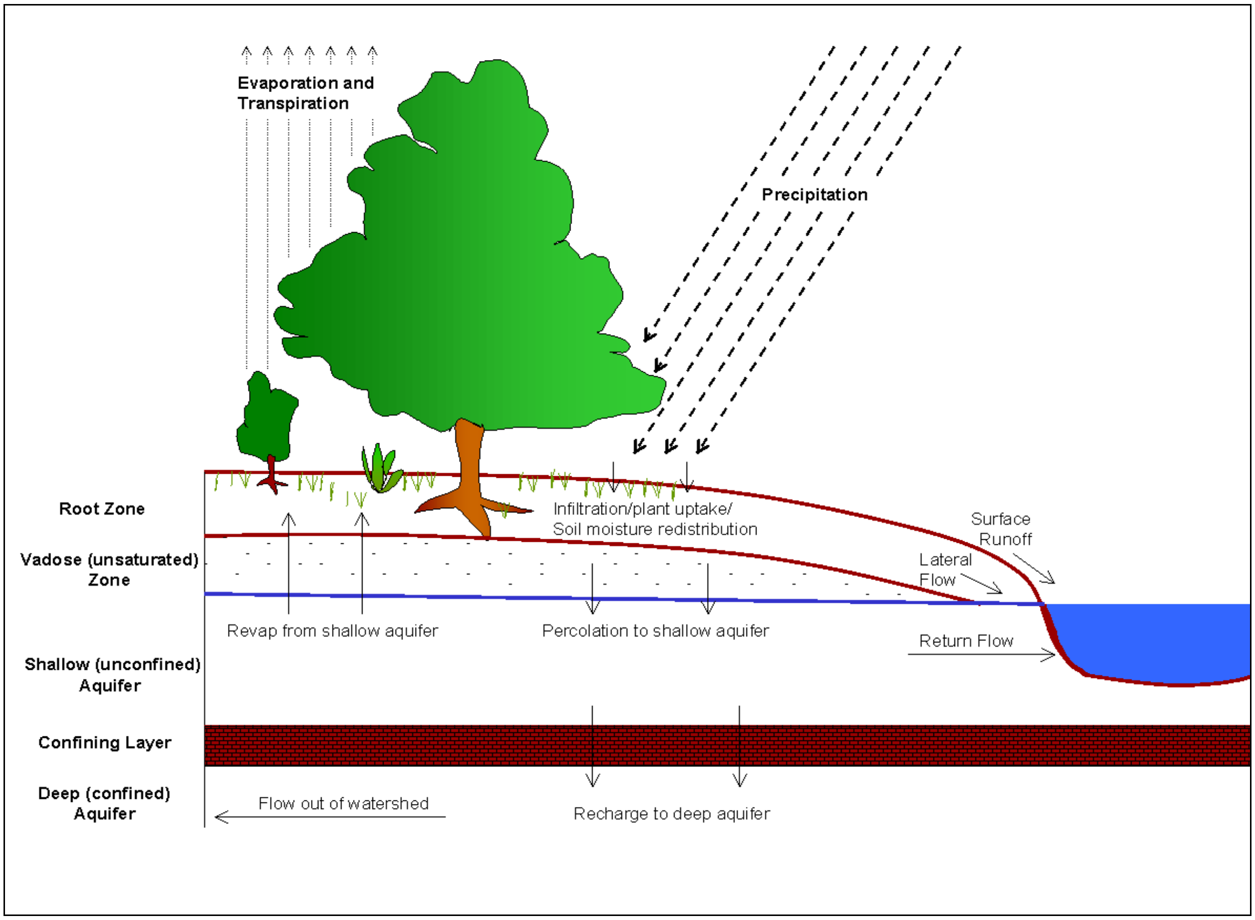

Figure 6. Schematic representation of the hydrologic cycle. source:(Neitsch *et al.,* 2002).

The subdivision of the watershed into subbasins enables the model to reflect differences in evapotranspiration for various crops and soils. Hydrologic response units (HRUs) are lumped land areas within the subbasin that are comprised of unique land cover, soil, and management combinations. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance. The following paragraphs describes the inputs and processes involved in the land phase of hydrological cycle.

2.2.1.2 Climate

Climate of the watershed provide the energy and moisture which control the water balance of the watershed. The climate variables required by SWAT include daily precipitation, maximum/minimum air temperatures, solar radiation, wind speed and relative humidity. These variables can be either entered into the model from observations or generated by the model itself. For basins where there are no observations, daily value for weather are generated from average monthly values. Precipitation data is generated or filled (for missing values) using a model developed by Nicks (1974). Maximum and minimum air temperatures are generated from a normal distribution. A modified exponential equation is used to generate daily mean wind speed given the mean monthly wind speed. A relative humidity model uses a triangular distribution to simulate the daily average relative humidity from the monthly average. Daily soil temperature is calculated at the soil surface and at the center of each soil layer. At the soil surface, it depends on snow cover, plant cover, residue cover, the bare soil surface temperature and the previous day's soil surface temperature. At the center of the soil layer, it depends on surface temperature, mean annual air temperature and the depth in the soil at which variation in temperature due to changes in climatic conditions no longer occurs.

2.2.1.3 Hydrology

As precipitation descends, it may be intercepted and held in the vegetation canopy or fall to the soil surface. Water on the soil surface will infiltrate into the soil profile or flow overland as runoff. Runoff moves relatively quickly toward a stream channel and contributes to short-term stream response. Infiltrated water may be held in the soil and later evapotranspired or it may slowly make its way to the surface-water system via underground paths. The potential pathways of water movement simulated by SWAT in the HRU are illustrated in figure 7.

Canopy Storage.

Canopy storage is the water intercepted by vegetative surfaces (the canopy) where it is held and made available for evaporation. When using the curve number method to compute surface runoff, canopy storage is taken into account in the surface runoff calculations. However, if methods such as Green & Ampt are used to model infiltration and runoff, canopy storage must be modeled separately. SWAT allows the user to input the maximum amount of water that can be stored in the canopy at the maximum leaf area index for the land cover. This value and the leaf area index are used by the model to compute the maximum storage at any time in the growth cycle of the land cover/crop. When evaporation is computed, water is first removed from canopy storage.

Infiltration

Infiltration refers to the entry of water into a soil profile from the soil surface. As infiltration continues, the soil becomes increasingly wet, causing the rate of infiltration to decrease with time until it reaches a steady value. The initial rate of infiltration depends on the moisture content of the soil prior to the introduction of water at the soil surface. The final rate of infiltration is equivalent to the saturated hydraulic conductivity of the soil. Because the curve number method used to calculate surface runoff operates on a daily time-step, it is unable to directly model infiltration. The amount of water entering the soil profile is calculated as the difference between the amount of rainfall and the amount of surface runoff. The Green & Ampt infiltration method does directly model infiltration, but it requires precipitation data in smaller time increments.

Redistribution

Redistribution refers to the continued movement of water through a soil profile after input of water (via precipitation or irrigation) has ceased at the soil surface. Redistribution is caused by differences in water content in the profile. Once the water content throughout the entire profile is uniform, redistribution will cease. The redistribution component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow, or percolation, occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is governed by the saturated conductivity of the soil layer. Redistribution is affected by soil temperature. If the temperature in a particular layer is 0°C or below, no redistribution is allowed from that layer.

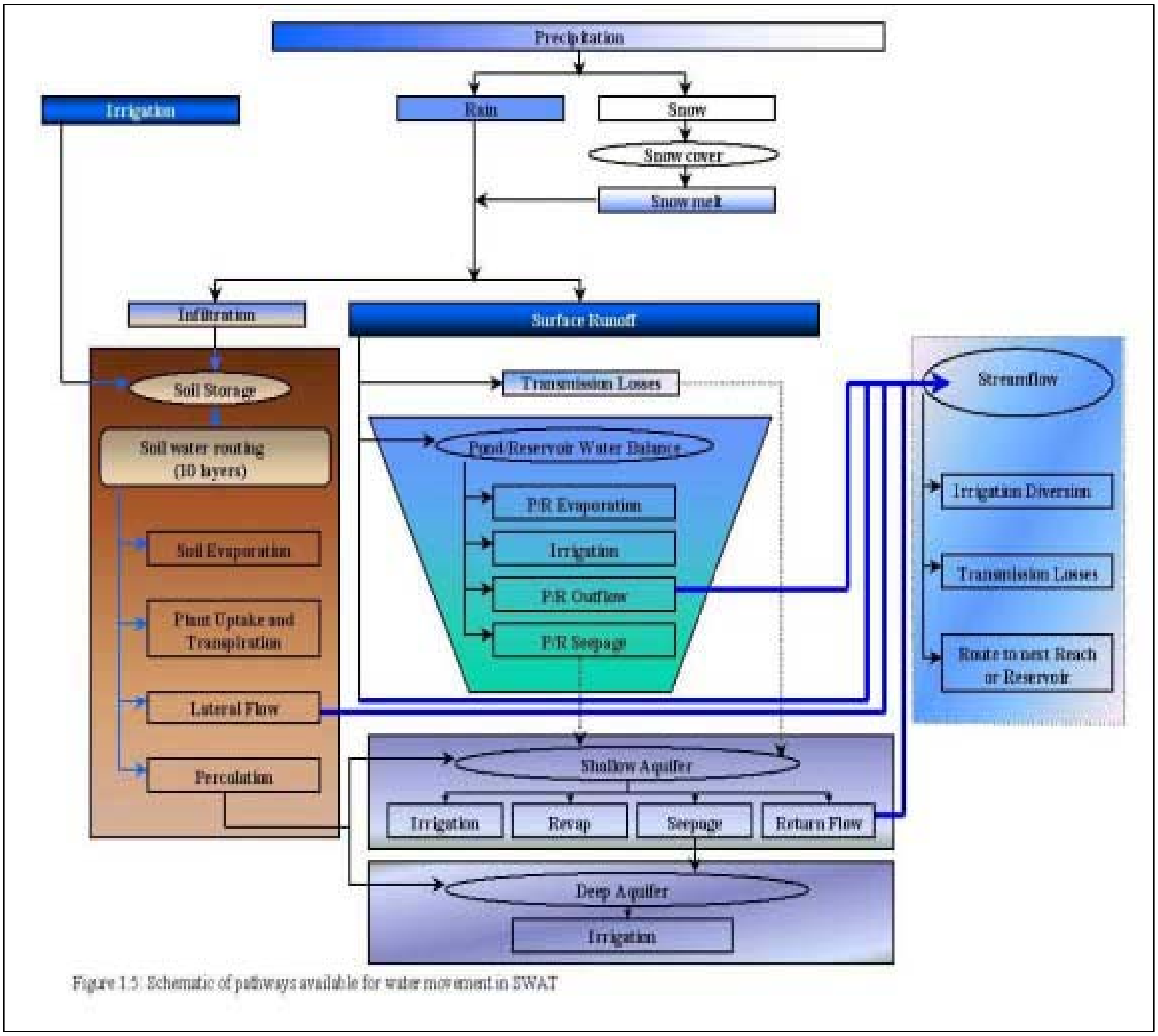

Figure 7. Schematic of pathways available for water movement in SWAT. Source (Neitsch *et al.*, 2002)

Evapotranspiration

Evapotranspiration is a collective term for all processes by which water in the liquid or solid phase at or near the earth's surface becomes atmospheric water vapor. Evapotranspiration includes evaporation from rivers and lakes, bare soil, and vegetative surfaces; evaporation from within the leaves of plants (transpiration); and sublimation from ice and snow surfaces. The model computes evaporation from soils and plants separately as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index (area of plant leaves relative to the area of the HRU). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index.

Potential Evapotranspiration

Potential evapotranspiration is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water. This rate is assumed to be unaffected by micro-climatic processes such as advection or heat-storage effects. The model offers three options for estimating potential evapotranspiration: Hargreaves (Hargreaves et al., 1985), Priestley-Taylor (Priestley and Taylor, 1972), and Penman-Monteith (Monteith, 1965).

Lateral Subsurface Flow

Lateral subsurface flow, or interflow, is streamflow contribution which originates below the surface but above the zone where rocks are saturated with water. Lateral subsurface flow in the soil profile (0-2m) is calculated simultaneously with redistribution. A kinematic storage model is used to predict lateral flow in each soil layer. The model accounts for variation in conductivity, slope and soil water content.

Surface Runoff

Surface runoff, or overland flow, is flow that occurs along a sloping surface. Using daily or sub-daily rainfall amounts, SWAT simulates surface runoff volumes and peak runoff rates for each HRU.

SURFACE RUNOFF VOLUME is computed using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972) or the Green & Ampt infiltration method (Green and Ampt, 1911). In the curve number method, the curve number varies non-linearly with the moisture content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation. The Green & Ampt method requires sub-daily precipitation data and calculates infiltration as a function of the wetting front matric potential and effective hydraulic conductivity. Water that does not infiltrate becomes surface runoff. SWAT includes a provision for estimating runoff from frozen soil where a soil is defined as frozen if the temperature in the first soil layer is less than 0°C. The model increases runoff for frozen soils but still allows significant infiltration when the frozen soils are dry.

PEAK RUNOFF RATE predictions are made with a modification of the rational method. In brief, the rational method is based on the idea that if a rainfall of intensity i begins instantaneously and continues indefinitely, the rate of runoff will increase until the time of concentration, t_c, when all of the subbasin is contributing to flow at the outlet. In the modified Rational Formula, the peak runoff rate is a function of the proportion of daily precipitation that falls during the subbasin t_c, the daily surface runoff volume, and the subbasin time of concentration. The proportion of rainfall occurring during the subbasin t_c is estimated as a function of total daily rainfall using a stochastic technique. The subbasin time of concentration is estimated using Manning's Formula considering both overland and channel flow.

Ponds

Ponds are water storage structures located within a subbasin which intercept surface runoff. The catchment area of a pond is defined as a fraction of the total area of the subbasin. Ponds are assumed to be located off the main channel in a subbasin and will never receive water from upstream subbasins. Pond water storage is a function of pond capacity, daily inflows and outflows, seepage and evaporation. Required inputs are the storage capacity and surface area of the pond when filled to capacity. Surface area below capacity is estimated as a nonlinear function of storage.

Tributary Channels

Two types of channels are defined within a subbasin: the main channel and tributary channels. Tributary channels are minor or lower order channels branching off the main channel within the subbasin. Each tributary channel within a subbasin drains only a portion of the subbasin and does not receive groundwater contribution to its flow. All flow in the tributary channels is released and routed through the main channel of the subbasin. SWAT uses the attributes of tributary channels to determine the time of concentration for the subbasin.

Transmission Losses

Transmission losses are losses of surface flow via leaching through the streambed. This type of loss occurs in ephemeral or intermittent streams where groundwater contribution occurs only at certain times of the year, or not at all. SWAT uses Lane's method
described in Chapter 19 of the SCS Hydrology Handbook (USDA Soil Conservation Service, 1983) to estimate transmission losses. Water losses from the channel are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur in tributary channels.

Return Flow

Return flow, or base flow, is the volume of streamflow originating from groundwater. SWAT partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes return flow to streams outside the watershed (Arnold et al., 1993). Water percolating past the bottom of the root zone is partitioned into two fractions—each fraction becomes recharge for one of the aquifers. In addition to return flow, water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions or be directly removed by plant. Water in the shallow or deep aquifer may be removed by pumping.

2.2.1.4 Routing Phase of the Hydrologic Cycle

Once SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Williams and Hann, 1972). In addition to keeping track of mass flow in the channel, SWAT models the transformation of chemicals in the stream and streambed. Figure 8 illustrates the different in-stream processes modeled by SWAT.

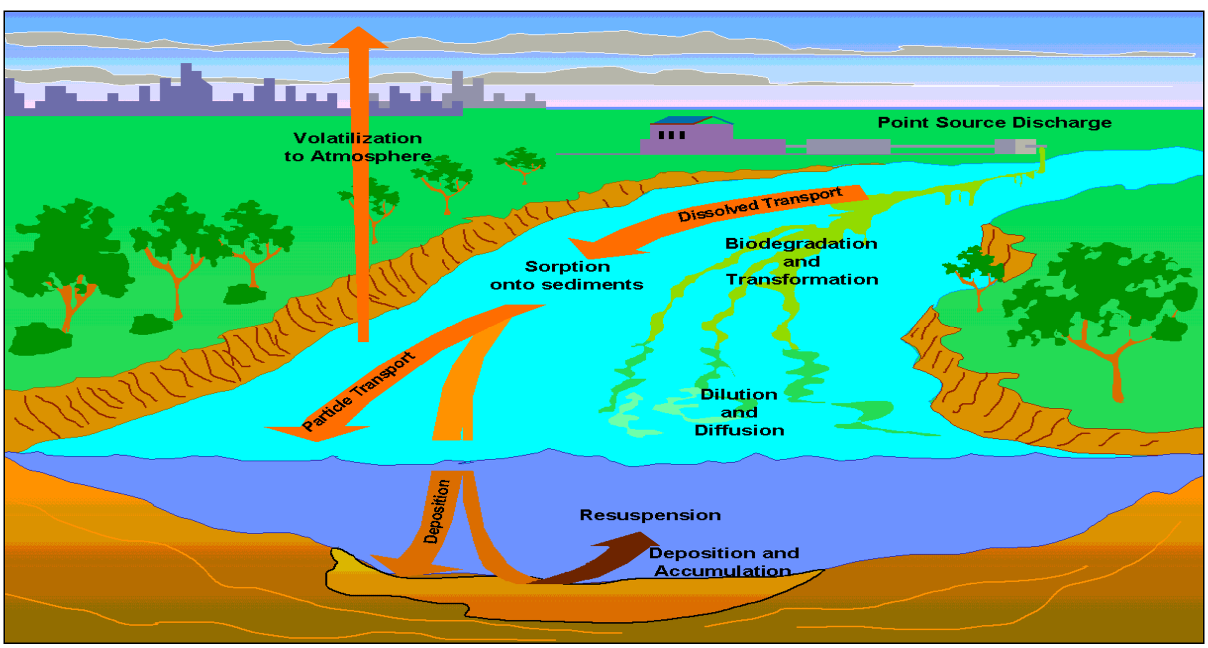

Figure 8. In-stream processes modeled by SWAT.
source:(Neitsch *et al.*, 2002).

Routing in the Main Channel or Reach
Routing in the main channel can be divided into four components: water, sediment, nutrients and organic chemicals.
Flood Routing
As water flows downstream, a portion may be lost due to evaporation and transmission through the bed of the channel. Another potential loss is removal of water from the channel for agricultural or human use. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method.

2.2.2 SWAT applications

The tool has been used in many places around the world for different purposes (van-Griensven *et al.*, 2006).

In USA, SWAT was used to analyze the long-term water quality impact of structural BMPs implemented during the Black Creek Project. This was achieved by developing a method to represent the functionality of structural BMPs in varying conditions in the SWAT model and then applying that method to the Black Creek watershed (Bracmort *et al.*, 2006). After performing sensitivity analysis and calibration, the model was applied in the project area. Results of the model runs showed that runoff volume and streamflow at the outlet of the Dreisbach and Smith Fry watersheds were not affected by implementation of BMPs. Sediment load results show that operation of the BMPs under good condition would reduce the average annual sediment yield from the Dreisbach watershed by approximately 32%, from 0.68 t/ha to 0.46 t/ha. The reduction rate for the BMPs in varying condition was nearly 10%. Predicted sediment yield in Smith Fry was decreased by about 16% and 7% under good and varying conditions, respectively. With Phosphorus, results showed that phosphorus yield at the outlet of the Dreisbach watershed decreased by nearly 25% (from 1.03 to 0.78 kg/ha) due to BMPs in good condition, while this reduction was about 10% at the Smith Fry outlet. Corresponding reductions for the scenario with BMPs in varying condition were nearly 17% at the Dreisbach watershed and 7% at the Smith Fry watershed.

In Europe it is used for implementation of Water Framework Directive with regard to water quality, ecology, climate change, hydrology and diffuse pollution modeling (van-Griensven *et al.*, 2006).

In Tanzania applicability of SWAT to model mountainous catchments was tested in Weruweru catchment at the foot slopes of Mt.Kilimanjaro. Results showed that the model successfully simulated the catchment processes where base flow in the catchment played a significant role in the hydrology as earlier pointed by other studies (Ndomba *et al.*, 2007). Also SWAT was also used in an un-gauged Simiyu river sub-catchment in Tanzania to model sediment yield. Results showed that the model could be used successfully in estimating sediment yield for un-gauged catchments (Ndomba *et al.*, 2005).

Also SWAT is an important tool used in the UNESCO FRIEND/NBCBN project which is being implemented in the Nile Basin Countries.

In this study, SWAT was used to model the catchment hydrology to reflect the current and future land development scenarios.

2.3 HEC-RAS model

2.3.1 Model Theory

In this research, Hydrologic Engineering Center River Analysis System (HEC-RAS) (Brunner, 2002) was used to route the flow produced by the SWAT model from the start of the Kirumi wetland to where the wetland is connected to lake Victoria.

HEC-RAS is software designed to perform a one dimensional hydraulic calculations in a full network of natural or artificial channels. It consists of graphical user interface, separate hydraulic analysis components, data storage and management capabilities, graphics and reporting facilities. The latest software of HEC-RAS version 4.0 Beta contains four one-dimensional river analysis components: steady flow water surface profile computations, unsteady flow water surface profile analysis, movable boundary sediment transport computations and water quality analysis. In this section, an overview of steady and unsteady water surface profile computations will be given as these two components apply to the research done in the Mara catchment.

2.3.1.1 Steady Flow Water Profiles

Under this component, calculations for sub-critical, supercritical and mixed flow regime water surfaces can be performed. Equations for basic profile calculations are done by solving the energy equations with an interactive procedure called standard step method. The energy equation is written as follows:

$$Y_2 + Z_2 + \frac{a_2 V_2^2}{2g} = Y_1 + Z_1 + \frac{a_1 V_1^2}{2g} + h_e \qquad 2.3.1$$

Where: Y_1, Y_2 = depth of water at cross sections
Z_1, Z_2 = elevation of the main channel inverts
V_1, V_2 = average velocities (total discharge/total flow area)
a_1, a_2 = velocity weighting coefficients
g = gravitational acceleration
h_e = energy head loss

Figure 9 shows the terms of the energy equation used in the model.

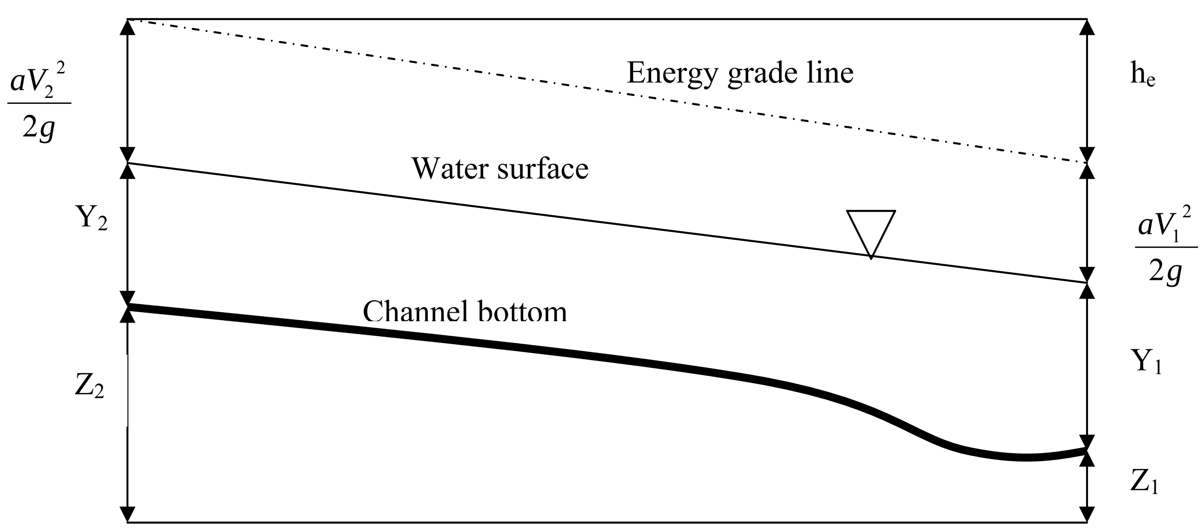

Figure 9. Terms of energy equation used in HEC RAS model.

The energy head loss (h_e) between two cross sections is comprised of friction losses and contraction or expansion losses. The equation for the energy head loss is as follows:

$$h_e = L\overline{S}_f + C\left|\frac{a_2 V_2^{\ 2}}{2g} - \frac{a_1 V_1^{\ 2}}{2g}\right| \text{.......................................} 2.3.2$$

Where: L = discharge weighted reach length

$\overline{S}_f$ = representative friction slope between two sections

C = expansion or contraction loss coefficient

The distance weighted reach length, L is calculated as:

$$L = \frac{L_{lob}\overline{Q}_{lob} + L_{ch}\overline{Q}_{ch} + L_{rob}\overline{Q}_{rob}}{\overline{Q}_{lob} + \overline{Q}_{ch} + \overline{Q}_{rob}} \text{.......................................} 2.3.3$$

Where: L_{lob}, L_{ch}, L_{rob} = cross section reach lengths specified for flow in the left overbank, main channel and right overbank, respectively.

$\overline{Q}_{lob}, \overline{Q}_{ch}, \overline{Q}_{rob}$ = arithmetic average of the flows between sections for the left overbank, main channel, and the right overbank, respectively.

Cross section subdivision for conveyance calculations

For determination of the conveyance, flow is sub divided into overbanks and the main channel according to the following equation:

$$Q = KS_f^{\ 1/2} \text{.......................................} 2.3.4$$

$$K = \frac{1.486}{n} AR^{2/3} \text{.......................................} 2.3.5$$

Where K conveyance for the subdivision

n Manning's roughness coefficient for subdivision

A Flow area for subdivision

R Hydraulic radius for subdivision (area/wetted perimeter)

The program sums up all the incremental conveyances in the overbanks to obtain the conveyances in the left and the right overbanks. The main channel is computed as a single conveyance element. The total conveyance is obtained by summing the three conveyances (left, channel and right).

Evaluation of mean kinetic energy head

HEC-RAS calculates a single water surface and mean energy for every cross section. The mean energy is calculated by flow weighted energy from the three subsections of the cross section. Figure 10 shows how mean energy would be calculated for a cross section with main channel and right overbank.

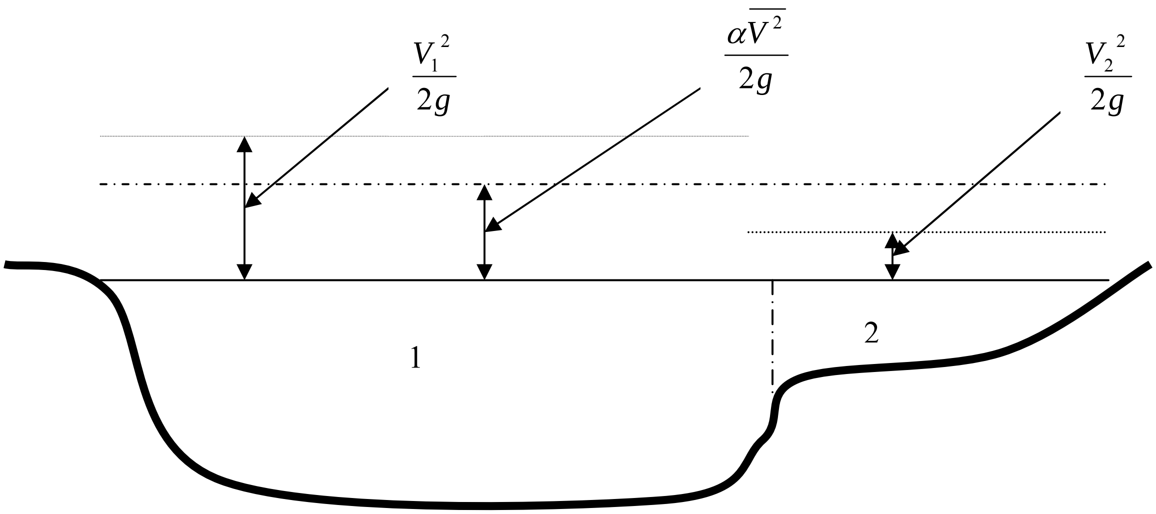

Figure 10. Calculation of mean energy in the cross section

V_1 is mean velocity for main channel
V_2 is mean velocity for overbank area

A velocity head weighting factor α is needed to calculate the mean kinetic energy. The value of α is calculated as follows:

Mean Kinetic Energy Head = Discharge-Weighted Velocity Head

$$\frac{\alpha\overline{V^2}}{2g} = \frac{Q_1\frac{V_1^2}{2g} + Q_2\frac{V_2^2}{2g}}{Q_1 + Q_2} \qquad 2.3.6$$

$$\alpha = \frac{2g\left[Q_1\frac{V_1^2}{2g} + Q_2\frac{V_2^2}{2g}\right]}{(Q_1 + Q_2)\overline{V}^2} \qquad 2.3.7$$

$$\alpha = \frac{Q_1V_1^2 + Q_2V_2^2}{(Q_1 + Q_2)\overline{V}^2} \qquad 2.3.8$$

In general, $\alpha = \frac{\left[Q_1V_1^2 + Q_2V_2^2 + \ldots + Q_NV_N^2\right]}{Q\overline{V}^2}$ where it is always computed in the three flow elements of the left overbank, right overbank and the channel.

Friction loss evaluation

Friction loss is evaluated as a product of $\overline{S}_f$ and L (equation 2.3.2) where $\overline{S}_f$ is the representative friction slope for a reach and L is defined by equation 2.3.3. The friction slope (slope of the energy gradeline) at each cross section is computed from Manning's equation:

$$S_f = \left(\frac{Q}{K}\right)^2 \quad \text{.......... 2.3.9}$$

Contraction and expansion loss

Contraction and expansion losses are evaluated by the following equation:

$$h_{ce} = C\left|\frac{\alpha_1 V_1^{\,2}}{2g} - \frac{\alpha_2 V_2^{\,2}}{2g}\right| \quad \text{.......... 2.3.10}$$

where C is the contraction or expansion coefficient.

The programe assumes that contraction occurs whenever the velocity head downstream is greater than the velocity head upstream. Expansion occurs when the velocity head upstream is greater than the velocity head downstream.

2.3.1.2 Unsteady Flow Routing

The physical laws governing the flow of water in a stream are the principle of conservation of mass (continuity) and the principle of conservation of momentum.

Continuity equation

Consider the elementary control volume shown in figure 11. Distance *x* is measured along the channel. At the midpoint of the control volume the flow and total area are denoted *Q(x,t)* and *AT* respectively. The total flow area is the sum of active area A and off-channel storage area *S*.

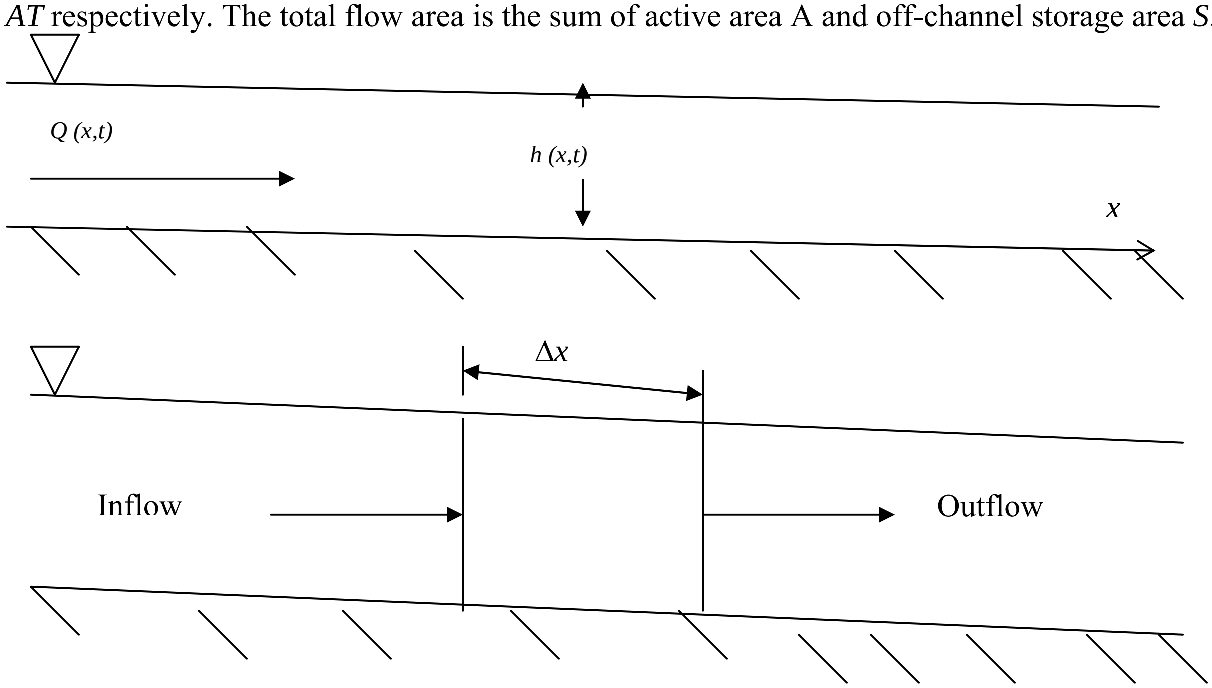

Figure 11. Control volume for continuity equation

Conservation of mass for a control volume states that the net rate of flow into the volume is equal to the rate of change of storage inside the volume.

Inflow rate $\quad Q - \frac{\partial Q}{\partial x}\frac{\Delta x}{2}$ 2.3.11

Outflow rate $\quad Q + \frac{\partial Q}{\partial x}\frac{\Delta x}{2}$ 2.3.12

The rate of change in storage $\frac{\partial A_T}{\partial t}\Delta x$..2.3.13

Assuming that x is small, the change in mass in the control volume is equal to :

$$\rho\frac{\partial A_T}{\partial t}\Delta x = \rho\left[\left(Q - \frac{\partial Q}{\partial x}\frac{\Delta x}{2}\right) - \left(Q + \frac{\partial Q}{\partial x}\frac{\Delta x}{2}\right) + Q_1\right] \quad \text{2.3.14}$$

Where Q_1 is the lateral flow entering the control volume and ρ is the fluid density. Simplifying and dividing through by $\rho\Delta x$ gives the final form of the continuity equation:

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} - q_1 = 0 \quad \text{2.3.15}$$

in which q_1 is the lateral inflow per unit length.

Momentum equation

Conservation of momentum is expressed by Newton's second law as:

$$\sum F_x = \frac{d\vec{M}}{dt} \quad \text{2.3.16}$$

Conservation of momentum for a control volume states that the net rate of momentum entering the volume (momentum flux) plus the sum of all external forces acting on the volume be equal to the rate of accumulation of momentum. The momentum flux is the fluid mass times the velocity vector in the direction of flow. Three forces are used to arrive at the final momentum equation: pressure, gravity and boundary drag or friction force. Derivations as done by Brunner (Brunner, 2002) gives expressions for each of the three forces as follows:

Pressure force: $F_n = -\rho g A\frac{\partial h}{\partial x}\Delta x$..2.3.17

where F_n is net pressure force

Gravitational force: $F_g = -\rho g A\frac{\partial z_0}{\partial x}\Delta x$..2.3.18

where F_g is gravitational force

Friction force: $S_f = \frac{Q|Q|n^2}{2.208R^{4/3}A^2}$..2.3.19

where R is the hydraulic radius, n is the Manning friction coefficient and S_f is the friction slope.

Momentum equation: $\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0$..................................2.3.20

These equations are implemented in HEC-RAS to solve one dimensional unsteady flow equations (Q and h) in an implicit finite difference scheme.

Model Accuracy, Stability and Sensitivity

Model accuracy can be defined as the degree of closeness of the numerical solution to the true solution. It depend on the assumptions and limitations of the model; accuracy of the geometric data; accuracy of the flow data and boundary conditions; and the numerical accuracy of the solution scheme.

Model stability refers to the ability of the model to suppress the growth of numerical errors which may hinder the computations. Stability is affected by the cross section spacing, computational time step, theta weighting factor for numerical solution and solution iterations.

2.3.2 Model Applications

This model was used by Armstrong *et al*,.(2004) to calculate river water-surface profiles for sub-critical flow regime at two different reaches of Green River (Armstrong *et al.*, 2004) and one reach of Sevenmile river with the aim of defining stream flow requirements for ecological purposes.

At the Colrain reach, Green river, a HEC-RAS model was run for a subcritical flow regime by use of the standard, upstream-step energy method. Input data for the model included cross-section geometry, estimated roughness coefficients, and initial boundary conditions. All surveyed cross sections were included in the HEC-RAS model. A templated cross section was added between sections 200 and 234, and two template cross sections were added between sections 234 and 285. For model calibration, water levels in the cross sections were measured at five different discharges, ranging from 7.00 ft3/s to 69.6 ft3/s. Initial roughness coefficients were determined for each cross section by back-calculation of Manning Equation at the calibration discharges. The calibration discharges were modeled at normal depth at the most downstream modeled section and a slope of 0.0008 ft/ft was input as a downstream boundary condition. The discharges used for model calibration (7.00, 8.70, 12.0, 25.0, and 69.6 ft3/s) were determined from stage-discharge ratings at the Little River streamflow-gaging station. The HEC-RAS model was calibrated by changing roughness coefficients for each cross section as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The calibration accuracy was 0.0 ft over the entire reach for the measured discharges. Indicators of the bankfull water line were identified in the field. Discharges that corresponded to the bankfull water line were determined from the calibrated model to be about 220 ft3/s. The calibrated HEC-RAS model was used to produce a staging table of hydraulic parameters for 80 discharges between 1 and 400 ft3/s for the cross sections at stations 200, 234, 285, and 341. The cross sections at stations 234 and 285 were used for determination of streamflow requirements by use of the R2Cross and Wetted Perimeter methods. The staging table was used to determine streamflow requirements using R2Cross criteria.

At Williamstown reach, Green river, a HEC-RAS model was run for a subcritical flow regime by use of the standard, upstream-step energy method. Input data for the model included cross section geometry, estimated roughness coefficients, and initial boundary conditions. All cross sections were included in the HEC-RAS model. A templated cross-section was added between cross sections 163, 206, and 244. For model calibration, water levels in the cross sections were measured at five different discharges, ranging from 6.90 ft3/s to 122 ft3/s. Initial roughness coefficients were determined for each cross section by back-calculation of Manning Equation at the calibration discharges. The calibration discharges were modeled at normal depth at the most downstream modeled section and a slope of 0.0100 ft/ft was input as a downstream boundary condition. The discharges used for model calibration (6.90, 14.00, 17.5, and 122 ft3/s) were determined from stage-discharge ratings at the Green River streamflow-gaging station. The HEC-RAS model was calibrated by changing roughness coefficients for each cross section as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The calibration accuracy was 0.0063 ft over the entire reach for the measured discharges. Indicators of the bankfull water line were identified in the field.

Discharges that corresponded to the bankfull waterline were determined from the calibrated model to be about 200 ft3/s. The calibrated HEC-RAS model was used to produce a staging table of hydraulic parameters for 49 discharges between 1 and 320 ft3/s for the cross sections at stations 100, 163, 206, and 244. The cross sections at stations 163, 206, and 244 were used for determination of streamflow requirements by use of the R2Cross and Wetted Perimeter methods. The staging table was used to determine streamflow requirements by using R2Cross criteria.

At Spencer reach, Sevenmile river, a HEC-RAS model was used to calculate water-surface profiles. The model was run for a subcritical flow regime by use of the standard, upstream-step energy method. Input data for the model included cross section geometry, estimated roughness coefficients, and initial boundary conditions. All surveyed cross sections were included in the HEC-RAS model. Two templated cross-sections were added between stations 127 and 139, one between stations 139 and 146, and one between stations 146 and 155. For model calibration, water levels in the cross sections were measured at four different discharges, ranging from 2.70 ft3/s to 10 ft3/s. Initial roughness coefficients were determined for each cross section by back-calculation of Manning Equation at the calibration discharges. The calibration discharges were modeled at normal depth at the most downstream modeled section and a slope of 0.0066 ft/ft was input as a downstream boundary condition. The discharges used for model calibration (2.70, 4.10, 6.00, and 10.0) were determined from stage-discharge ratings at the Little River streamflow-gaging station. The HEC-RAS model was calibrated by changing roughness coefficients for each cross section as required until calculated water-surface altitudes matched measured water-surface altitudes with reasonable accuracy. The calibration accuracy was 0.0032 ft over the entire reach for the measured discharges. Indicators of the bankfull water line were identified in the field. Discharges that corresponded to the bankfull water line were determined from the calibrated model to be about 120 ft3/s. The calibrated HEC-RAS model was used to produce a staging table of hydraulic parameters for 49 discharges between 1 and 200 ft3/s for cross sections at stations 100, 127, 139, 146, and 155. Cross sections at stations 127, 139, 146, and 155 were used for determination of streamflow requirements by use of the R2Cross and Wetted Perimeter methods. The staging table was used to determine streamflow requirements using R2Cross criteria.

2.4 IHA model

2.4.1 Model Theory

A basic goal of ecosystem management is to sustain ecosystem integrity. This is achieved by protecting native biodiversity and the ecological (and evolutionary) processes that create and maintain that diversity. Faced with the complexity inherent in natural systems, achieving that goal will require that resource managers explicitly describe desired ecosystem structure, function, and variability; characterize differences between current conditions and those that are desired; define ecologically meaningful and measurable indicators that can mark progress toward ecosystem management and restoration goals and incorporate adaptive strategies into resource management plans (Richter *et al.*, 1996).

The biotic composition, structure, and function of aquatic, wetland, and riparian ecosystems depend largely on the hydrologic regime (Sparks, 1995) . Intra-annual variation in hydrologic conditions is essential to successful life cycle completion for many aquatic, riparian, and wetland species. Inter-annual variation in hydrologic conditions often plays a major role in the population dynamics of these species through influences on reproductive success, natural disturbance, and biotic competition {Poff, 1990 #67}. Modifications of hydrologic regimes can indirectly alter the composition, structure, or function of aquatic, riparian and wetland ecosystems through their impacts on physical habitat characteristics, including water temperature, oxygen content, water chemistry, and substrate particle sizes {Poff, 1990 #67}.

Effective ecosystem management of aquatic, riparian, and wetland systems requires that existing hydrologic regimes be characterized using *biologically-relevant* hydrologic parameters, and that the degree to which human-altered regimes differ from natural or preferred conditions be related to the status and trends of the biota. Ecosystem management efforts should be considered experiments, testing the need to maintain or restore natural hydrologic regime characteristics in order to sustain ecosystem integrity. Unfortunately, few limnology studies have closely examined hydrologic influences on ecosystem integrity, in part because commonly-used statistical tools are poorly suited for characterizing hydrologic data into biologically relevant attributes. The lack of appropriate or robust statistical tools has in turn constrained knowledge about the effects of hydrologic alteration on ecosystem integrity. Without such knowledge, ecosystem managers will not be compelled to protect or restore natural hydrologic regime characteristics (Richter *et al.*, 1996).

IHA statistically characterizes the temporal variability in hydrologic regimes using biologically relevant statistical attributes. It then quantifies hydrologic alterations associated with presumed perturbations (such as dam operations, flow diversion, or intensive conversion of land uses in a watershed) by comparing the hydrologic regimes from "pre-impact" and "post-impact" time frames (Richter *et al.*, 1996).

The general approach for IHA is to first define a series of biologically-relevant hydrologic attributes that characterize *intra-annual* variation in water conditions and then use an analysis of the *inter-annual* variation in these attributes as the foundation for comparing hydrologic regimes before versus after a system has been altered by various human activities. The IHA method has four basic steps:

1. *Define the data series (e.g., streamgauge or well records) for pre- and post-impact periods in the ecosystem of interest.*
2. *Calculate values of hydrologic attributes* -- Values for each of 32 ecologically-relevant hydrologic attributes are calculated for each year in each data series, i.e., one set of values for the pre-impact data series and one for the post-impact data series.
3. *Compute inter-annual statistics* -- Compute measures of central tendency and dispersion for the 32 attributes in each data series, based on the values calculated in step 2. This produces a total of 64 inter-annual statistics for each data series (32 measures of central tendency and 32 measures of dispersion).
4. *Calculate values of the Indicators of Hydrologic Alteration* -- Compare the 64 inter-annual statistics between the pre- and post-impact data series, and present each result as a percentage deviation of one time period (the post-impact condition) relative to the other (the pre-impact condition).

The method equally can be used to compare the state of one system to itself over time (e.g., pre- versus post-impact as just described); or it can be used to compare the state of one system to another (e.g., an altered system to a reference system), or to compare current conditions to simulated results based on models of future modification to a system.

The basic data used in estimating all attribute values are daily mean water conditions (e.g., levels, heads, flow rates). The same computational strategies will work with any regular-interval hydrologic data, such as monthly means; however, the sensitivity of the IHA method for detecting hydrologic alteration is increasingly compromised with time intervals longer than a day. Detection of certain types of hydrologic impacts, such as the rapid flow fluctuations associated with hydropower generation at dams, may require even shorter interval data (e.g., hourly).

Hydrologic Attributes

Hydrologic conditions can vary in four dimensions within an ecosystem (three spatial dimensions and time). However, if the spatial domain is restricted to a specific point within a hydrologic system (such as a measurement point in a river, a lake, or an aquifer), the hydrologic regime can be defined in terms of one temporal and one spatial dimension -- changes in water conditions (e.g., levels, heads, rates) at a single location over time. Such temporal changes in water conditions are commonly portrayed as plots of water condition against time, or hydrographs. The goal is to characterize the temporal variation of hydrologic conditions using attributes that are biologically relevant, yet also sensitive to human influences such as reservoir operations, ground water pumping, and agricultural diversions.

Many different attributes of hydrologic regimes can be used to characterize the "physical habitat templates" (Poff and Ward, 1990) that shape the biotic composition of aquatic, wetland, and riparian ecosystems. The IHA method is based on 32 biologically-relevant hydrologic attributes, divided into five major groups to statistically characterize intra-annual hydrologic variation. These 32 attributes are based upon five fundamental characteristics of hydrologic regimes:

1) the *magnitude* of the water condition at any given time is a measure of the availability or suitability of habitat, and defines such habitat attributes as wetted area or habitat volume, or the position of a water table relative to wetland or riparian plant rooting zones;
2) the *timing* of occurrence of particular water conditions can determine whether certain life cycle requirements are met, or influence the degree of stress or mortality associated with extreme water conditions such as floods or droughts;
3) the *frequency* of occurrence of specific water conditions such as droughts or floods may be tied to reproduction or mortality events for various species, thereby influencing population dynamics;
4) the *duration* of time over which a specific water condition exists may determine whether a particular life cycle phase can be completed, or the degree to which stressful effects such as inundation or desiccation can accumulate;
5) the *rate of change* in water conditions may be tied to the stranding of certain organisms along the water's edge or in ponded depressions, or the ability of plant roots to maintain contact with phreatic water supplies.

The 32 IHA parameters provide a detailed representation of the hydrologic regime for the purpose of assessing hydrologic alteration. Most importantly, they entail hydrologic statistics commonly employed in limnology studies because of their great ecological relevance (e.g., (Poff and Ward, 1990)). Also, because certain stream flow levels shape physical habitat conditions within river channels, hydrologic characteristics that might aid in detection of physical habitat alteration in lotic systems are also identified. For example, changes in the central tendency of annual maxima might suggest changes in river morphology (Leopold, 1994).

Sixteen of the hydrologic parameters focus on the magnitude, duration, timing, and frequency of extreme events, because of the pervasive influence of extreme forces in ecosystems and geomorphology (Leopold, 1994); the other 16 parameters measure the central tendency of either the magnitude or rate of change of water conditions.

2.4.2 IHA Applications

This method was used by Ritcher et al., (1996) in Roanoke River, North Carolina-USA to assess the effect of building a dam on the flow regime of the river. The method used hydrological data before and after the dam to analyse how the characteristics of flow had changed by introduction of the dam (Richter *et al.*, 1996).

One of the impacts of flood control operations on the Roanoke is the virtual elimination of high-magnitude flooding. Floods in excess of 8500 m3/s occurred in only five of the post-dam years, whereas floods greater than this size occurred in every pre-dam year.

Also, the pulsing behavior of the Roanoke River has been severely impacted, as both high and especially low pulses now occur with substantially greater frequency. The average duration of pulses is, on the other hand, much shorter in the post-dam period. This is a byproduct of hydropower generation, wherein water is stored in the reservoir until sufficient head is attained to efficiently generate power, then rapidly released through the dam turbines. The effect on the hydrologic regime is to create a greater frequency of high and low pulses of lesser duration, and also to increase the number of hydrograph rises and falls. The magnitude and timing of the annual minima have changed, with a shift from higher, fall season to lower, mid-winter annual lows. This probably results from attempts to capture winter flows for later spring and summer use in hydropower generation.

2.5 Methodology

Methodology which was used to achieve the objectives is summarized in figure 12. The activities include literature review, data collection, and analysis using hydroinfoarmatics tools and drawing conclusions. Recommendations of environmental flow is finally recommended and areas for further studies shown.

First, literature was consulted to find what kind of similar studies have been conducted, where, how and what were the results. This was done by searching information using IHE library, TU Delft library, Dar es Salaam University library, internet search engines and different world catalogues for books and scientific journals.

After reviewing literature, preparations for data collection from different sources were made. Identification of the type of data required for answering the research questions, where to get it and how to use it, was conducted.

To answer the first and second research questions, two models were used; SWAT and HEC-RAS. A SWAT model was used to simulate the catchment hydrology where precipitation data for 13 stations and flow data from one station were used. Data which had to be collected included spatial (digital elevation model, land use map and soil map), weather (precipitation, temperature, solar radiation, wind speed or relative humidity, point discharge data), water use and river flow. However, only precipitation and flow data were available from the sources.

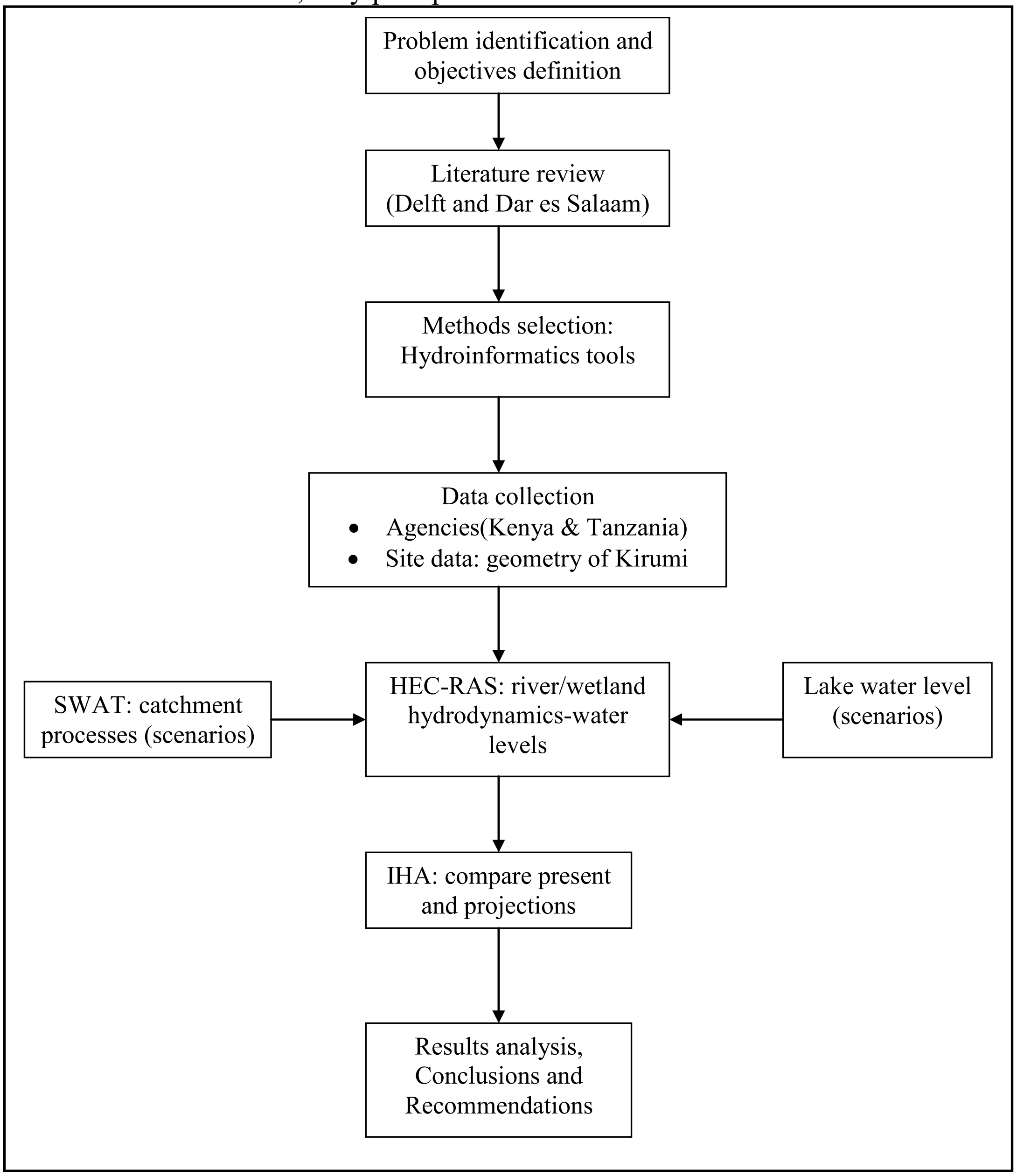

Figure 12: Schematization of the methodology to undertake the study.

A HEC-RAS hydrodynamic model was used to simulate the lower part of the river with wide flood plains and wetlands. Data needed for this model include geometric descriptions (schematization of the river system, cross-sections) and flow data (flow regime and boundary conditions for steady or unsteady flow). A grid of points was used to take elevations and coordinates using tape measure with a weight and GPS. The model used output of the SWAT model as upstream boundary condition and Lake Victoria water level as downstream boundary condition. This model showed the hydroperiods of the Kirumi wetland and how they relate to the catchment processes simulated by SWAT. Two scenarios of the catchment and lake levels were simulated.

The results of simulation of the scenarios were used in IHA model to assess the impacts of the human interventions on the upper parts of the catchment on Kirumi wetland water levels. The model performed statistical analysis of the wetland water levels for periods relating to the pre impact and post impact scenarios.

3. Data collection

Data was collected from 22nd October 2007 to 22nd January 2008 in different areas in Tanzania. Two main types of data were of importance for the research, namely field data for building a HEC RAS model and secondary data for both SWAT and HEC RAS models.

Other qualitative oral information about the history of the Mara wetland was obtained from two different indigenous people. They seemed to suggest that the issue of the wetland increase in size is due to sedimentation rather than other catchment processes. They remember the independency rains of 1961 which opened the river channel which was small. Since then, flooding has increased and the size of the wetland has also been increasing.

3.1 Field Data (for HEC-RAS model)

Field data collection for HEC RAS model included doing water depth sounding and taking water surface elevation of Kirumi wetland stretch of about 12 km. Water surface elevation at seven cross-sections was taken using a GPS. Soundings were done with the help of the weight tied to the rope with tape measure. Care was taken to account for the weight depth on the soundings. However, the GPS readings for water levels were not accurate. The GPS use was then restricted to recording coordinates of the sounded points in the cross sections only. Instead, the water surface elevation for each cross section was obtained by use of either a google earth map or topo sheet maps (Series Y742, sheet 12/2, edition 2-TSD and series Y742, sheet 13/1, edition 2-TSD) depending on the closeness to the lake water surface elevation which was assumed at 1134 m amsl (Musoma port bench mark) (figures 13 to 16).

Figure 13. Making soundings of the river cross section

Figure 14. Weight attached to the tape measure

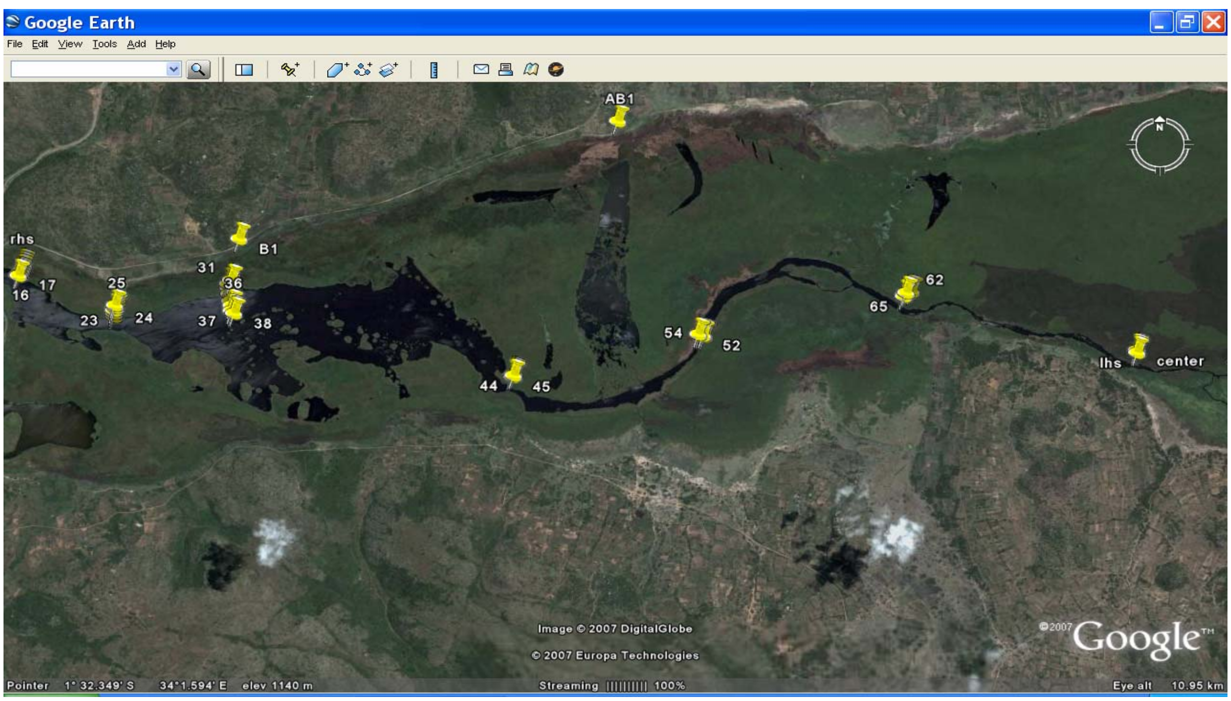

Figure 15. Locations of cross sections along the river

Figure 16. Testing the accuracy of the GPS in reading elevation

Using the recorded coordinates, distances between the sounded points and the whole cross section was calculated in google earth maps. Also, the reach lengths (distances between cross sections) were calculated in this way. The channel reach lengths were calculated along the thalweg. The overbank reach lengths were calculated along the anticipated path of centre of mass of the overbank overflow using google earth map.

The resulting cross sections (shown in figures 14 to 20) were obtained by subtracting the sounded depths of the cross sections from the water surface elevation of the points with respect to mean sea level datum.

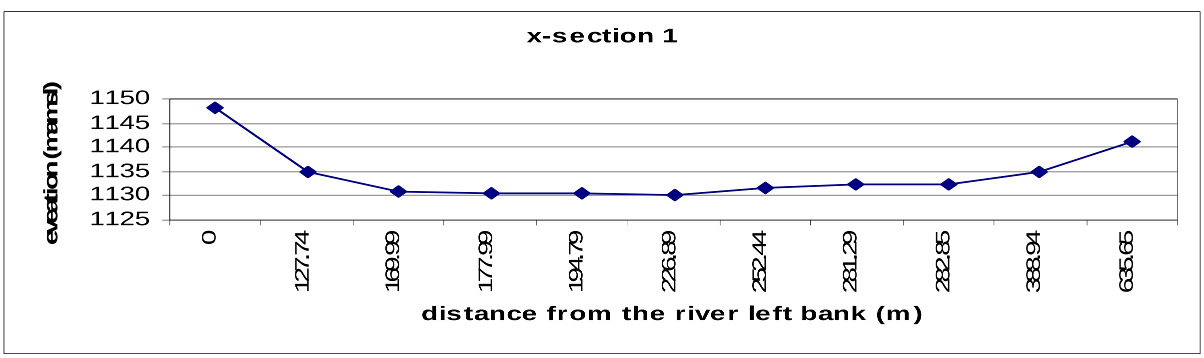

Figure 17. Profile at cross section 1

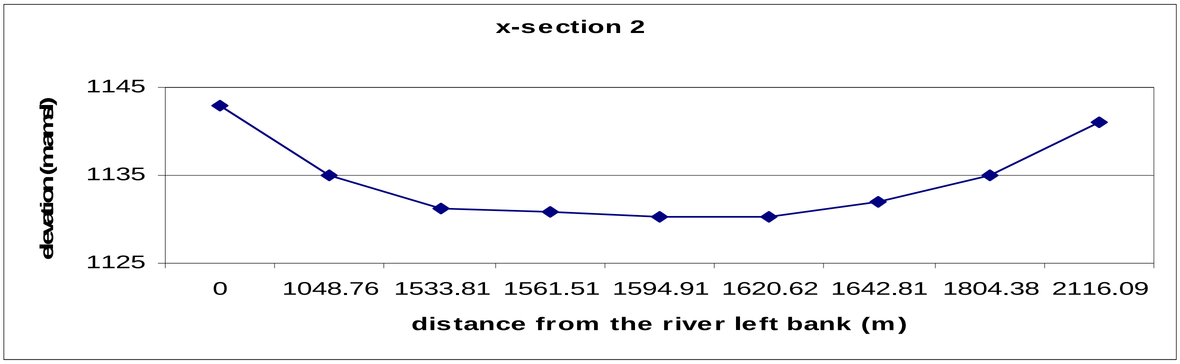

Figure 18. Profile at cross section 2

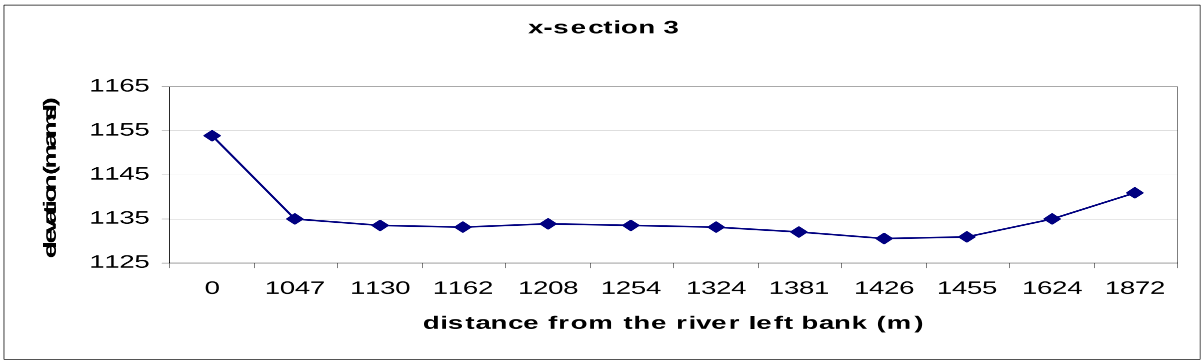

Figure 19. Profile at cross section 3

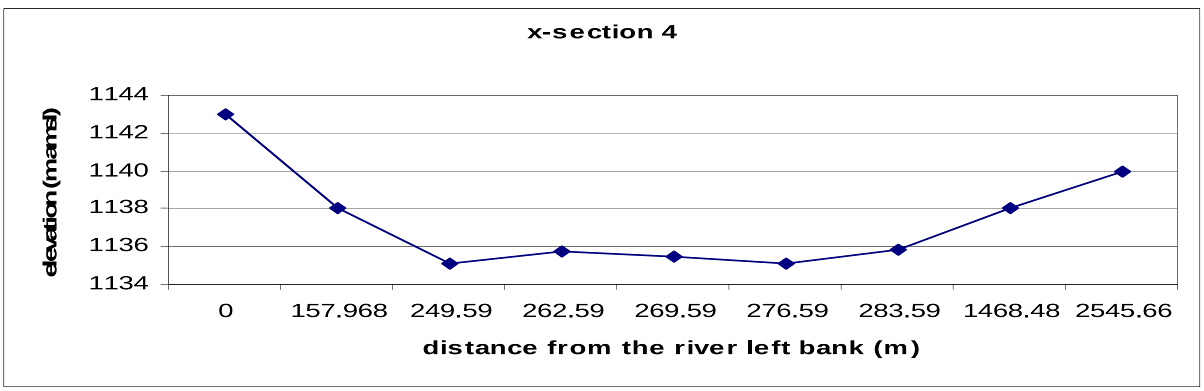

Figure 20. Profile at cross section 4

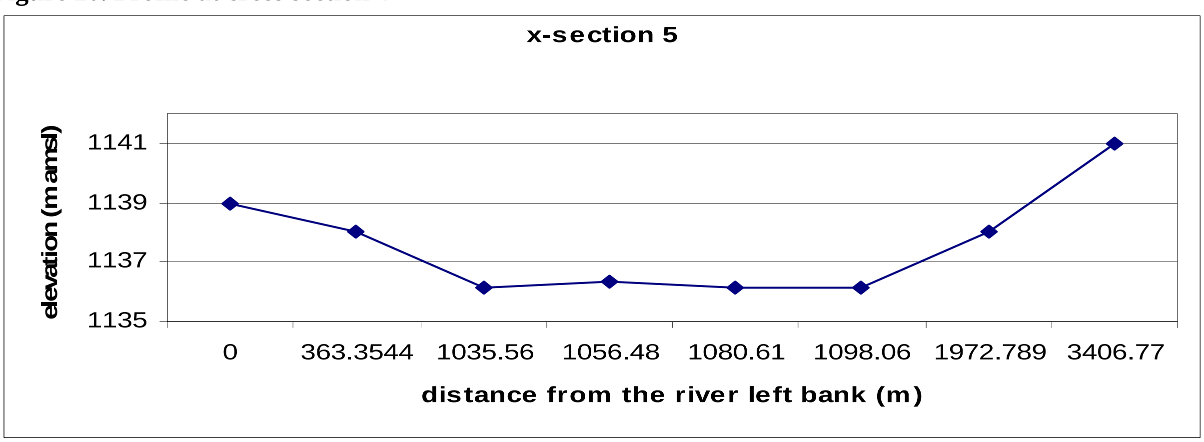

Figure 21. Profile at cross section 5

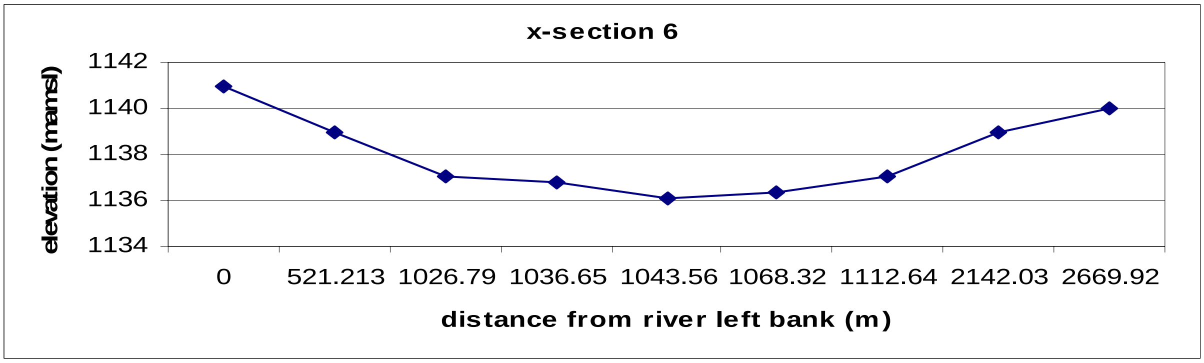

Figure 22. Profile at cross section 6

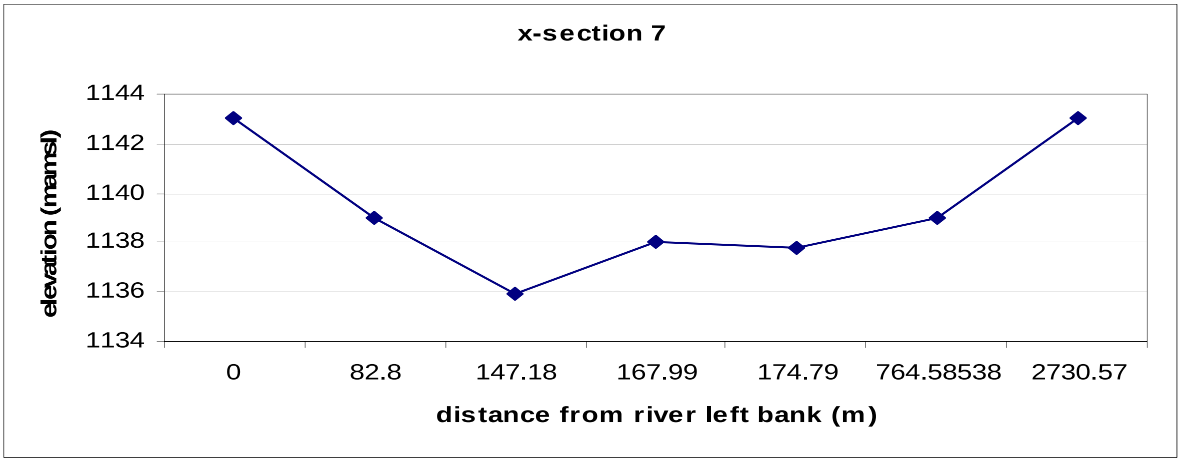

Figure 23. Profile at cross section 7

3.2 Secondary data (for SWAT/HEC-RAS models)

Secondary data collected were mainly precipitation and flow data for the catchment. Maximum and minimum temperature data were collected for only two stations (090636261 and 09135001) for a period from 1986 to 2003. However, the temperature data were not used in the swat model since other Africa temperature stations were used.

3.2.1 Precipitation data

Precipitation data was availed from Dr. P. Valimba, a University of Dar es Salaam researcher, who was also doing some work in this same Mara catchment (Table 1). Twenty six (26) stations of precipitation data were available from the catchment for both Kenyan and Tanzania parts. However one station had a very short data period and was not used. Twenty five stations were analysed further for use in the SWAT model. However, most of the stations had a lot of missing data and some had very short periods of data. Although SWAT can generate data for missing values, this option did not give sensible results, may be due to too many gaps in the data.

In order to solve this problem, missing values were to be filled first, before using them again in the model. Excel spreadsheet was used to run correlation analysis for the stations in the catchment. The analysis showed that the stations were not correlated at all, with an exception of two stations (Table 2) which had a correlation coefficient of 0.5. However, the two stations (TCN and SAVH) with a good correlation could not be used since their time extend were not the same.

Table 1. Precipitation stations for Mara catchment

Station information details used in swat model						Availability		
S.No.	WMO code	Station name	Lat	Long	Alt	From	To	swat table name
1	09035079	SOTIK, TENWIK MISSION	-0.75	35.37	2007	1960	1998	STM
2	09035227	BOMET DISTRICT OFFICE	-0.78	35.33	1924	1960	1992	BDO
3	09035236	CHEPALUNGU FOREST STATION	-0.90	35.10	1840	1961	1998	CFS
4	09035260	KOIWA ESTATE,KERICHO	-0.62	35.32	1986	1968	1998	KEK
5	09035265	BOMET WATER SUPPLY	-0.78	35.35	1921	1967	1997	BWS
6	09035284	MULOT POLICE POST	-0.93	35.43	1829	1973	2000	MPP
7	09035285	ABOSSI POLICE POST	-0.92	35.05	2073	1973	2000	APP
8	09035302	NYANGORES FOREST STATION	-0.70	35.43	2219	1979	2002	NFS
9	09035312	MERIGI CHIEF'S CENTRE	-0.78	35.40	2134	1981	2000	MCC
10	09035313	OLOKYIN MARKET	-0.95	35.38	1829	1982	2000	0LM
11	09133000	MUSOMA MET.	-1.50	33.80	1147	1921	1999	MUSOMA
12	09133002	SHIRATI MISSION	-1.13	33.98	1158	1944	1997	SHIRATI
13	09134008	NYABASSI (NYARERO)	-1.35	34.57	1829	1943	1993	NYABASI
14	09134011	SOTIK DIV AGRI OFFICE	-1.00	34.88	1981	1960	2002	SDAO
15	09134019	NTIMARU CHIEF'S OFFICE	-1.33	34.68	1805	1960	1998	NCO
16	09134026	TARIME HYDROMET	-1.33	34.33	1280	1969	1999	TARIME
17	09134027	LOLGORIEN POLICE POST	-1.23	34.82	1669	1969	1993	LPP
18	09134039	OLOOLOLO GAME POST	-1.25	34.98	1737	1973	1987	OGP
19	09135004	NGORINGORI DISPENSARY NAROK	-1.07	35.52	1890	2001	2002	NDN
20	09135008	SOTIK,KABOSON GOSPEL MISSION	-1.00	35.23	1646	1960	1986	SKGM
21	09135010	SOTIK, AITONG VET. HOUSE	-1.18	35.25	1829	1960	2000	SAVH
22	09135012	TALEK CAMP NAROK	-1.45	35.25	1585	1963	1964	TCN
23	09135019	LEMEK MAASAI FARM	-1.10	35.40	1898	1966	1993	LMF
24	09135026	GOVERNOR'S CAMP	-1.28	35.08	1585	1973	2000	GOC
25	09135035	KICHWA TEMBO CAMP	-1.23	35.02	1887	1973	2002	KTC

Table 2. Correlation of the precipitation stations using daily data

	MUSOMA	*Goc*	*Ktc*	*Mcc*	*Mpp*	*app*	*Tcn*	*Tarime*	*SKGM*	*Shirati*	*SDAO*	*Savh*	*Olm*	*OGP*	*NYABASI*	*NFS*
MUSOMA	1															
Goc	0.14	1														
Ktc	0.11	0.36	1													
Mcc	0.18	0.17	0.22	1												
Mpp	0.15	0.21	0.17	0.30	1											
App	0.15	0.26	0.17	0.26	0.23	1										
Tcn	0.08	0.00	0.00	0.00	0.00	0.00	1									
Tarime	0.22	0.16	0.11	0.16	0.15	0.13	0.00	1								
SKGM	0.13	0.28	0.00	0.18	0.26	0.28	0.36	0.14	1							
Shirati	0.29	0.13	0.06	0.14	0.15	0.10	0.23	0.20	0.16	1						
SDAO	0.07	0.09	0.31	0.16	0.18	0.09	0.16	0.07	0.24	0.06	1					
Savh	0.16	0.25	0.45	0.21	0.23	0.25	0.50	0.17	0.27	0.13	0.20	1				
Olm	0.14	0.17	0.28	0.17	0.21	0.23	0.00	0.17	0.23	0.15	0.17	0.17	1			
OGP	0.08	0.19	0.00	0.14	0.12	0.13	0.00	0.04	0.19	0.09	0.04	0.17	0.07	1		
NYABASI	0.16	0.16	0.14	0.15	0.16	0.15	0.16	0.19	0.18	0.16	0.08	0.15	0.15	0.07	1	
NFS	0.16	0.21	0.13	0.43	0.31	0.21	0.00	0.18	0.21	0.16	0.09	0.21	0.16	0.10	0.14	1

A trial to determine an equation for fitting daily values for two stations (MPP and NFS) with similar time extension, resulted into an equation and a plot depicted in figure 24 whose coefficient of determination was $R^2= 0.23$.

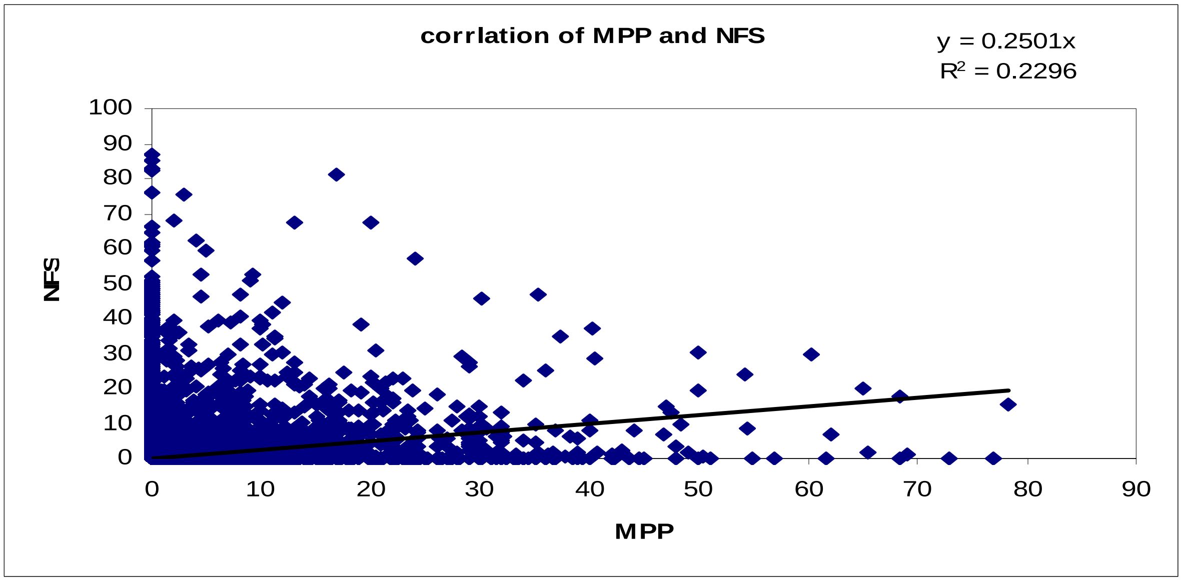

Figure 24. Correlation between rainfall stations

Then, neighbouring stations were used to fill gaps in other stations with missing value. The procedure was to use the nearest station to fill missing data for another station (figure 25).

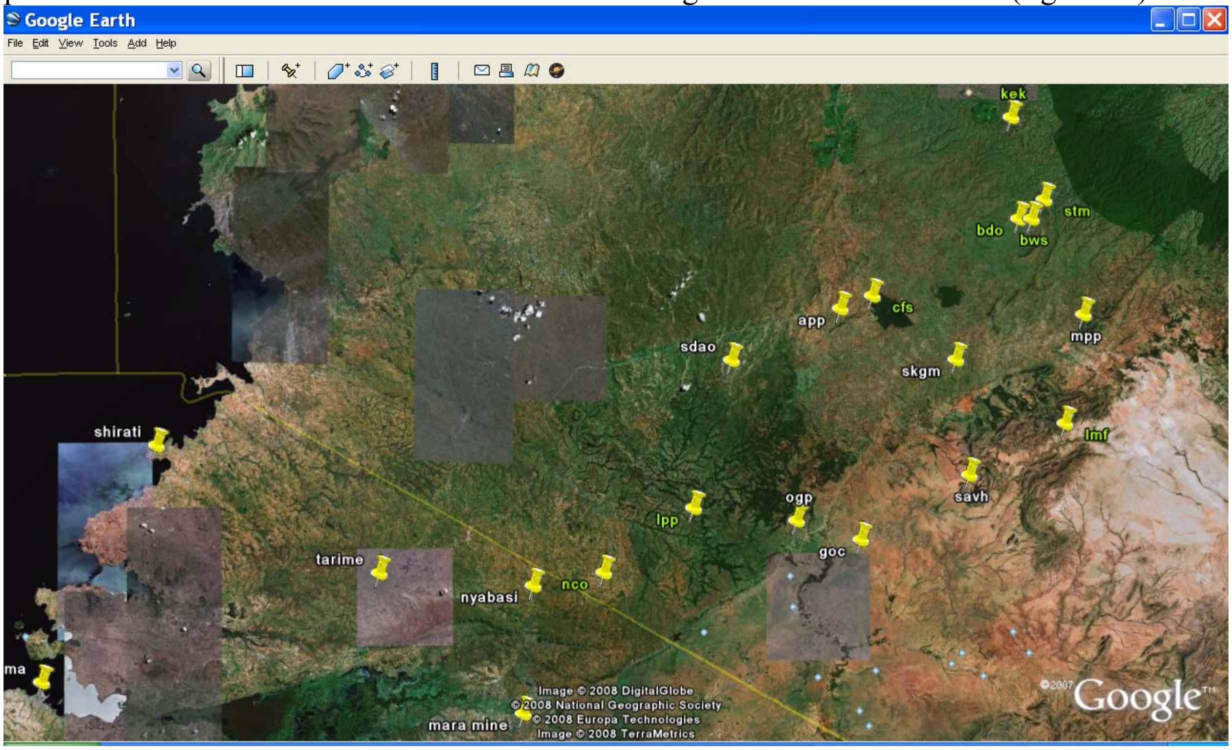

Figure 25. A map showing rainfall stations in the catchment

If the nearest station had no data in that period, then the next nearest station was used. In this way, data for fourteen (14) stations were generated from 1973 to 1997 and these values were used in the SWAT model.

3.2.2 River flow data

In this category, river gauging stations data for flow and water levels were collected. Flow data (at the beginning of the Kirumi wetland -5H3) were from the University of Dar es Salaam source while the water level (at the end of the wetland-5H2) data were obtained from the Ministry of Water at Dar es Salaam- Tanzania. Flow data extended from 1970 to April 1994 (Appendix 1). The water levels data extended from 1970 to 1978. The issue of missing data was again a problem although not as serious as in the rainfall data.

Missing data were, however filled using monthly average flows which were generated by Sacramento model (EAC-Secretariat, 2006) and observed the peak and mean flows to be 645.16 m^3/s and 27.24 m^3/s respectively. In a study conducted by Mutie *et al.(*2006), they looked the effects of land use change on river flows (Mutie *et al.*, 2006). It was found that in 1973, at this gauging station, the simulated peak and mean flows were 827 m^3/s and 35.26 m^3/s respectively. These two studies have similar results and therefore the flow data was more or less accurate/reliable.

3.2.3 Correlation of the flow and the precipitation data

Correlation analysis between daily precipitation and daily flow data was done. Results showed that there was no strong correlation between any of the precipitation data and the flow (Table 3). All stations above the gage station of flow showed very weak correlation. Musoma and Shirati stations which showed very weak positive correlation are situated outside the catchment.

Table 3. Correlation between daily precipitation and flow.

Station	Correlation-R
APP	-0.026
GOC	-0.016
MCC	-0.016
MPP	-0.030
MUSOMA	0.003
NFS	-0.004
NYABASI	-0.008
OGP	-0.015
OLM	-0.035
SAVH	-0.044
SDAO	-0.018
SHIRATI	-0.002
SKGM	-0.019
TARIME	-0.013

This fact (no or weak correlation) was also evident when flow and precipitation data were plotted on the same graph. The flow pattern is not similar to the rainfall pattern as depicted in figure 26.

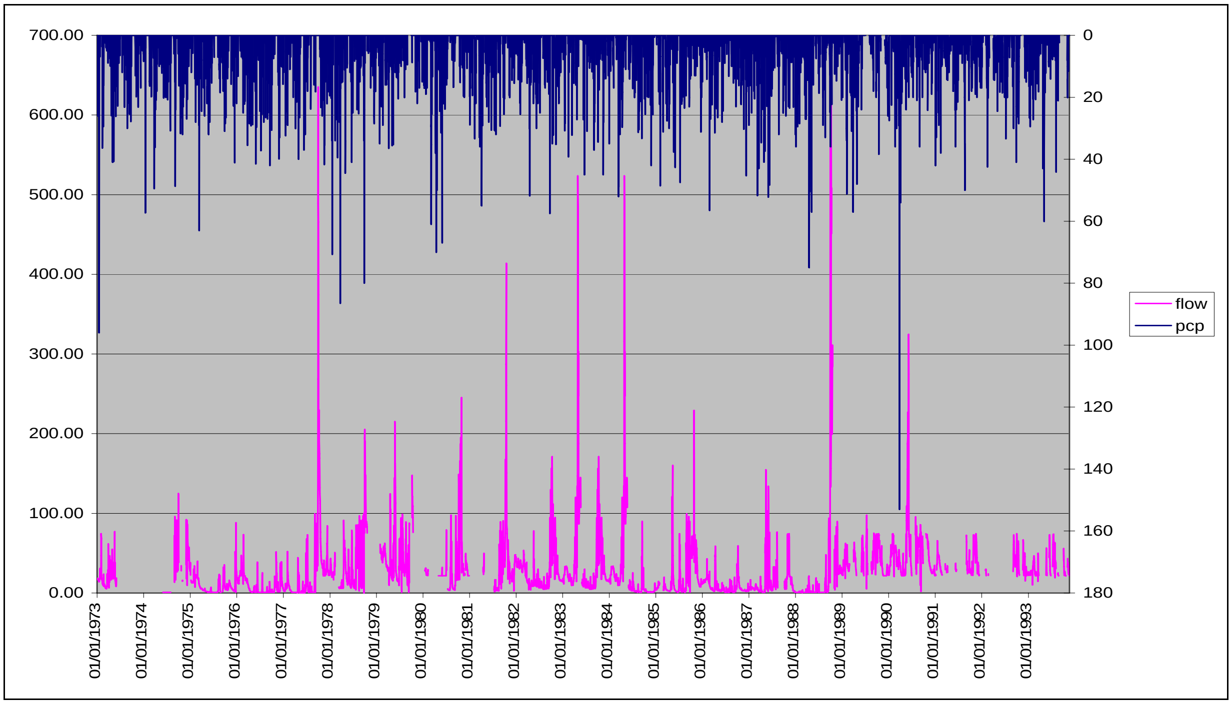

Figure 26. Plot of precipitation and flow for APP and 5H3 respectively.

Daily rainfall data was then used to derive monthly rainfall values (Appendix 1) which were used for SWAT model calibration as an attempt to improve the model results. When correlation analysis was done again, results showed some improvement especially among the rainfall stations (Table 4). However little correlation was shown between many precipitation stations and the flow data.

Table 4. Correlation among monthly precipitation and monthly flow

	nyabasi	nco	lpp	goc	ogp	sdao	app	cfs	savh	lmf	skgm	kek	bdo	bws	stm	mpp	flow
nyabasi	1																
nco	0.18	1															
lpp	0.13	0.62	1														
goc	0.26	0.55	0.62	1													
ogp	0.34	0.31	0.38	0.38	1												
sdao	0.09	0.25	0.23	0.31	0.08	1											
app	0.27	0.57	0.61	0.60	0.41	0.24	1										
cfs	0.03	0.45	0.30	0.69	0.18	0.21	0.23	1									
savh	0.16	0.50	0.63	0.62	0.62	0.52	0.58	0.21	1								
lmf	0.20	0.44	0.50	0.59	0.20	0.50	0.50	0.60	0.59	1							
skgm	0.32	0.53	0.54	0.69	0.75	0.58	0.65	0.73	0.70	0.64	1						
kek	0.02	0.45	0.51	0.49	0.29	0.19	0.53	0.20	0.40	0.41	0.45	1					
bdo	0.22	0.55	0.57	0.62	0.46	0.31	0.66	0.28	0.66	0.50	0.70	0.62	1				
bws	0.20	0.54	0.58	0.59	0.45	0.28	0.64	0.27	0.63	0.55	0.67	0.63	0.92	1			
stm	0.04	0.22	0.22	0.28	0.08	0.14	0.30	0.17	0.16	0.36	0.28	0.29	0.36	0.39	1		
mpp	0.24	0.47	0.56	0.66	0.45	0.56	0.61	0.30	0.72	0.63	0.80	0.58	0.73	0.65	0.34	1	
flow	-0.09	0.24	0.27	0.16	0.13	0.11	0.18	0.31	0.20	0.25	0.24	0.41	0.27	0.28	0.14	0.32	1

3.2.4 Correlation of the flow and the water level data

Flow data at upstream gauging station 5H3-Mara Mine and stage data at the downstream gauging station 5H2 would be used for building the HEC-RAS model. Correlation analysis for monthly data was carried out for years from 1970 to 1978. Results (figure 27) show that there exists a good correlation (R=0.51), though not strong, between the flow upstream and water level down. This may suggest the independence of the water level downstream from catchment processes upstream.

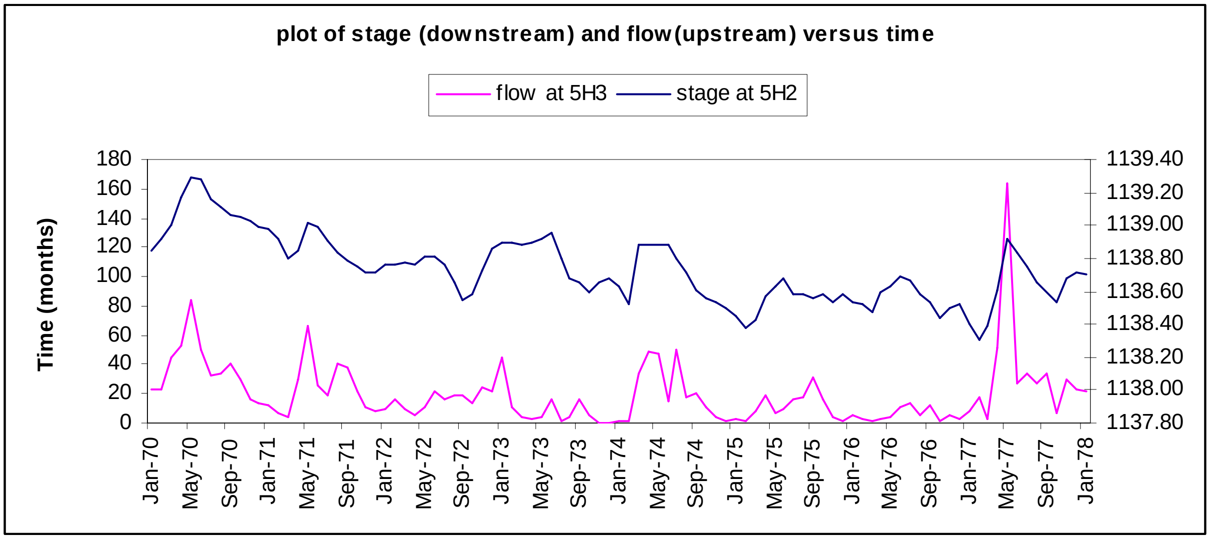

Figure 27. Correlation between measured flow and lake water level

4. Models building

4.1 SWAT model

4.1.1 Introduction

The Mara catchment swat model was built using 90 m Digital Elevation Model (DEM) from NASA, Shuttle Radar Topographic Mission (SRTM) (http://www.ambiotek.com/srtm). The SRTM 90m DEM's are provided in a 5x5 deg mosaic tiles. The ASCII files of two tiles (srtm_4313 and 4413) were downloaded and processed in ArcGIS to produce the required DEM.

Soil map was obtained from Food and Agriculture Organization of the United Nations (FAO, 1995) which provides almost 5000 soil types at a spatial resolution of 10 kilometres with soil properties for two layers (0-30 cm and 30-100 cm depth). Further soil properties (e.g. particle-size distribution, bulk density, organic carbon content, available water capacity, and saturated hydraulic conductivity) were obtained from Reynolds et al. (1999) or by using pedotransfer functions implemented in the model Rosetta (http://www.ars.usda.gov/Services/docs.htm?docid=8953).

Landuse map was obtained from USGS Global Land Cover Characterization (GLCC) database (http://edcsns17.cr.usgs.gov/glcc/glcc.html) with a spatial resolution of 1 kilometre and 24 classes of landuse representation. The parameterization of the landuse classes (e.g. leaf area index, maximum stomatal conductance, maximum root depth, optimal and minimum temperature for plant growth) is based on the available SWAT landuse classes and literature research.

4.1.2 Watershed Delineation

Delineation of the Mara catchment was done in several steps. First the DEM was loaded and projections set to Lambert Azimuthal with central meridian set at 20 and the reference Latitude at 5. To define the hydrologic response units (HRU), a threshold area of 60000 ha (about 600 km^2) was provided in the model (figure28). An outlet within the basins was specified using a location table and the watershed main outlet specified at the mouth of the river into Lake Victoria.

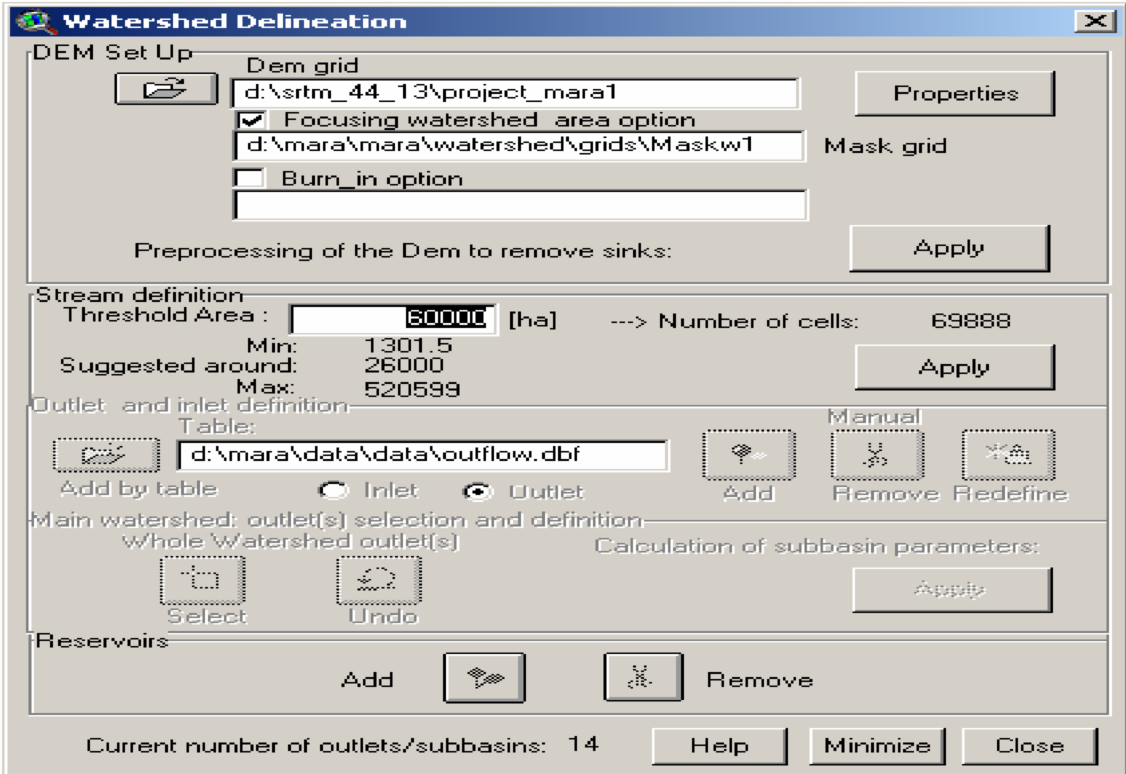

Figure 28. Watershed delineation

The resulting watershed is shown in figure 29.

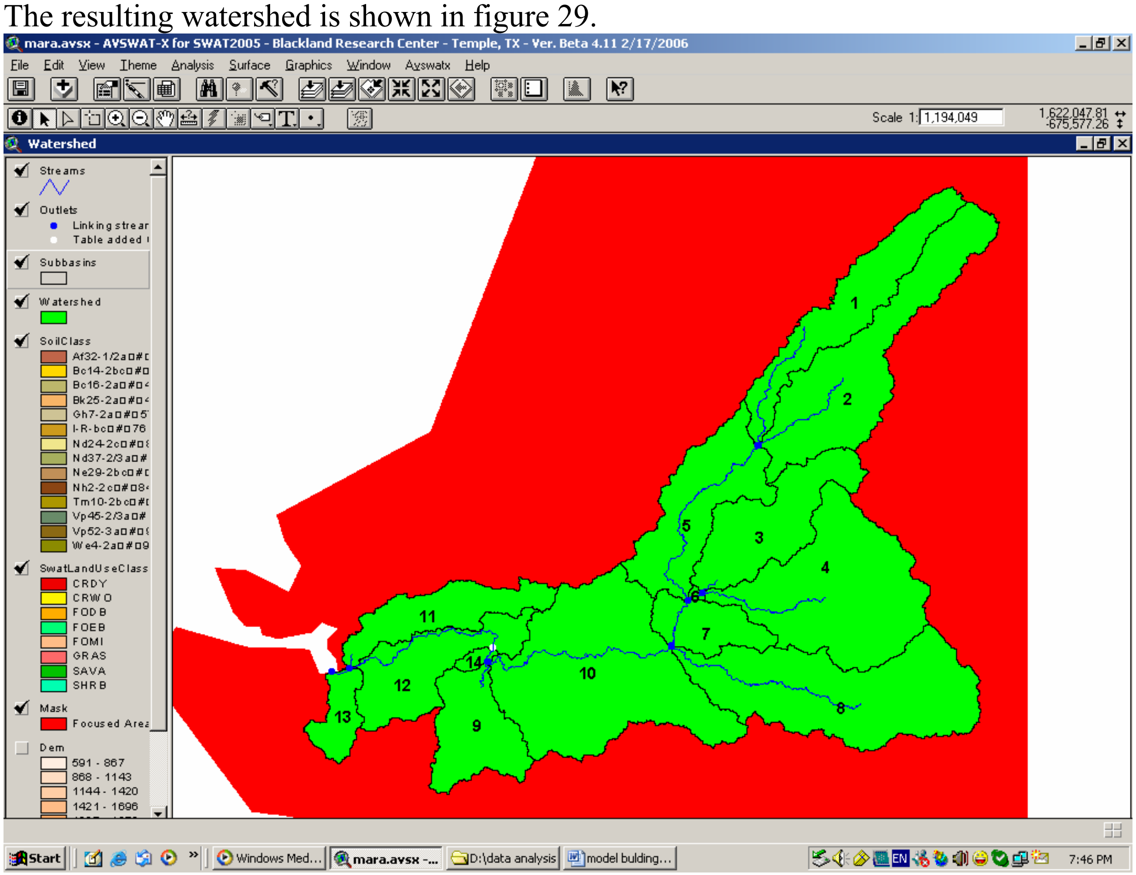

Figure 29. Subbasins of the catchment

4.1.3 Land use and Soil definition

The Landuse and soil themes were then loaded as shown in figure 30. Each of them was reclassified and then overlayed to enable the model determine the area and hydrologic parameters of each land-soil category simulated within each sub-watershed.

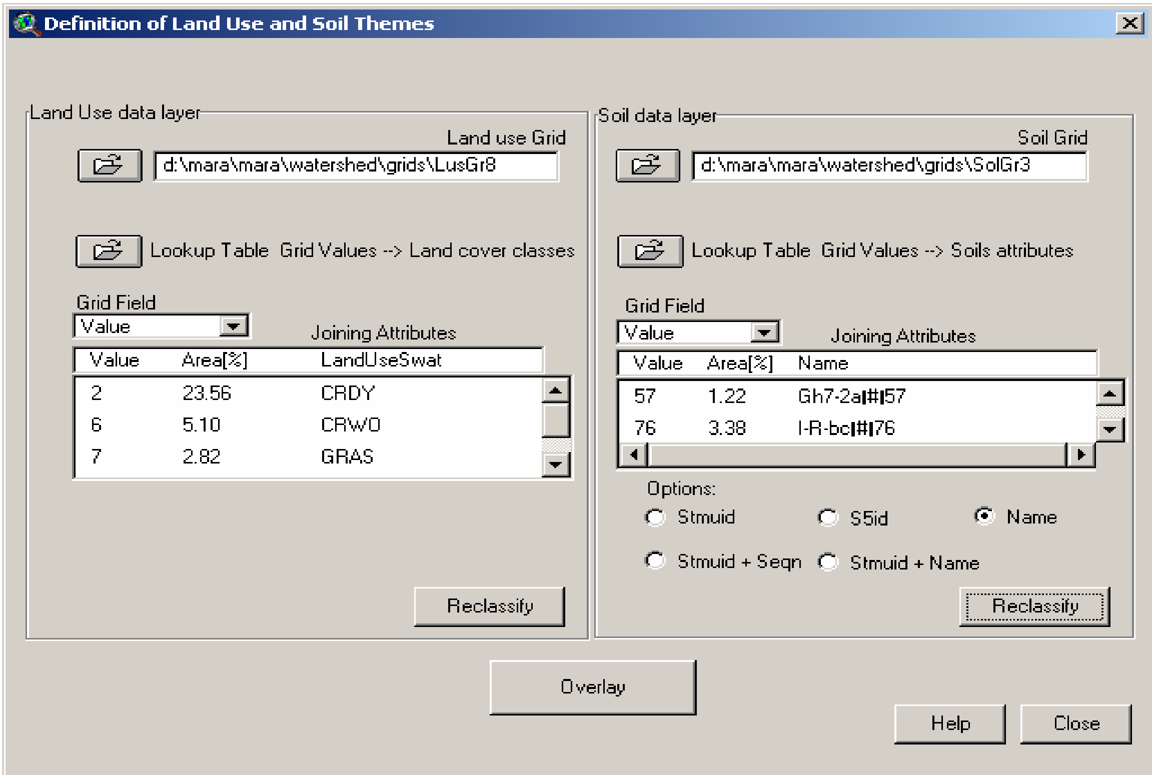

Figure 30. Landuse and soil definition

After this step, the definition of the hru distribution was done as shown in figure 31. This enables the model to reflect differences in the evapotranspirations and other hydrological conditions for different land covers/crops. The multiple hydrologic response units option was used where land use percent over sub-basin area was set at 0 % while for soil class percentage was set at 10 %. At this stage, the water shed delineation process is completed and new swat view is activated (figure 32).

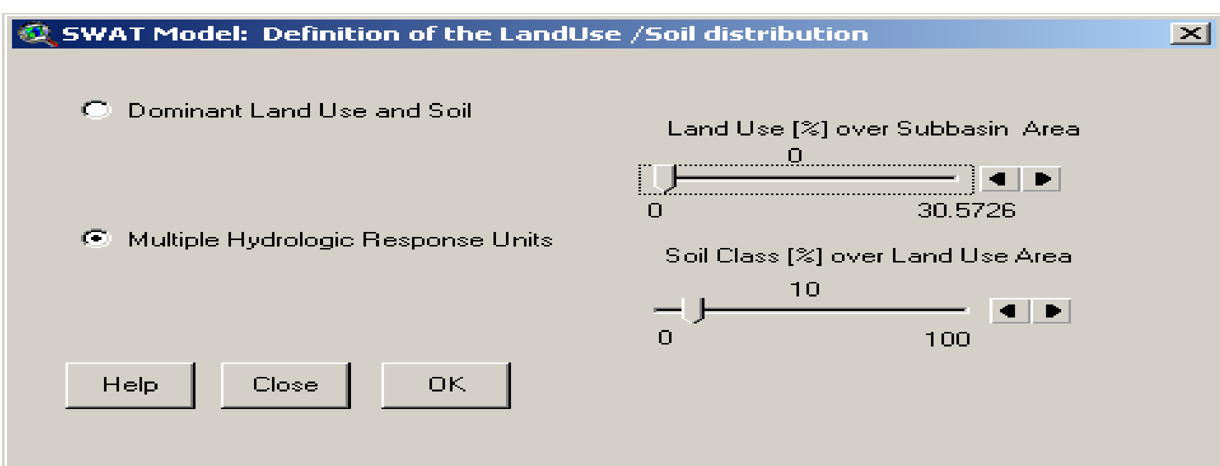

Figure 31. Specifying thresholds for land use and soil class

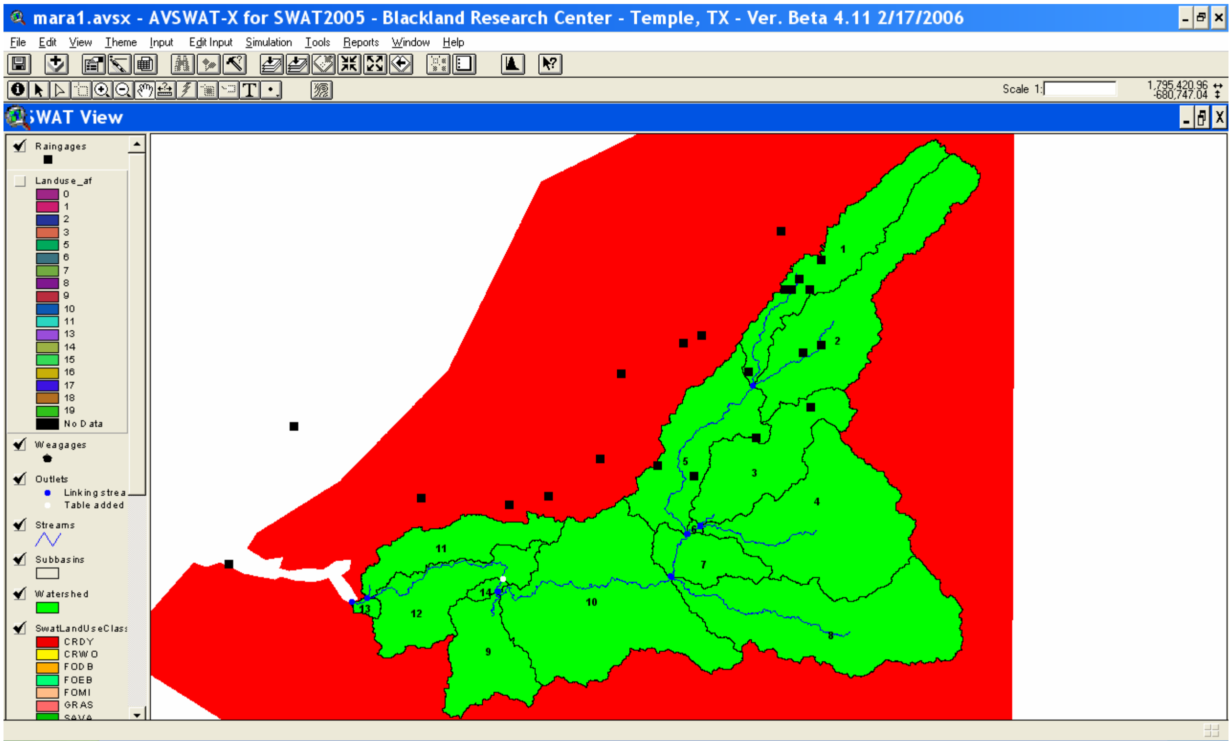

Figure 32. SWAT view

4.1.4 Weather data definition

Next step was to impart weather data for the basin as shown in figure 33. Rainfall data was imported from the location table for eleven stations in the Mara catchment. Temperature data was not available, so simulation was opted for. Nile basin data were used for the weather simulation data. Solar radiation, wind speed and relative humidity data were not available for the catchment. So simulations were done to generate these data.

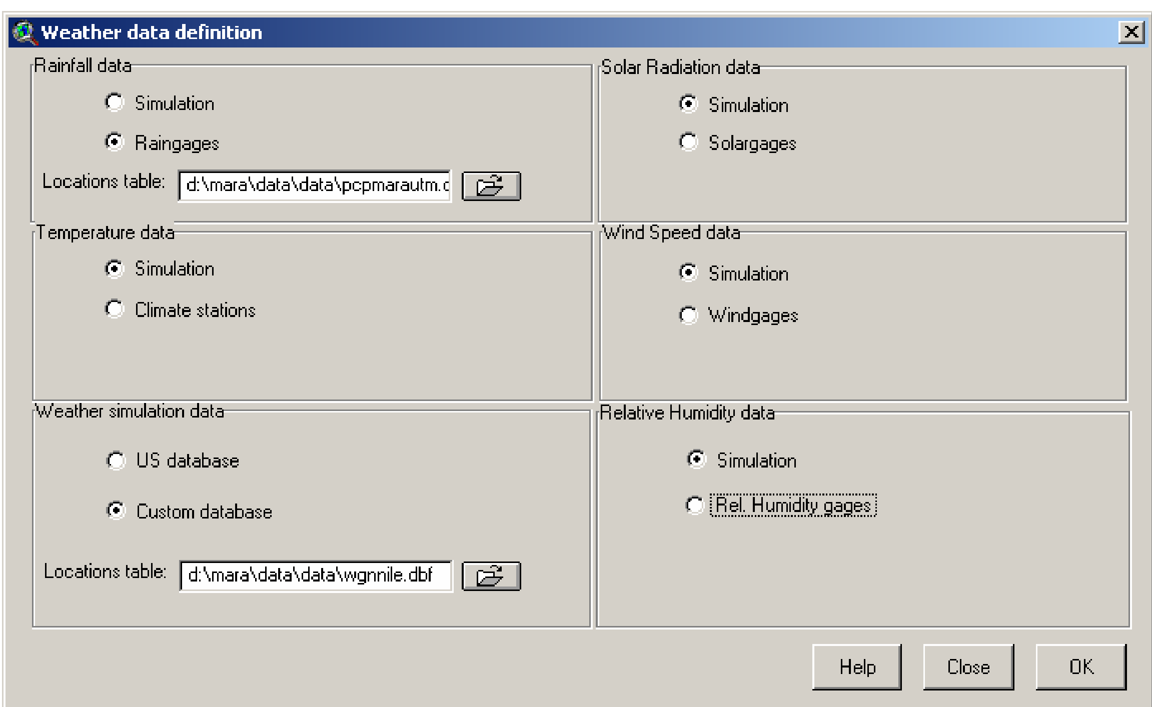

Figure 33. Definition of weather data

After this step, input files were written by choosing **write all** command. At this point, the model was set up ready for running by choosing the simulation period, method for generating rainfall and frequency of results print out (figure 34).

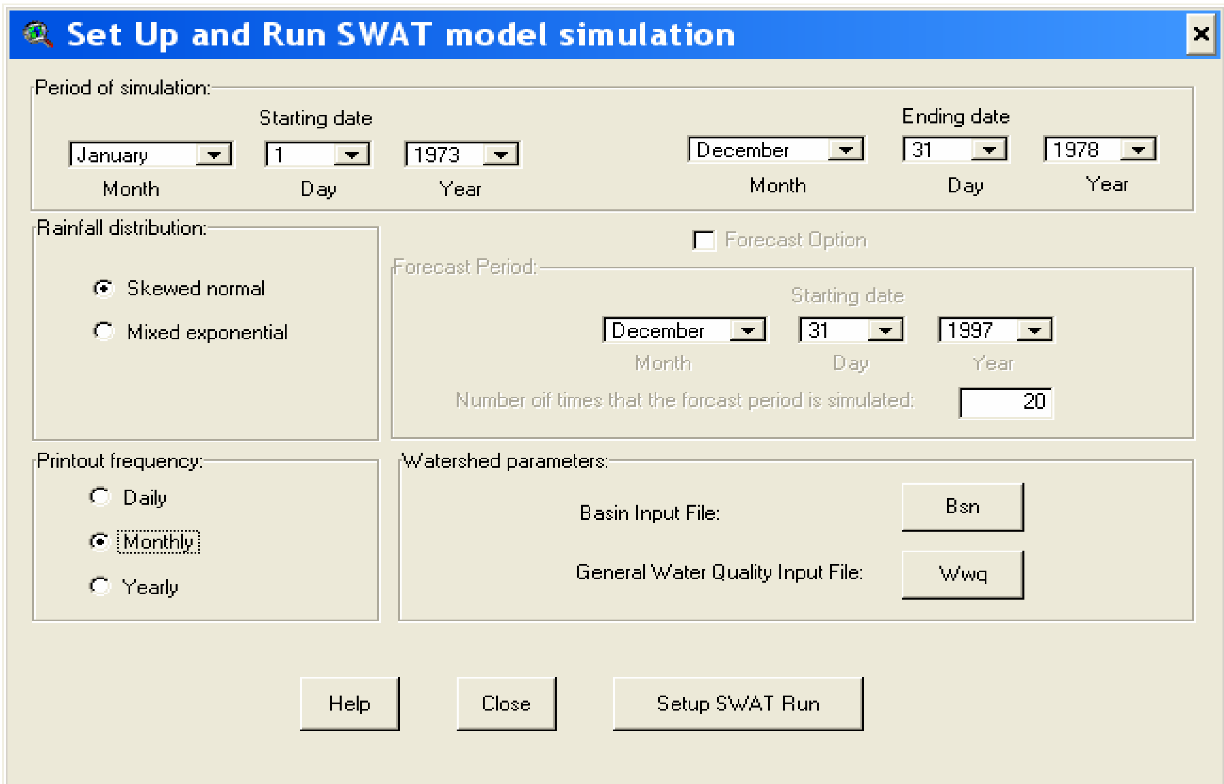

Figure 34. Setting up simulation

4.1.5 Sensitivity Analysis

Next step was to carry out sensitivity analysis to determine the most sensitive parameters in the catchment which affects the model output. The sensibility analysis is done by varying parameters value and checking how the model reacts. If a small change on a given parameter value results on a remarkable change on the model output, this parameter is said to be sensitive to the model. The variation of parameters values is mostly done by either increasing or decreasing parameters values.

An LH-OAT method was used perform the sensitivity analysis. LH-OAT (Latin Hypercube-One Factor at a Time) combines the OAT design and Latin Hypercube sampling by taking the Latin Hypercube samples as initial points for OAT design.

The concept of the Latin-Hypercube Simulation is based on the Monte Carlo Simulation but uses a stratified sampling approach that allows efficient estimation of the output statistics. The Latin-Hypercube sampling is commonly applied in water quality modelling due to its efficiency and robustness. The main drawback is the assumptions on linearity.

OAT (One-factor-At-a-Time) design is an example of an integration of a local to a global sensitivity method. As in local methods, each run has only one parameter changed, so the changes in the output in each model run can be unambiguously attributed to the input parameter changed. This approach has the advantage of a lack of reliance on predefined (tacit or explicit) assumptions of relatively few inputs having important effects, monotonicity of outputs with respect to inputs, or adequacy of low-order polynomial models as an approximation to the computational model.

The LH-OAT sensitivity analysis method combines thus the robustness of the Latin Hypercube sampling that ensures that the full range of all parameters has been sampled with the precision of an OAT designs assuring that the changes in the output in each model run can be unambiguously attributed to the input changed in such a simulation leading to a robust and efficient sensitivity analysis method (van-Griensven).

Table 5 Shows 27 parameters involved in the sensitivity analysis with the corresponding objective functions and output positions.

Table 5. Parameters used in the sensitivity analysis

	Parameter	Description	Objective function	Output
1	SMFMX	Maximum melt rate for snow(mm/ºC/day)	28	28
2	SMFMN	Minimum melt rate for snow(mm/ºC/day)	28	28
3	ALPHA_BF	Base flow alpha factor (days)	2	9
4	GWQMN	Threshold depth of water in the shallow aquifer required to return flow to occur (mm)	28	28
5	GW_REVAP	Groundwater 'revap' coefficient	28	28
6	REVAPMN	Threshold depth of water in the shallow aquifer required for 'revap' to occur (mm)	28	28
7	ESCO	Plant evaporation compensation factor	5	2
8	SLOPE	Average slope steepness (m/m)	11	5
9	SLSUBBSN	Average slope length (m/m)	10	14
10	TLAPS	Temperature laps rate (ºC/km)	28	28
11	CH_K2	Effective hydraulic conductivity in main channel alluvium (mm/hr)	4	11
12	CN2	SCS run-off curve number for moisture condition II	1	1
13	SOL_AWC	Available water capacity (mm/mm soil)	6	3
14	surlag	Surface run-off lag coefficient	3	8
15	SFTMP	Snowfall temperature (Ward *et al.*)	28	28
16	SMTMP	Snow melt base temperature (Ward *et al.*)	28	28
17	TIMP	Snow pack temperature lag factor	28	28
18	GW_DELAY	Groundwater delay (days)	28	28
19	rchrg_dp	Groundwater recharge to deep aquifer (fract)	28	28
20	canmx	Maximum canopy index	8	6
21	sol_k	Soil conductivity (mm/hr)	9	7
22	sol_z	Soil depth	7	4
23	sol_alb	Moist soil albedo	14	13
24	epco	Plant evaporation compensation factor	15	12
25	ch_n	Manning coefficient for channel	13	15
26	blai	Leaf area index for crop	28	28
27	BIOMIX	Biological mixing effinciency	12	10

The analysis for five years simulation showed that the first ten parameters shown in figure 35 were the most sensitive. These values were used to carry out the calibration of the model.

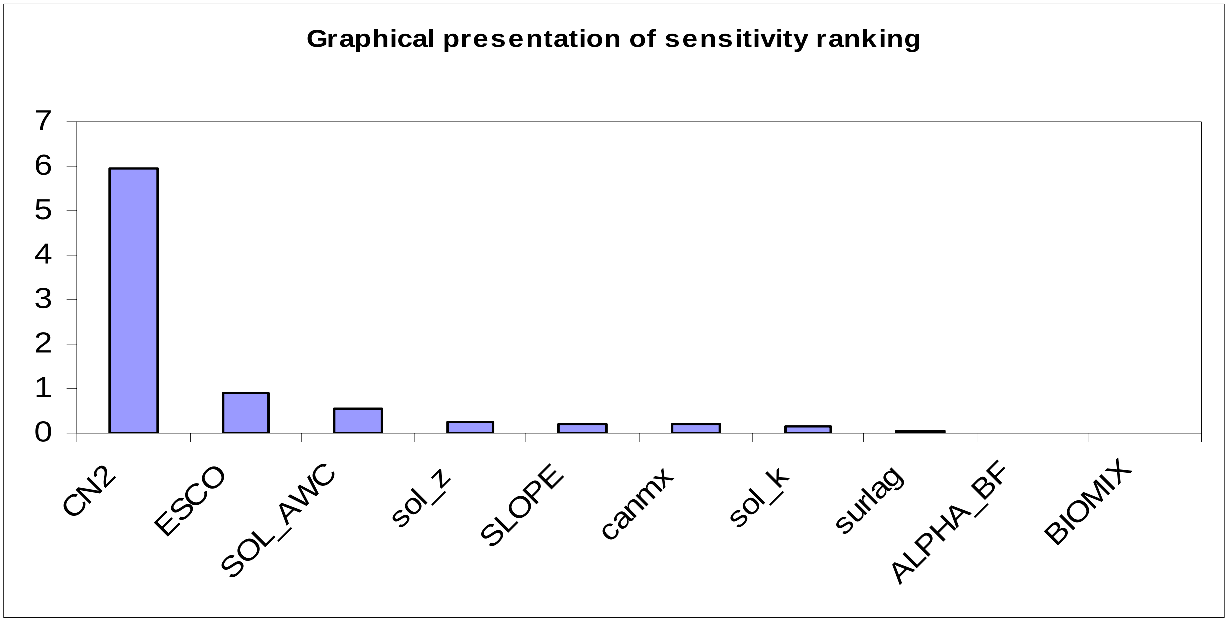

Figure 35. Result of the sensitivity analysis

4.1.5 Calibration

After sensitivity analysis, the model was calibrated to make sure that the model (software and data) represents reality in the catchment. Calibration consists of modification of model parameter values and comparison of predicted output to measured data based on a predefined objective function.

In this research, an automatic calibration method called PARASOL – Parameter Solutions Methods (van-Griensven) was used to perform the calibration of the model. Parasol uses the Shuffled Complex Evolution Algorithm (SCE-UA), which is a global search algorithm for minimization. The algorithm combines the direct search method of the simplex procedure with the concept of a controlled random search, a systematic evolution of points in the direction of global improvement, competitive evolution and the concept of complex shuffling.

Two type of objective functions were used in the autocalibration. The first one used The Sum of the squares of the residuals (SSQ): similar to the Mean Square Error method (MSE) which tries to match a simulated series to a measured time series.

$$SSQ = \sum_{i=1,n} \left[x_{i,measured} - x_{i,simulated} \right]^2$$

with n the number of pairs of measured ($x_{measured}$) and simulated ($x_{simulated}$) variables.

The SSQ yielded very bad results with R^2 value of 0.0137. This showed that there was no correlation between input (rainfall) and the output (flow) (figure 36).

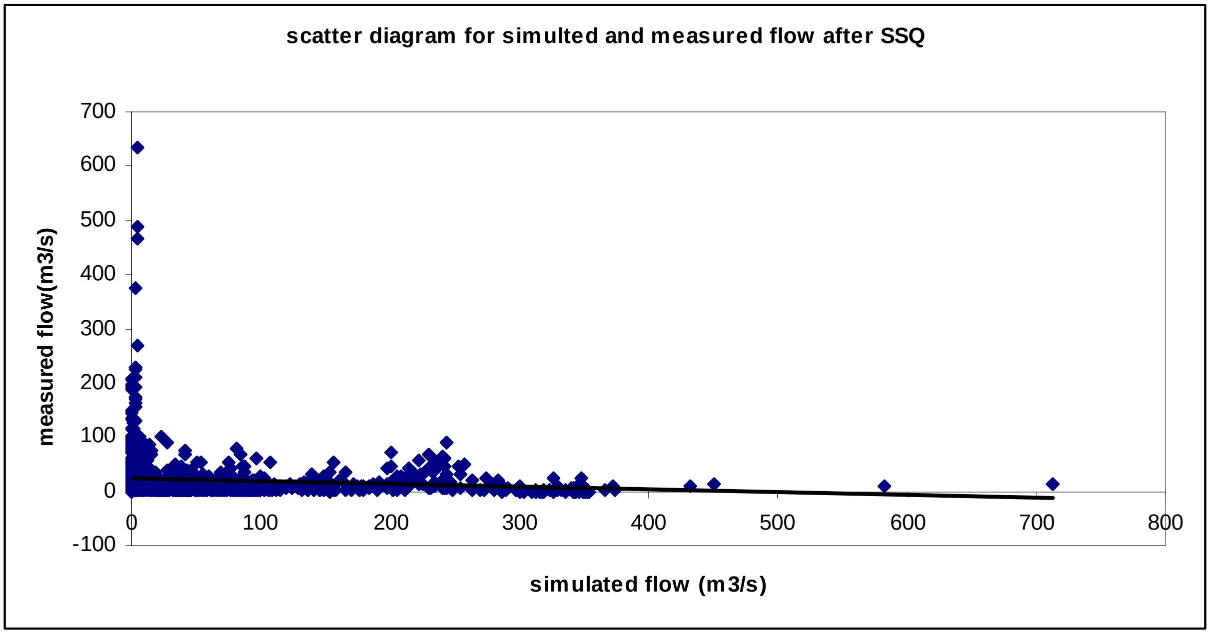

Figure 36. Correlation of the measured against the simulated flows

The next alternative was use the ranking method (SSQR). This method aims at the fitting the frequency distributions of the observed and the simulated series. As opposed to the SSQ method, the time of occurrence of a given value of the variable is not accounted for in the SSQR method was employed to check if the water balance was right. After independent ranking of the measured and the simulated values, new pairs are formed and the SSQR is calculated as

$$SSQR = \sum_{j=1,n} \left[x_{j,measured} - x_{j,simulated} \right]^2$$

where j represents the rank.

This method generated good results (figure 37) suggesting that the catchment water balance would be fine.

At this point, the model could not be used for representing the catchment processes until some degree of confidence was attained as to whether it was correct.

This problem, as hinted in the data analysis section, may have been caused by incorrect data. To ascertain that the model was correctly built, and that data was a problem, analysis of the monthly water yield from the model and the monthly precipitation input into the model was done. Results showed that there was a good correlation between the inputs (precipitation) and the output (water yield) (figure 38) indicating that the model was performing correctly and that data was the real problem.

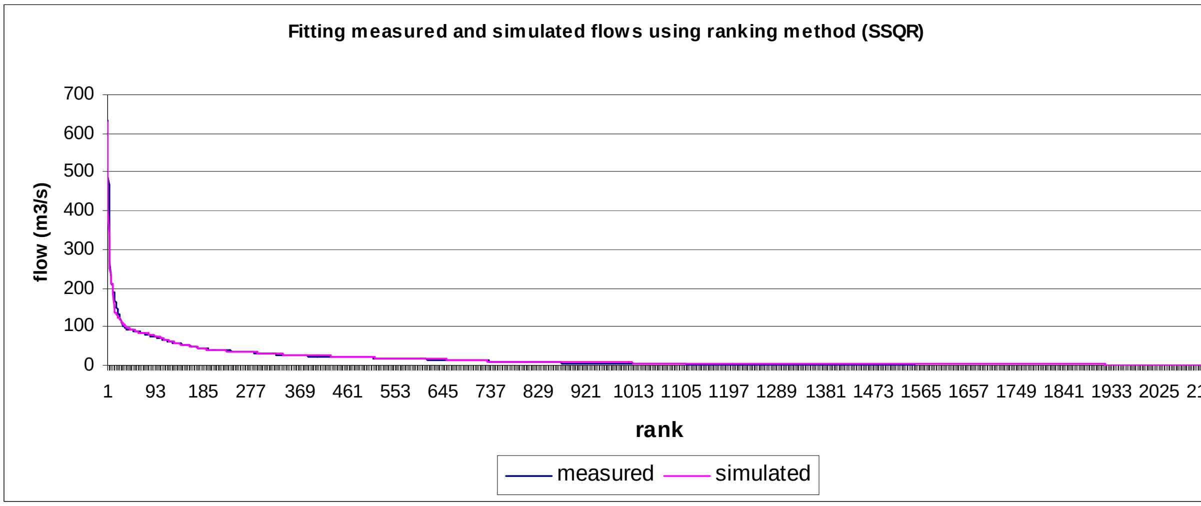

Figure 37. Fitting the measured and simulated flows using ranking method

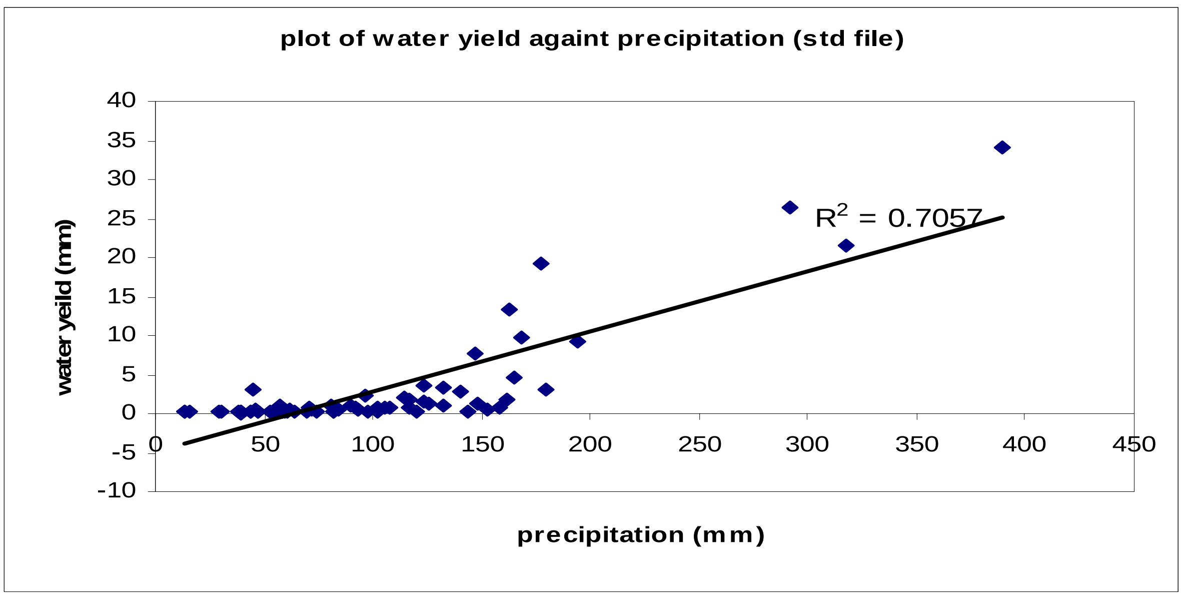

Figure 38. Testing the correctness of the model performance

4.1.6 Improvements of the model

The model calibration process went through different stages in trying to get a representation of the catchment processes. These stages included first setting up a model using the rainfall data with gaps and letting the software fill in the gaps. The calibration results of this simulation were not fine. Next alternative was to fill the gaps in the daily rainfall values from neighboring stations. Again the simulation with this data gave bad results also. After this, calibration with two objective functions was employed but resulted in no improvements in the calibration results. Then, new stations which fell outside the catchment were also added and the resulting simulation did not give the anticipated results. The next alternative was to perform monthly calibration. Although the rainfall data had better correlation among themselves and the flow, the calibration results were better (Nash-Sutcliffe coefficient of 0.65). Table 6 contains results of the calibration for different alternatives.

Table 6. Results (Nash-Sutcliffe coefficient) of calibrations

S/No.	Data description	Nash-Sutcliffe Coefficient
1	Calibration with rainfall data as they are	-1.19
2	Calibration with rainfall data with missing values filled by values from adjacent stations	-11.21
3	Calibration using two objective functions (SSQ and SQQR) with the filled stations	-0.034
4	Calibration after adding rainfall stations from outside the catchment	0.14
5	Calibration using monthly data (rainfall and flow) after adding stations	0.65

With these improvements, the simulations for the current and future scenarios used parameters from the monthly calibration which gave the best results (among the worst) as depicted in figure 39 . This figure shows that the model was not successfully calibrated and therefore could not be validated.

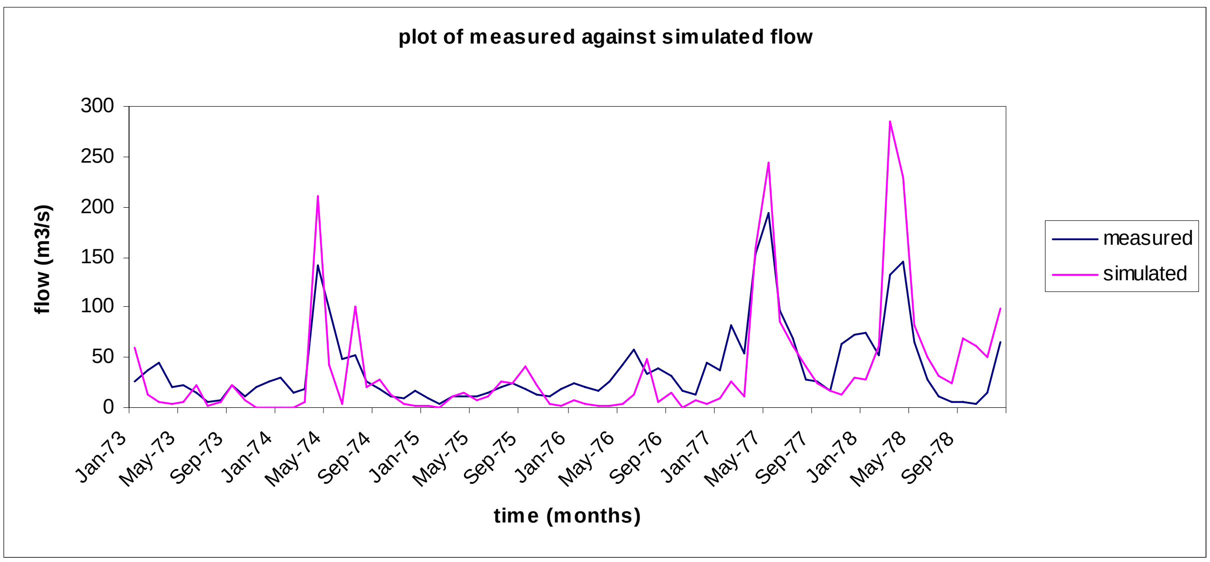

Figure 39. Fitting the measured against the simulated flow

4.2 HEC RAS model

4.2.1 Introduction

HEC-RAS model was used to route the runoff generated by SWAT model in upper part of the catchment, through Kirumi wetland into the lake Victoria. The model result is the water surface elevations in the Kirumi wetland for current situation and a future projected scenario. The future scenario was created by changing the land use in the upper catchment in the SWAT model and the resulting flow routed through the HEC-RAS model again as was the case for the current situation. Also the downstream boundary condition (lake levels) was also increased/decreased by about a meter from the current situation to create the future scenario.

The HEC RAS model uses geometry data of the river schematics, steady flow and unsteady flow data to simulate the water surface elevations. The geometry data defines how the various reaches are connected, the cross section data, reach lengths and the energy loss coefficients.

4.2.2 River system schematics

Under this section, information about the river name, reach name, stations name and cross section information are provided into the model.

In this research, the river name was Mara, there was only one reach (Kirumi) of about 12 km stretch with seven river stations within the reach and therefore seven river cross sections (figure 40).

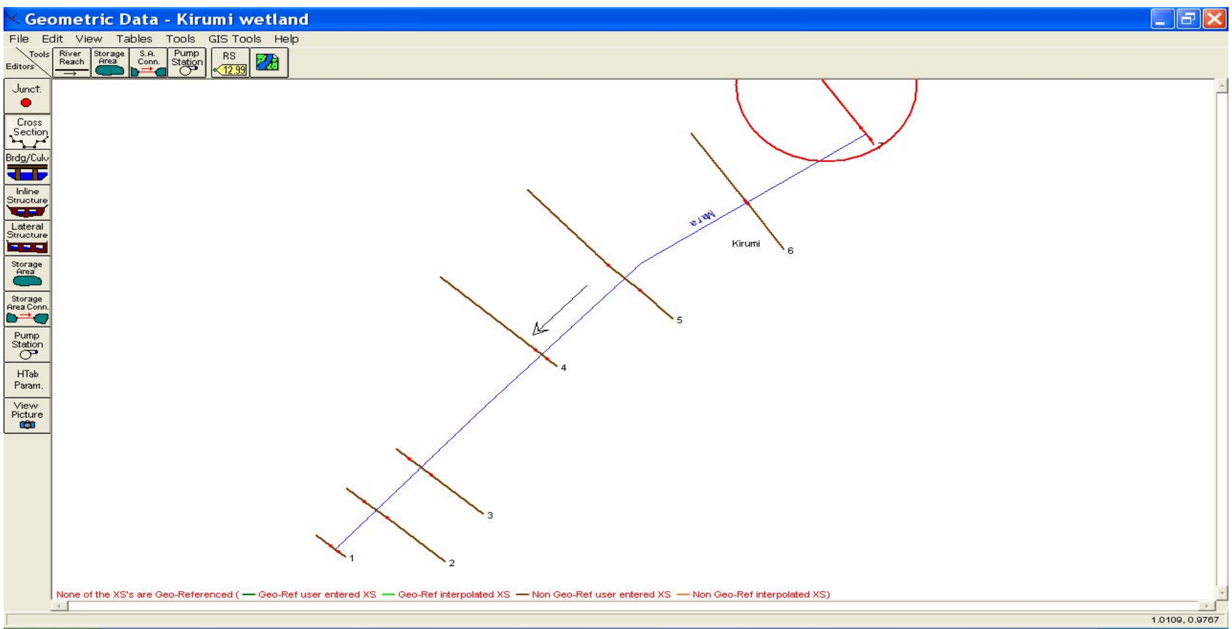

Figure 40. River system schematics

The Kirumi reach had seven cross sections which contained information about the boundary surface level. This levels were obtained by subtracting the water surface elevation from the sounded depth on the open water way. To establish the water's edge, extrapolation was used between the end of the open water and the wetland area established from the google earth map. Downstream reach lengths were measured distance between the cross sections. The cross sections were measured perpendicular to the flow lines and across the entire flood plain (figure 41).

The main channel downstream reach length was calculated along the thalweg. The overbank downstream reach lengths were calculated along the center of mass of the overbank flow. Manning's n values for the main channel and the overbank/flood plain were taken form literature considering the situation of the river (Brunner, 2002). The main channel bank stations-which marks the start of the river overflow to flood plain- were set on either side of the channel depending on the shape of the river cross section. Default values for coefficients of contraction were always used.

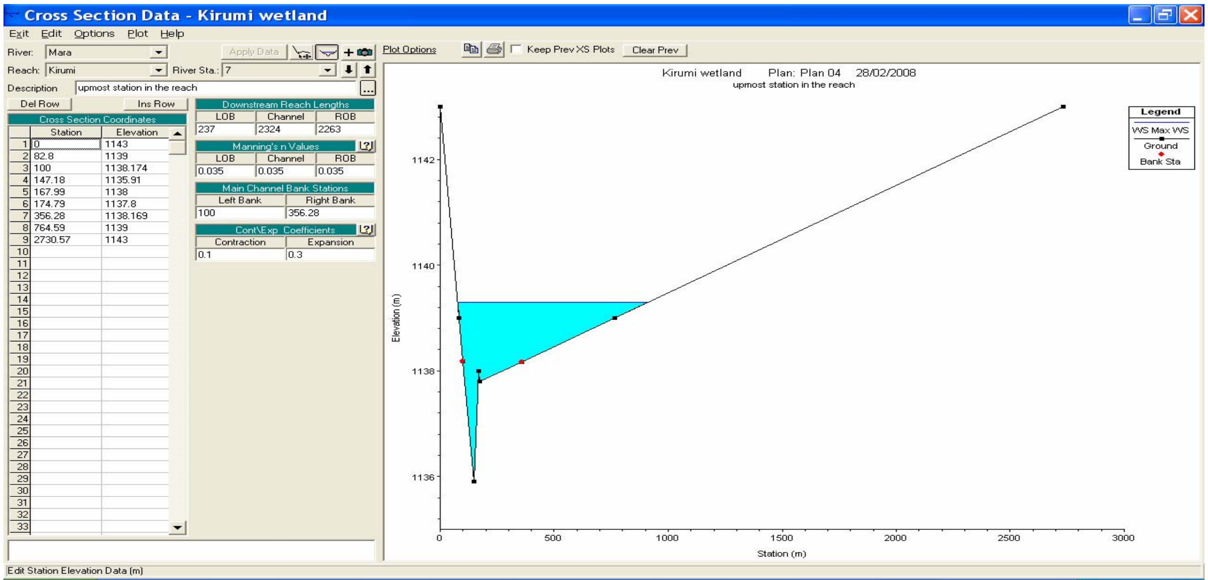

Figure 41. Cross sectional profile across Kirumi wetland

4.2.3 Unsteady flow simulation

The next step was to input unsteady flow simulation data (figure 42). In this, boundary and initial conditions were specified. Boundary conditions are required at all external boundaries of the system as well as any desired internal locations. Initial flow was required at the start of the simulation. The upstream boundary condition was specified as a flow hydrograph at gauging station (Mara Mine 5H3) (figure 43) and the downstream boundary condition was the stage hydrograph at a gauging station (Kirumi 5H2) (figure 44). The flow and stage hydrographs were entered in the model using HEC-DSSvue, a data storage system. Flow of 2 m3/s second was randomly set as an initial condition.

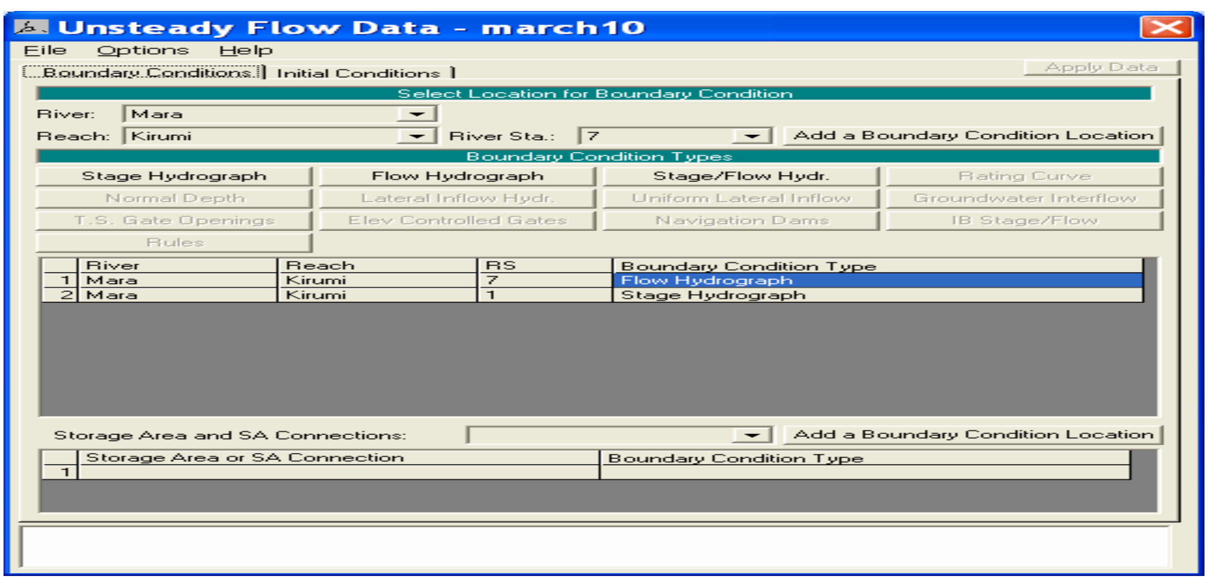

Figure 42. Providing unsteady flow simulation data

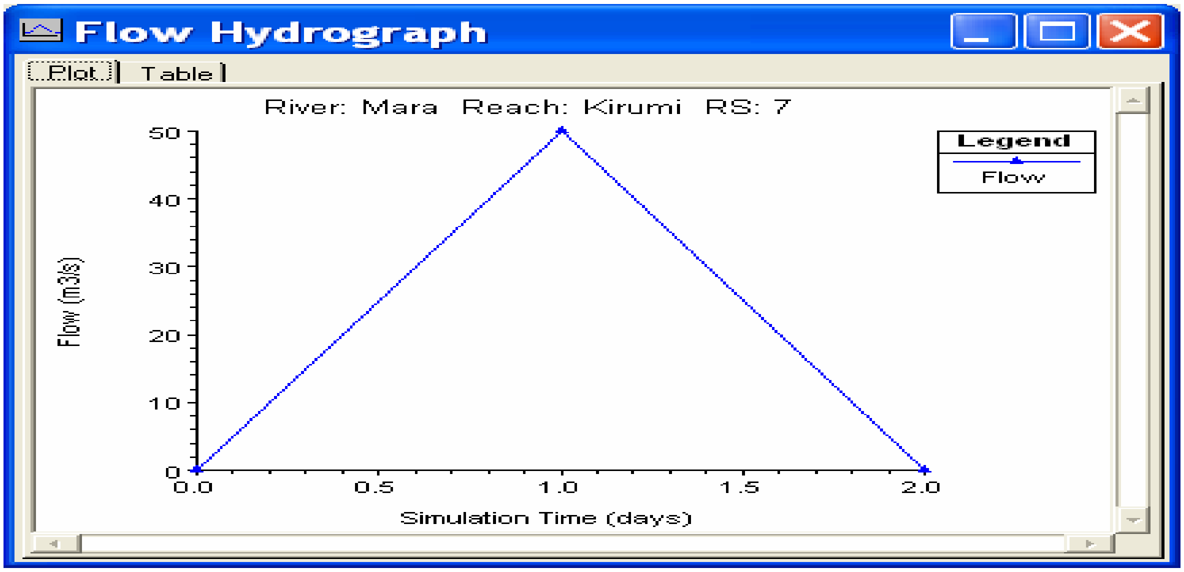

Figure 43. Trial upstream boundary condition

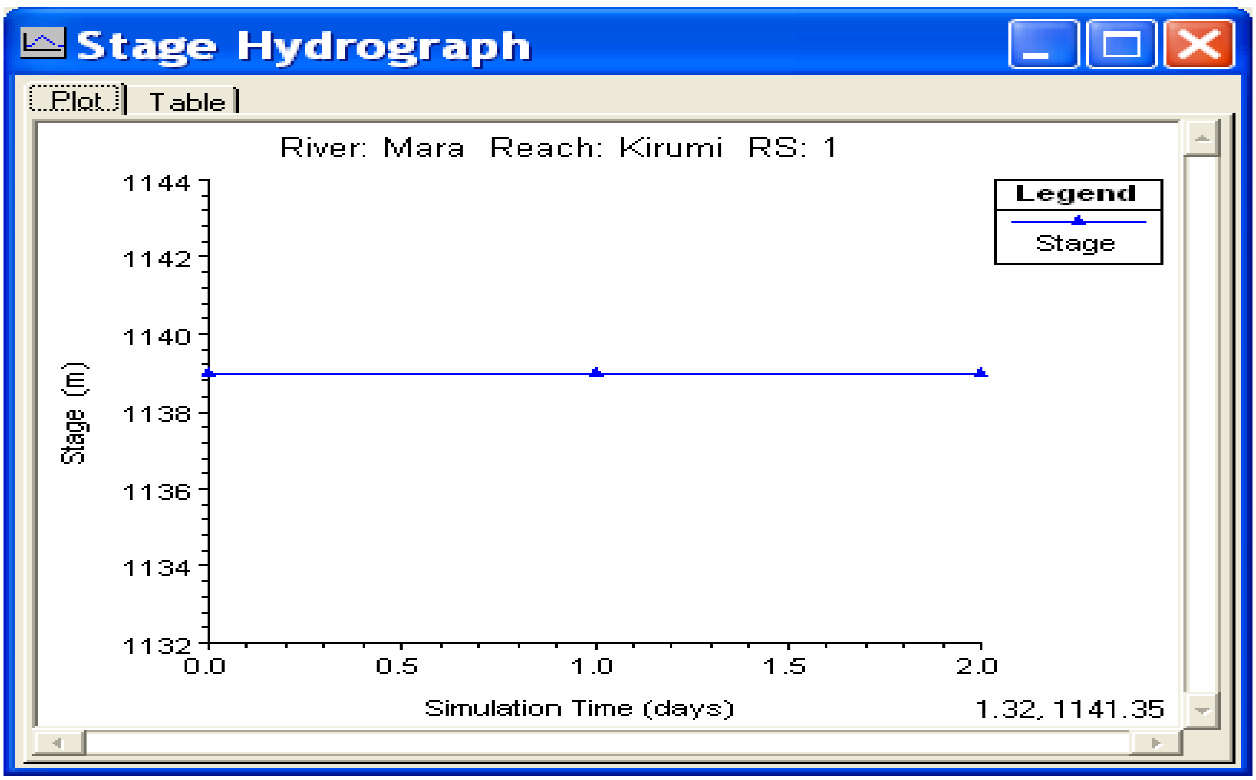

Figure 44. Trial downstream boundary condition

The next step was to perform the unsteady flow simulations. In this stage, the plan which identifies the geometry and unsteady flow data to be used, and the programs to be run are selected. Then simulation start and end times, the computational time step, output time step and the type of the flow regime (mixed or sub critical) (figure 45) were also selected.

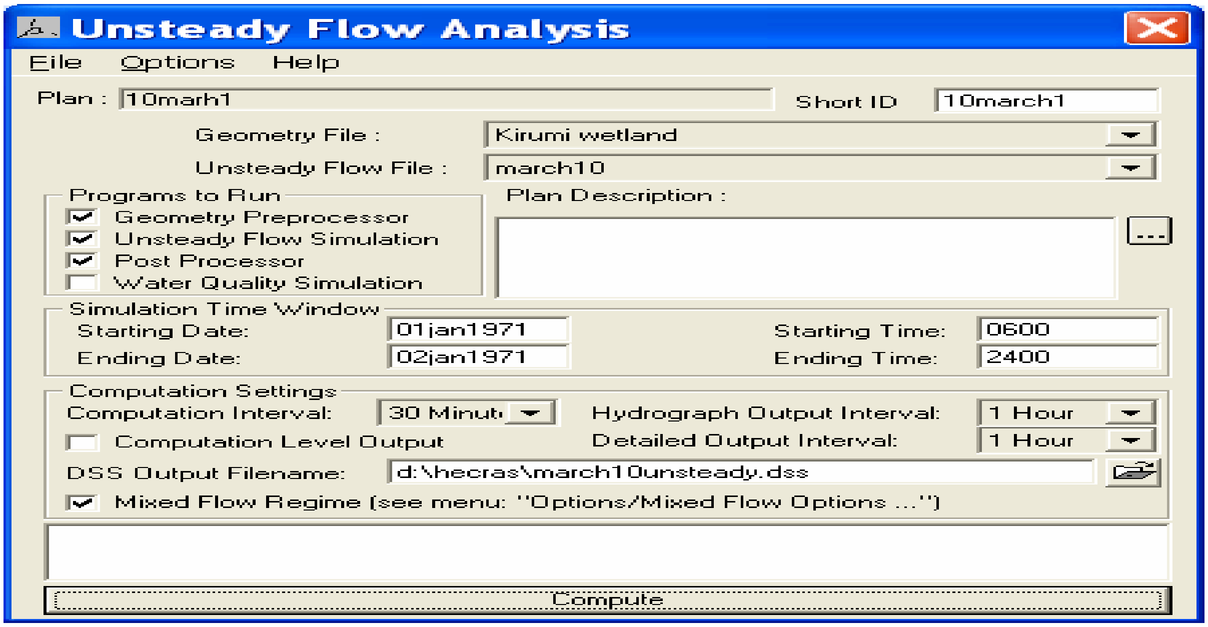

Figure 45. Setting up a trial unsteady flow simulation

Then, the model was run for two days. The results showed that the model did not respond to any changes in the upstream boundary conditions. This was due to the influence of the backwater effect from the lake or might have been caused by poor geometry. All the rating curves at the cross sections in between had constant water levels (figures 46 to 48).

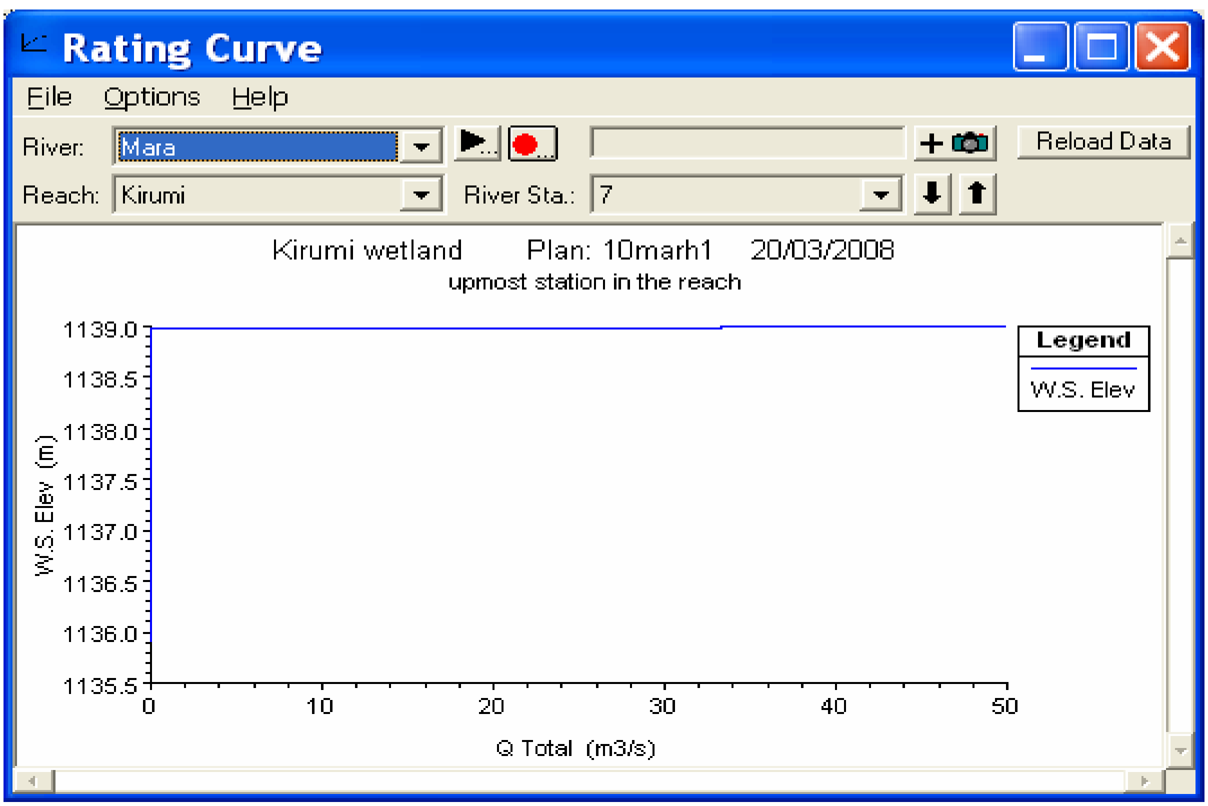

Figure 46. Rating curve at cross section 7

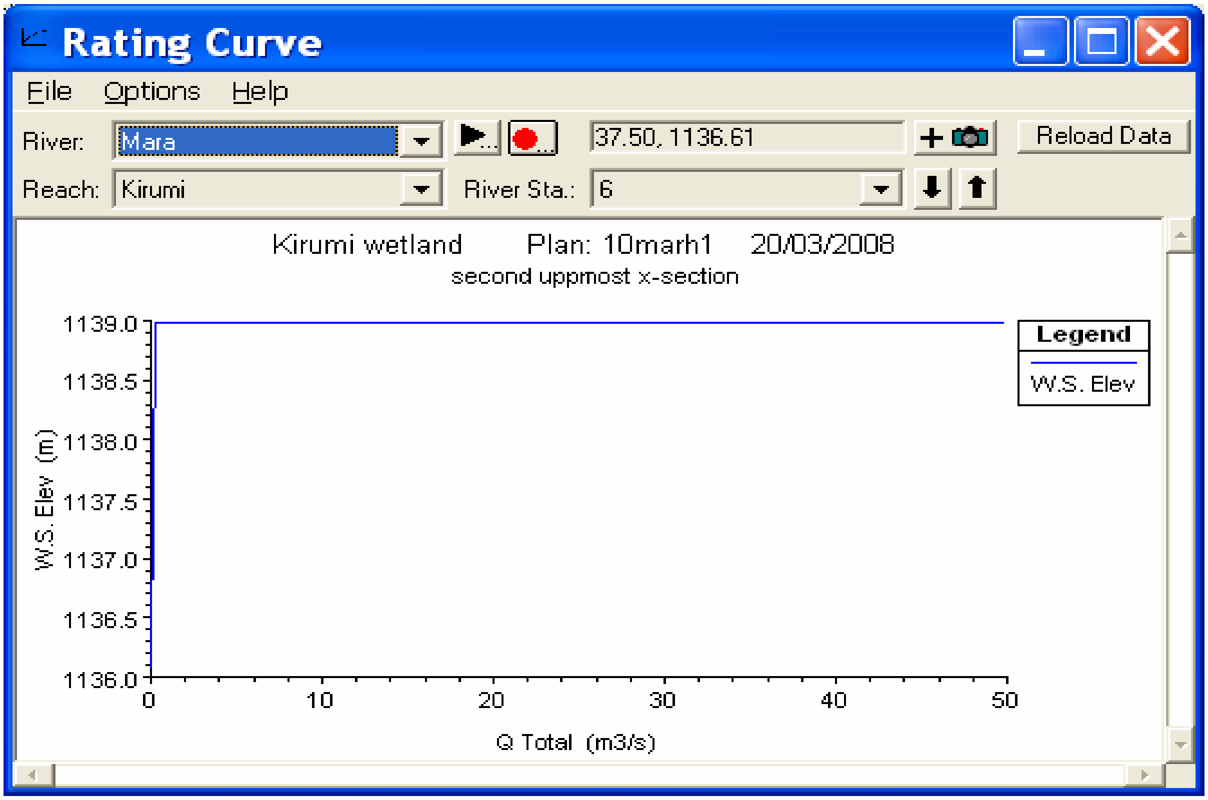

Figure 47. Rating curve at cross section 6

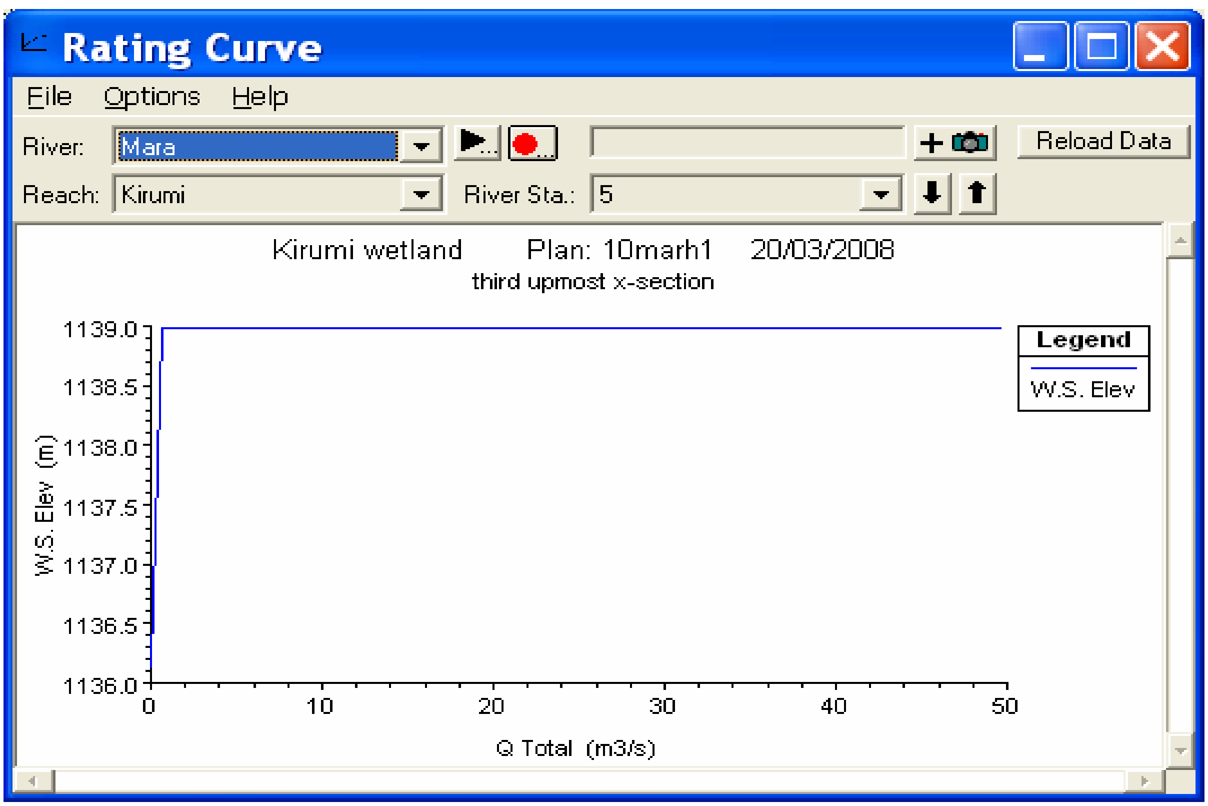

Figure 48. Rating curve at cross section 5

This necessitated the extension of the geometry data to the area outside the influence of the backwater effects. Two cross sections were added upstream to this effect. These cross sections were approximated using the last upmost measured cross section. The resulting model was run and results showed the elimination of the backwater effects. Figures 49 & 50 show the new geometry and positions of the cross sections (cross section 9 being the up most). Figures 51to 52 show the resulting rating curves.

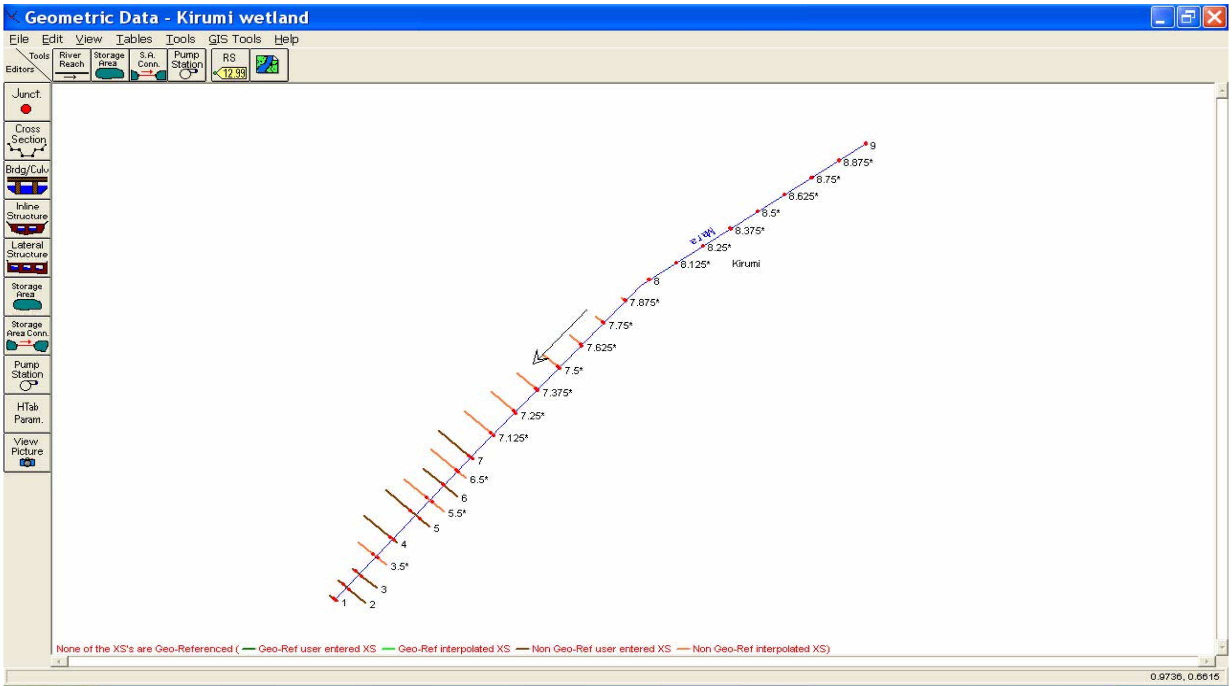

Figure 49. Revised river schematics with more cross sections

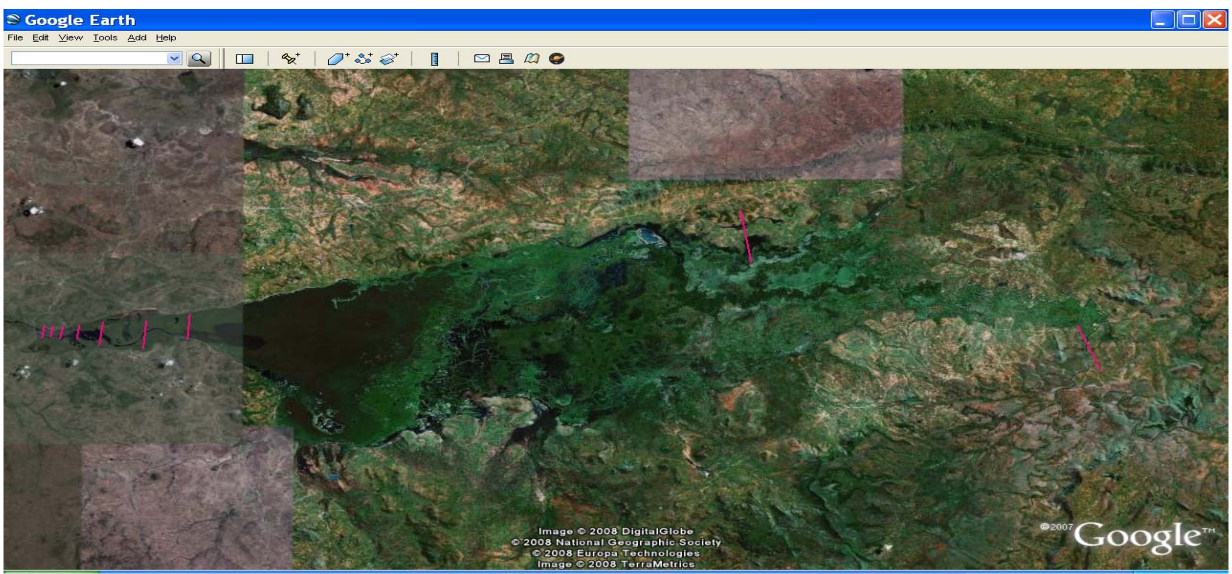

Figure 50. Locations of the cross sections in the wetland

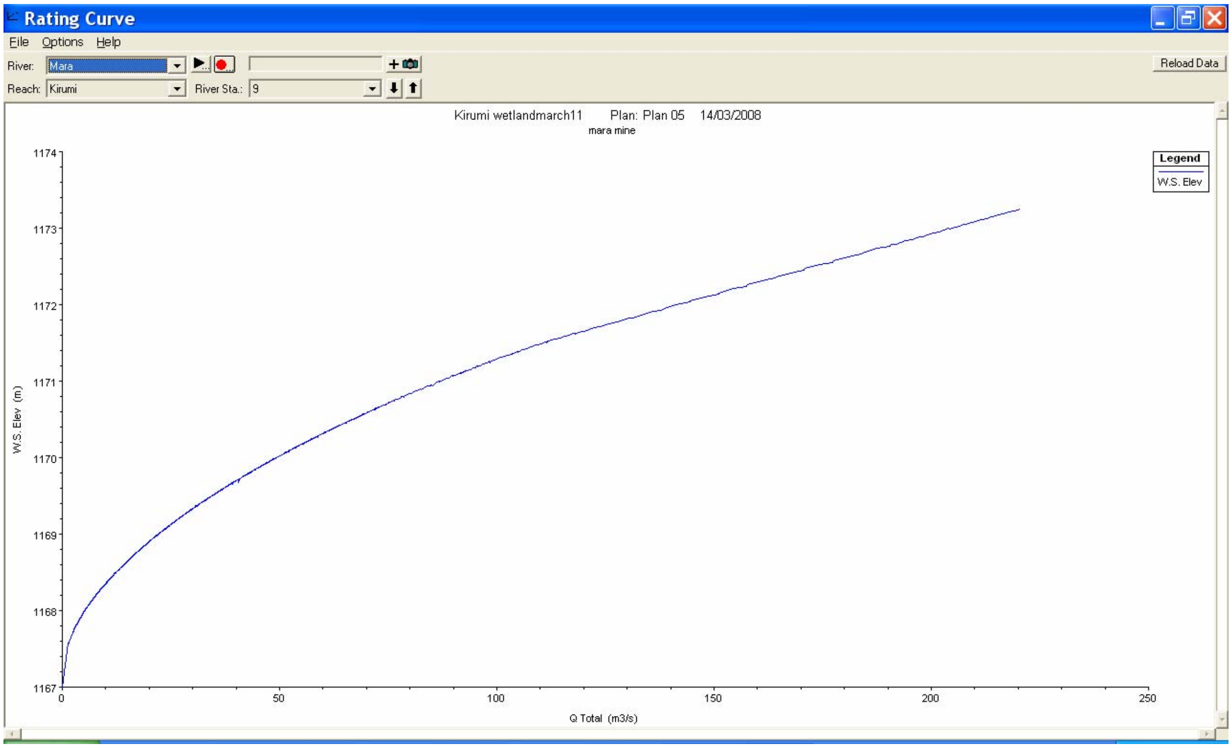

Figure 51. Rating curve at new cross section 9

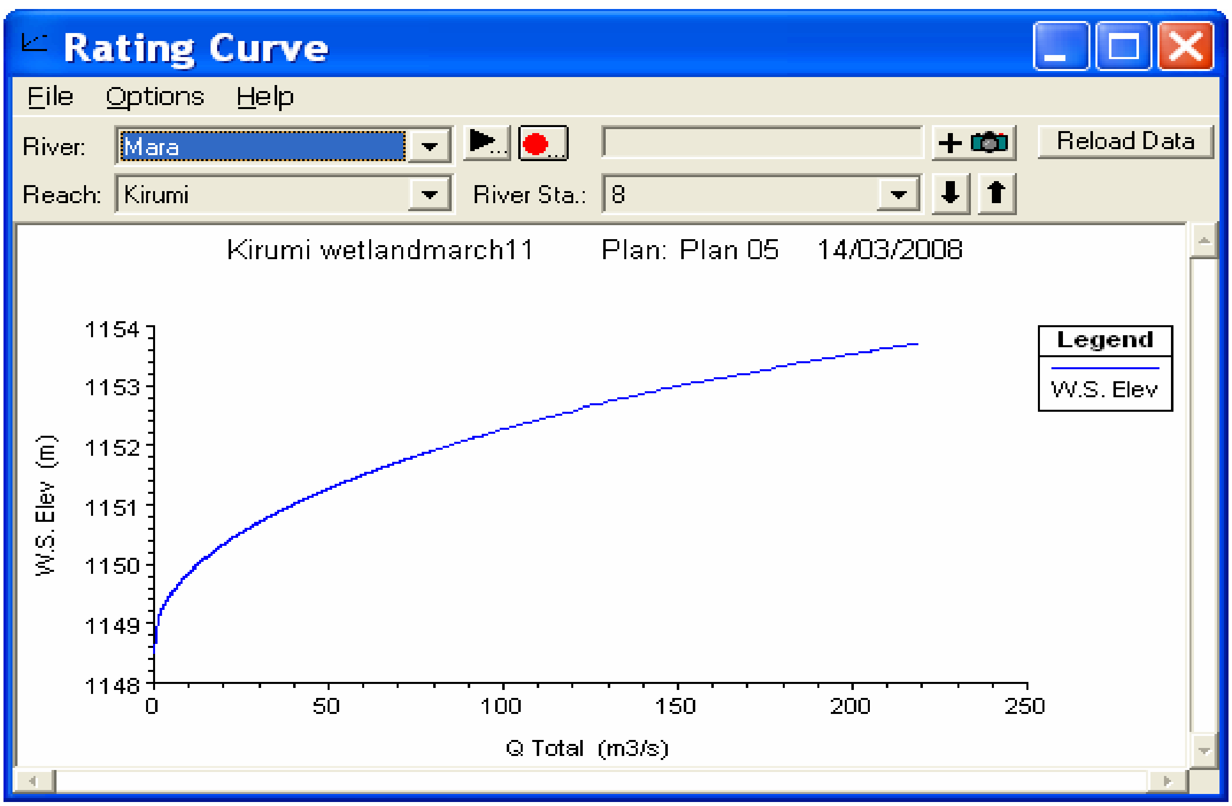

Figure 52. Rating curve at new cross section 8

4.2.4 Model calibration

Calibration is the adjustment of a model's parameters, such as roughness coefficients, s that it reproduces observed data to an acceptable accuracy. In this study, no field data was measured for the model calibration due to equipment malfunctioning and there was no any gauging station in between the upstream and downstream boundary conditions. In the absence of calibration data, the model parameters were changed just to check its sensitivity. Manning's n value at cross section 9 was changed from 0.035 to 0.06 and the water surface changed from 1170.0 m to 1170.5 m (figures 49&50). This showed that the model was correctly built and could be used for water surface simulation of the wetland.

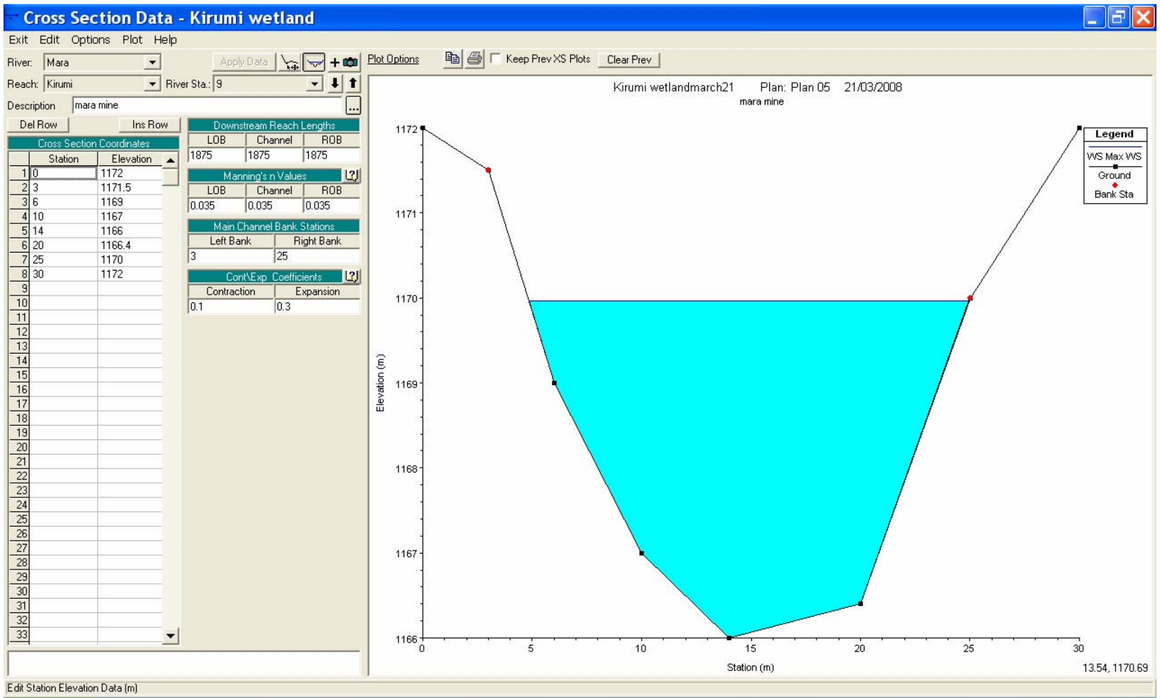

Figure 53. Water surface profile at cross section 9

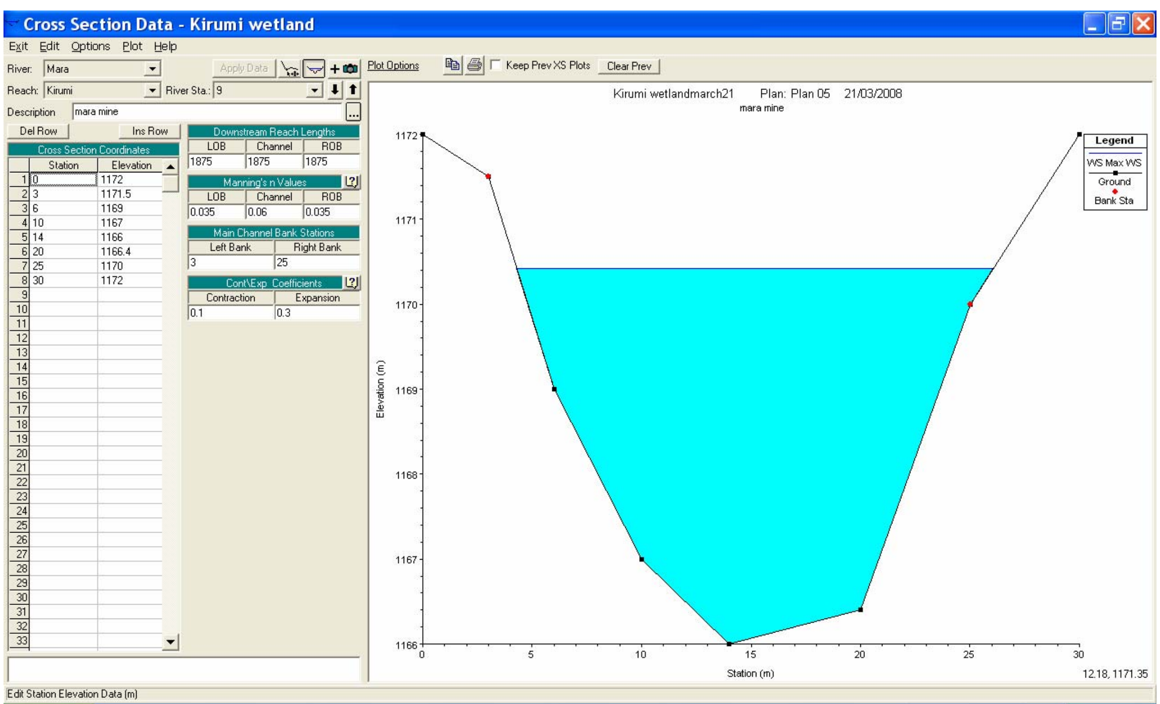

Figure 54. Water surface profile at cross section 9 with an increased n value

4.3 IHA model

4.3.1 Introduction

In the HEC RAS model, the current scenario (lake levels and flows from the upstream catchment for 25 years) was analysed to give water surface profiles at the selected nine cross sections in the wetland. Then, the lake water levels were lowered by two meters, and the catchment land use increased by fifty percent for two land uses (CRWO and CRDY). The water surface profiles for this new scenario were also analysed for 25 years. This IHA tool was used to compare the two scenarios using parameters described in table 7 which fall under five categories: magnitude of monthly water conditions; magnitude and duration of annual extreme water conditions; timing of annual extreme water conditions; frequency and duration of high and low pulses; and rate and frequency of water condition changes (NTC, 2007).

Table 7. Summary of IHA parameters and their ecosystem influences

IHA Parameter Group	Hydrologic Parameters	Ecosystem Influences
1. Magnitude of monthly water conditions	Mean or median value for each calendar month	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and duration of annual extreme water conditions	Annual minima, 1-day mean Annual minima, 3-day means Annual minima, 7-day means Annual minima, 30-day means Annual minima, 90-day means Annual maxima, 1-day mean Annual maxima, 3-day means Annual maxima, 7-day means Annual maxima, 30-day means Annual maxima, 90-day means Number of zero-flow days Base flow index: 7-day minimum flow/mean flow for year	• Balance of competitive, ruderal, and stress- tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in

		lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
3. Timing of annual extreme water conditions	Julian date of each annual 1-day maximum Julian date of each annual 1-day minimum	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms
4. Frequency and duration of high and low pulses	Number of low pulses within each water year Mean or median duration of low pulses (days) Number of high pulses within each water year Mean or median duration of high pulses (days)	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
5. Rate and frequency of water condition changes	Rise rates: Mean or median of all positive differences between consecutive daily values Fall rates: Mean or median of all negative differences between consecutive daily values Number of hydrologic reversals	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility streamedge (varial zone) organisms

4.3.2 Model building

Data of all the nine water profiles for the pre-impact and post impact periods were read into the model. Data file name, units and hydrological year information were specified (figure55). Although the unit of the data was meters, flow units were chosen because of the software limitation. The pre-impact period analysed was from 1973 to 1997 and this represented the current situation. The post-impact period was from 1998 to 2022 and represented a scenario with changes in the lake water level and the catchment land use.

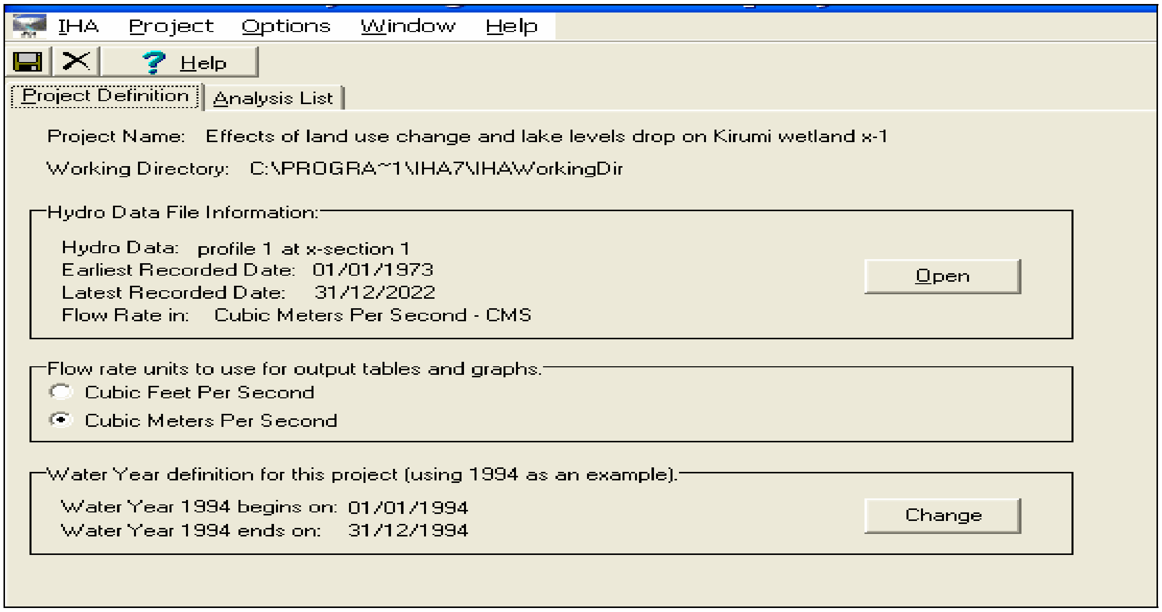

Figure 55. Defining the project data in IHA model

Next step was to set up the analysis properties where different information regarding the titles of the analysis, years, days and statistics were given into the model (figure 56).

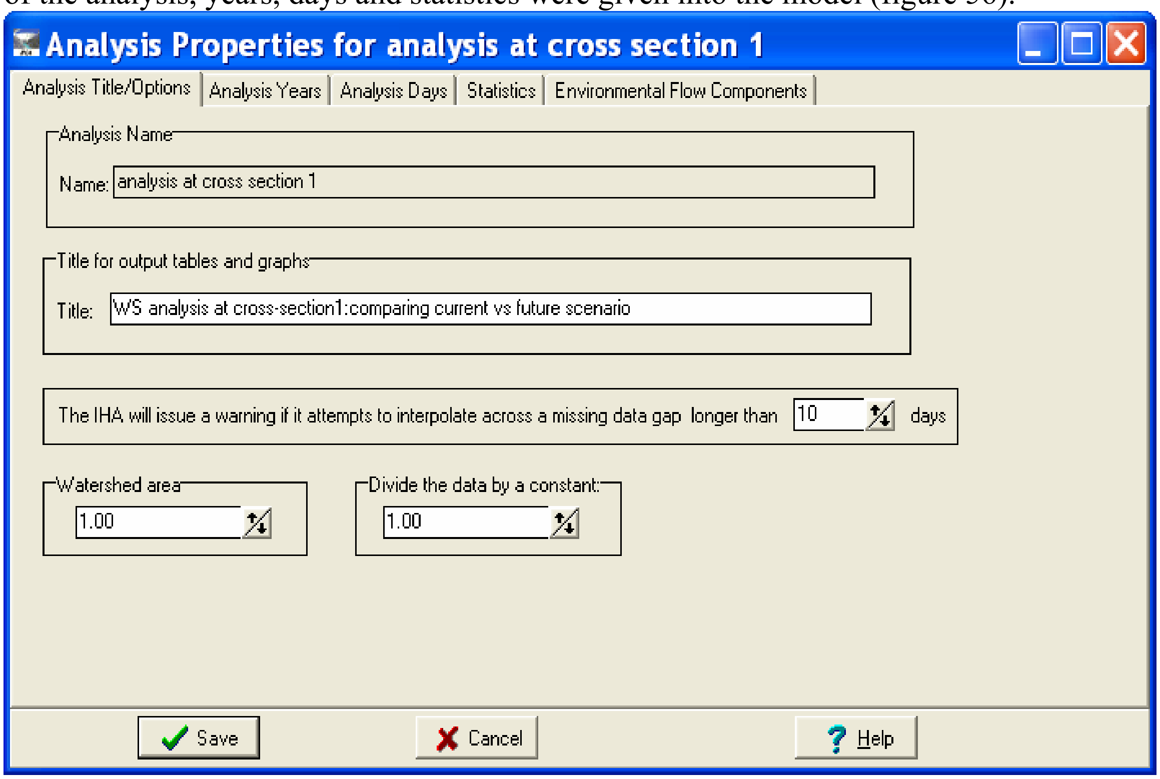

Figure 56. Defining analysis data in IHA model

After this step, the analysis was run, and the results were ready for interpretation.

5. Results

5.1 SWAT results

The first scenario simulated was that showing how things have been in the catchment for twenty five years from 1973 to 1997 (current situation). This period was chosen due to its completeness in data (more data available in this period, does not mean no missing data) for rainfall and flow. The other scenario simulated reflected a development in the catchment where the land use increased by 50% for cropland/woodland mosaic (CRWO) and dryland cropland and pasture (CRDY). This was also simulated for 25 years. Consequently, the other land uses had to decrease proportionally to compensate for the increase. However, the timing for this change (how long it takes to happen) and the effects of climate change were not included in the analysis.

The purpose of using SWAT model in this research was to make use of its capability of incorporating landuse changes in the model for the aim of assessing the effect of the landuse changes in the catchment to the flow in to the Kirumi wetland and its ecosystem.

Results (Appendix 2) showed no big difference between the two scenarios. The difference in water yield was only 1.28 mm (a change of about 1%). Table 8 has a summary of the flow simulation for the two scenarios. This shows that the changes in the catchment do not change the catchment water balance.

Table 8. Summary of the flow simulations for the two scenarios

Average annual basin values			
parameter	Present situation	Future situation	Expalanation
Prec	1330.10	1330.10	Precipitation
LSQ	33.79	37.06	Lateral soil flow
GWQ	55.64	53.65	Ground water (shallow aquifer) flow
RQ	1.85	1.75	Revap (shallow aq)
DAR	3.03	2.92	Deep aquifer recharge
TAR	60.51	58.31	Total aquifer recharge
TWYLD	89.43	90.71	Total water yield
POS	62.20	60.02	Percolation out of soil
ET	1239.60	1166.20	Evapotranspiration
PE	2401.40	2377.00	Potential evapotranspiration

The results (flow hydrographs) were used as upstream boundary condition for simulating the hydraulics of the Kirumi wetland.

5.2 HEC RAS results

This model was built for modeling the water surface profile in the Kirumi wetland where 9 cross sections were used to build the model. Two scenarios were simulated, the current situation, and future scenario where it was assumed that the lake level would drop by 2 meters and in the cathment, landuse would increase by 50% for two CRWO and CRDY. The results of the SWAT model was used as the upstream boundary condition and the measured water levels of the lake as the downstream boundary condition. Results of the simulations (surface water levels at cross sections) are summarized in figures 57 to 65. More results (flow at the cross sections) are attached as Appendix 3.

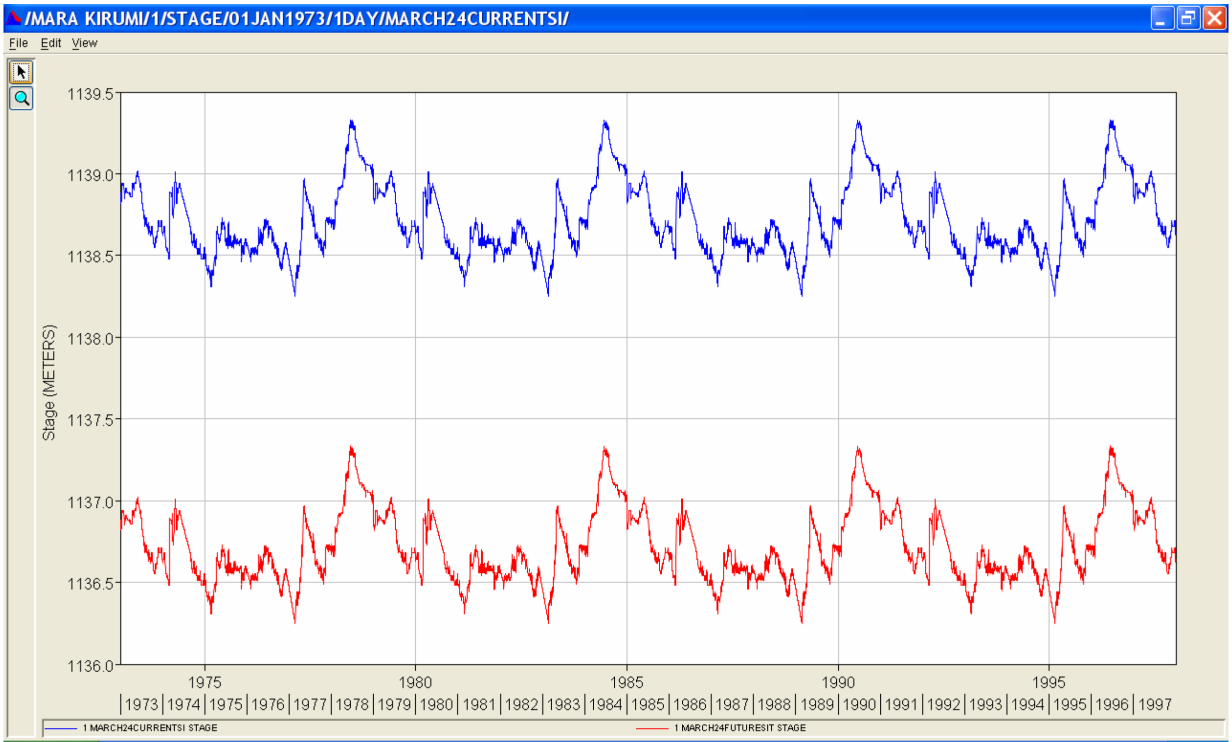

Figure 57. Water surface profile at cross sectio1, current and future situation

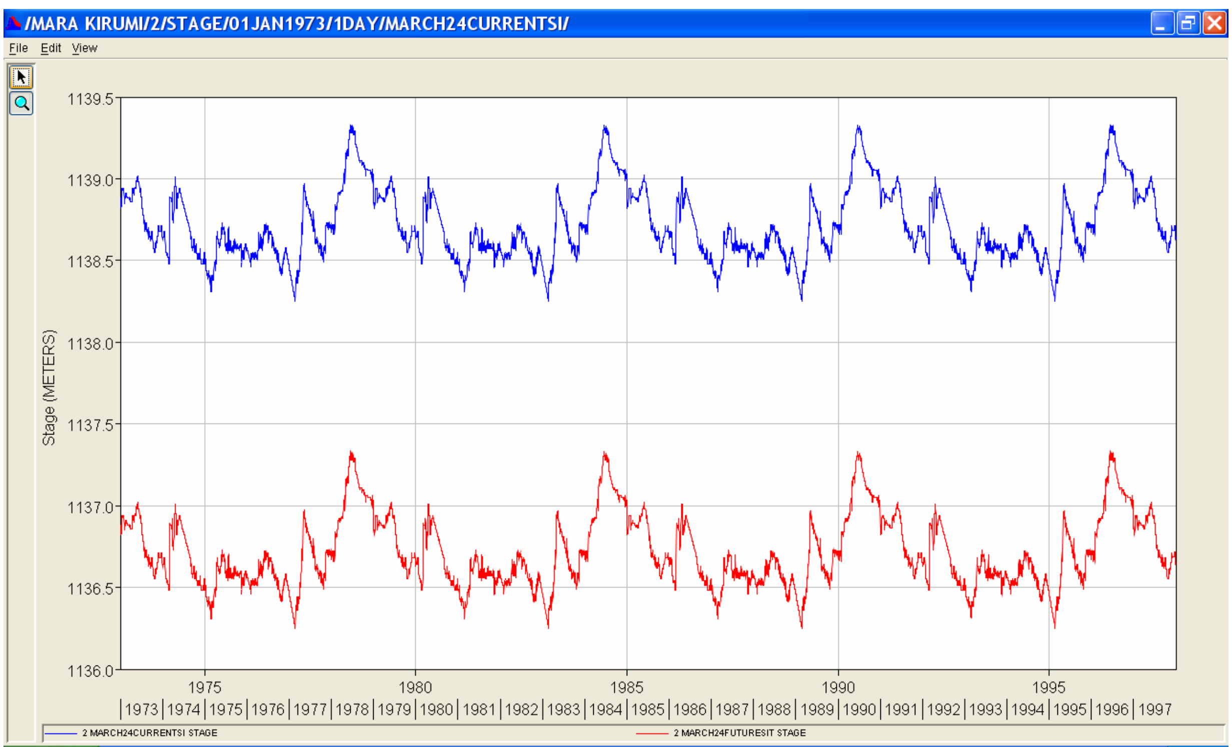

Figure 58. Water surface profile at cross section2, current and future situation

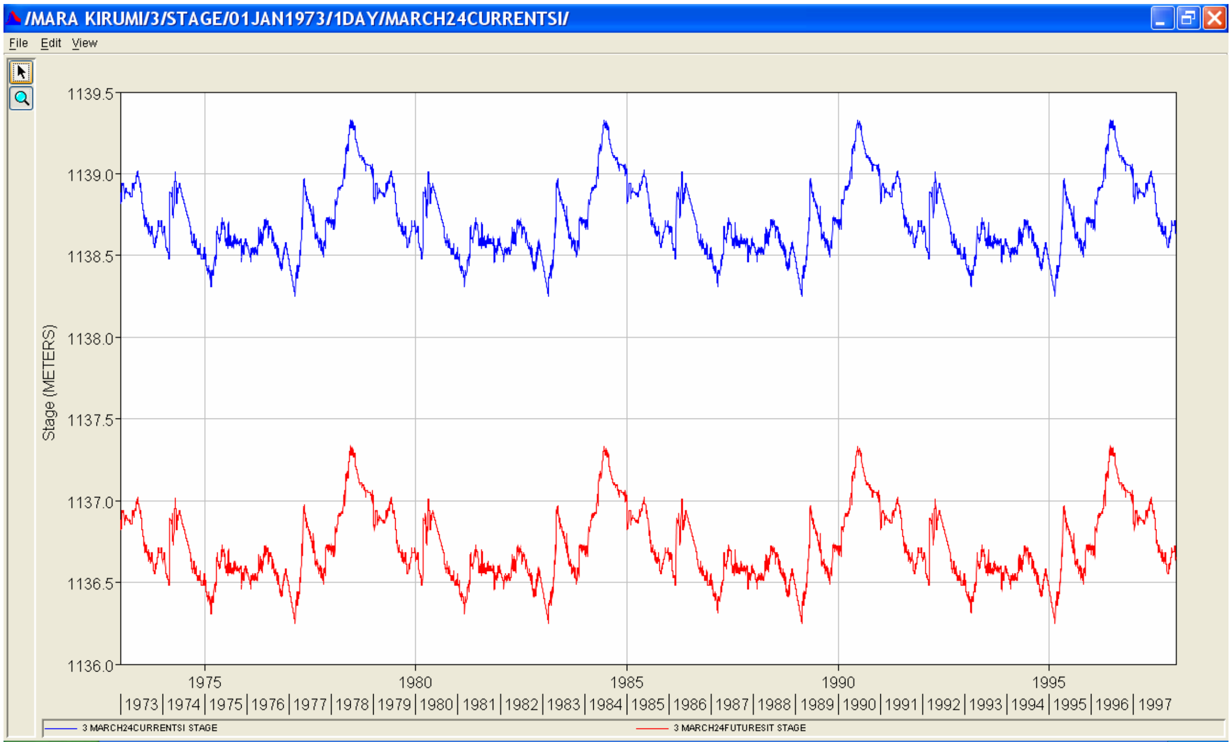

Figure 59. Water surface profile at cross section 3, current and future situation

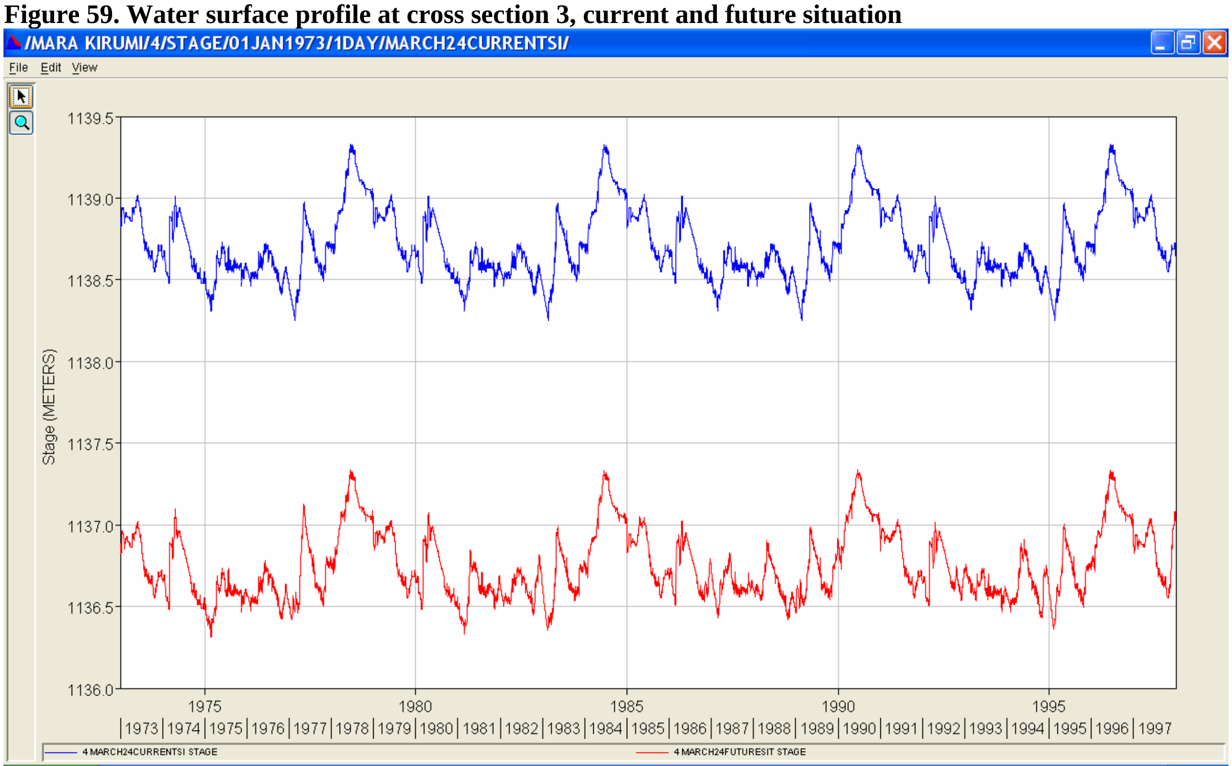

Figure 60. Water surface profile at cross section 4, current and future situation

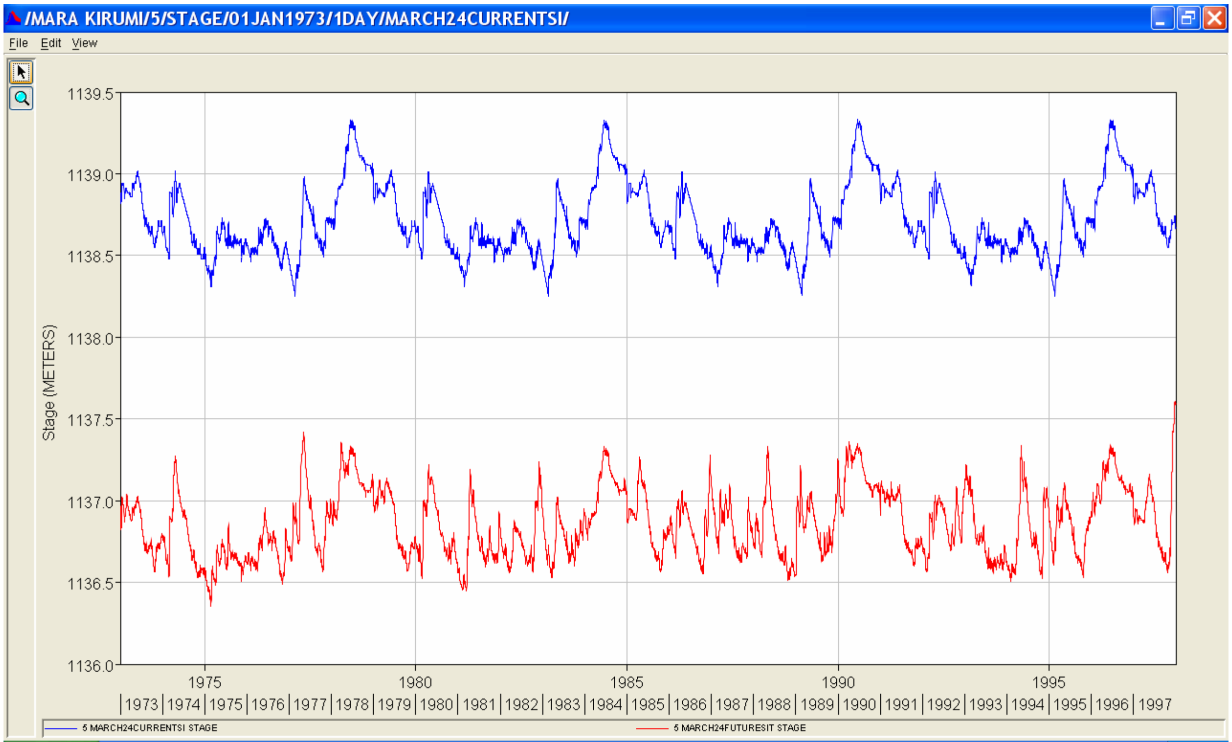

Figure 61. Water surface profile at cross section 5, current and future situation

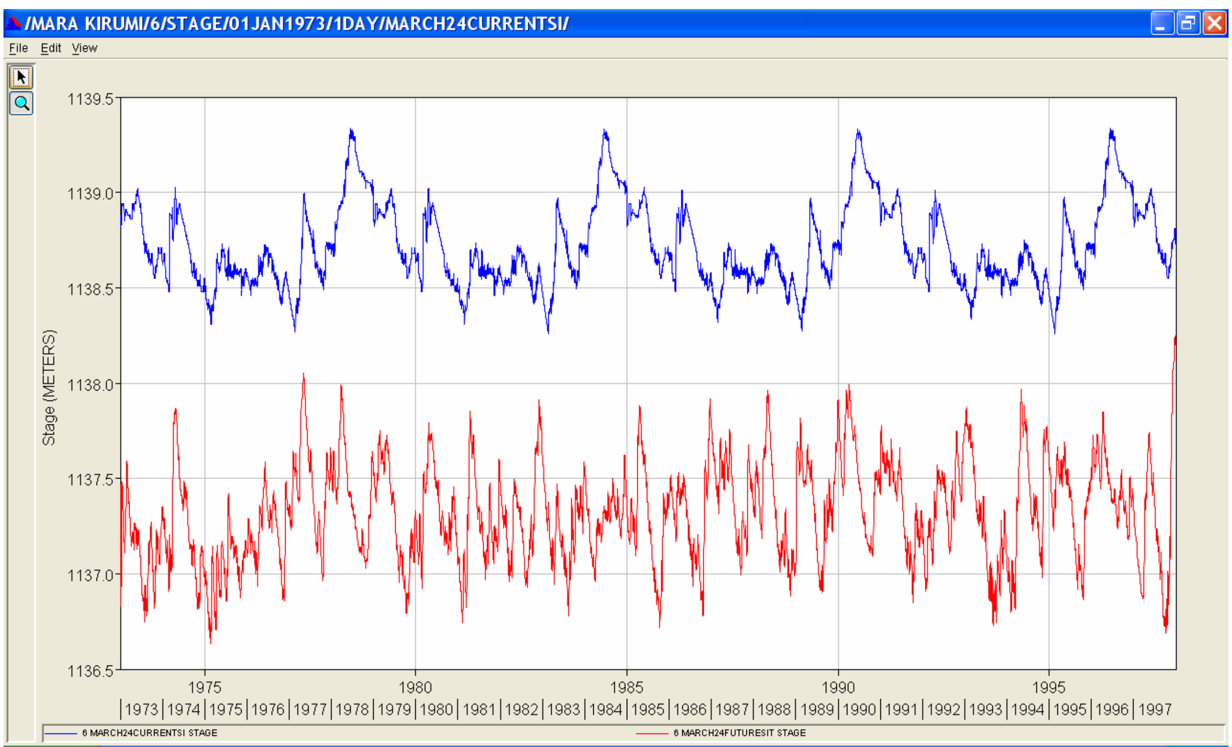

Figure 62. Water surface profile at cross section 6, current and future situation

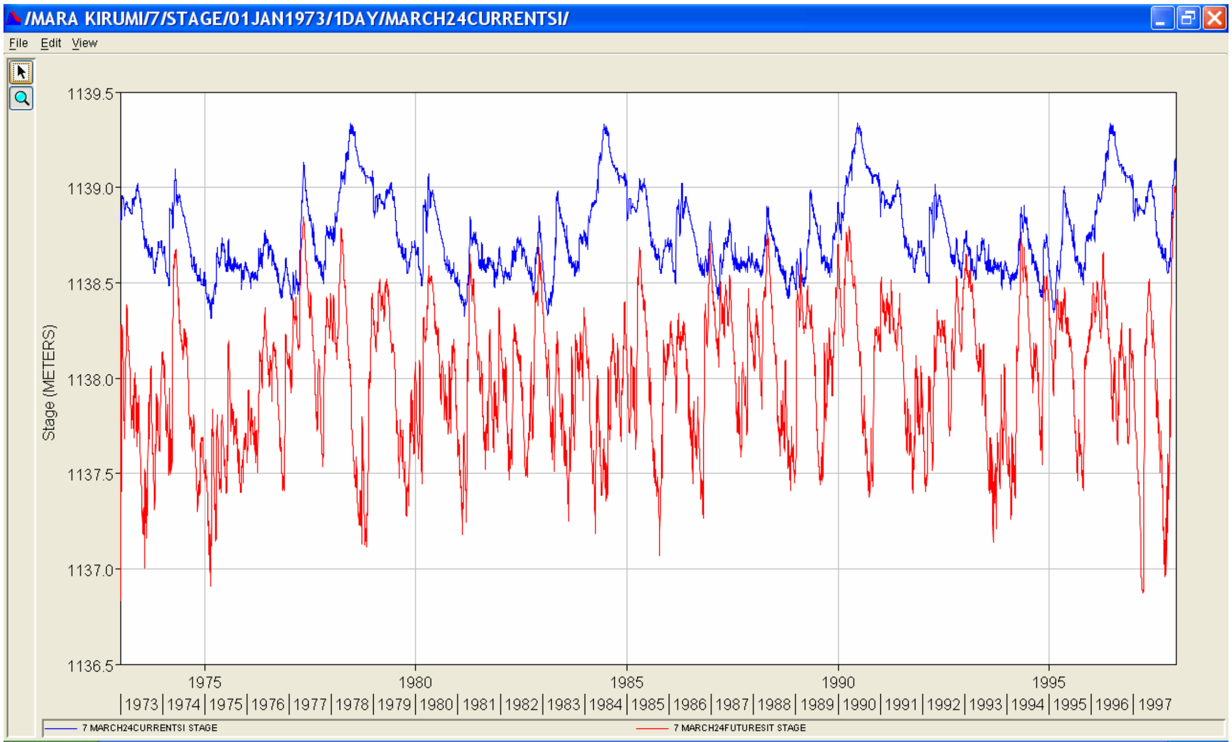

Figure 63. Water surface profile at cross section 7, current and future situation

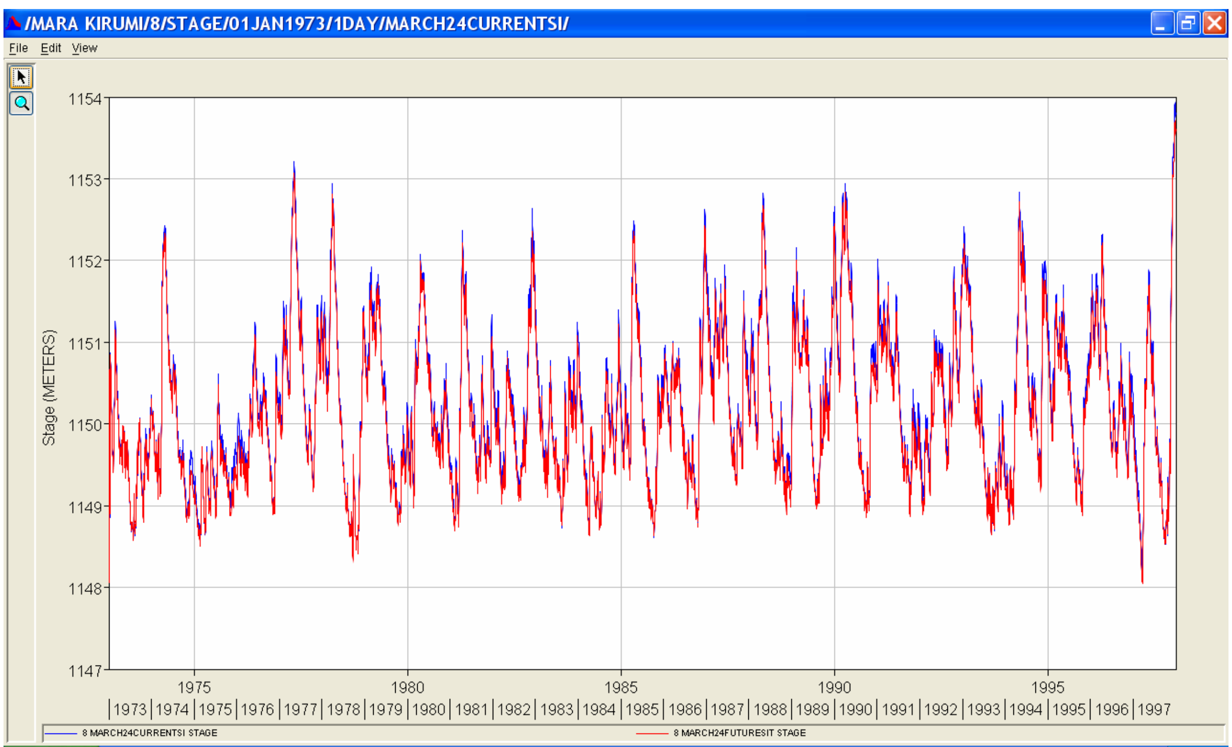

Figure 64. Water surface profile at cross section 8, current and future situation

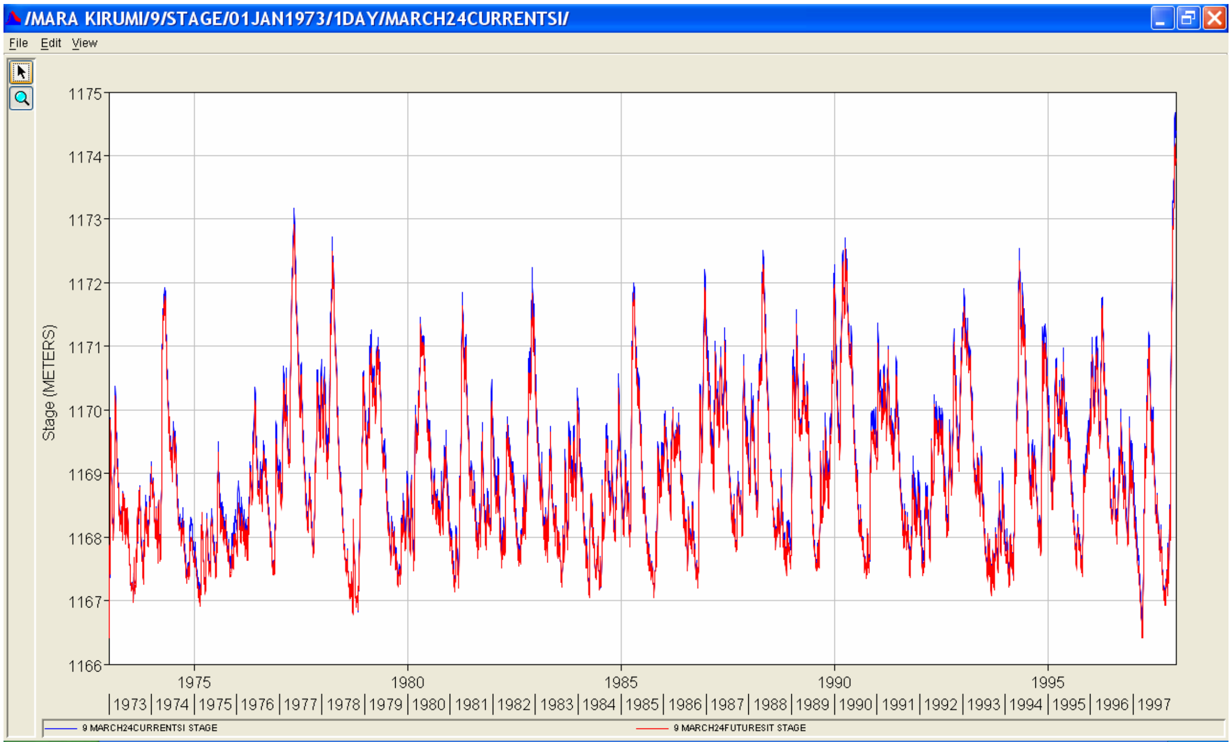

Figure 65. Water surface profile at cross section 9, current and future situation

5.3 IHA results

This model compared the two scenarios to check if there were considerable changes in IHA parameters for each cross section. Figures 66 to 74 present the hydrologic alteration results of the parameters in the three categories of the data. Appendix 4 contains the complete results.

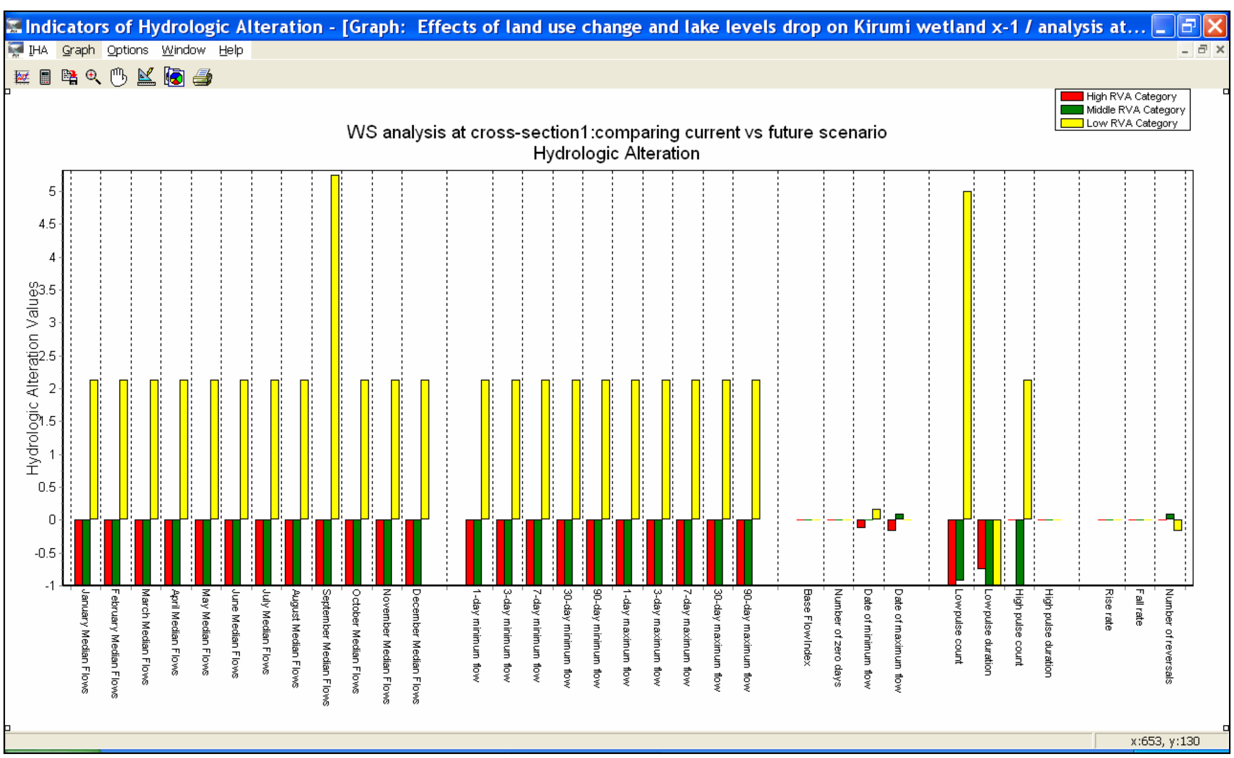

Figure 66. Results of hydrologic alteration at cross section 1

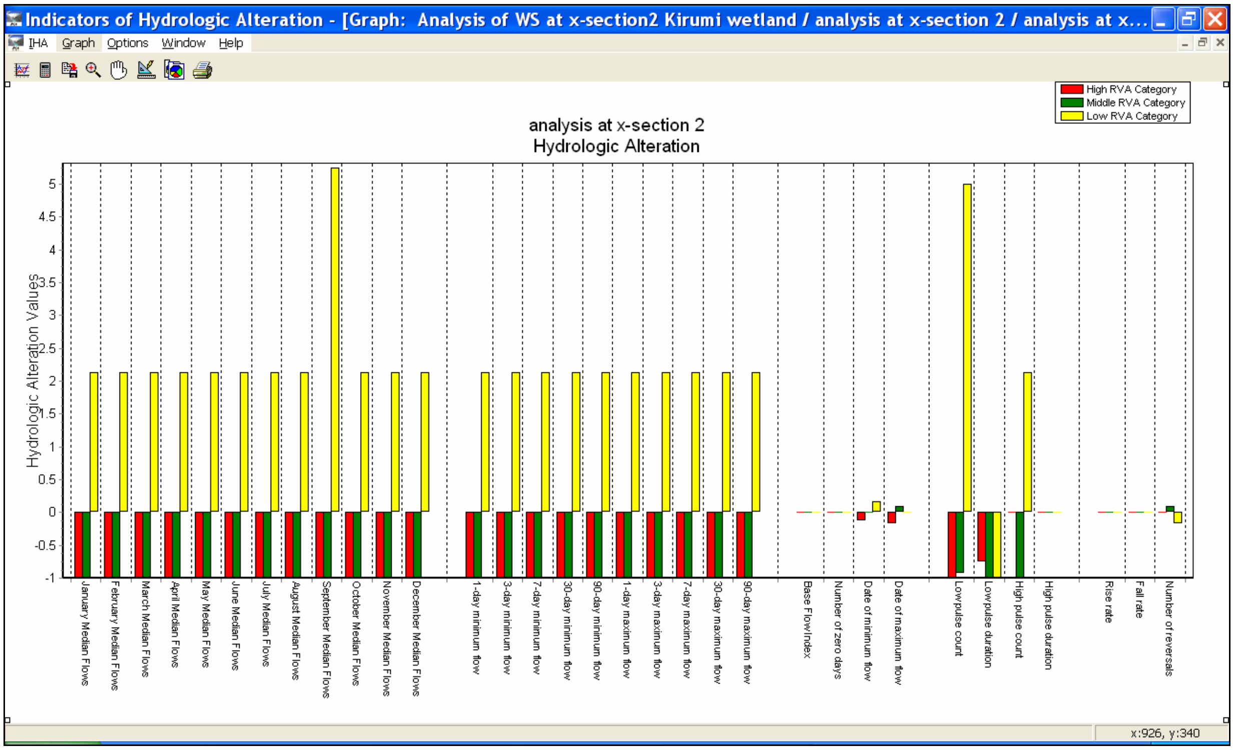

Figure 67. Results of hydrologic alteration at cross section 2

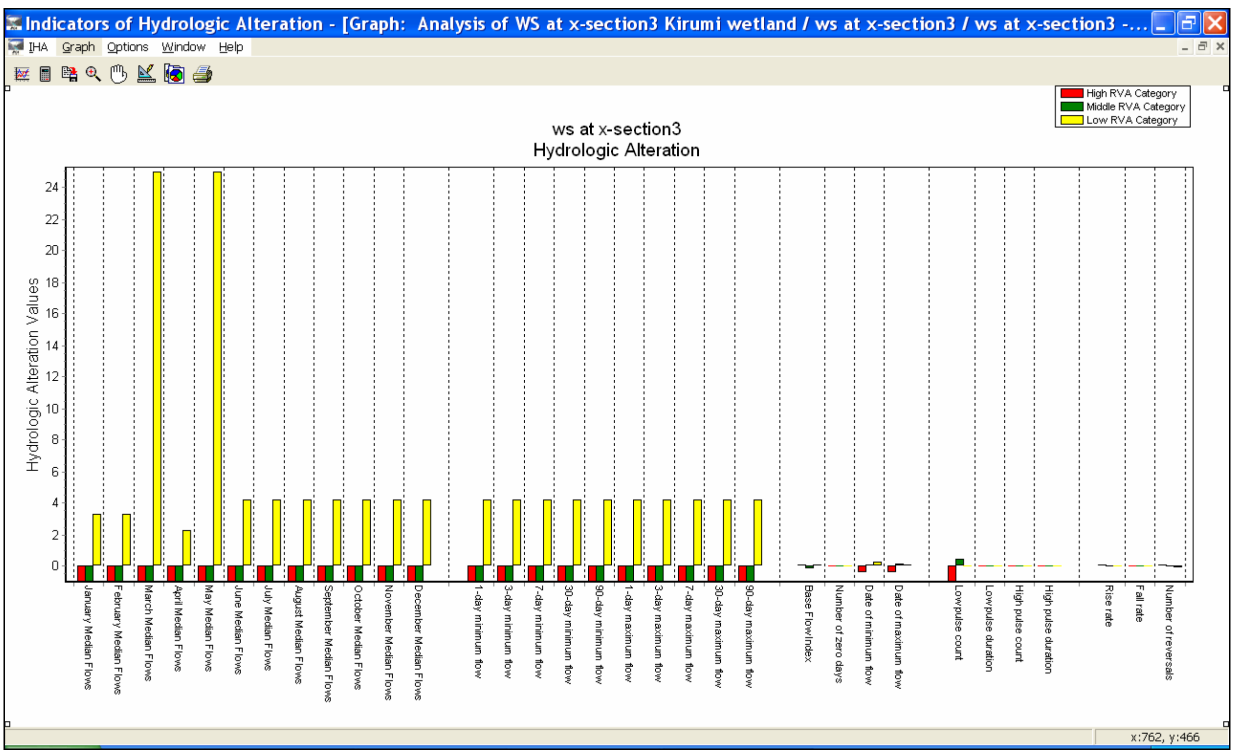

Figure 68. Results of hydrologic alteration at cross section 3

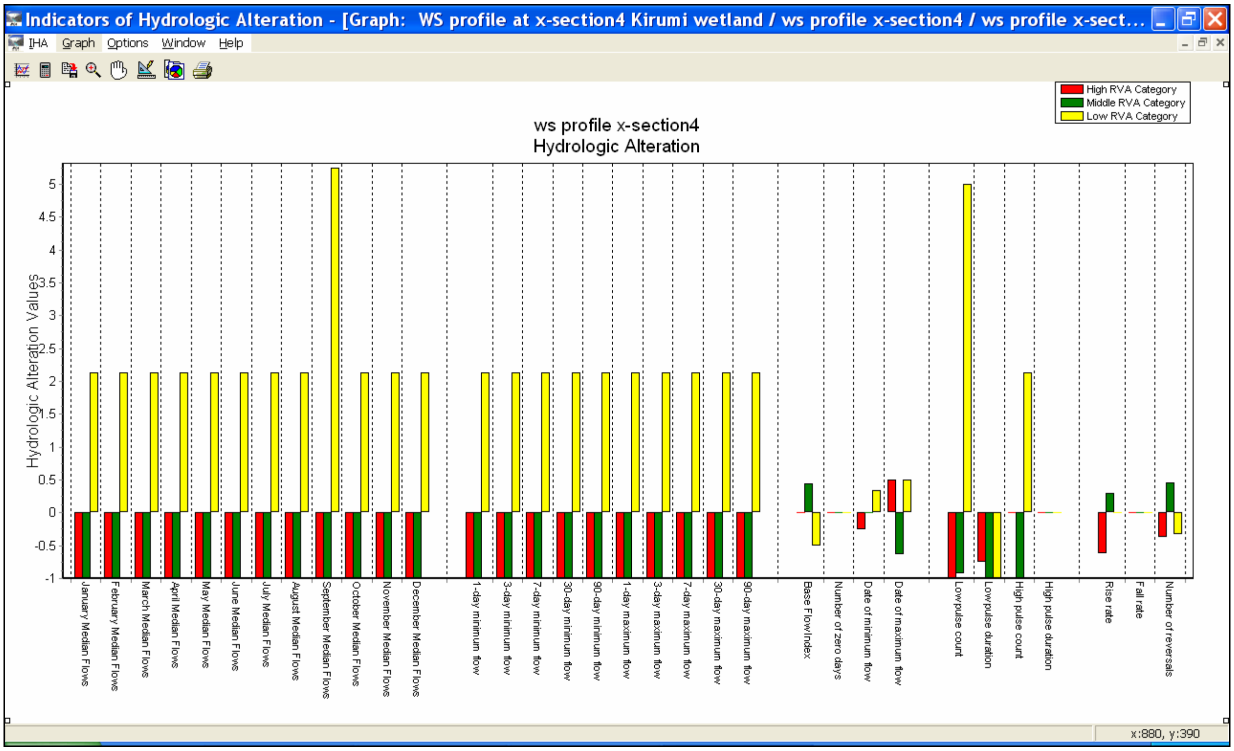

Figure 69. Results of hydrologic alteration at cross section 4

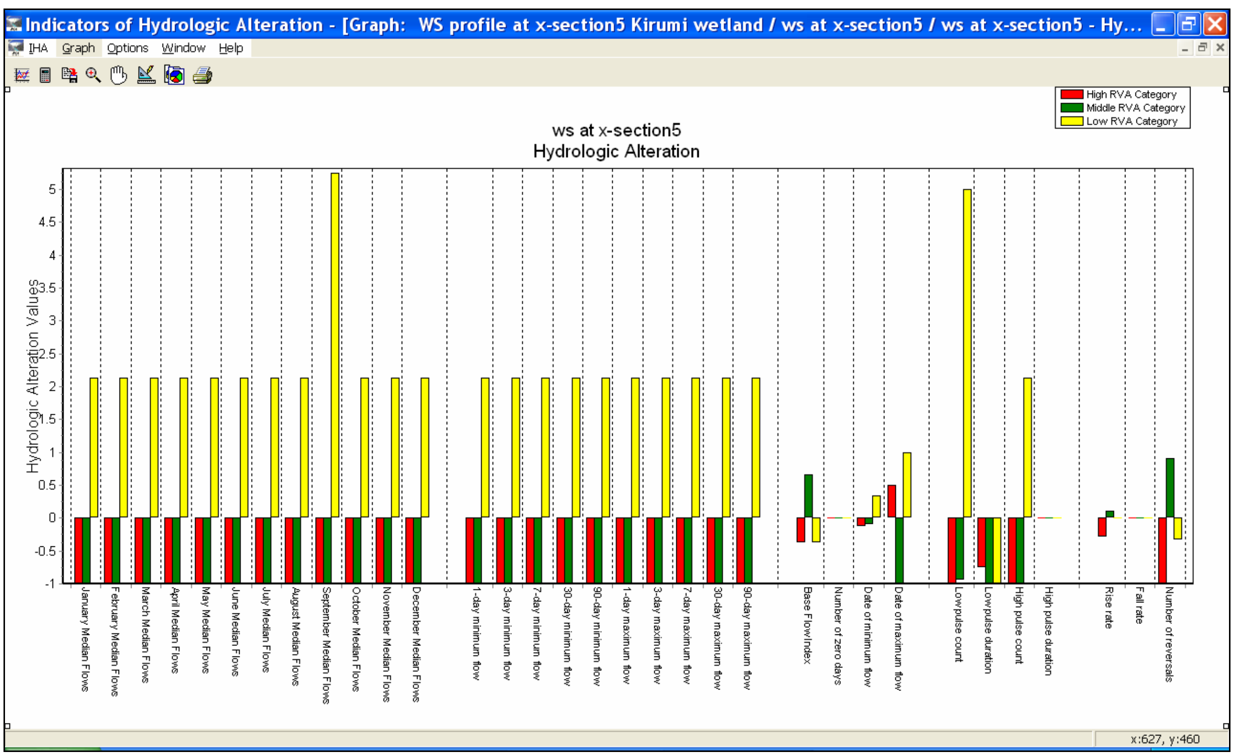

Figure 70. Results of hydrologic alteration at cross section 5

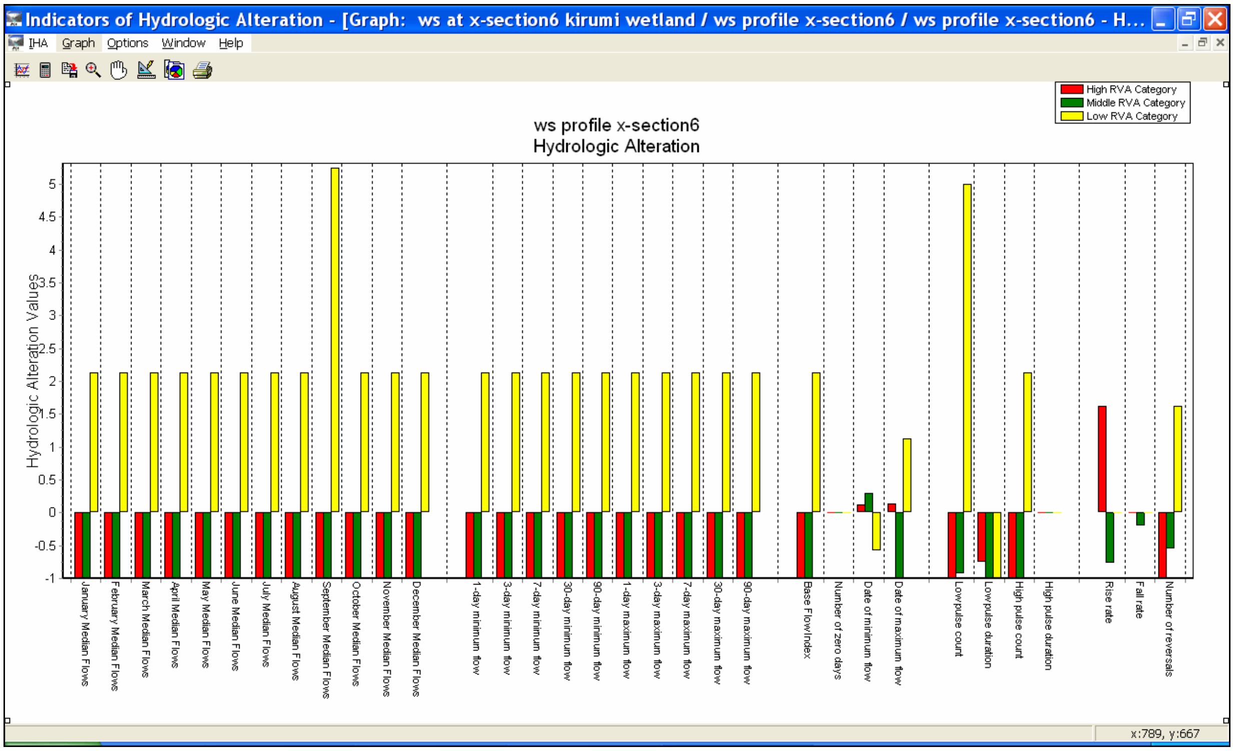

Figure 71. Results of hydrologic alteration at cross section 6

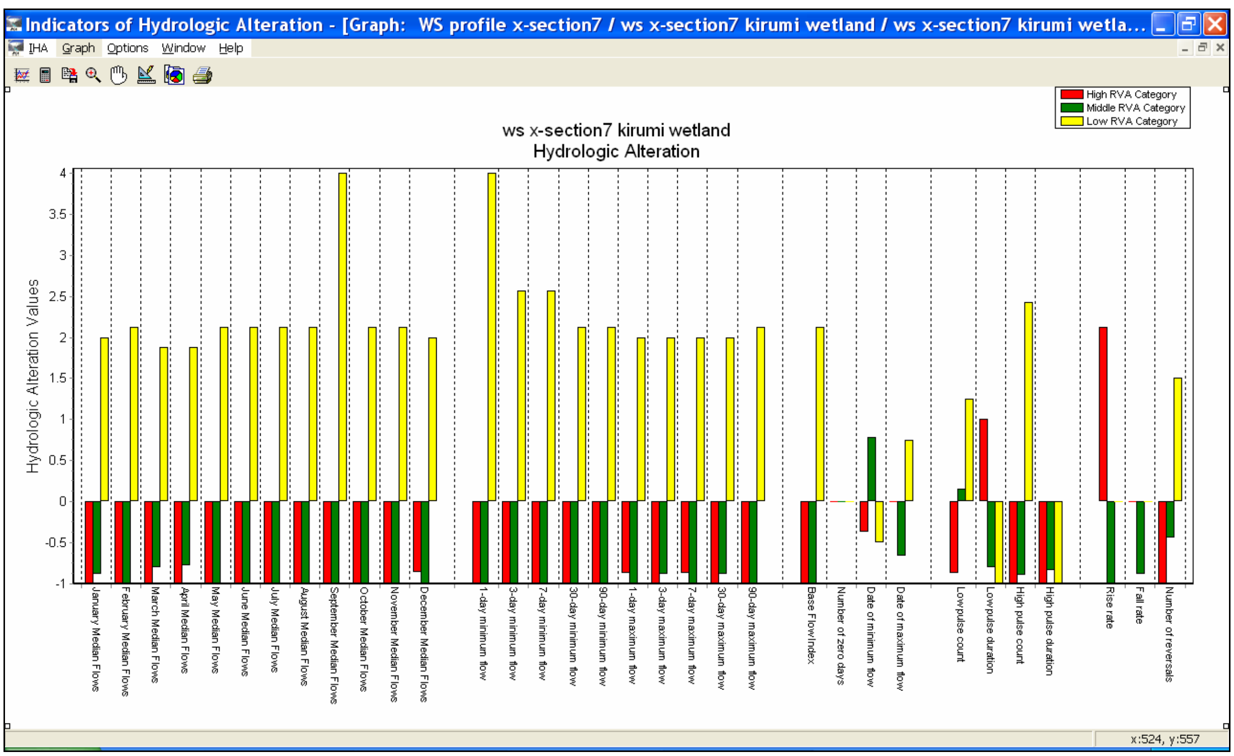

Figure 72. Results of hydrologic alteration at cross section 7

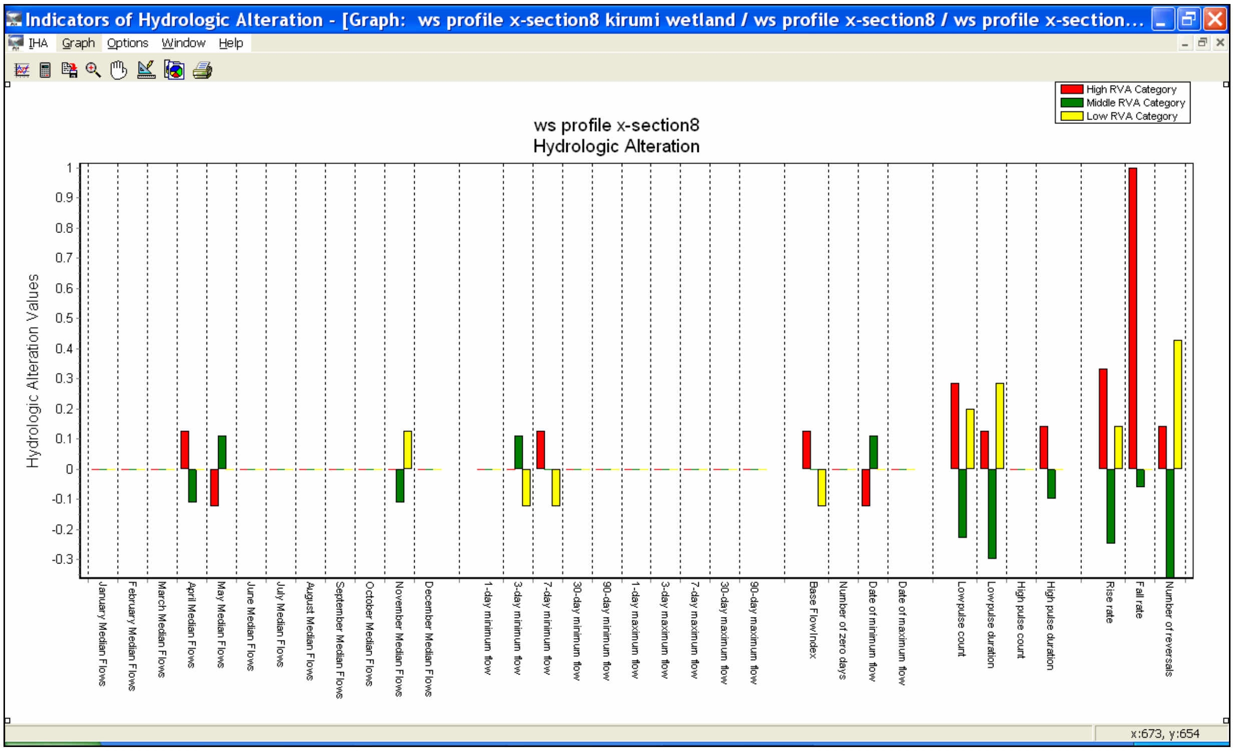

Figure 73. Results of hydrologic alteration at cross section 8

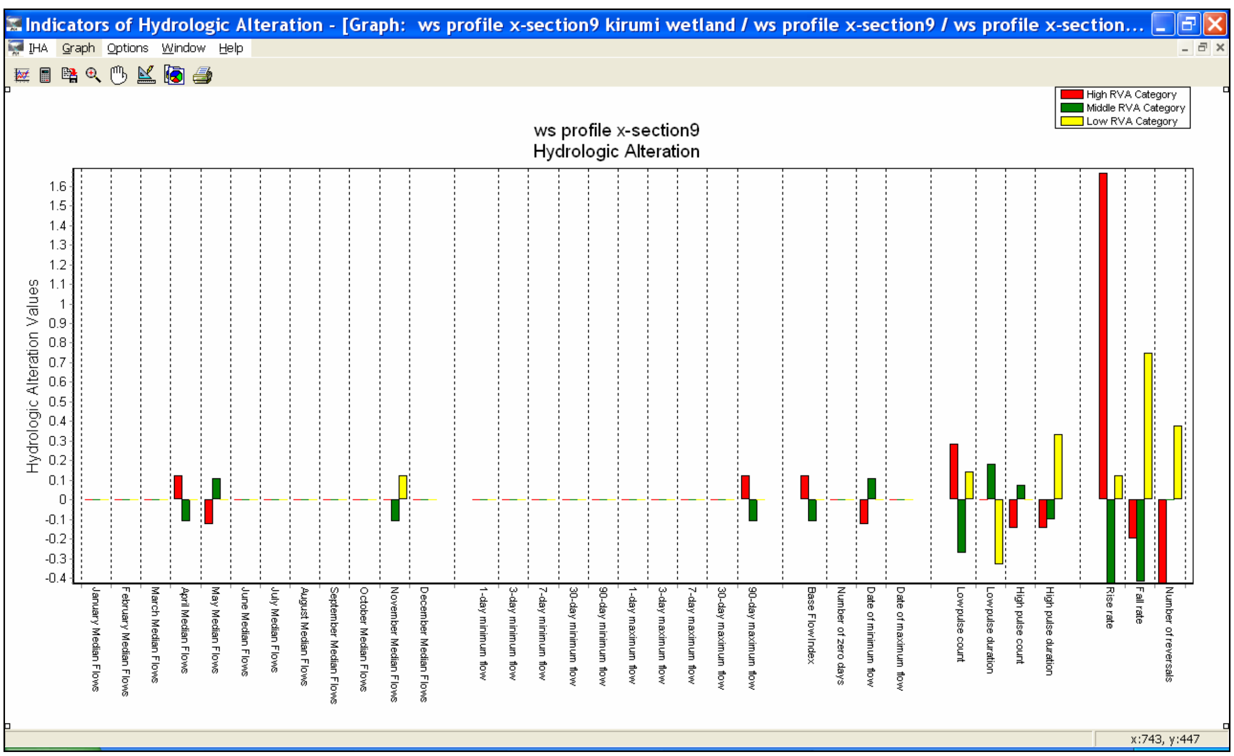

Figure 74. Results of hydrologic alteration at cross section 9

5.4 Uncertainties associated with the results

The results of the simulations of the three models are subject to errors due to different sources. Systematic errors may be due to the instruments used in measuring water levels, flows and rainfall. Recorder's inexperience may also contribute to the systemic errors in the readings.

Also, in this research, three models were used where each model has its own errors induced in the results.

Another source of errors was the inability to get the real altitudes used in the HEC RAS and IHA models due to inability of the GPS used to capture the information.

The inability to calibrate the SWAT model to acceptable level, and absence of data for calibrating the HEC RAS model also adds to the uncertainties associated with the models results.

Efforts to reduce uncertainties of the results yielded no good results mainly due to insufficient data. As pointed earlier, a lot of gaps were found in the data sets for rainfall, flow and stage.

6. Discussion of results

6.1 SWAT

Overall water balance

The overall water balance for the basin for the two scenarios is as depicted in figure 75. In the present scenario, most of the water (93%) entering the catchment through precipitation leaves through evapotranspiration. In the future scenario, the amount leaving through evapotranspiraton is reduced to 88%. The decrease is attributed to the less demand of the new land use to transpire water. In both cases surface run off is very small (zero) and the total water yield is almost the same (only 1.4% increase).

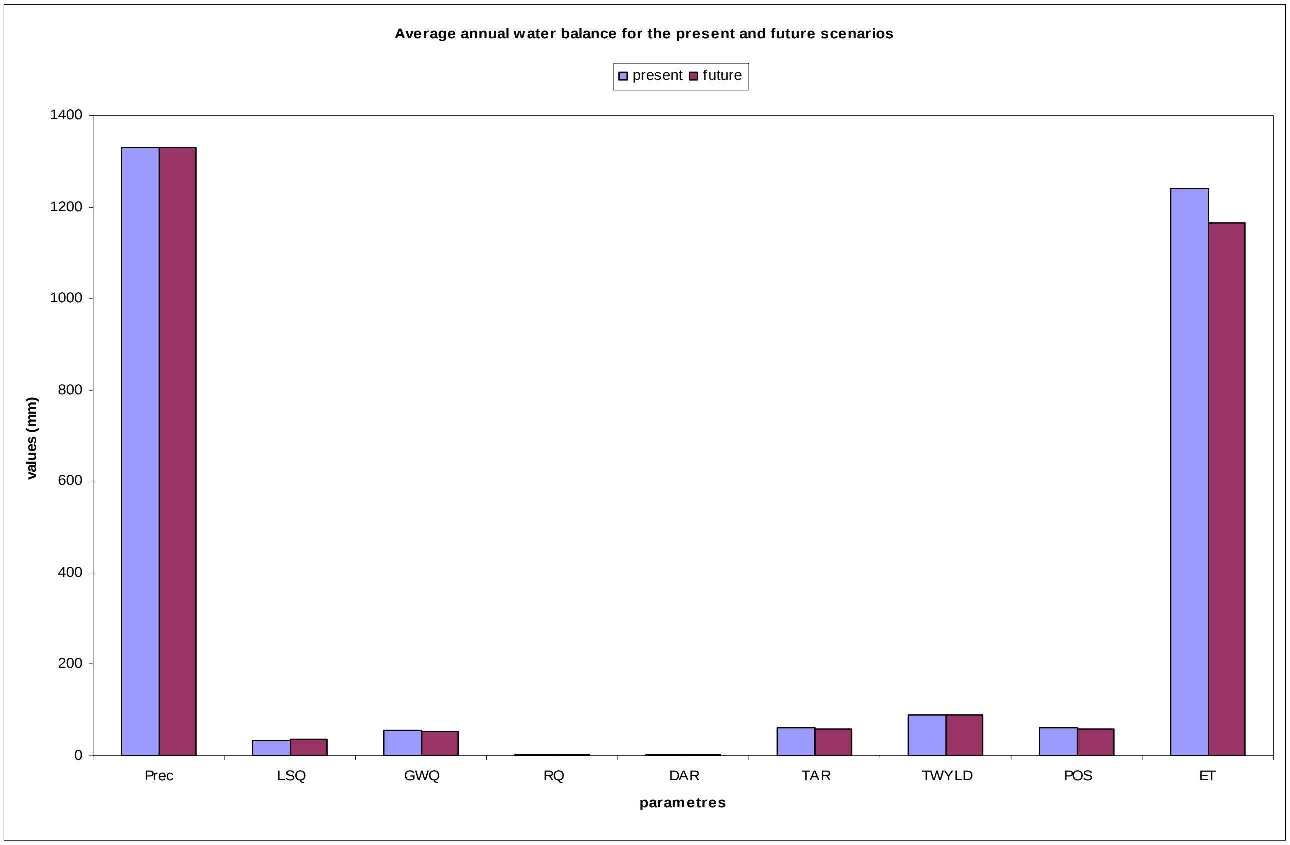

Figure 75. Overall catchment water balance

Months from March to May have more rainfall (about 200 mm) (figure 76). Evapotranspiration, though high (about 130 mm) during March through May, does not fall much during the other moths (remains at about 100 mm) since it is affected more by solar energy rather than the available water. Water yield remains almost constant throughout the year. This is due to the absence of surface run off which responds immediately to rainfall. Water yield, therefore depends entirely on the lateral soil flow (LSQ) and the groundwater flow (GWQ). However, the water yield increases a little bit when rainfall is plenty (in March through May and in December). The lack of surface rainfall explains the fact that although the catchment has a lot of rainfall (average annual precipitation 1330 mm), the water yield (gauge flow measurements at Mara Mine) is very small.

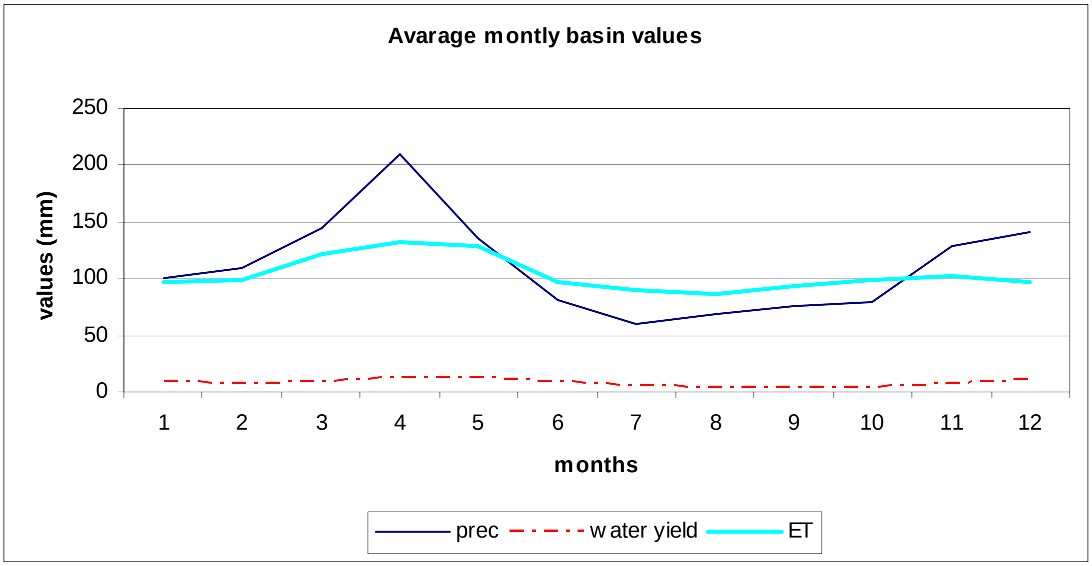

Figure 76. Catchment average monthly values (prec, surface runoff, water yield, evapotranspiration)

The result of this model shows that there is no marked difference in hydrology between the current land use and the future land use when two uses are increased by 50%. The flow simulated at the monitoring gauging station for the 25 year (table 8) is not very different for the two cases.

6.2 HEC RAS

The model was run for two scenarios, the first one (current) depicting trends from year 1973 to 1997 in the lake level and the catchment. The second scenario was run for another 25 years, depicting the future catchment situation where landuse for CRDY and CRWO would increase by 50% and lake level drop by 2 meters. The aim was to get the water surface profiles at the cross section 1 to 9 in the wetland. Results (as shown in figures 57 to 65 above) suggest that the water surface profiles in the wetland are controlled by the lake levels due to the backwater effect. Figures 77 through 79 show the maximum, average and minimum water levels along the wetland at the nine cross section for the two scenarios. Cross sections 1 through 7 are in the lower part of the wetland. As their elevation are almost similar, their water surface profiles do not change and are influenced by the lake water level. Cross sections 8 and 9 are not influenced by the lake level, rather by flow from upstream.

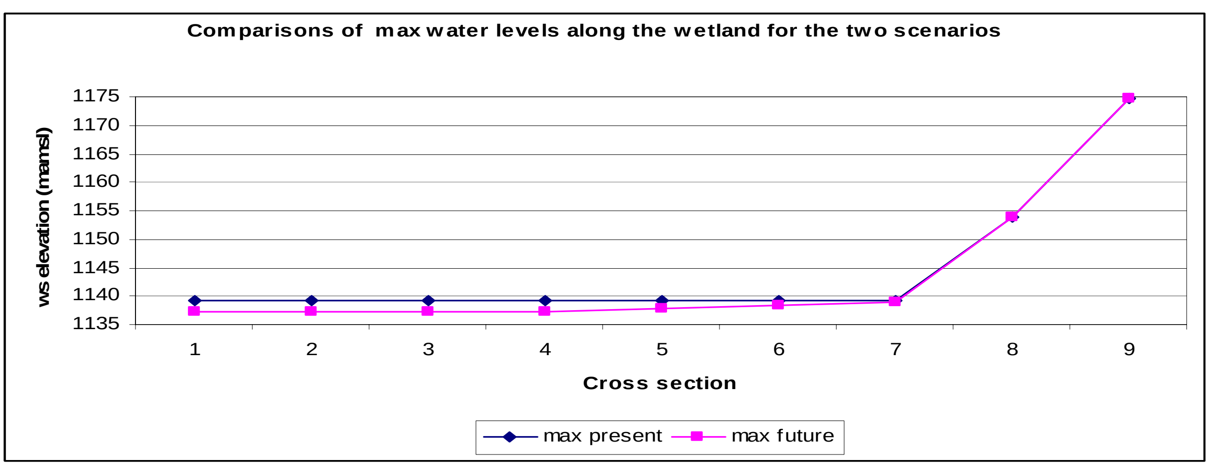

Figure 77. Comparison of max water levels along the wetland for the two scenario

This suggests that if lake levels drop down to the pre-sixties levels of 1134, the wetland might be affected in terms of the extension. However, IHA models will give some insight with regard to ecosystem effects.

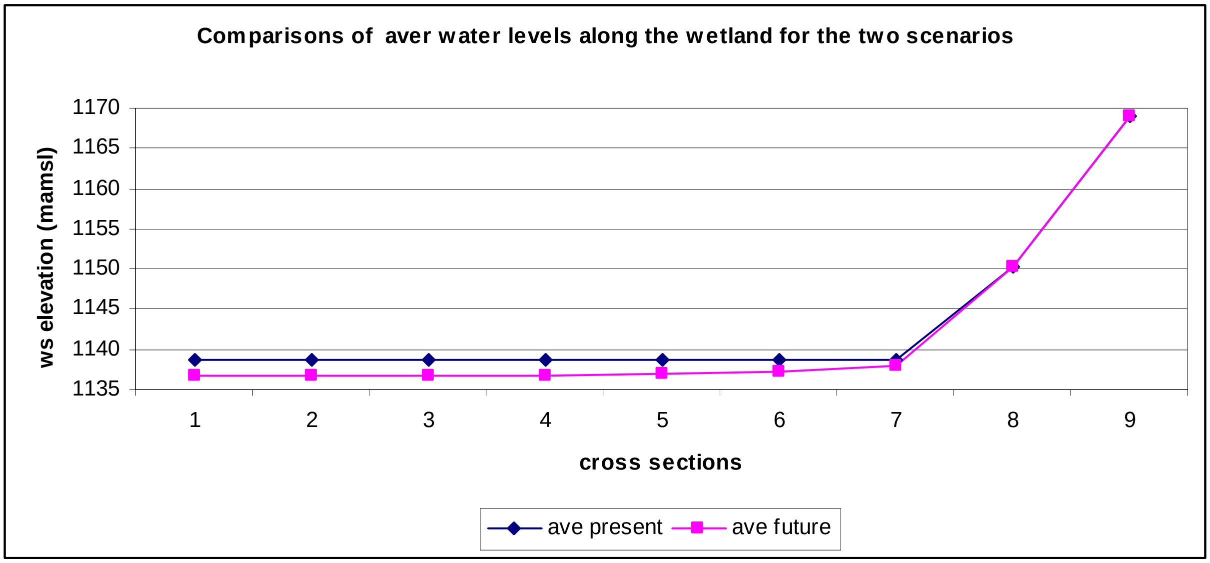

Figure 78. Comparison of average water levels along the wetland for the two scenario

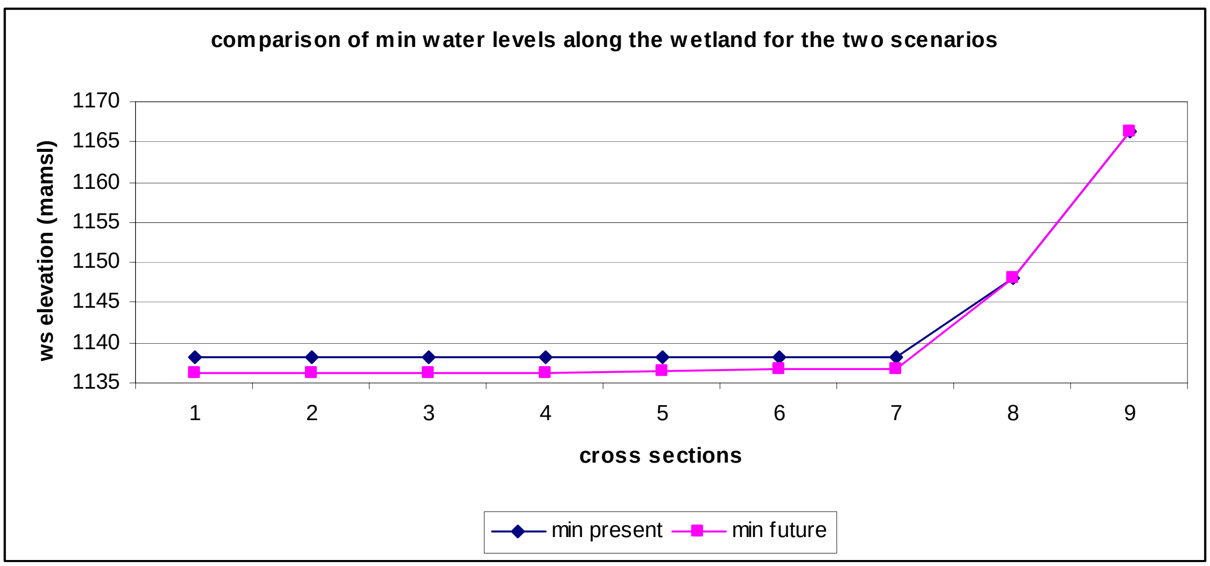

Figure 79. Comparison of minimum water levels along the wetland for the two scenario

6.3 IHA

This model was used to compare the current situation with the future scenario to see if there was some marked differences in the IHA parameters. Comparisons were done for each cross section with the use of range of variability approach (RVA) where all the hydrologic parameters were assigned hydrologic alteration values. Tables 9 to 11 show the values for the hydrologic alterations for lowest category, middle category and highest category.

Categories are defined in the ranges of up to 33rd percentiles as lowest category, 34th to 67th percentiles as middle category and above 67th percentiles as high category. Positive hydrologic alteration value (highest value of infinity) signifies that frequency of values in a category have increased from pre-impact to the post-impact periods. Negative hydrologic alteration values (lowest -1) means that the frequency of values in a category has decreased in the post-impact period compared to the pre-impact period.

Comparing the pre-impact and post impact values in Kirumi wetland for the nine cross sections, parameter group one (magnitude of water conditions), results show that the frequencies in the middle and high categories for cross sections 1 to 7 have decreased. This is explained by the fact that these cross sections are influenced more by the lake levels. Since the lake water levels have droped, this section has been affected. In cross sections 8 and 9, frequencies in the middle and high ranges have not changed significantly. In the low category, in the first seven cross sections the frequencies have increased. In cross sections 8 and 9 the frequencies have not changed significantly.

Table 9. IHA values for parameters of group 1

parameter	x-1			x-2			x-3			x-4			x-5			x-6			x-7			x-8			x-9		
	low	middle	high	low	middle	high	low	middle	high	low	middle	high	low	middle	high	low	middle	high	low	middle	high	low	middle	high	low	middle	high
Gr #1																											
Jan	2.1	-1.0	-1.0	2.1	-1.0	-1.0	3.3	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.0	-0.9	-1.0	0.0	0.0	0.0	0.0	0.0	0.0
Feb	2.1	-1.0	-1.0	2.1	-1.0	-1.0	3.3	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0
Mar	2.1	-1.0	-1.0	2.1	-1.0	-1.0	25.0	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	1.9	-0.8	-1.0	0.0	0.0	0.0	0.0	0.0	0.0
Apr	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.3	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	1.9	-0.8	-1.0	0.0	-0.1	0.1	0.0	-0.1	0.1
May	2.1	-1.0	-1.0	2.1	-1.0	-1.0	25.0	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	0.0	0.1	-0.1	0.0	0.1	-0.1
Jun	2.1	-1.0	-1.0	2.1	-1.0	-1.0	4.2	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	2.1	-1.0	-1.0	2.1	-1.0	-1.0	4.2	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	2.1	-1.0	-1.0	2.1	-1.0	-1.0	4.2	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0
Sept	5.3	-1.0	-1.0	5.3	-1.0	-1.0	4.2	-1.0	-1.0	5.3	-1.0	-1.0	5.3	-1.0	-1.0	5.3	-1.0	-1.0	4.0	-1.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0
Oct	2.1	-1.0	-1.0	2.1	-1.0	-1.0	4.2	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	0.0	0.0	0.0	0.0	0.0	0.0
Nov	2.1	-1.0	-1.0	2.1	-1.0	-1.0	4.2	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	0.1	-0.1	0.0	0.1	-0.1	0.0
Dec	2.1	-1.0	-1.0	2.1	-1.0	-1.0	4.2	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.1	-1.0	-1.0	2.0	-1.0	-0.9	0.0	0.0	0.0	0.0	0.0	0.0

This shows that while cross sections 1 to 7 are affected by lake water levels, cross sections 8 and 9 are only influenced by the upstream catchment processes. In this case, since the two scenarios simulated upstream gave no significant differences, this fact is also reflected in the indifference in the hydrologic alteration values in cross sections 8 and 9.

In group two parameters, the analysis shows that for cross sections1 to 7 the middle and high categories have negative values meaning that their frequencies have decreased in the post-impact period. In cross sections 8 and 9 there is no change for the two periods. The low category the hydrologic alteration values are positive for cross sections 1 to 7 showing that the frequencies have increased in the post impact period, and zero for 8 and 9 showing that the change in the two periods is not there.

Analysis of parameters regarding timing of annual extreme water condition events (parameter group three) shows that that there is no significant difference between the two periods as most values are close to zero.

Table 10. IHA values for parameters of group 2

parameter		Gr #2	1-day min	3-day min	7-day min	30-day min	90-day min	1-day max	3-day max	7-day max	30-day max	90-day max	Number of zero days	Base flow index
x-1	low		2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1		0.0
	middle		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	0.0	0.0
	high		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0		0.0
x-2	low		2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1		0.0
	middle		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	0.0	0.0
	high		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0		0.0
x-3	low		4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2		0.1
	middle		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	0.0	-0.1
	high		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0		0.1
x-4	low		2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1		-0.5
	middle		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	0.0	0.4
	high		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0		0.0
x-5	low		2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1		-0.4
	middle		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	0.0	0.7
	high		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0		-0.4
x-6	low		2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1		2.1
	middle		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	0.0	-1.0
	high		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0		-1.0
x-7	low		4.0	2.6	2.6	2.1	2.1	2.0	2.0	2.0	2.0	2.1		2.1
	middle		-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-0.9	-1.0	-0.9	-1.0	0.0	-1.0
	high		-1.0	-1.0	-1.0	-1.0	-1.0	-0.9	-1.0	-0.9	-1.0	-1.0		-1.0
x-8	low		0.0	-0.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0		-0.1
	middle		0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	high		0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.1
x-9	low		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		0.0
	middle		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-0.1
	high		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1		0.1

In group four parameters (frequency and duration of high stage and low pulses), the low pass counts in the post impact period has increased for most cross sections in the low range, decreased in most cross sections for middle range and the high categories. Low pulse duration has decreased in the post impact period for cross sections 1 to 7 and remains unchanged for cross sections 8 and 9. High pulse counts have increased in the low category for cross sections 1 to 7 and no change for 8 and 9. In the middle category, the high pulse counts have decreased in the post impact period. All these facts are attributable to the lake water level effects in the wetland.

In group five parameters (rate and frequency of water condition changes), rise and fall rates are not changing significantly. This is due to the fact that the rise/fall of the water level in the wetland is a very slow. The post impact period is not different from the pre impact periods due to the fact that the lake levels drives the wetland dynamics.

Table 11. IHA values for parameters of groups 3,4 and 5.

parameter		Gr #3	Date of min	Date of max	Gr #4	Low pulse count	Low pulse dur	High pulse count	High pulse dur	Gr #5	Rise rate	Fall rate	Number of reversals
x-1	low		0.2	0.0		5.0	-1.0	2.1					-0.2
	middle		0.0	0.1		-0.9	-1.0	-1.0			0.0	0.0	0.1
	high		-0.1	-0.2		-1.0	-0.8				0.0		0.0
x-2	low		0.2	0.0		5.0	-1.0	2.1					-0.2
	middle		0.0	0.1		-0.9	-1.0	-1.0			0.0	0.0	0.1
	high		-0.1	-0.2		-1.0	-0.8				0.0		0.0
x-3	low		0.3	0.1									-0.1
	middle		0.1	0.2		0.4		0.0			0.0	0.0	0.0
	high		-0.4	-0.4		-1.0					0.1		0.1
x-4	low		0.3	0.5		5.0	-1.0	2.1					-0.3
	middle		0.0	-0.6		-0.9	-1.0	-1.0			0.3	0.0	0.5
	high		-0.3	0.5		-1.0	-0.8				-0.6		-0.4
x-5	low		0.3	1.0		5.0	-1.0	2.1					-0.3
	middle		-0.1	-1.0		-0.9	-1.0	-1.0			0.1	0.0	0.9
	high		-0.1	0.5		-1.0	-0.8	-1.0			-0.3		-1.0
x-6	low		-0.6	1.1		5.0	-1.0	2.1					1.6
	middle		0.3	-1.0		-0.9	-1.0	-1.0			-0.8	-0.2	-0.6
	high		0.1	0.1		-1.0	-0.8	-1.0			1.6		-1.0
x-7	low		-0.5	0.8		1.3	-1.0	2.4	-1.0				1.5
	middle		0.8	-0.7		0.2	-0.8	-0.9	-0.8		-1.0	-0.9	-0.4
	high		-0.4	0.0		-0.9	1.0	-1.0	-1.0		2.1		-1.0
x-8	low		0.0	0.0		0.2	0.3	0.0	0.0		0.1	0.0	0.4
	middle		0.1	0.0		-0.2	-0.3	0.0	-0.1		-0.3	-0.1	-0.4
	high		-0.1	0.0		0.3	0.1	0.0	0.1		0.3	1.0	0.1
x-9	low		0.0	0.0		0.3	0.0	-0.1	-0.1		0.1	0.8	0.4
	middle		0.1	0.0		-0.3	0.2	0.1	-0.1		-0.4	-0.4	0.0
	high		-0.1	0.0		0.3	0.0	-0.1	-0.1		1.7	-0.2	-0.4

6.4 Research questions addressed

6.4.1 Effects of the lake water level and the catchment hydrology to Kirumi wetland

Analysis of the hydraulics of the wetland by HEC RAS model has shown that the wetland water surface profiles at the different cross sections are mostly affected by the lake water levels. The catchment land use changes modelled in this research have shown no marked difference in the resulting outflow from the catchment and do not affect the wetland water surface profiles especially the lower part (cross sections 1 to 7), where the effect of backwater is very significant.

6.4.2 Response of the wetland to new lake/catchment management scenarios

Analysis by IHA model has shown that the statistical properties which are relevant for ecosystem functions have not changed significantly as the lake levels dropped by two meters and the catchment land use changed .This suggests that the new scenario is still in a stage where ecosystem functions of the wetland have not been altered significantly and may be adopted as a scenario which provides environmental flows. However, the allowable/tolerable changes to the parameters affecting the ecosystem have to be set out by the managers/users of the ecosystems according to their management objectives of the wetland.

7. Conclusions and Recommendations

7.1 Conclusions

The objective of this study was to assess the environmental flows required to sustain the ecosystem functions of Kirumi wetland. This has been achieved through the use of three different hydroinformatics tools: SWAT, HEC RAS and IHA models. The results, however, are subject to a lot of uncertainties because of the poor quality and quantity of data used in the models. This resulted into difficulties in calibrating the SWAT model and impossible to calibrate the HEC RAS model.

SWAT model

SWAT model, which is a physically based model, with a daily time step was used to model the flow produced from the upper catchment and the resulting flows used as upstream boundary condition for the HEC RAS model. The model comprised of 14 subbsasins and 168 HRUs. The advantage of the model is that it incorporates all processes of the catchment. This fact was utilized in this research where the land use was varied in trying to evaluate the effects on the catchment hydrology between the current and the new scenarios in the catchment. There was no marked difference in the water yield of the catchment between the two scenarios.

HEC RAS model

A HEC RAS model for the Kirumi wetland was built with one reach and nine cross sections. The lake water level provided the downstream boundary condition and the resulting flow of SWAT model provided the downstream boundary condition. Two scenarios were simulated using the current lake levels and catchment hydrograph, and then using lake levels assuming a drop of two meters and 50% increase in CRWO and CRDY land use change upstream. The resulting water surface profiles at the nine cross sections suggests that the lake water levels drives the water levels in the wetland. Regardless of the variations in the upstream boundary flow hydrograph, the water levels fro cross sections 1 to 7 are not changing. Cross sections 8 and 9 respond to changes in the inflow hydrograph since they are outside the area under backwater effect.

IHA model

IHA model compared the hydrologic characteristics of the wetland for the two scenarios simulated in the HEC RAS model. The model used hydrologic parameters which matter in the ecosystem functioning. The parameters included the magnitude of the monthly water conditions, magnitude and duration of annual extreme water conditions, timing of annual extreme water conditions, frequency and duration of high and low pulses, and rate and frequency of water condition changes. The model was able to draw a contrast between the current and the future scenario in terms of these parameters. However, the level of changes in the wetland regarded as acceptable or not depends on the management objectives set by the stakeholders. Though, the changes registered between the two scenarios are, to my own view, not very significant. It would therefore be fair to say that even if the lake levels drop by two meters and the land use upstream changes, the wetland ecosystem functions will still be sustained. Therefore, the future scenario (two meter lake water level drop and 50% increase in CRWO/CRDY in the catchment) still presents a sustainable possibility for the Kirumi wetland.

Therefore, with respect to the sustainability of the Kirumi wetland, the future scenario presents a lake and catchment management options which meet the environmental flow requirements of the Kirumi wetland.

Relevance of the study to NBI-DSS

This study was sponsored by the WRMP of the NBI with the objective of strengthening the capacity of the member Countries to undertake integrated water resources management with respect to the Nile River Basin. This specific study used the tools which are already in use in the Nile Basin Projects and their applicability to the basin can not be overemphasized. Decisions to be made with regard to the use of the resource has to be grounded on sound knowledge of the systems in the basin and Hydroinformatics tools are very powerful towards achieving that goal. So, yes, my study at IHE and particularly the MSc. work lays the grounds firmly for future endeavors in the NBI-DSS practices.

7.2 Recommendations

The uncertainties associated with these results are very big. This is partly attributed to the less quality data used in the models. In view f this, the following are recommended:

- Data acquisition in the catchment should be strengthened in order to reduce uncertainties related to the use of the data for different purposes
- Improvements should be made in analysing the data before using it in the models. This might improve the outcomes of the results.
- To complement the inadequate data, other sources of data like remotely sensed and global data, should be used for analysis and building the models
- This work should be continued in order to refine the outcomes of the SWAT model.

With regard to the extension of the wetland, the HEC RAS model, being a one dimensional model, was not suited for this purpose. The model gives only a single water surface elevation for each cross section. In view of this, it is recommended that more detailed model should be used to model the wetland extension. Also studies involving sediment loadings and dynamics might help in answering the questions regarding the expansion of the wetland with time.

The IHA model was very useful in deciding the alterations to the hydrologic parameters which matter in the ecosystem functioning. Although the results for this research might not be valid for implementation due to the uncertainties associated with data, the use of the model is highly recommended for preliminary studies of environmental flow requirements, especially in areas where a change is expected or effected in the management of the resource.

Finally, a scenario incorporating climate change is recommended to be investigated in order to narrow the uncertainties of the results. Also, more lake scenarios should be studies to answer the question as to which level may the lake level be lowered without affecting the wetland.

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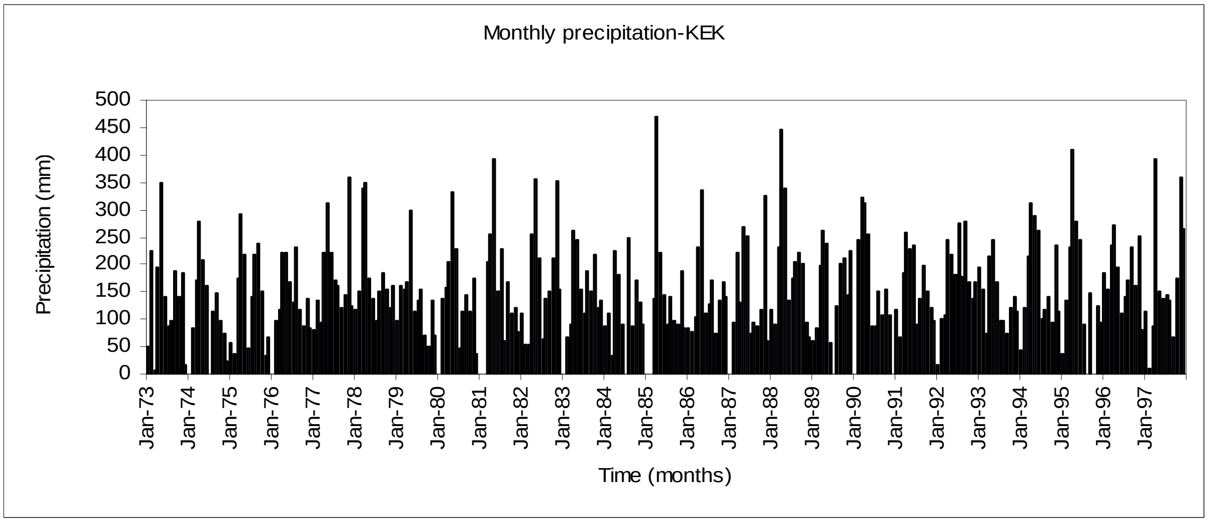
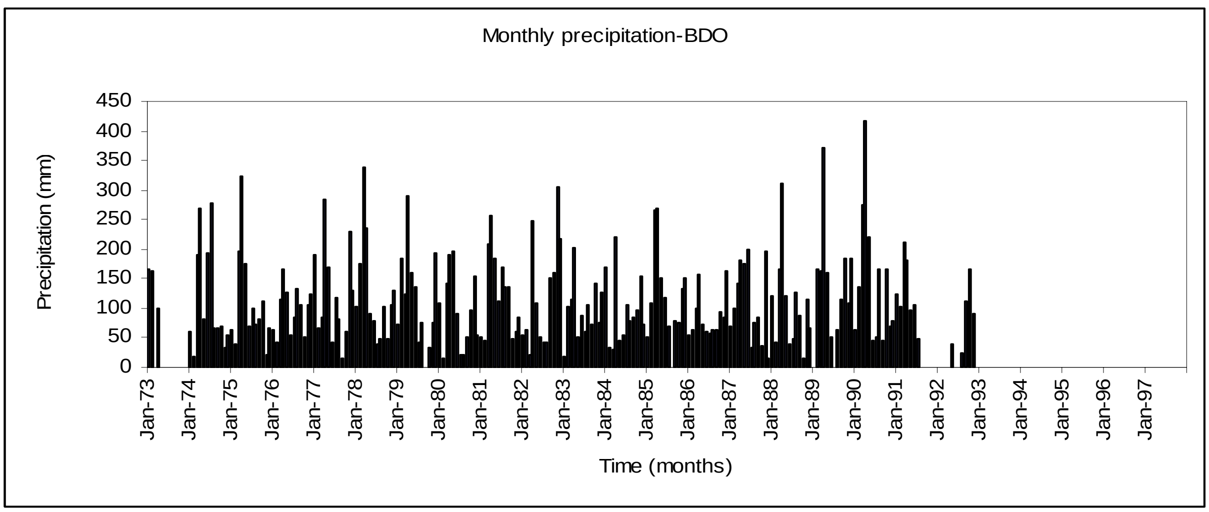
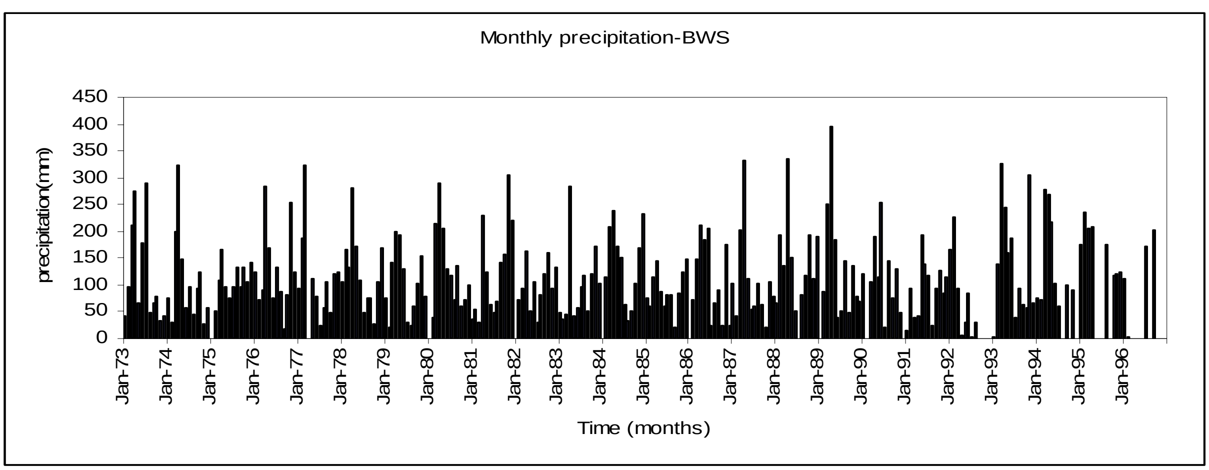
Appendices

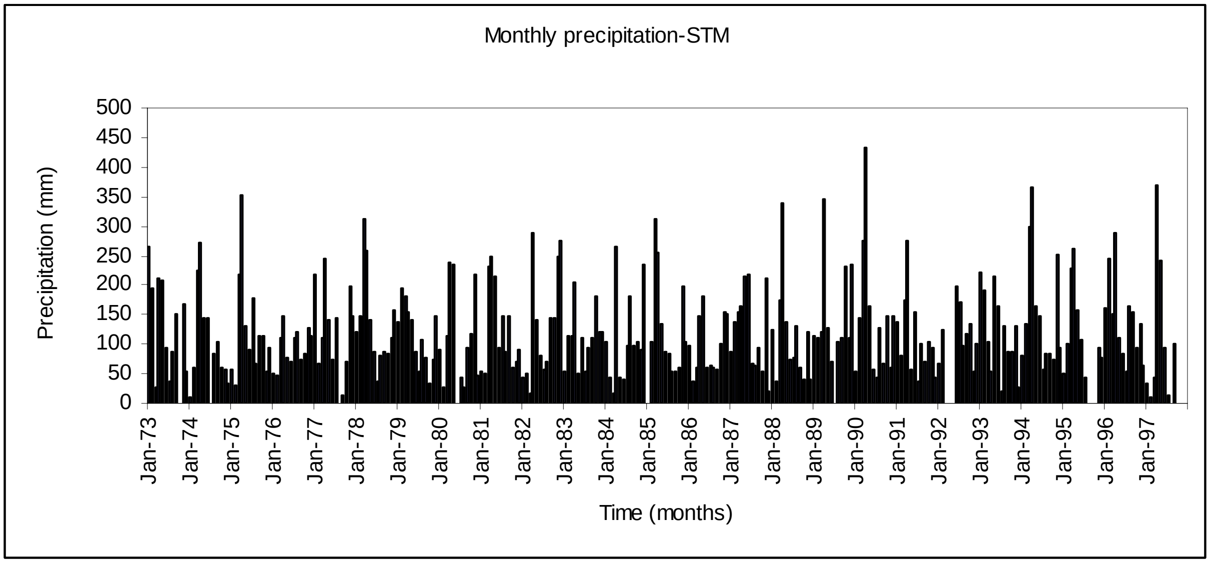
Appendix 1: Precipitation and River flow data of Mara catchment

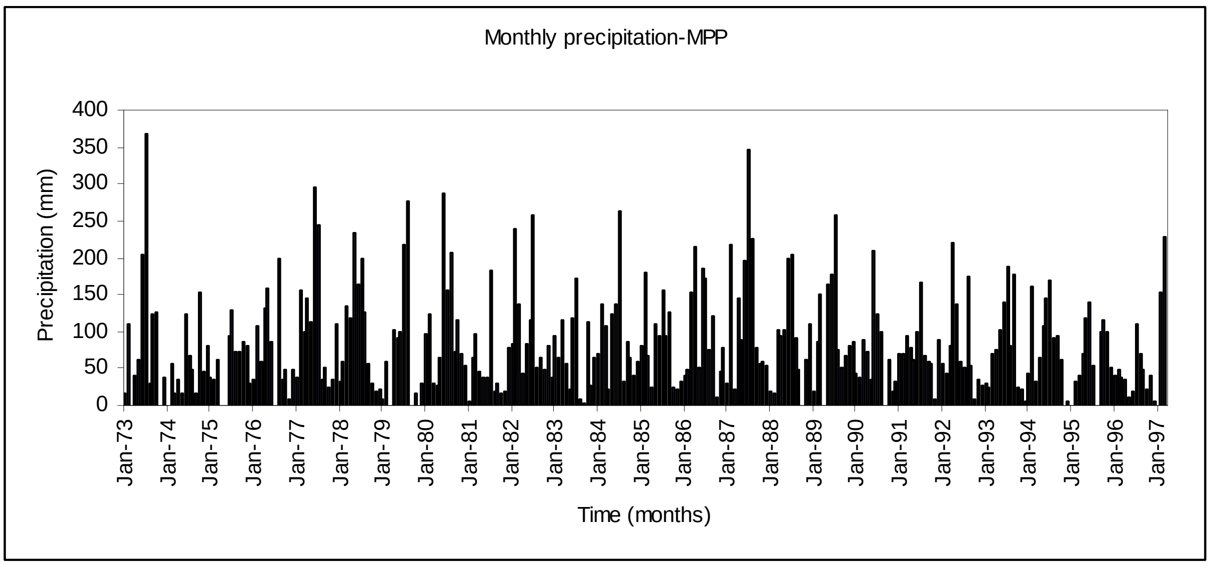
1.1 Monthly Precipitation data for different stations in Mara catchment








Monthly precipitation-STM
Precipitation (mm)
0
50
100
150
200
250
300
350
400
450
500
Jan-73
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Time (months)


Monthly precipitation-MPP
Precipitation (mm)
0
50
100
150
200
250
300
350
400
Jan-73
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
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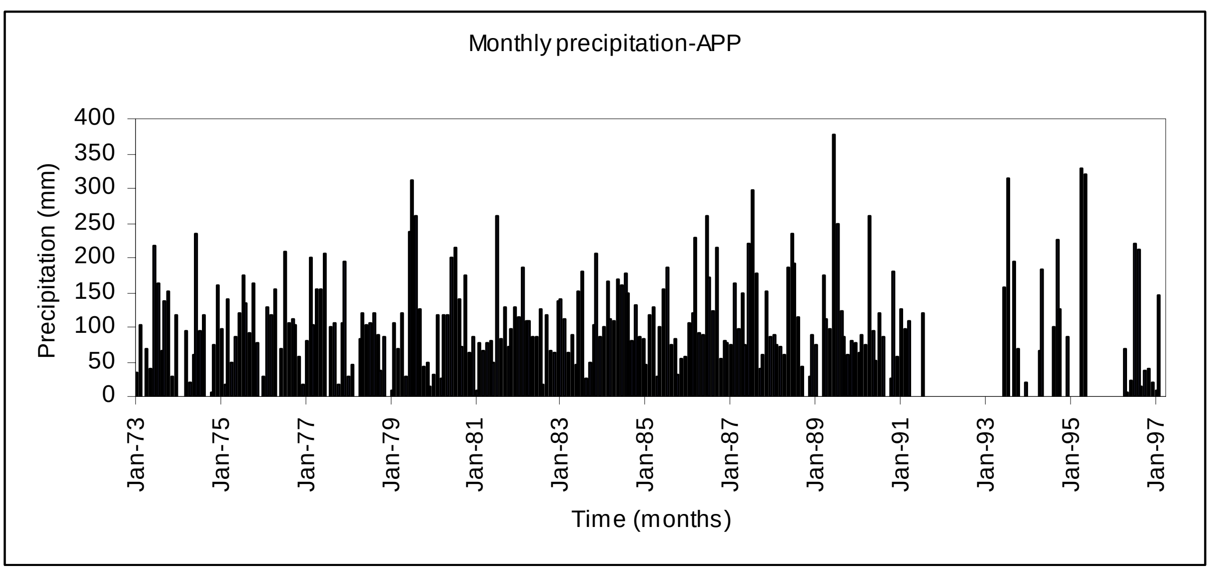
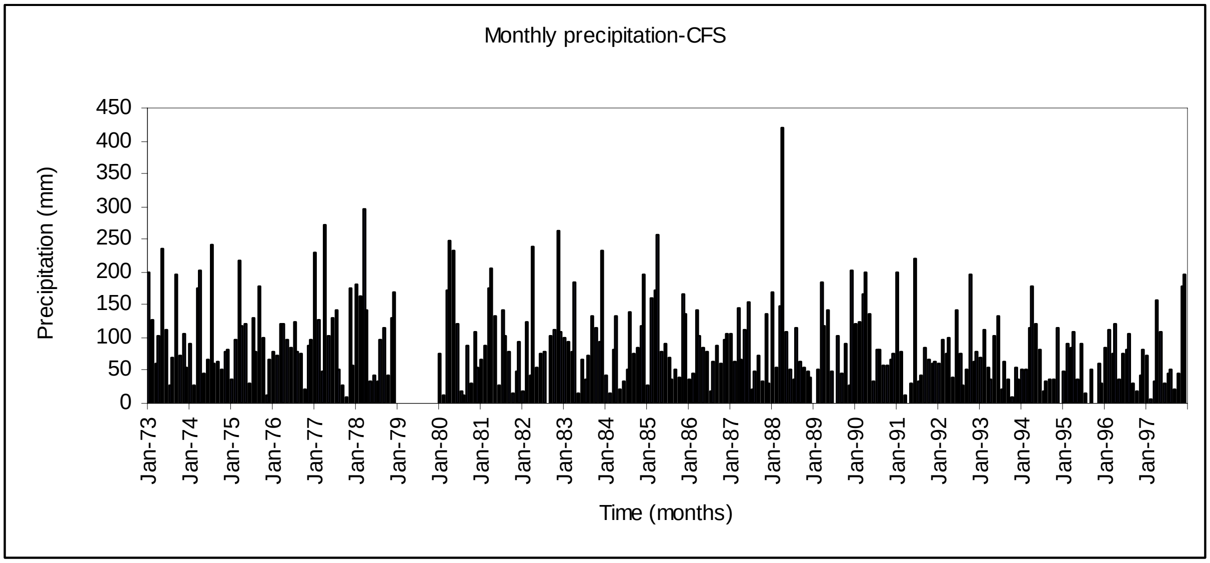
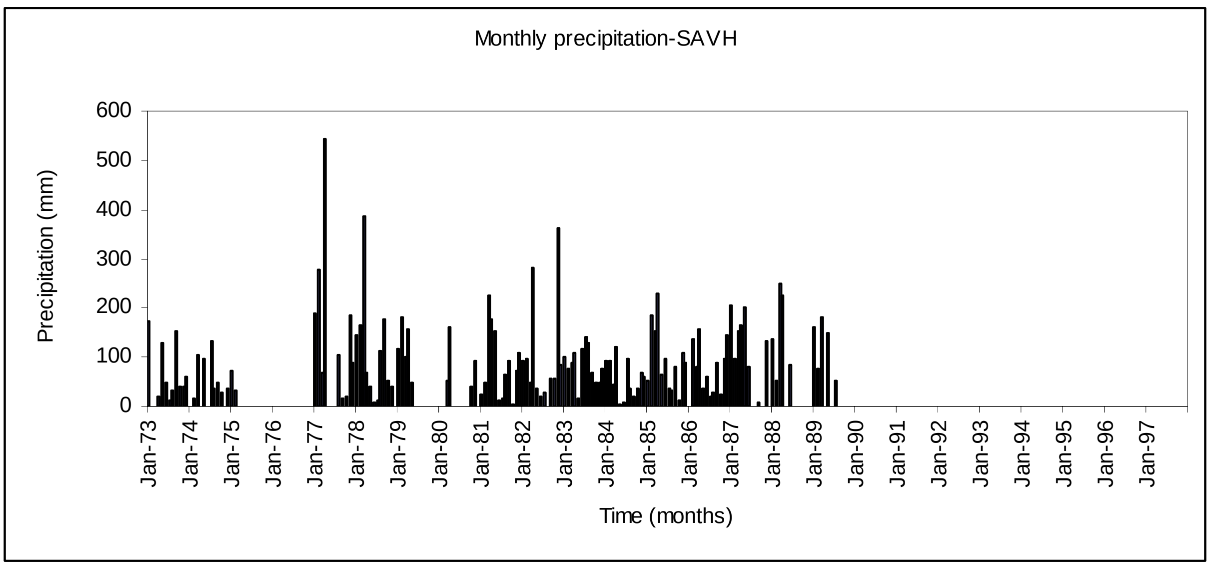
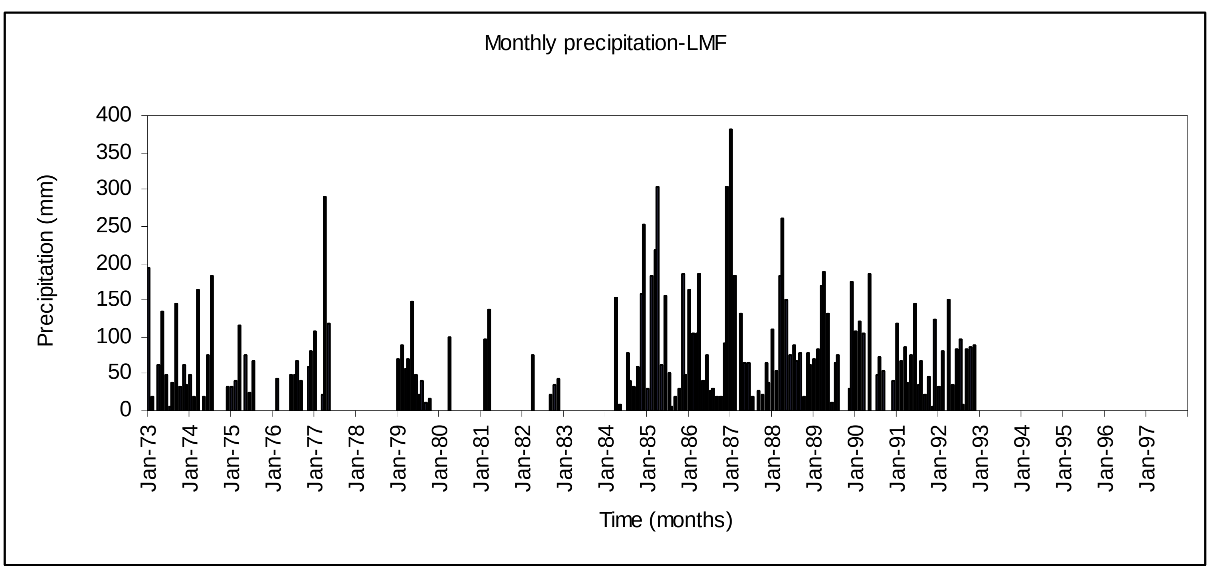
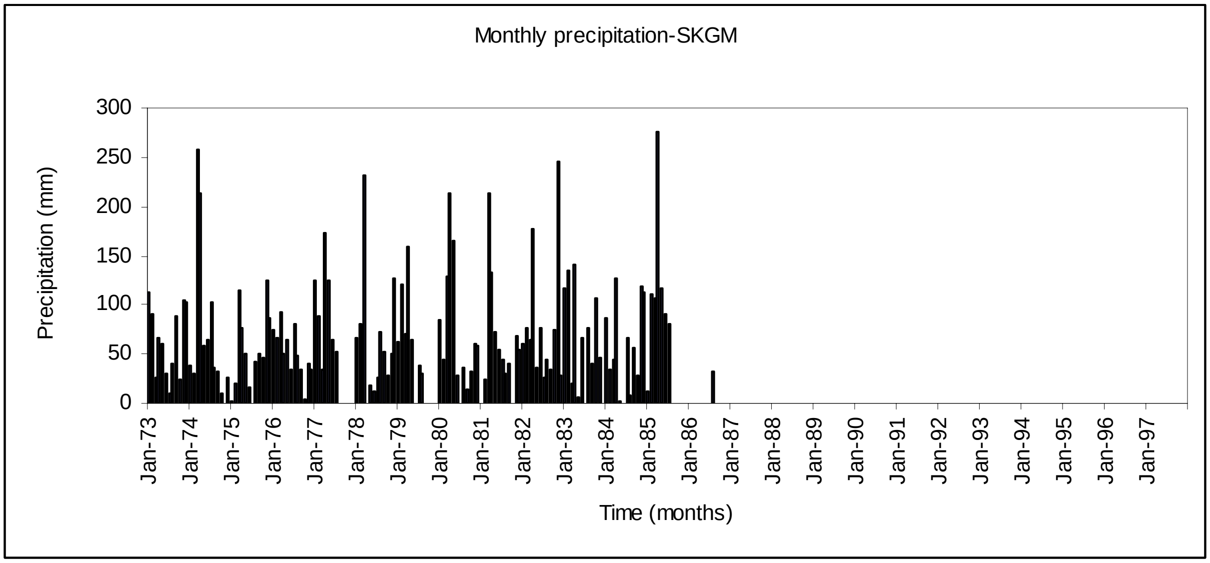
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Time (months)

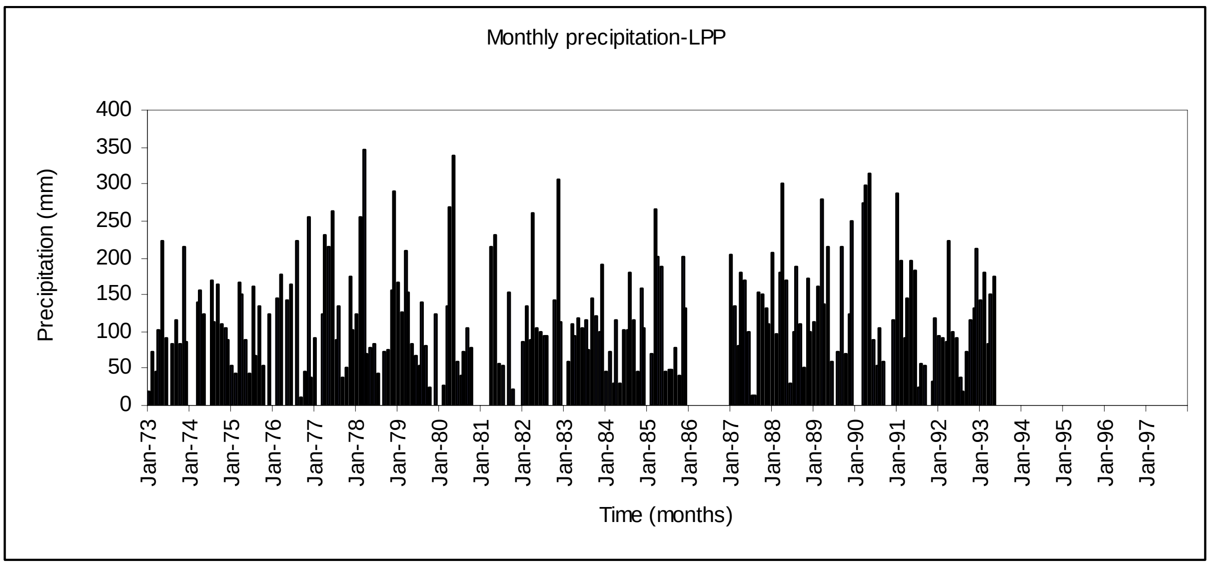

Monthly precipitation-APP
Precipitation (mm)
0
50
100
150
200
250
300
350
400
Jan-73
Jan-75
Jan-77
Jan-79
Jan-81
Jan-83
Jan-85
Jan-87
Jan-89
Jan-91
Jan-93
Jan-95
Jan-97
Time (months)

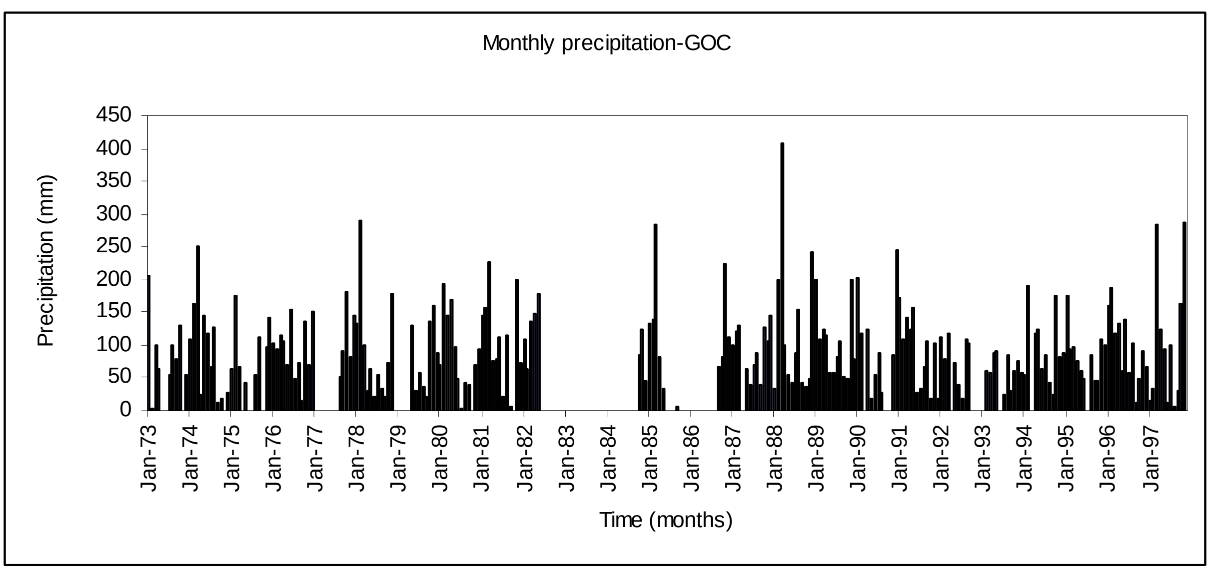

Monthly precipitation-CFS
Precipitation (mm)
450
400
350
300
250
200
150
100
50
0
Jan-73 Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97
Time (months)

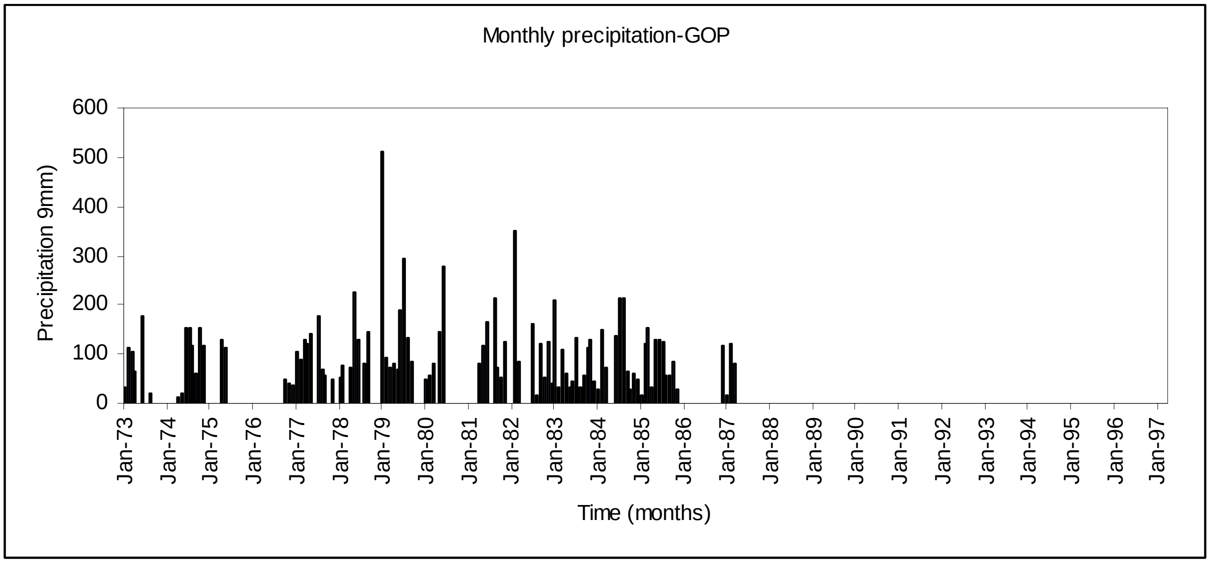

Monthly precipitation-SAVH
Precipitation (mm)
600
500
400
300
200
100
0
Jan-73 Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97
Time (months)

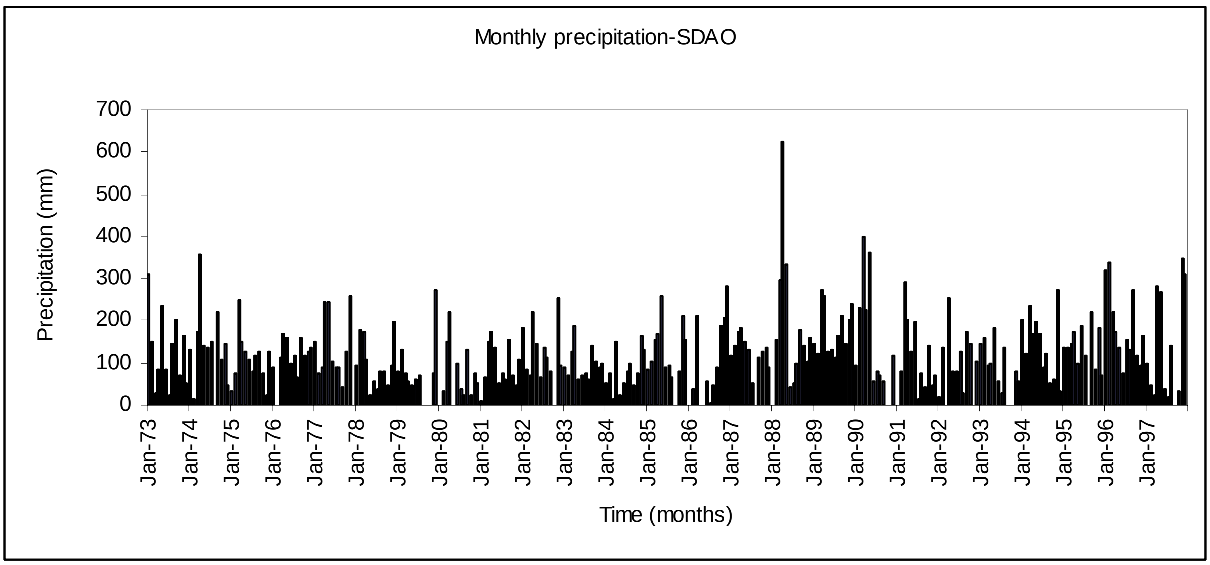

Monthly precipitation-LMF
Precipitation (mm)
400
350
300
250
200
150
100
50
0
Jan-73 Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97
Time (months)

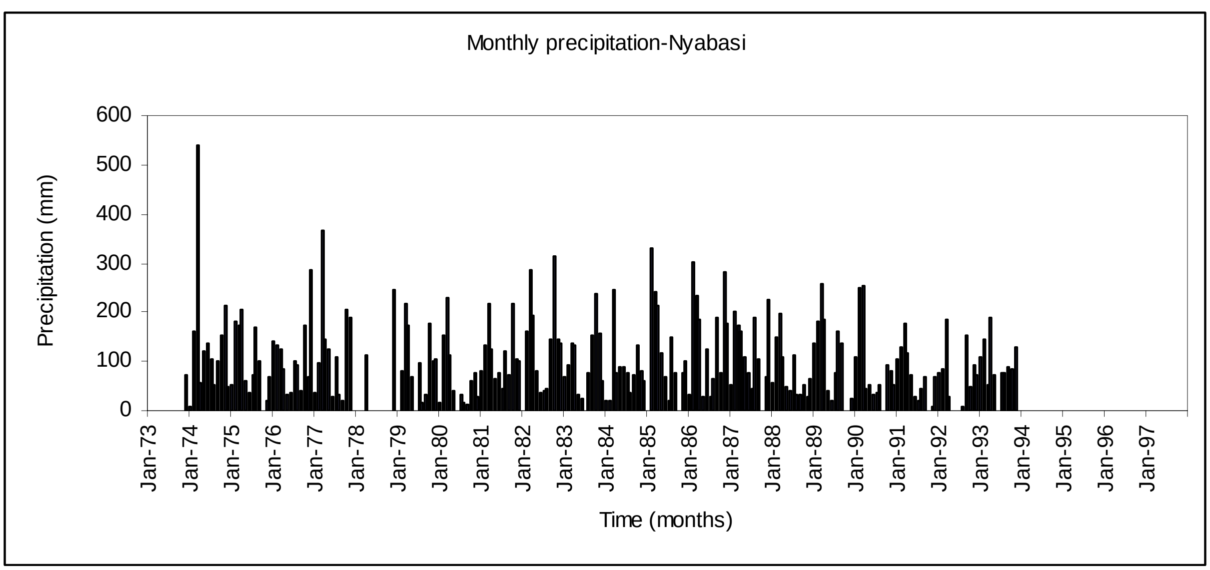

Monthly precipitation-SKGM
Precipitation (mm)
300
250
200
150
100
50
0
Jan-73 Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97
Time (months)

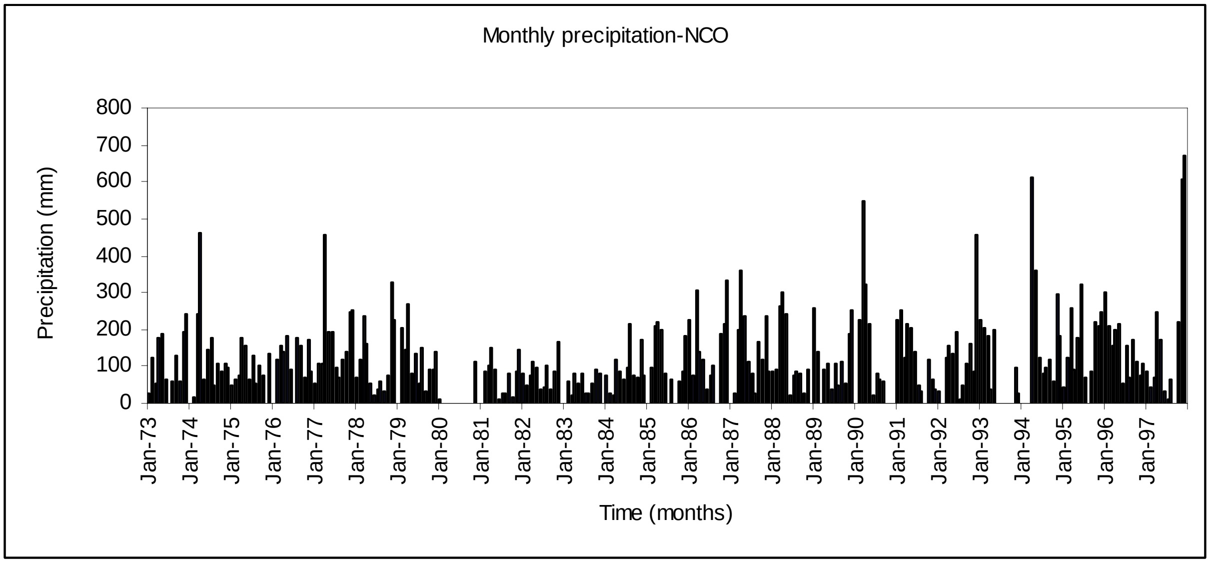

Monthly precipitation-LPP
Precipitation (mm)
400
350
300
250
200
150
100
50
0
Jan-73 Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97
Time (months)

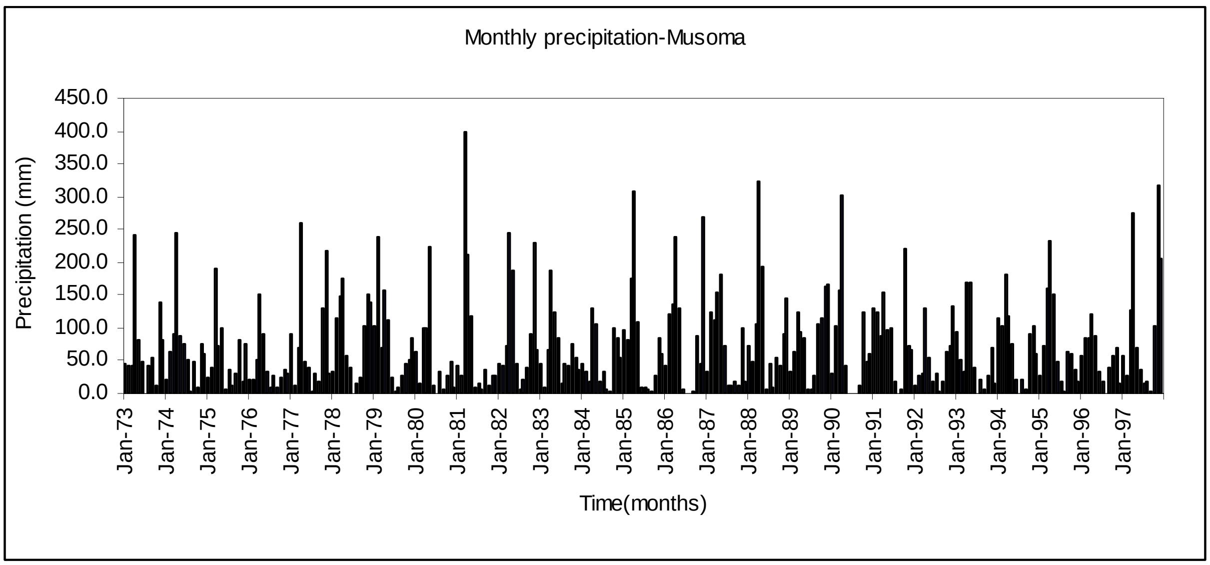

Monthly precipitation-GOC
Precipitation (mm)
450
400
350
300
250
200
150
100
50
0
Jan-73 Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97
Time (months)

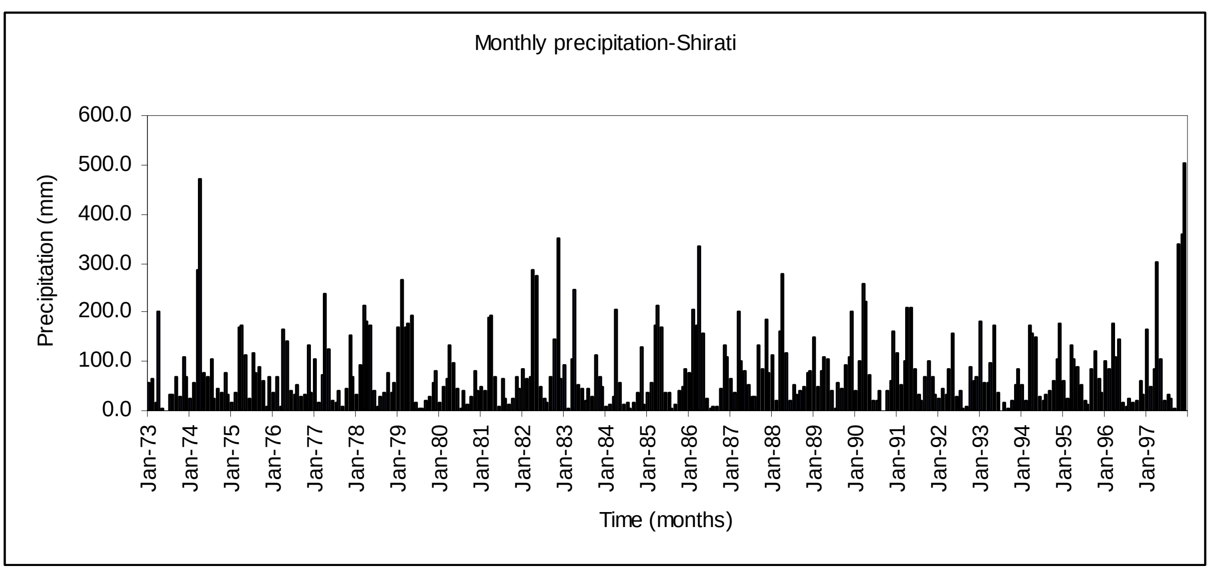

Monthly precipitation-GOP
Precipitation 9mm)
600
500
400
300
200
100
0
Jan-73
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Time (months)

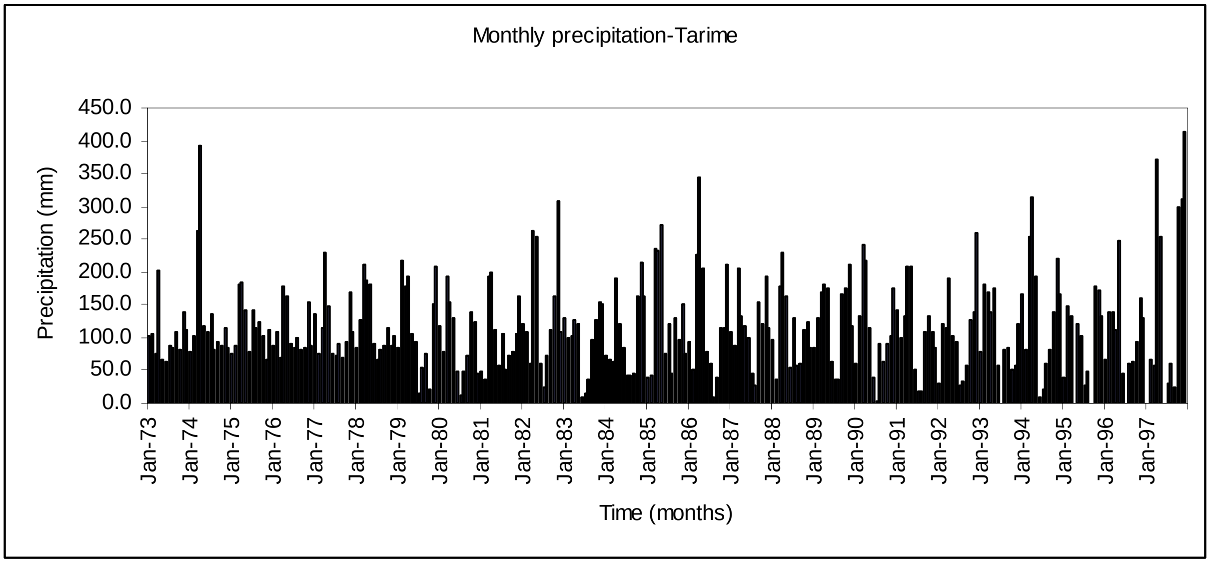

Monthly precipitation-SDAO
Precipitation (mm)
700
600
500
400
300
200
100
0
Jan-73
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Time (months)


Monthly precipitation-Nyabasi
Precipitation (mm)
600
500
400
300
200
100
0
Jan-73
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Time (months)

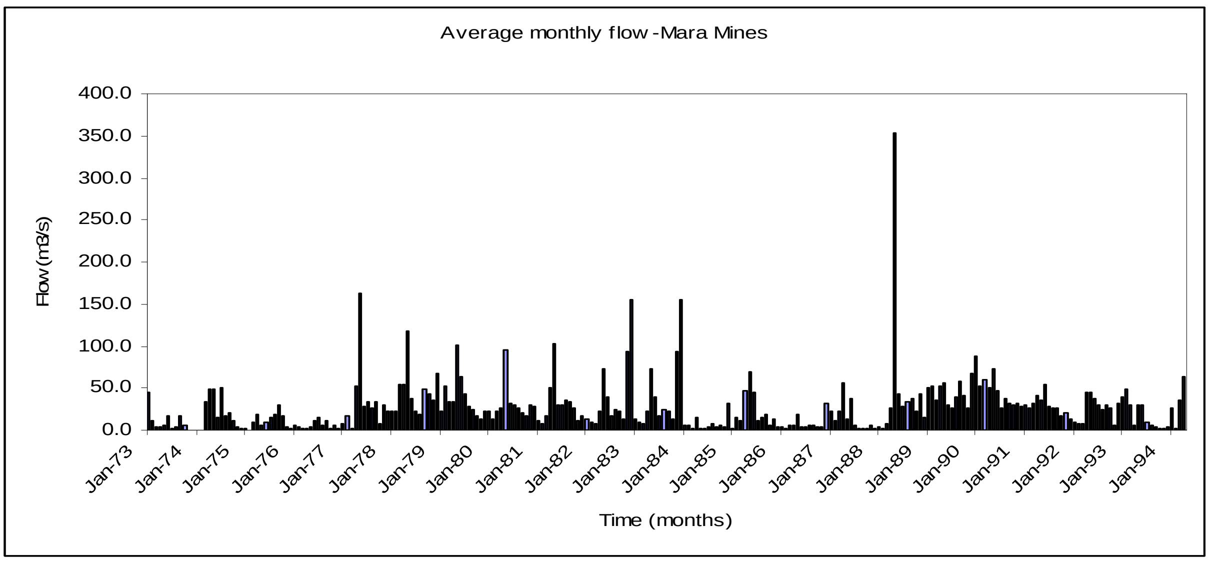

Monthly precipitation-NCO
Precipitation (mm)
800
700
600
500
400
300
200
100
0
Jan-73
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Time (months)


Monthly precipitation-Musoma
Precipitation (mm)
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
Jan-73
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Time(months)


Monthly precipitation-Shirati
Precipitation (mm)
600.0
500.0
400.0
300.0
200.0
100.0
0.0
Jan-73
Jan-74
Jan-75
Jan-76
Jan-77
Jan-78
Jan-79
Jan-80
Jan-81
Jan-82
Jan-83
Jan-84
Jan-85
Jan-86
Jan-87
Jan-88
Jan-89
Jan-90
Jan-91
Jan-92
Jan-93
Jan-94
Jan-95
Jan-96
Jan-97
Time (months)

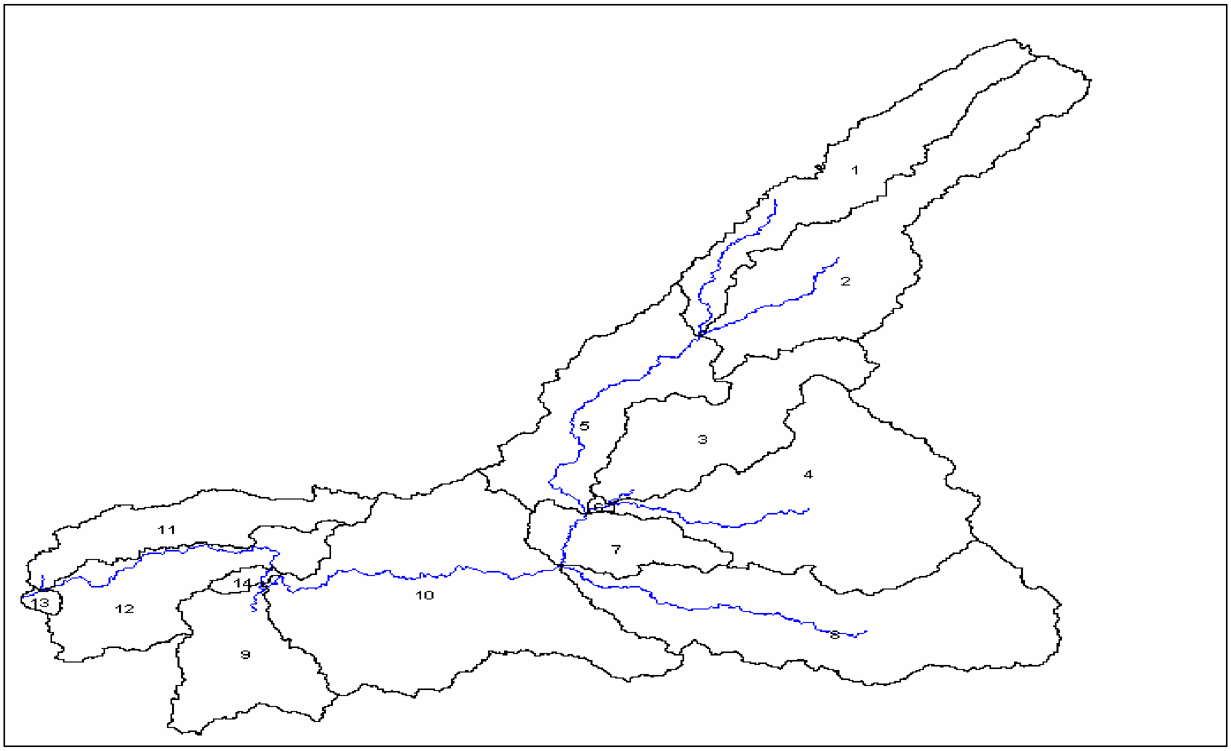


1.2 Average Monthly flow data for Mara Mine gauging station

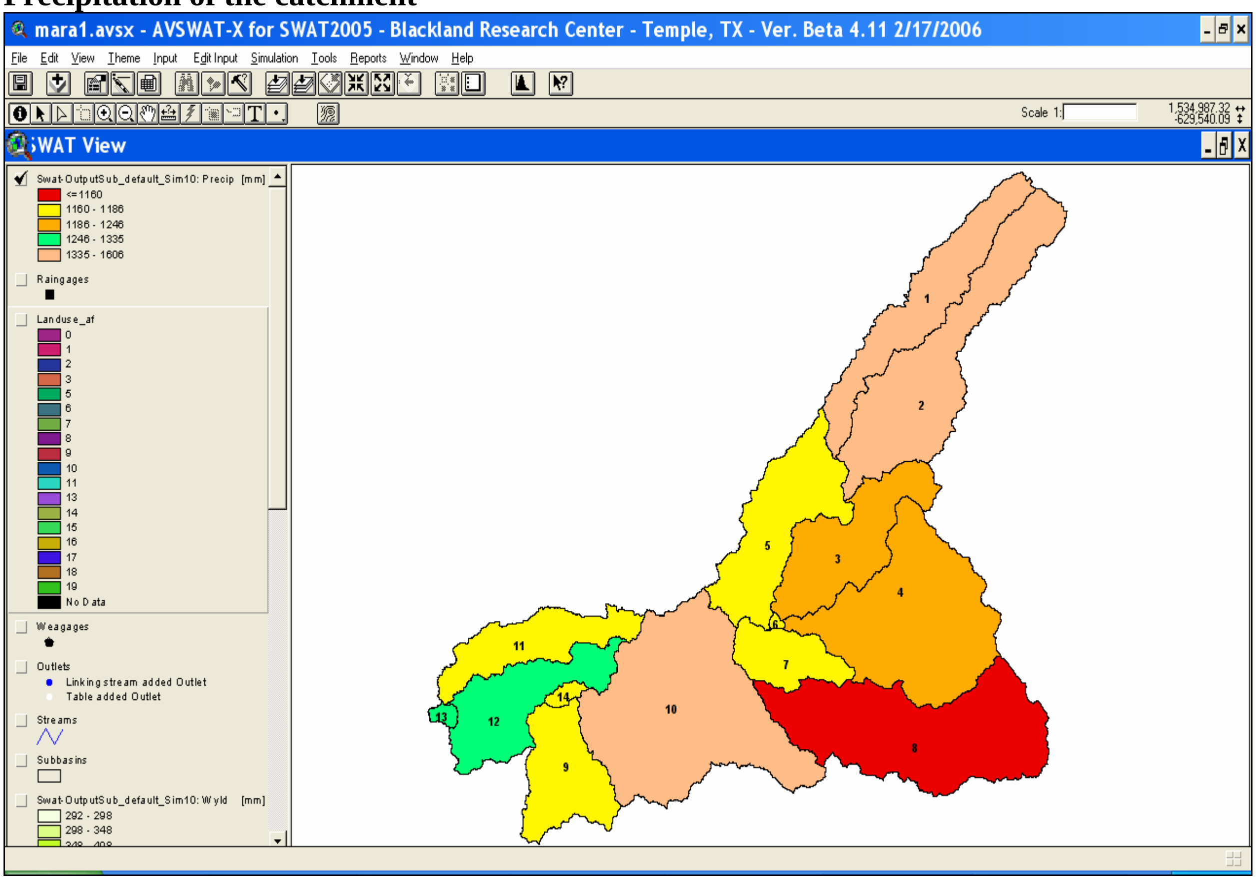


Appendix 2: SWAT model results

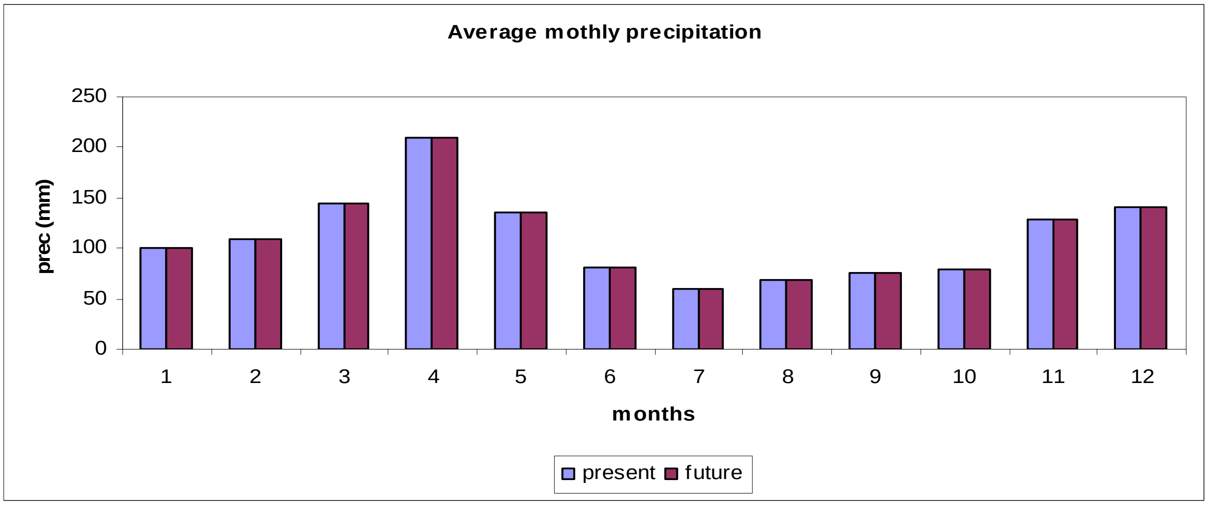
Subbasins of the catchment

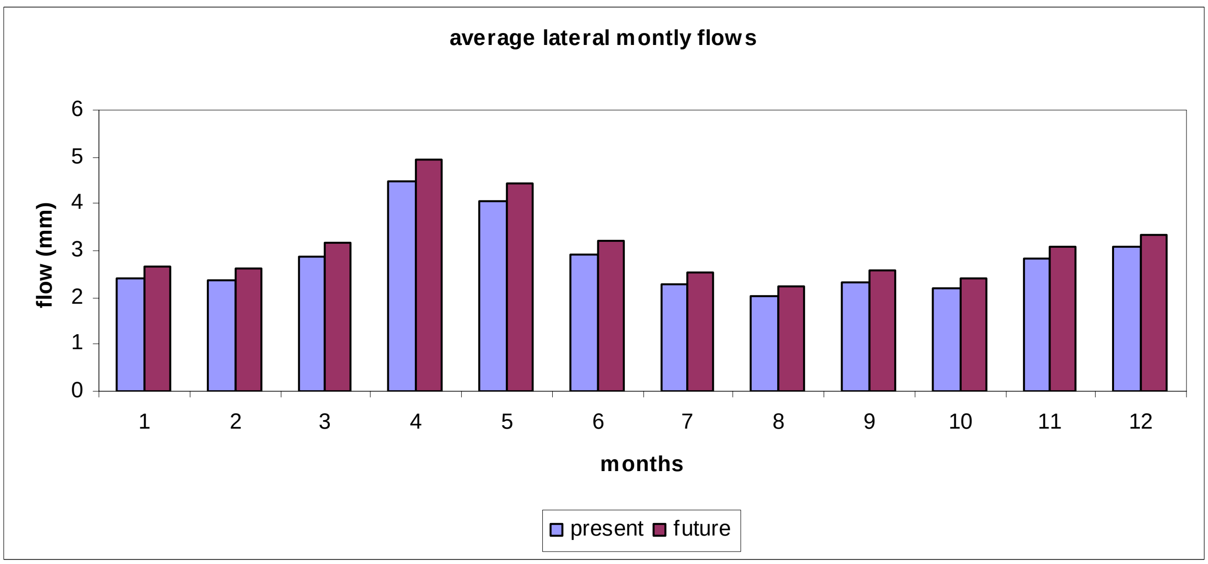


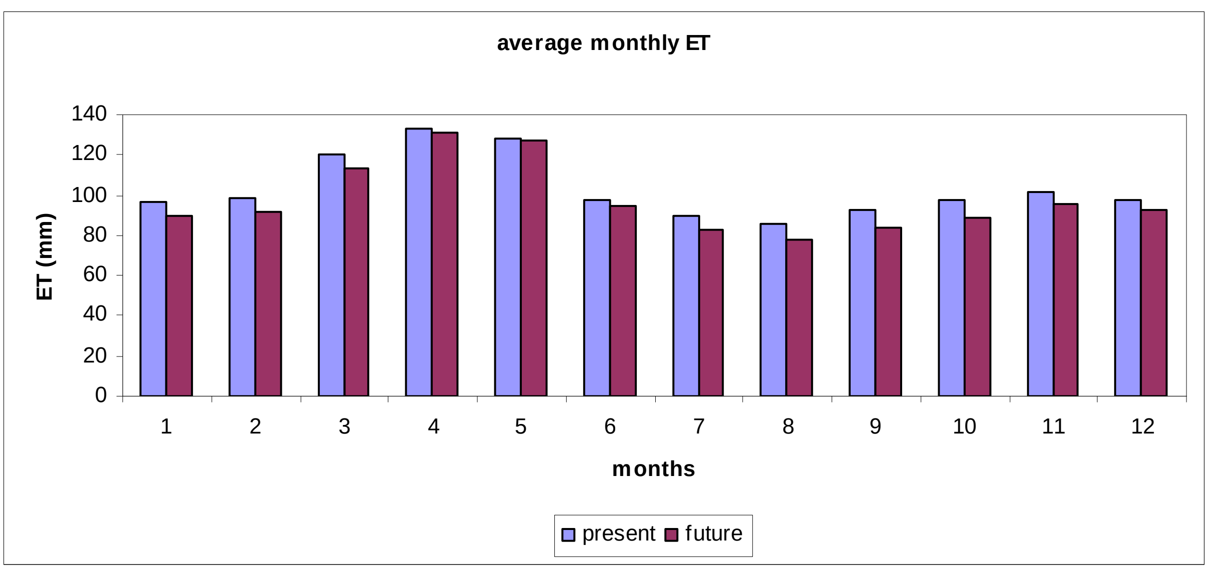
Precipitation of the catchment

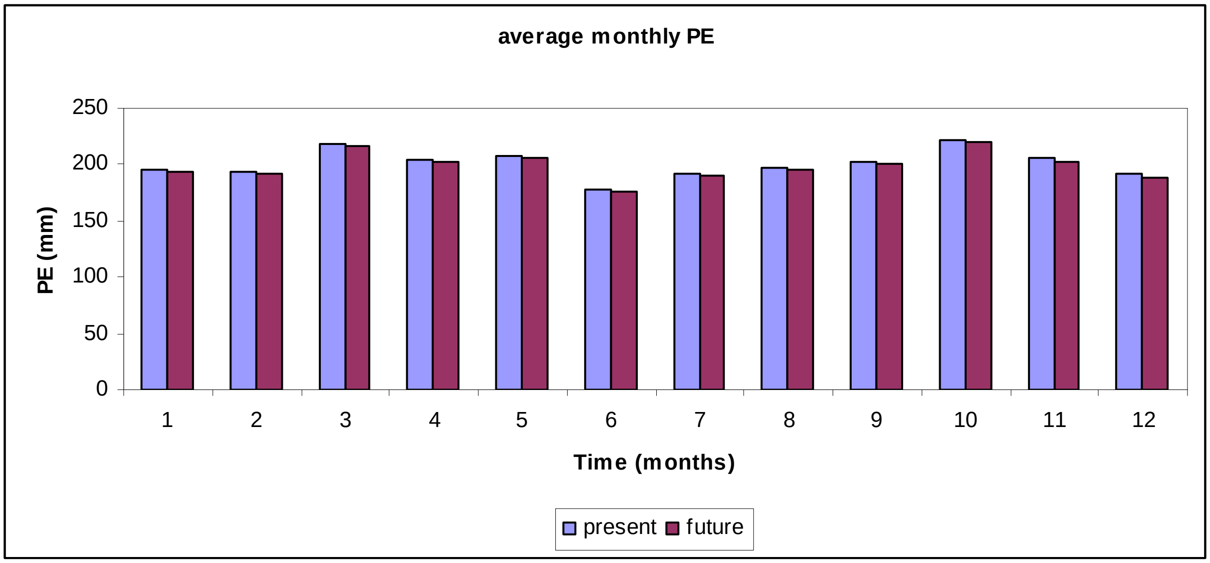


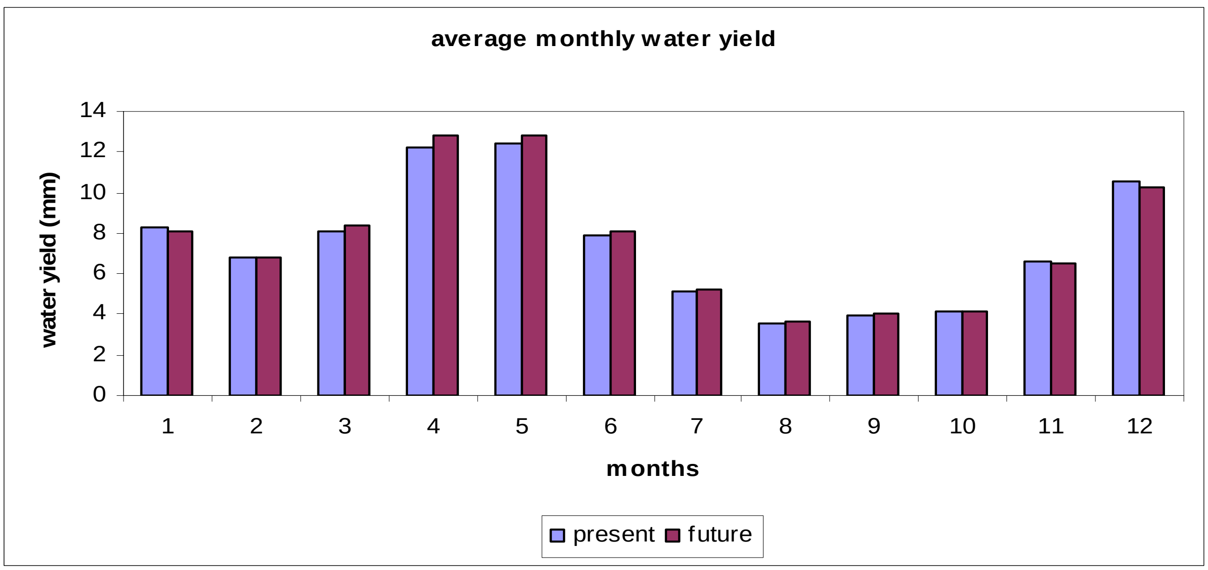
Plots of the summary of average monthly values for present and future scenarios

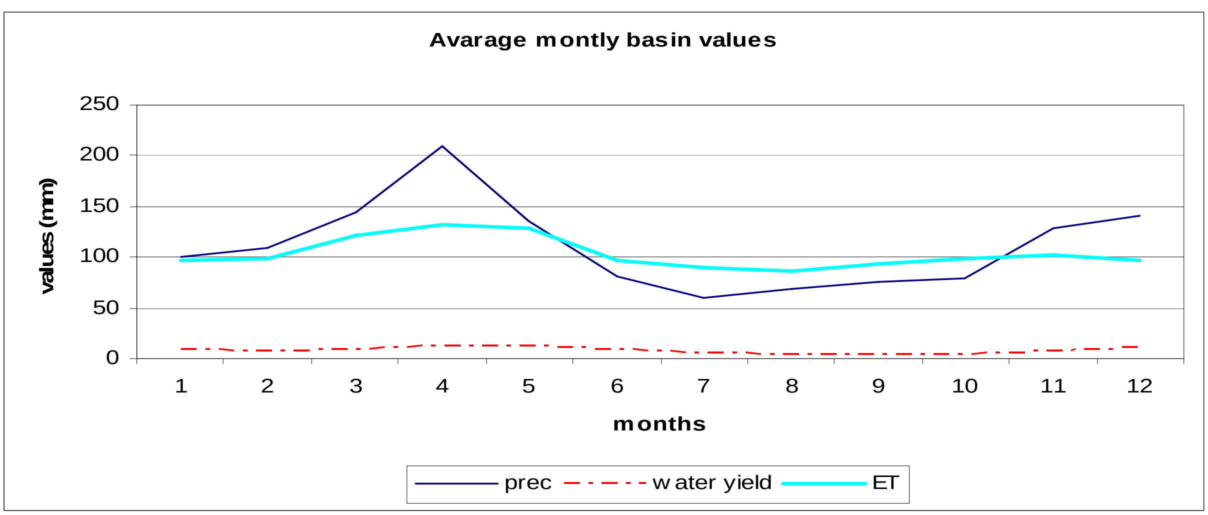




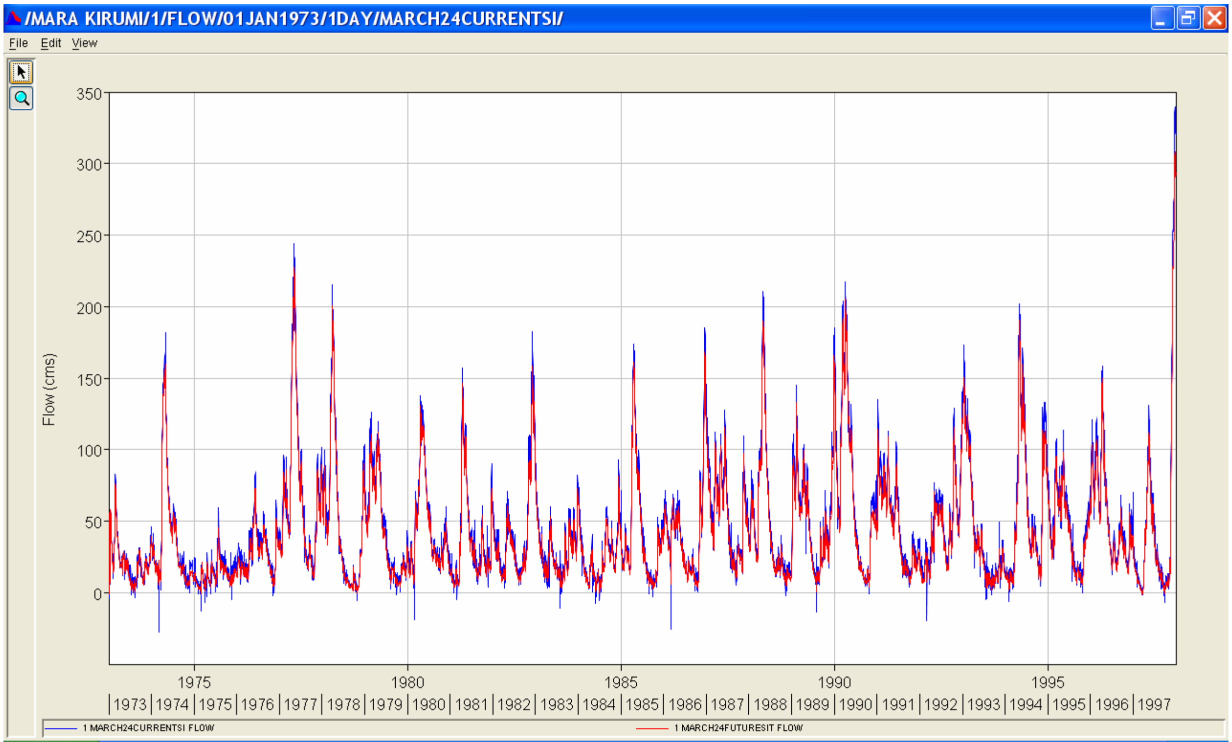



average monthly PE
PE (mm)
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (months)
present
future

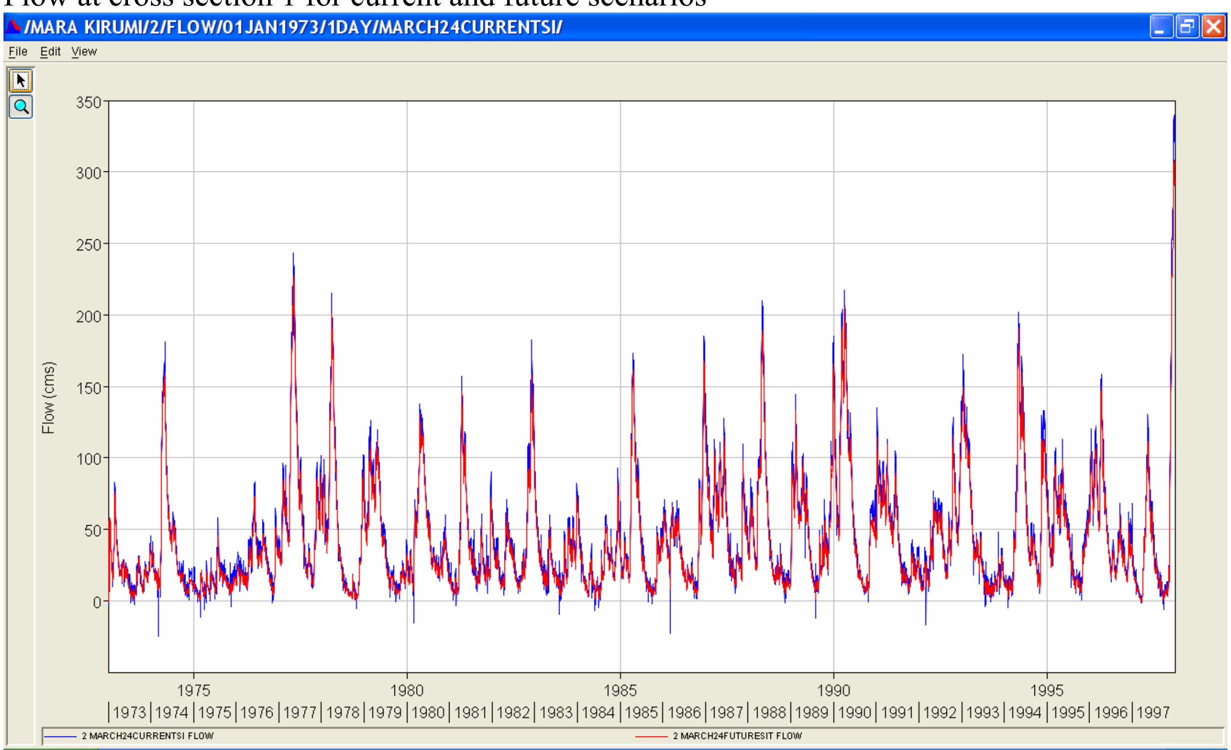

average monthly water yield
water yield (mm)
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
11
12
months
present
future


Avarage montly basin values
values (mm)
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
11
12
months
prec
w ater yield
ET

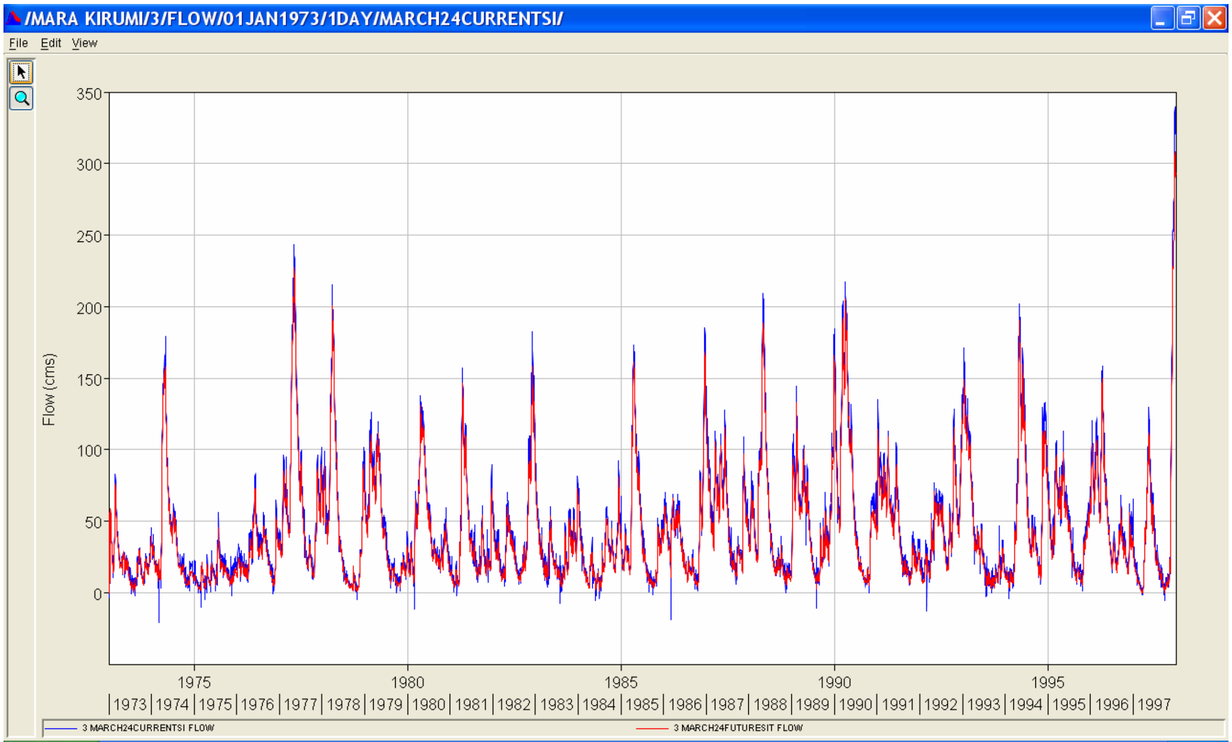
Appendix 3: HEC-RAS model results
3.1 Flow across the nine cross sections for the current and future scenario



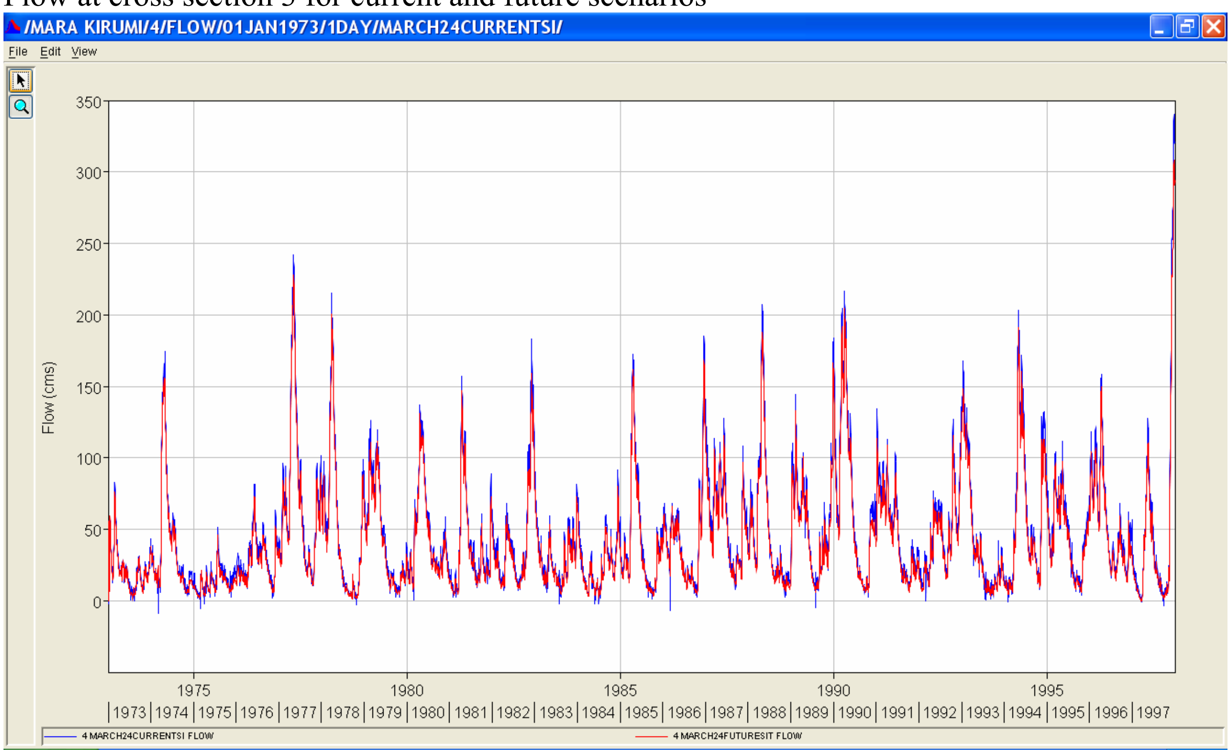
Flow at cross section 1 for current and future scenarios



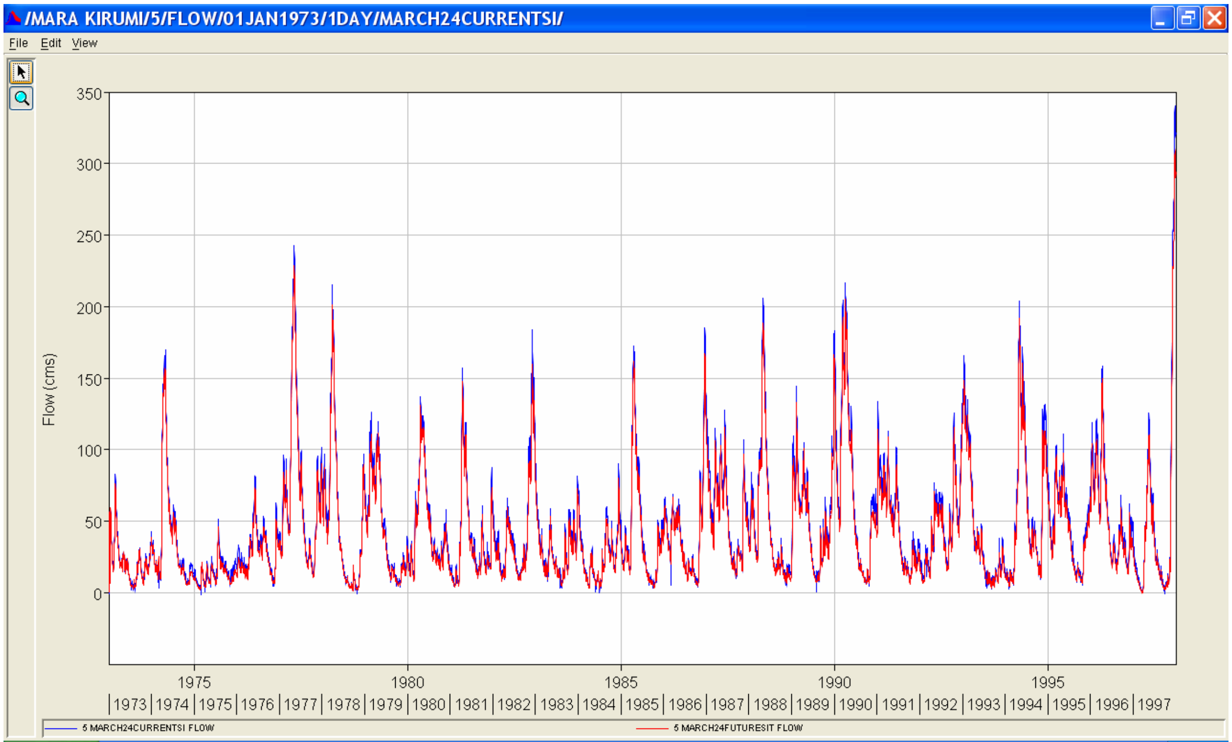
Flow at cross section 2 for current and future scenarios



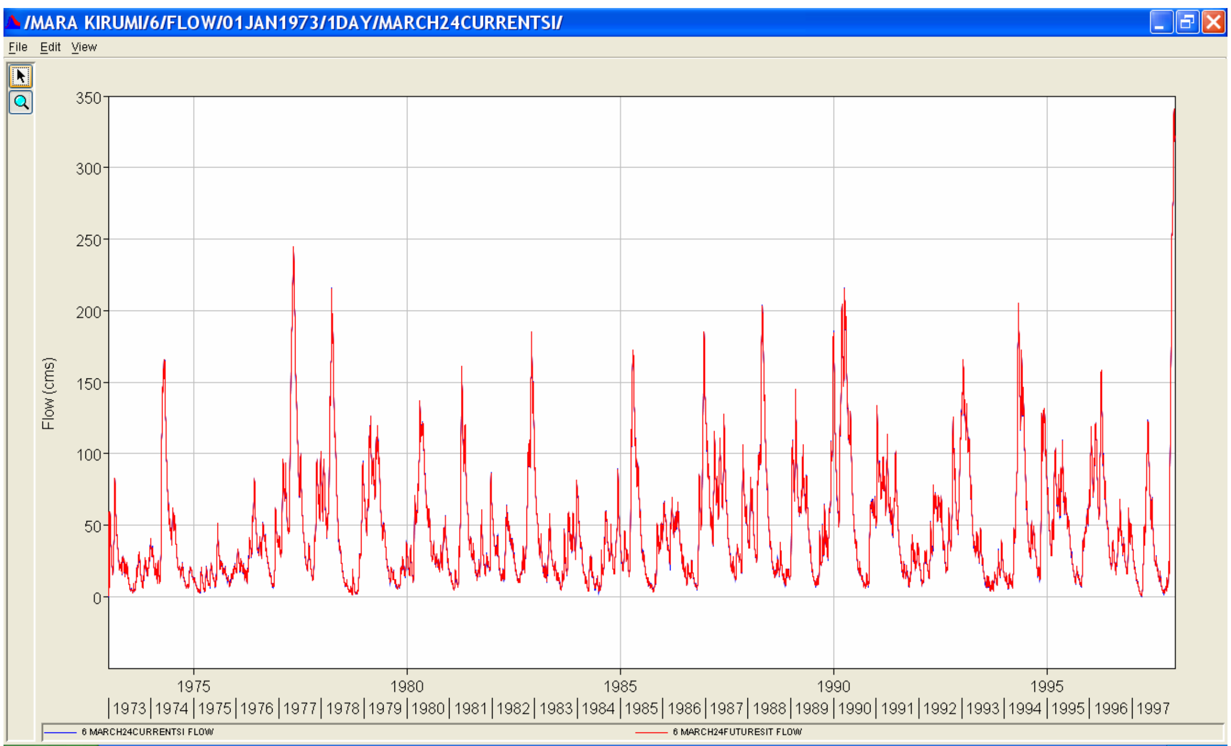
Flow at cross section 3 for current and future scenarios



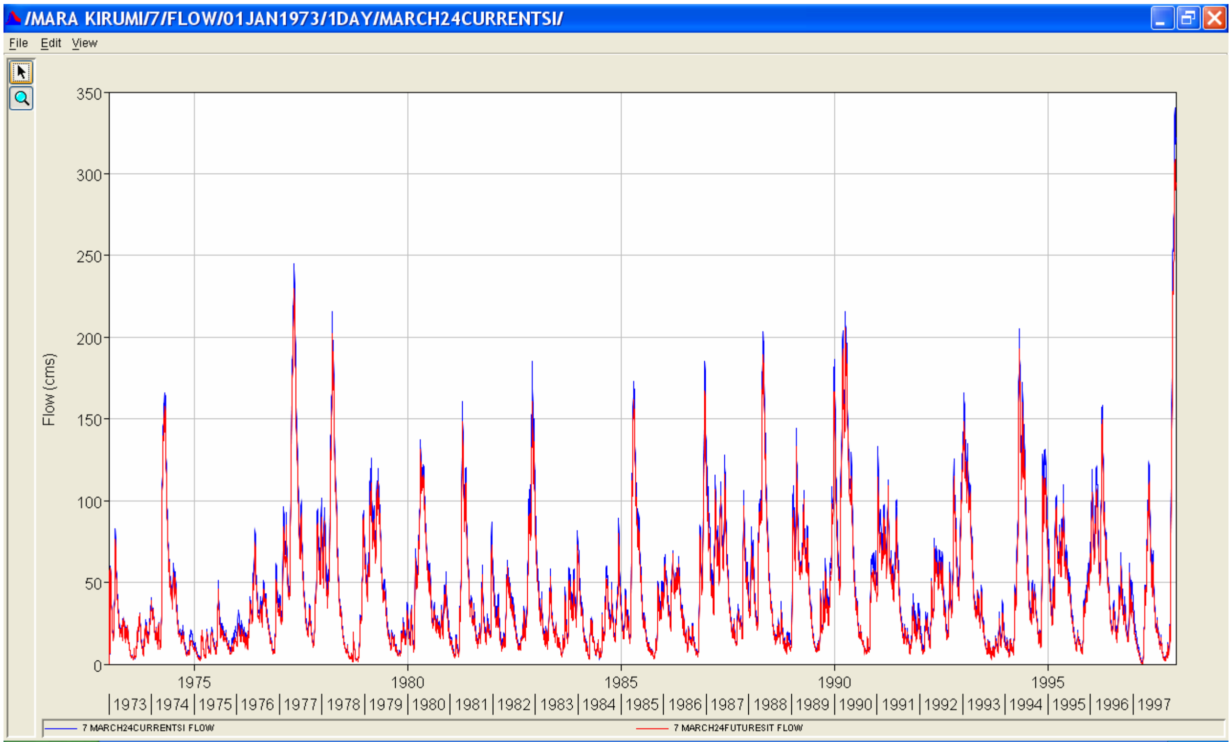
Flow at cross section 4 for current and future scenarios



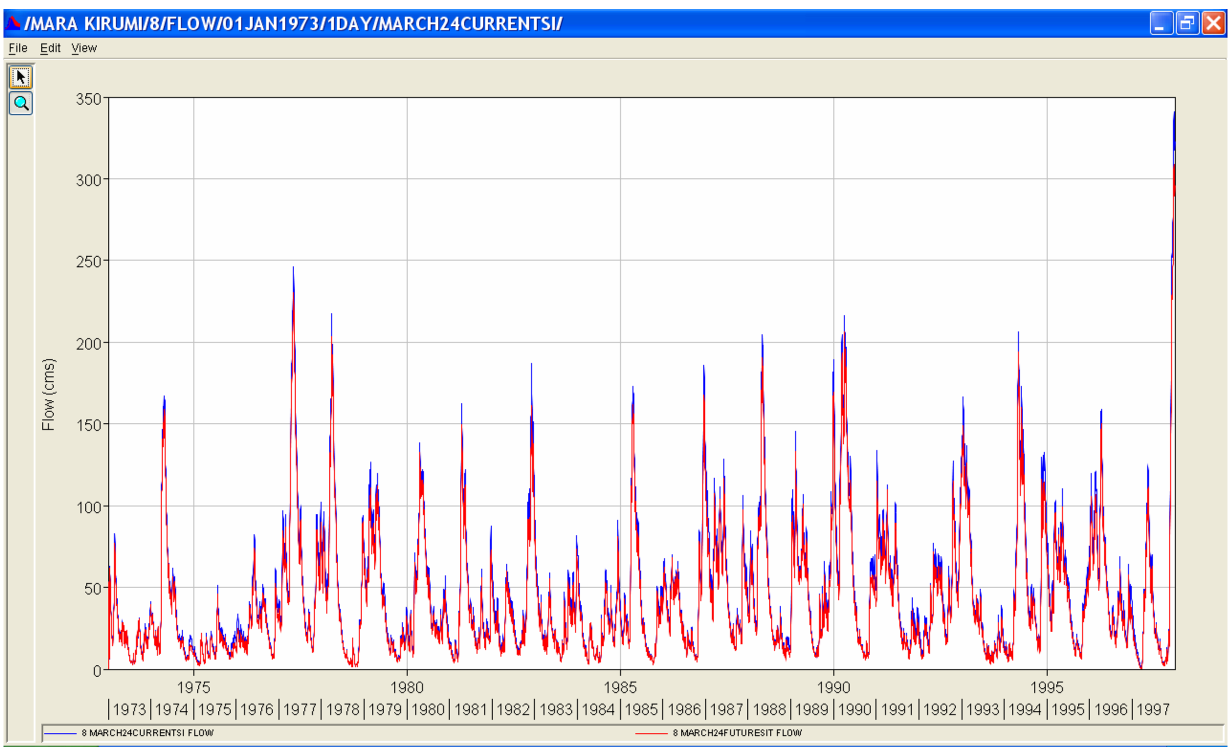
Flow at cross section 5 for current and future scenarios



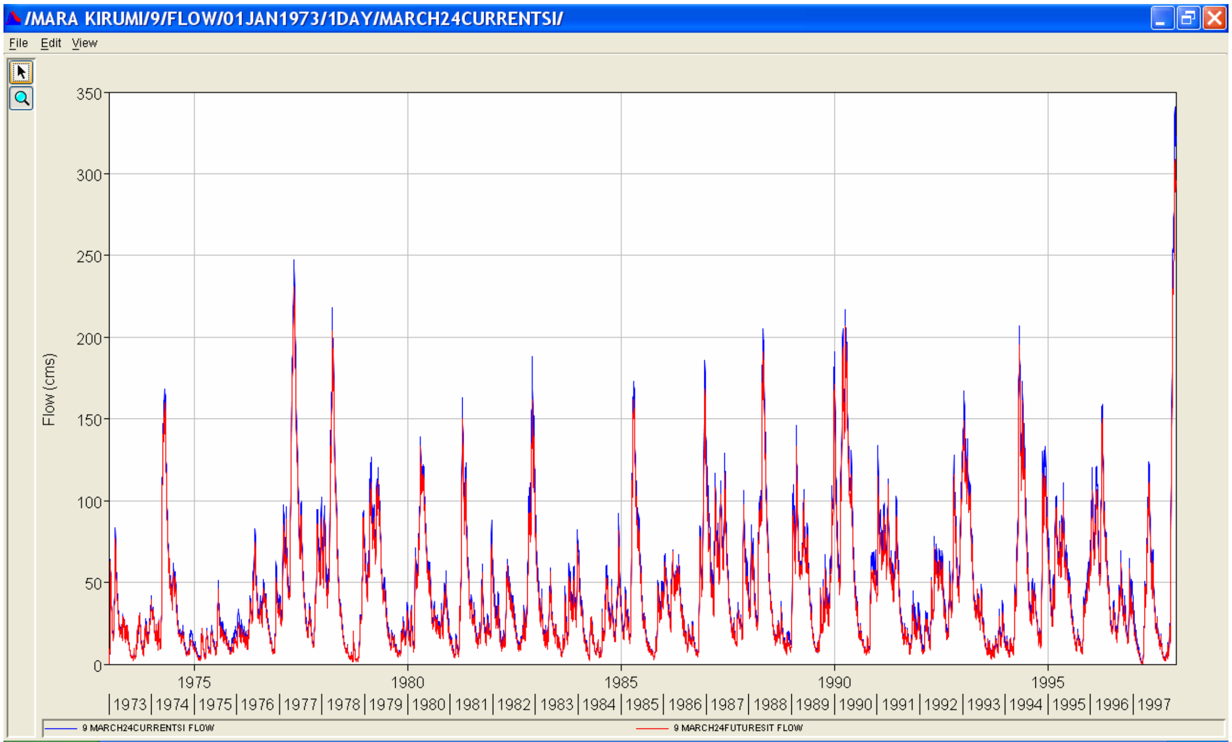
Flow at cross section 6 for current and future scenarios



Flow at cross section 7 for current and future scenarios



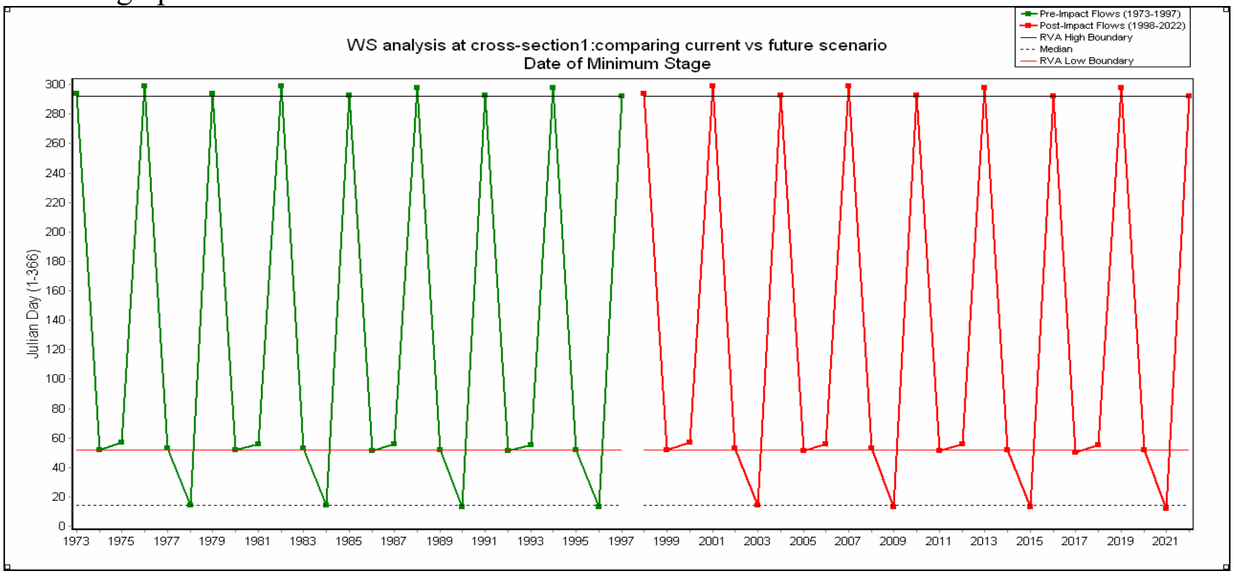
Flow at cross section 8 for current and future scenarios

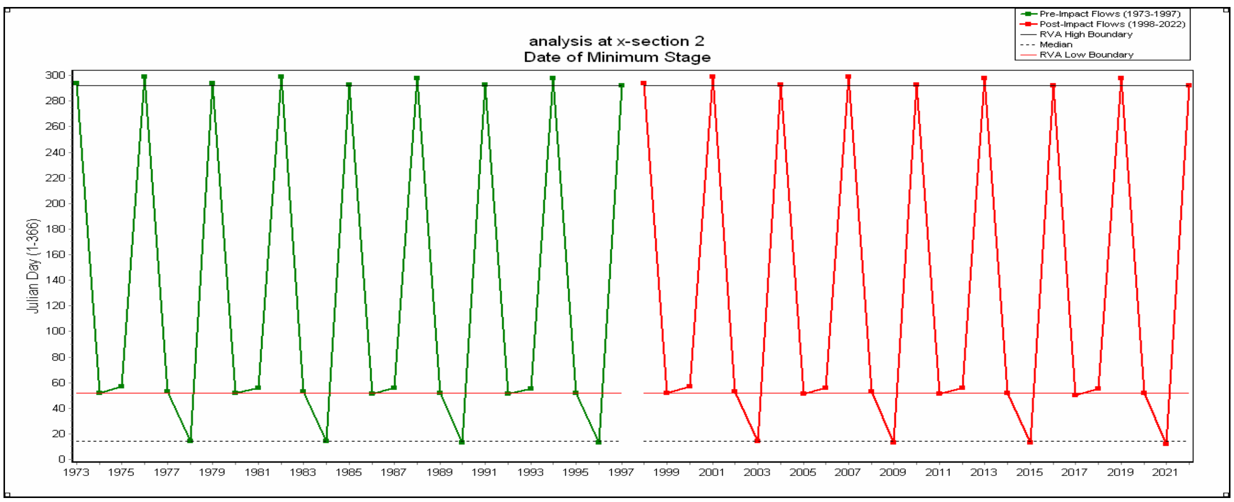


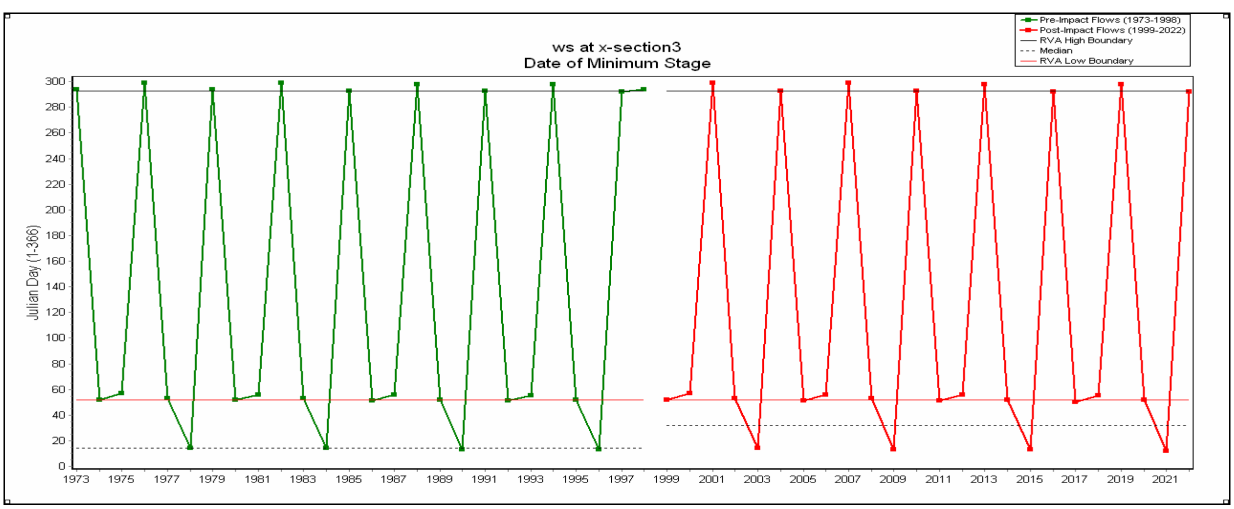
Flow at cross section 9 for current and future scenarios

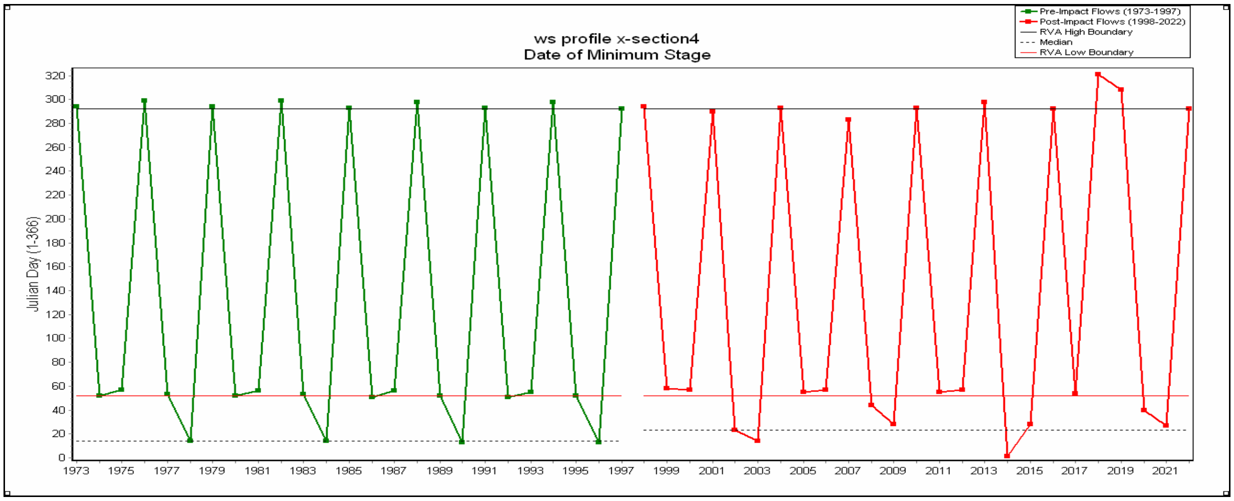
Appendix 4: IHA model results

4.1 IHA graphs

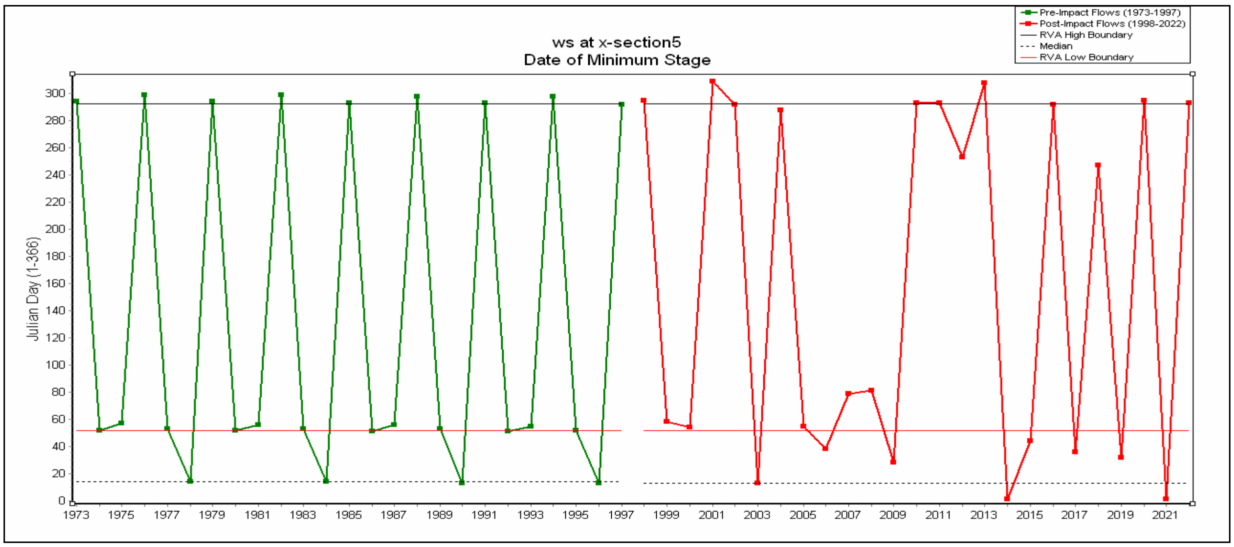






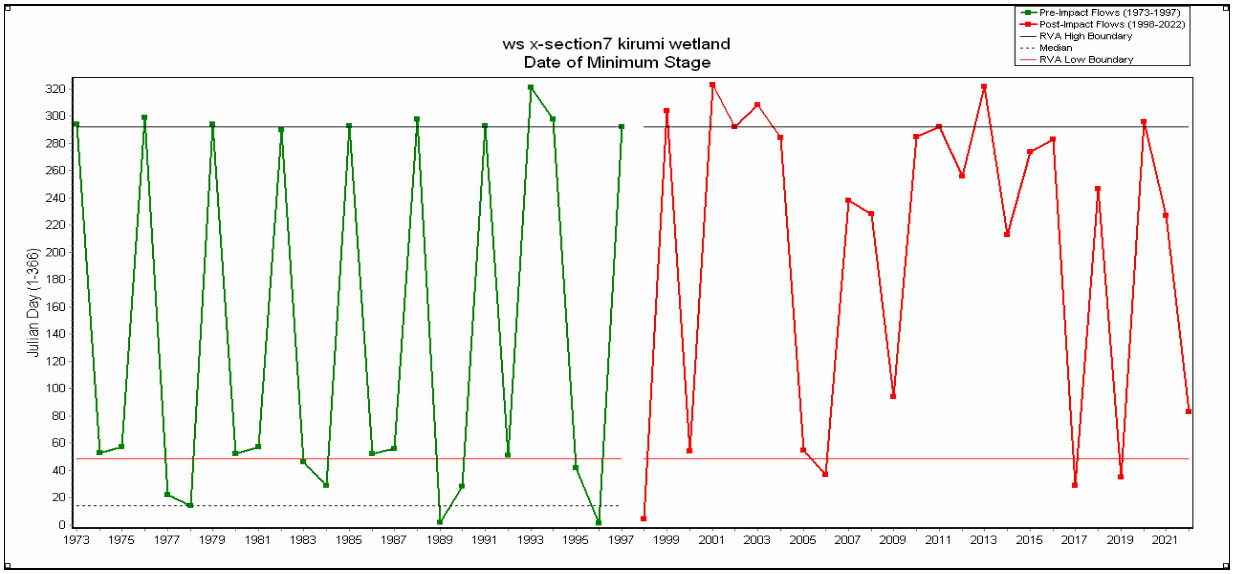


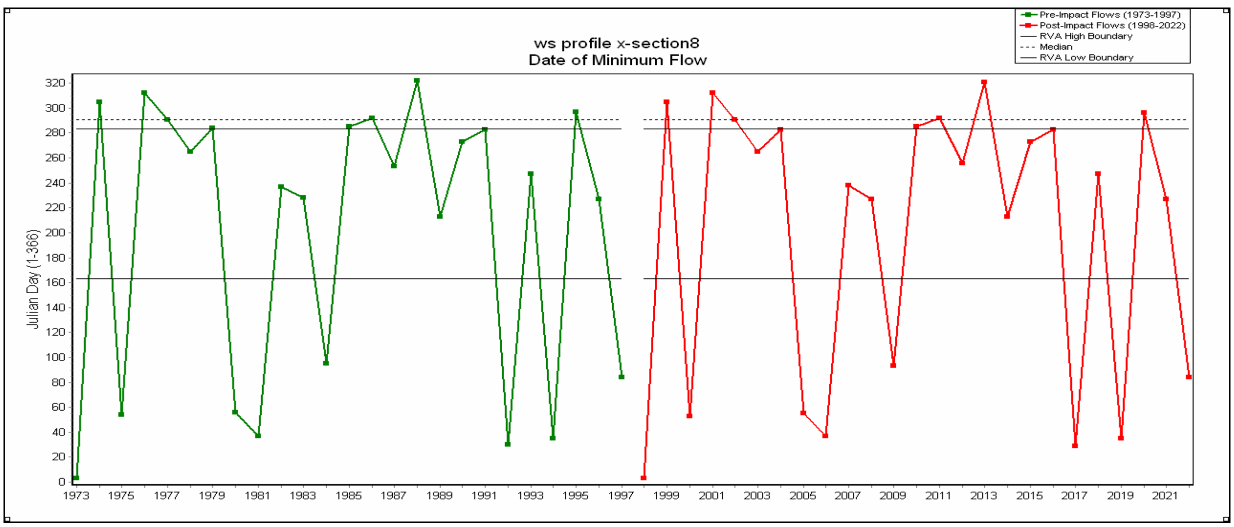
ws profile x-section4
Date of Minimum Stage
Pre-Impact Flows (1973-1997)
Post-Impact Flows (1998-2022)
RVA High Boundary
Median
RVA Low Boundary
Julian Day (1-366)

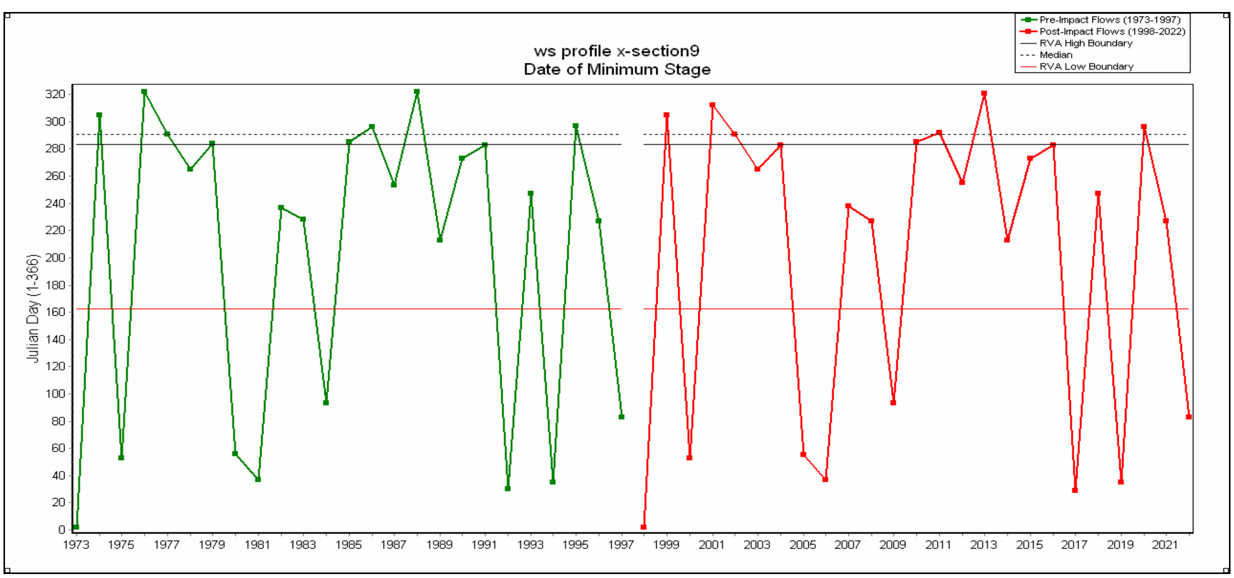


ws at x-section5
Date of Minimum Stage
Pre-Impact Flows (1973-1997)
Post-Impact Flows (1998-2022)
RVA High Boundary
Median
RVA Low Boundary
Julian Day (1-366)

ws profile x-section6
Date of Minimum Stage
Pre-Impact Flows (1973-1997)
Post-Impact Flows (1998-2022)
RVA High Boundary
Median
RVA Low Boundary
Julian Day (1-366)


ws x-section7 kirumi wetland
Date of Minimum Stage
Pre-Impact Flows (1973-1997)
Post-Impact Flows (1998-2022)
RVA High Boundary
Median
RVA Low Boundary
Julian Day (1-366)


ws profile x-section8
Date of Minimum Flow
Pre-Impact Flows (1973-1997)
Post-Impact Flows (1998-2022)
RVA High Boundary
Median
RVA Low Boundary
Julian Day (1-366)


ws profile x-section9
Date of Minimum Stage
Pre-Impact Flows (1973-1997)
Post-Impact Flows (1998-2022)
RVA High Boundary
Median
RVA Low Boundary
Julian Day (1-366)