LANDCOVER DYNAMICS AND HYDOLOGICAL FUNCTIONING OF WETLANDS IN THE USANGU PLAINS IN TANZANIA

BY

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ABSTRACT

In the Usangu Plains of the Upper Great Ruaha River Catchment in Tanzania, the hydrology of the wetlands and the downstream flow regime changes in response to changes in land use and cover was investigated through analysis of remotely sensed images and modelling. A hydrological model for the Eastern wetland that accounts for the water balance was developed. This model was used to evaluate the hydrology of the Eastern wetland in response to changes in land use and cover and the amount of inflows into the Eastern wetland required to maintain a specified outflow downstream of the wetland. A small wetland locally called *Ifushiro* located in the upstream of the Eastern wetland was also investigated to evaluate its contribution to dry season flows. The analysis involved a detailed hydrometric monitoring and modelling using Visual MODFLOW software. The *Ifushiro* wetland was shown to have no contribution to dry season flow, since much of its water was lost through evaporation. The hydrology of the Eastern wetland was shown to be modulated by the changes in land use and cover on the upstream. Since 1958, increasing diversions of water has caused average dry season inflows to the Eastern wetland to decrease from approximately 15.0 m^3s^{-1} to 4.3 m^3s^{-1}. This has led to a reduction in the average minimum dry season surface area of the wetland from approximately 160 km^2 to 93 km^2. Since the early 1990s the decrease in dry season water-levels within the wetland has resulted in prolonged periods of zero flow in the Great Ruaha River, with severe consequences for the ecology of the Ruaha National Park. The wetland model enabled calculation of the inflows required to maintain specified discharges. To maintain a flow of 0.5 m^3s^{-1}, as the minimum required flow for maintenance of fish

habitat and the current ecology of the Park, requires an average dry season inflow of approximately 7.0 m^3s^{-1} into the Eastern wetland in the dry season. The results from this research demonstrate the value of combining different research methods/approaches and the use of simple models to examine system functioning to assist decision-making.

DECLARATION

I Japhet Joel Kashaigili, hereby declare to the Senate of Sokoine University of Agriculture, that this thesis is my own original work and has not been submitted for a higher degree award in any other University.

Signature: --

Date: 22/11/2006

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This thesis is dedicated to:

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and

To my beloved wife Saverina and sons Jovan Kashaija, Kennedy Muchunguzi and Steven Tumsiime for their love and perseverance

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LIST OF ABBREVIATIONS

AET	actual evapotranspiration
amsl	above mean sea level
ARIDA	Assessment of the Regional Impact of Drought in Africa
AVHRR	Advanced Very High Resolution Radiometer
BACAS	Bureau for Agricultural Consultancy and Advisory Services
BBM	Building Block Methodology
CIR	Colour-Infrared Aerial Imagery
DANIDA	Danish International Development Agency
DRIFT	Downstream Response to Imposed Flow Transformations
DRM	Desktop Reserve Model
DWAF	Department of Water Affairs and Forestry
EFA	environmental flows assessment
EFR	environmental flow requirement
EM	electromagnetic
EMC	ecological management class
ERDAS	Earth Resource Data Analysis System
ERS-1	European Remote-Sensing Satellites
ET	evapotranspiration
ETM+	Enhanced Thematic Mapper plus
FAO	Food and Agriculture Organization
FDC	flow duration curve
FORS	Friends of Ruaha Society

GCP	ground control point
GIS	Geographical Information System
GPS	Global Positioning System
GRR	Great Ruaha River
GRRC	Great Ruaha River Catchment
ha	hectare
IFIM	Instream Flow Incremental Methodology
IRS	Indian Remote Sensing Satellites
IUCN	International Union for Conservation of Nature
IWMI	International Water Management Institute
JERS-1	Japanese Earth Resources Satellite
KAKAKUONA	Tanzania Wildlife Magazine
km^2	square kilometre
LIDAR	LIght Detection And Ranging
m^2	square meter
m^3	cubic meter
m^3s^{-1}	cubic meter per second
MAE	mean absolute error
MAR	Mean Annual Runoff
MATI	Ministry of Agriculture Training Institute
mbgl	meter below ground level
ME	mean error
MLC	maximum likelihood classifier

MODFLOW	Modular Three–Dimensional Finite Difference Ground Water Flow
ms^{-1}	meter per second
MSS	Multi-Spectral Scanner
NEMC	National Environment Management Council
NRCS	Natural Resources Conservation Service
PET	potential evapotranspiration
PHABISM	Physical Habitat Simulation System
PVC	polyvinyl chloride
RADASAT	Radar Satellite
RBWO	Rufiji Basin Water Office
RIPARWIN	Raising Irrigation Productivity and Releasing Water for Intersectoral Needs
RMSE	root mean square error
RNP	Ruaha National Park
SFWMD	South Florida Water Management District
SIR-C	Spaceborne Imaging Radar C-band
SMUWC	Sustainable Management of Usangu Wetlands and its Catchment
SPOT	Satellite Pour l'Observation de la Terra
SUA	Sokoine University of Agriculture
SWMRG	Soil-Water Management Research Group
TM	Thematic Mapper
USDA	United State Department of Agriculture

UTM	Universal Transverse Mercator
WCMC	World Conservation Monitoring Centre
WMO	World Meteorological Organization
WWF	World Wildlife Fund

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

It is now widely recognised that the impact of human society on the environment is beginning to threaten the basic foundation upon which humans depend for food, shelter and well-being. Of all the resources that are important to people, perhaps the one under greatest pressure is water (Schofield *et al.,* 2003). Reports by Dinar and Subramarian (1997) and the United Nations (1997) have revealed that water availability is declining in most parts of the world. In contrast, human population is increasing and economic activities such as irrigated agriculture and industrial processes are on the increase reflecting an increased demand for water. While these activities are being carried out, the environment is threatened with an increased water use by such sectors as irrigation which draws about 70% of all the global water (WMO, 1997). Traditionally, the focus has been on providing enough water for human needs, with little attention to the environment, and this has threatened the sustainability of many wetlands worldwide.

Wetlands are valuable ecosystems that depend on the supply of water for their continued functioning. In addition to supporting immense biodiversity, they play an important role in maintaining environmental quality and sustaining livelihoods. In Africa millions of people depend on wetlands for livelihood benefits derived from the ecological functions they perform (Denny, 1991). In Tanzania, wetlands support extensive trading and transport systems, fishing grounds, agro-pastoral activities, hydrological processes, the harnessing of the river flow for irrigation and sustained hydroelectric power generation (Kamukala, 1993). Concerning the hydrological functions, wetlands play an important role in the hydrological cycle. They recharge groundwater, control pollution and provide habitats and breeding grounds for fish and wildlife (Botts, 1982; Nshubemuki, 1993). Moreover, wetlands control floods by storing precipitation and gradually releasing the water over an extended period of time (Kikula *et al.*, 1996). This, therefore, diminishes the possible destructive effects of floods. Also, through this mechanism, water supply to downstream areas is spread over an extended period of the year, hence ensuring continuous water supply to these areas. However, it is important to note that not all wetlands perform all these functions; there is variability in performance in some of the wetlands. For example, when saturated they may increase runoff and hence increase flood flows (McCartney, 1998). Wetlands are also highly suitable for agriculture because of the availability of water and the usually high soil fertility derived from the nutrient rich sediments eroded from upland areas (Kamukala, 1993; Mihayo, 1993). Wetlands have been, and are, the basis of community economic activities. They generate many benefits and spread risks especially during periods of water scarcity by providing a source of arable land and grazing. In this way they contribute to sustaining rural livelihoods and increasing food security. However, wetlands are sensitive ecosystems that are subject to stress as a result of changes in land use, resources extraction, water regulation, drainage and pollution (van den Bergh *et al.*, 2001). Reducing the stress on wetlands requires a spatial matching between physical planning (land use and water management), hydrological and ecological process, and economic processes (van den Bergh *et al.*, 2001).

In the Usangu Plains within the Great Ruaha River catchment (GRRC), the wetlands and the Great Ruaha River (GRR) are under threat due to increased water diversion for irrigation upstream of the wetlands. The problem has been aggravated by development of irrigated agriculture, and increased human immigration into wetland areas (SMUWC (2001 a, b; Kashaigili *et al.*, 2005a). Because of increased water abstractions from rivers in both wet and dry season, the amount of water flowing into the wetlands has continued to decrease with time, leading to serious water shortages in and downstream of the wetlands. This is reported to be a common problem, particularly during dry seasons when people experience water shortages for domestic use and animal drinking, less pasture for animals, less area for fish breeding and growth and less area suitable for wildlife. Tourism in the Ruaha National Park (RNP), located downstream of the Usangu wetlands, also suffers as the GRR dries up (Kashaigili *et al.*, 2005a, b; Kadigi *et al.*, 2004; SMUWC, 2001a).

The main challenge in the Usangu Plains, like in many other parts of the world, is how to ensure supply of water into the wetlands to maintain their functioning and ensure year-round outflows downstream to the Great Ruaha River given the present competing water demands among sectors. This is important, since every aquatic ecosystem requires a certain amount of water to maintain its ecological integrity. But some of the most challenging questions are how much water is required to sustain specific levels of environmental benefits, how to balance the various sectoral water demands, and how much water resource is available. These questions are the subject of the ongoing debate and research on how to achieve sustainable allocation of water resources in the world. In this case knowledge of wetlands hydrology and quantification of water inputs and outputs are necessary prerequisites to understanding wetland environment and determining their vulnerability to changes.

1.2 Definition and classification of wetlands

According to Maltby (1986) a wetland is "a collective term for ecosystems whose formation has been dominated by water and whose processes and characteristics are largely controlled by water". Cowardin *et al.* (1979) defined wetlands as "lands of transition between terrestrial and aquatic systems where the water table is usually at or near the surface of the land or the land is covered by shallow water". Smith (1980) described wetlands as "a halfway world between terrestrial and aquatic ecosystems and exhibit some of the characteristics of each". It is important to note that there are many definitions of wetlands found in literature, most of which were formulated out of perceptions. In that context, difficulties have been encountered in deciding the definition to be used. Krause (1999) associated the difficulties with their great variety, size, location, hydrologic conditions, vegetation, soil, and function. Furthermore, Krause (1999) argued that the situation is complicated by the use of common wetland terms, which lack standardization and can vary in definition both regionally and internationally. Mitsch and Gosselink (1993) associated the difficulties in defining wetlands with their highly dynamic character and the boundaries, while Palela (2000) linked it with the geographical extent, and the wide variety of hydrologic conditions in which they are found. Mitsch and Gasselink (1993) adding to their earlier assertions argued that the definition difficulties usually arise on the edges of wetlands, toward either wetter or drier conditions and emphasized that the frequency of flooding is the variable that has made the definition of wetlands particularly controversial. According to Mitsch and Gasselink (1993), the common distinguishing characteristics of wetlands include: presence of water, unique soil conditions that differ from adjacent uplands, and presence of vegetation adapted to the wet conditions (hydrophytes).

The Ramsar Convention (1971) in Article 1, defines wetland as "areas of marsh, fen, peat land or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salty, including areas of marine water the depth of which at low tide does not exceed six meters". With the exception of the Ramsar definition, the remaining definitions that have been cited above, tend to either stress on the importance of water in wetlands and pay little attention to other aspects of wetlands (Maltby, 1986), or are highly generalised, assuming that all wetlands possess the same characteristics. The Ramsar Convention (1971) definition has been able to describe and capture the diversity and variety of wetlands. It tends to include characteristics that distinguish one wetland type from the other, indicating the differences in terms of character and origin and it is widely accepted.

Nevertheless, there is no universally agreed classification of wetland types (Schuijt, 2002). This is because there is a continuum between wet and dry environments and most classification systems impose an "artificial" hierarchy. In most cases, wetlands have been classified based on their sources of water and nutrients, according to their hydrological regime, soil type and vegetation structure (Schuijt, 2002). According to

Roggeri (1995) wetlands are characterized according to geomorphological units (the main sources of water and nutrients) and ecological units, in particular vegetation. According to the Ramsar Classification of Wetland (Kabii, 1998), it divides wetlands into three main categories, which are marine/coastal wetlands, inland wetlands and man-made wetlands.

The marine and coastal wetlands include estuaries, inter-tidal marshes, brackish, saline and freshwater lagoons, mangrove swamps, as well as coral reefs and rocky marine shores such as sea cliffs. Inland wetlands refer to such areas as lakes, rivers, streams and creeks, waterfalls, marshes, peat lands and flooded meadows. Man-made wetlands include canals, paddy fields, aquaculture ponds, water storage areas and even wastewater treatment areas. The three classifications of wetlands presented in the previous paragraphs show the immense diversity of wetlands. At the same time, wetlands contain an enormous diversity of functions. The combination of this diversity in wetlands and within wetlands makes them valuable ecosystems (Schuijt, 2002).

1.3 Distribution of wetlands

Wetlands are ecosystems that occupy about 6% of the world's land surface (Williams, 1990; Schuijt, 2002). The percentage of wetland area in Africa is approximately 1% to 16% (WCMC, 1992) of the total area of the continent (Koohafkan *et al.*, 1998). Other estimates exist (Table 1), ranging from 220 000 km^2 to 1 250 000 km^2 (Bullock *et al.*, 1995). These wetlands vary in type from saline coastal lagoons in West Africa to fresh and brackish water lakes in East Africa.

Table 1.1: Different estimates of total wetland extent in Africa

Source	Estimated wetland area km^2
Balek, 1989	340 000
Denny, 1991	> 345 000
Drijver and Marchand (University of Leiden), 1985	600 000 – 700 000
Andriesse *et al.*, 1994	220 000 – 520 000
FAO (based on Soil Map of the World), 1992	1 250 000

Source: Bullock *et al,* (1995) cited in Noor, 1996 - modified

In Tanzania, it is estimated that wetlands cover almost 10% of the country's surface area (NEMC/WWF/IUCN, 1990). Natural freshwater wetlands cover approximately 79,450 km^2 (i.e., 7% of the total land area) of the country of which about 27,000 km^2 (i.e., 3% of the total land area) are permanent and seasonal freshwater swamps, marshes and seasonal floodplains (Bakobi, 1993). Also there are coastal mangrove systems with inter-tidal mudflats and a number of artificial impoundments constructed for hydropower production and irrigation (Kamukala, 1993).

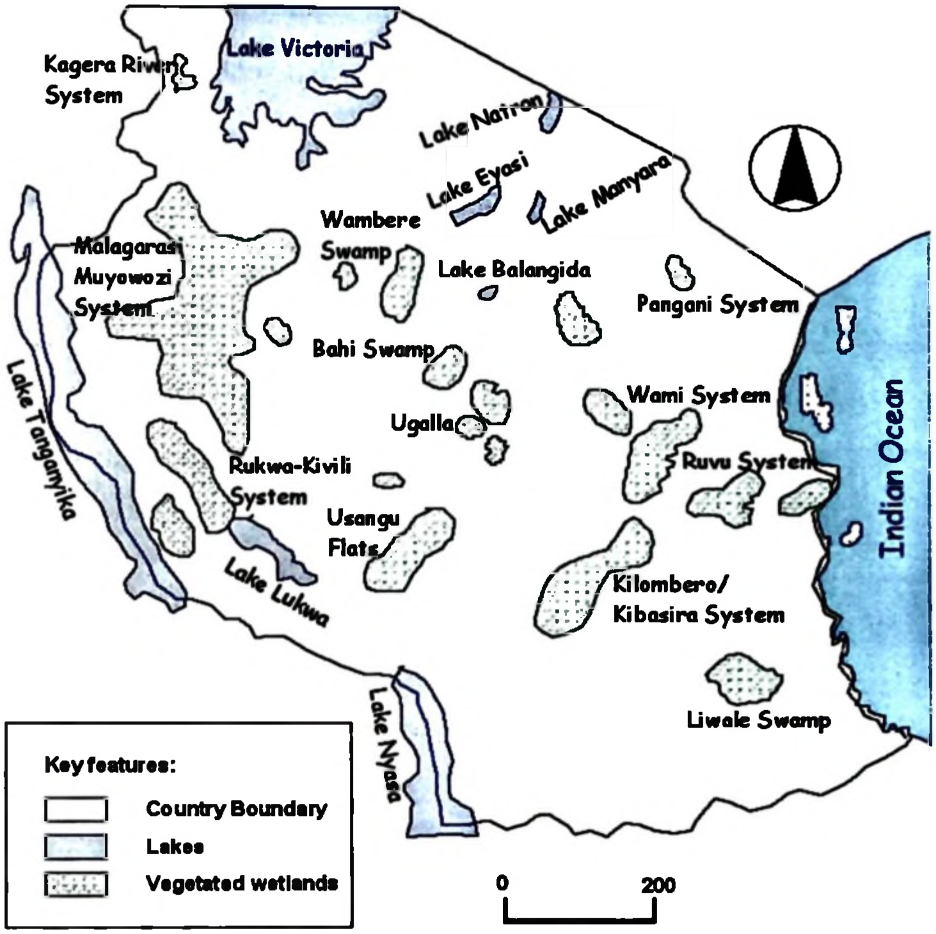


Figure 1.1: Major wetlands of Tanzania

Source: Modified from Kamukala and Crafter (1993)

The Usangu wetlands cover an area of about 1800 km^2 containing a mix of seasonally flooded open grassland (*mbuga*), seasonally flooded woodland, and a perennially flooded swamp (*Ihefu*) also referred to as the Utengule swamp (SMUWC, 2001a).

1.4 Functions of wetlands

The recognition of wetland functions has historically revolved around environmental issues such as bio-diversity and wildlife habitat (Krause, 1999). Wetlands provide several useful functions for enhancing and maintaining the environment. Detailed account of the different wetland functions can be found in (Carter, 1986; de Laney, 1995; Hughes and Heathwaite, 1995; Acreman, 2000) and are summarized in Table 1.2.

Table 1.2: General wetland functions[1]

Physical and hydrologic functions
Disperse, desynchronize, and/or store flood flows Trap and deposit sediments Reduce erosion by stabilizing river banks and shorelines Provide sinks for urban runoff Recharge aquifers
Biological and biochemical functions
Wildlife habitat Nutrient source and sink (assimilation), and transformation Primary production (i.e. biomass) Assimilation and immobilization of contaminates
Economic functions
Directly harvestable products: hay, peat, forestry, fish Indirect enhancements of water quality and quantity
Societal functions
Aesthetics Educational resource Recreation, research, and cultural values.

Source: Carter, 1986; Hughes and Heathwaite, 1995; de Laney, 1995

As natural ecosystems, wetlands are essential part of the ecology, and like any other resource they posses social and economic benefits in human life, whether directly or

[1] Note that not all wetlands perform all these functions

indirectly (de Voogt *et al*., 2000; KAKAKUONA, 2001). In developing countries there is still a direct dependence on wetlands for maintenance of traditional subsistence activities. For example, in the Usangu Plains, wetlands are used for farming, fishing, hunting, bee keeping, wildlife, thatch materials collection, fuel, timber, medicinal plants collection and livestock herding. In this case, the Usangu wetlands make an important contribution to the livelihoods of rural poor communities. Apart from using the wetlands directly, people also benefit indirectly from wetland functions or services. For instance, as floodwater flows out over a floodplain wetland, the water is temporarily stored; this reduces the peak river level and delays the time of the peak, which is a benefit to riparian dwellers downstream (Acreman, 2000).

Nevertheless, wetland processes are controlled by hydrologic conditions (i.e. water regimes) and any alterations on these may lead to changes on the wetland structure and productivity (Carter, 1999). There are regional and local issues affecting water regimes of wetlands. Regional issues include river regulation; diversion and abstraction (Davis *et al.*, 2001) including excessive inundation and aquifer draw down, while local impacts include hydrological alterations associated with urban and agricultural development. According to Howard (1992), the major threats to wetlands in Africa include competition for resources, especially water, conversion of wetlands for agricultural and urban purposes.

1.5 Problem statement and justification of the study

Sustainable management and allocation of water resources among competing demands and between sectors requires comprehensive understanding of different water requirements among the different sectors. However, a decision on environmental water provision requires a comprehensive analysis on the ecosystem dynamics and spatial hydrological response under varying water conditions. This is vital for environmental water safeguard, which, advocates environmental water provision and is one of the important issues in the debate of integrated water resources management (IWRM) in river basins. But, such information is not readily available. Therefore, a gap in knowledge still exists on how to evaluate water requirements among different sectors (i.e., wetlands, rivers). This is experienced more in developing countries, for basins or catchment characterised with high competing water demands like the Great Ruaha River catchment. Numerous stakeholders of wetlands with different interests lay claims on the wetlands functions that do not always coincide. In this conflict of interest, those stakeholders that have a stake in the conversion of the wetlands have mostly overshadowed those stakeholders that are dependent on the protection of the wetland functions. This can be attributed mainly to information failures regarding both spatial relationships and the consequences of land use, water management, pollution and infrastructure.

The Usangu wetlands pose a complex set of environmental pressures and associated management problems. There are important gaps in the understanding of the hydrology of the wetlands and the consequences of changes in land uses/covers that have taken place over time. Understanding these is vital for improving water resource management in the catchment. Hence, an understanding of the wetland's hydrological functioning is essential for assessing its vulnerability to changes (Kashaigili *et al.*, 2005 b). Therefore sustained wetland functioning requires proper land use and water management. To achieve this, an integrated understanding of the spatial dynamics and hydrological balance of the wetland ecosystem among other factors is required.

Various studies have been conducted in the Great Ruaha River catchment. Most of these were centred on general assessment of water resources and utilization characteristics (e.g., water supply dynamics and causes of shortages, upstream/downstream competition for water and conflicts in the Great Ruaha River catchment (SMUWC, 2001a; Baur *et al.*, 2000; and Kikula *et al.*, 1996). Much is also known about the typologies of farming systems, livestock, land, water, fisheries, game, and forestry resources (SMUWC, 2001a). There is also a considerable knowledge on hydrological descriptions and modelling, water quality, and some environmental aspects, irrigation water use efficiency, management and development (Faraji and Masenza, 1992; UVIP, 1993; DANIDA/World Bank, 1995; Mwakalila, 1996; Mbonile *et al.*, 1997; DFID, 1998; Maganga and Juma, 2000; Lankford, 2001; SMUWC, 2001a; Yawson, 2003; and Machibya, 2003). Generally, these studies acknowledge the complexities and problems associated with irrigated agriculture and the potential that irrigation has in improving the livelihoods of people. Nevertheless, the studies do not inform much about means and mechanisms of ensuring water for the environment (i.e. the Usangu wetlands and GRR). Gaps still exist in knowledge, particularly on the impact of human modification of the hydrological regime of the

Usangu wetlands and on the magnitude of inflows required to maintain downstream flows through the Ruaha National Park.

Worldwide, there is a great effort to restore lost or degraded hydrological and biological functions of wetlands (KAKAKUONA, 2001). Likewise for the Usangu Plains wetlands, there is a need for ensuring the ecosystem functioning. Concerns about the Usangu wetland emanates from the fact that these wetlands perform various roles including supporting life and economic well being of people (over 700 000) living in and out of the Usangu Plains. It is also from the fact that *Ihefu* is an important breeding site for a number of wetland bird species (SMUWC, 2001a) and that it contains some of the highest concentrations of waterfowl in Tanzania. In addition, the Usangu wetlands, in particular the Eastern wetland acts as a regulator for downstream flows. Therefore, changes occurring inside the wetland have an impact on the downstream flows.

The changes are most arguably resulting from the growing competition over water resources like in the GRR catchment where there is serious competition between irrigated agriculture in the upper part of the catchment (in the Usangu Plains) and other water uses downstream, including the wetland, Ruaha National Park and the reservoir at Mtera (Figure 1.2).

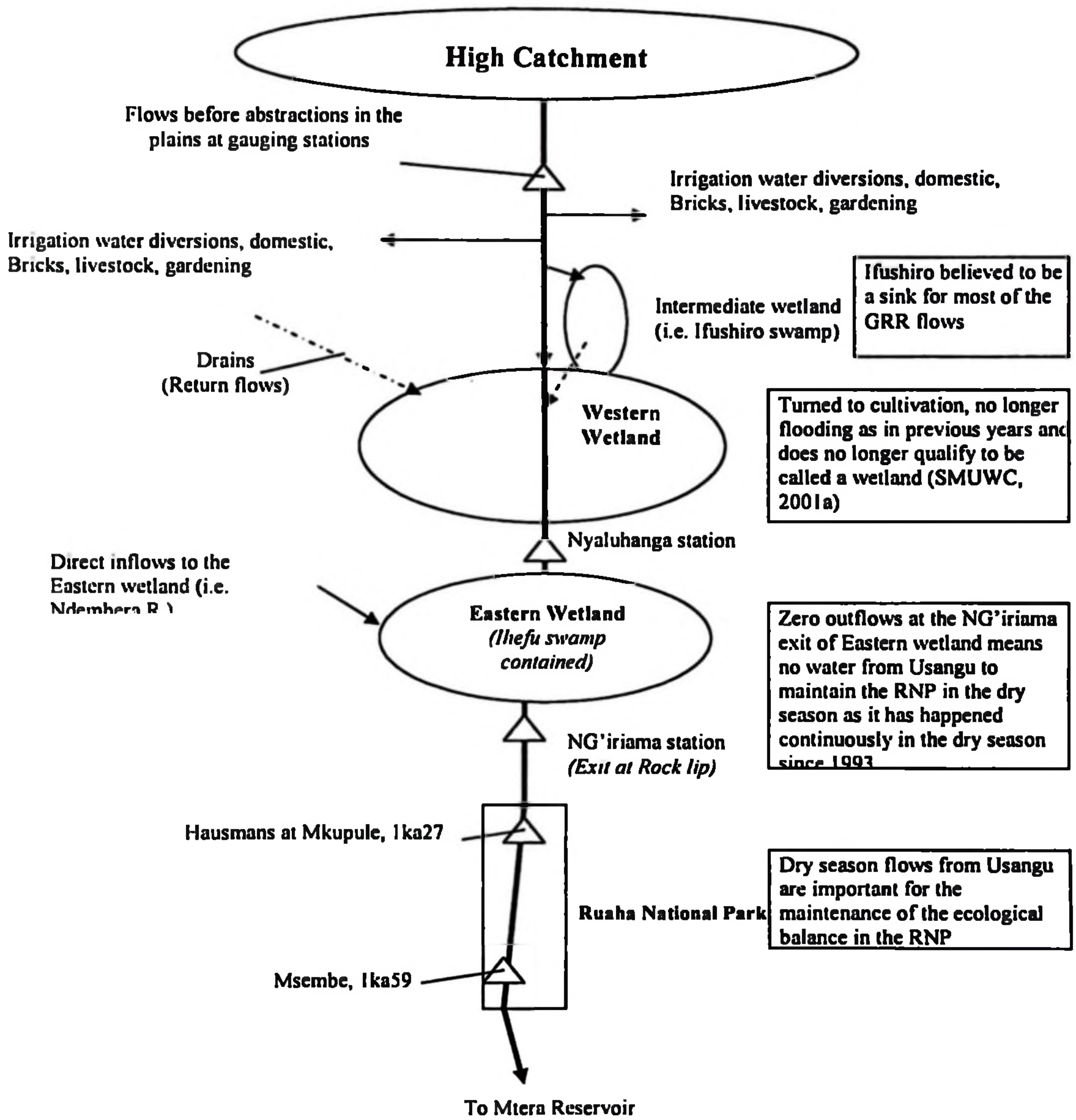


Figure 1.2: A schematic presentation of competing water uses in the study area

The GRR prior to 1994 was perennial (Plate 1) though dried up sometime in 1947, 1954 and 1977 and possibly in other years as well, but not repeatedly as it has been experienced from 1993 (SMUWC, 2001a; Kashaigili *et al.*, 2005a). The drying up of the Great Ruaha River which is associated with an increased competition for water has resulted in social conflicts between upstream and downstream users. The cessation of river flows (Plate 2) has led to adverse impacts on the fragile ecosystem of the Ruaha National Park. It has caused significant mortality of fish and hippopotami. It has also disrupted the lives of many animals that depend on the river as a source of drinking water (Plate 3), causing changes in their behaviour and leading to outbreaks of disease such as Anthrax (Kashaigili *et al.*, 2005b).

Photos by Sue Stolberger

Plate 1: The Great Ruaha River......Once upon a Time Ago

Plate 2: Situation of the Great Ruaha River through the Ruaha National Park in the dry season (2003)

Plate 3: Elephants digging for water in the dry riverbed of the Great Ruaha River (2003)

1.6 Objectives of the study

The main objective of the study was to improve the understanding of the hydrology of the Usangu wetlands and the hydrological implications of increased irrigation abstractions and land-use/cover changes in the catchment. This was to be achieved through the following specific objectives:

(i) To investigate changes in land use/ cover and the area of the Eastern wetland over time using satellite images,

(ii) To quantify changes in the flow regime downstream of the Eastern wetland in relation to changes in land-use and cover,

(iii) To investigate the dry season flow contribution from the Ifushiro wetlands through analysis of interactions between groundwater and wetland surface water,

(iv) To develop a wetland hydrological model to determine water fluxes and the water budget of the Eastern wetland, and

(v) To apply the model to evaluate flows into the wetland required to maintain target environmental flows downstream of the wetland in the dry season.

1.7 Research questions

The study attempted to answer the following research questions:

(i) What land use and cover changes have taken place in the Usangu wetlands and neighbouring areas for the period pre-1974, between 1974 and 1986, and post-1986?

(ii) What are the impacts of land use and cover changes on the hydrology of the Usangu wetlands?

(iii) What changes in flow regimes have occurred downstream of the Usangu wetlands as a result of changes in land use and cover?

(iv) How much water is contributed by intermediate wetlands to flows in the Great Ruaha River in the dry season?

(v) How much water is required as an environmental flow to wetlands and the Great Ruaha River in the dry season?

1.8 The conceptual framework of the study

The conceptual framework of this study is illustrated in Figure 1.3. In this context, the process of wetlands changes is explained by the dynamics of the land use and cover changes within and around the Usangu wetlands. The factors or forces responsible for the dynamics of wetlands can be grouped into two parts, namely the *socio-economic factors* and the *environmental factors*. Socio-economic factors include the institutional level and policies at both national and international level involved in natural resources management, laws and traditions such as rural livelihood systems, environmental protection laws, commercialisation of agricultural and wetlands products, land use and tenure systems, population pressure and poverty.

Environmental factors comprise two main categories namely the *biophysical factors* and *natural disasters*. Biophysical forces involve among others, site productivity factors (e.g. soil fertility, rainfall availability, water table, drainage, etc), relief and hydrology (i.e., hills, escarpments, river network, valleys, etc.), wildlife population (e.g., elephants) and species diversity (e.g., dominance of non-dominance of certain species). Natural disasters include unpredictable events that may have negative impacts on wetlands such as drought, fires, earthquake, and flooding.

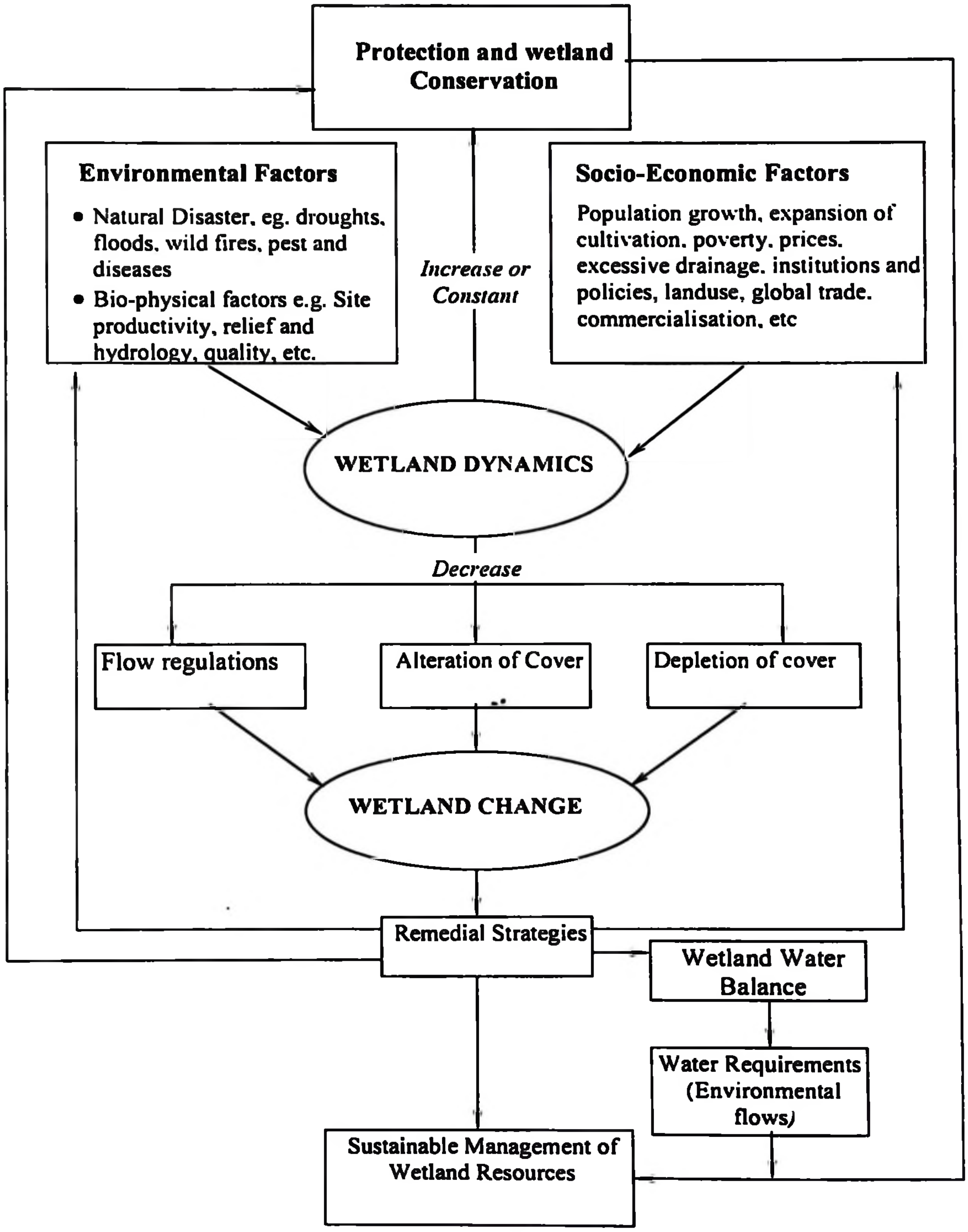


Figure 1.3: Conceptual framework of the study

These socio-economic and environmental factors present varying impacts on wetlands resources. The socio-economic factors/forces contribute to decrease of the wetlands resources through utilization or abstractions leading to decreased inflows that used to maintain wetlands. These could be in the form of water diversion for agriculture or cultivation in wetlands that affect the wetlands resources. Figure 1.4 demonstrates a problem tree highlighting a number of factors that impart stresses to the wetlands. The decrease in wetlands resources occurs in three forms mainly flow regulations into wetland, alteration and depletion of the wetlands cover. The alteration of the wetlands cover affects the wetlands structure and species composition. This leads progressively to wetlands loss and or degradation and if excessive, it ultimately ends to an irreversible wetland change. Wetlands depletion refers to the complete removal of the wetland cover through clearance for farming, for instance agriculture and animal husbandry, and settlements.

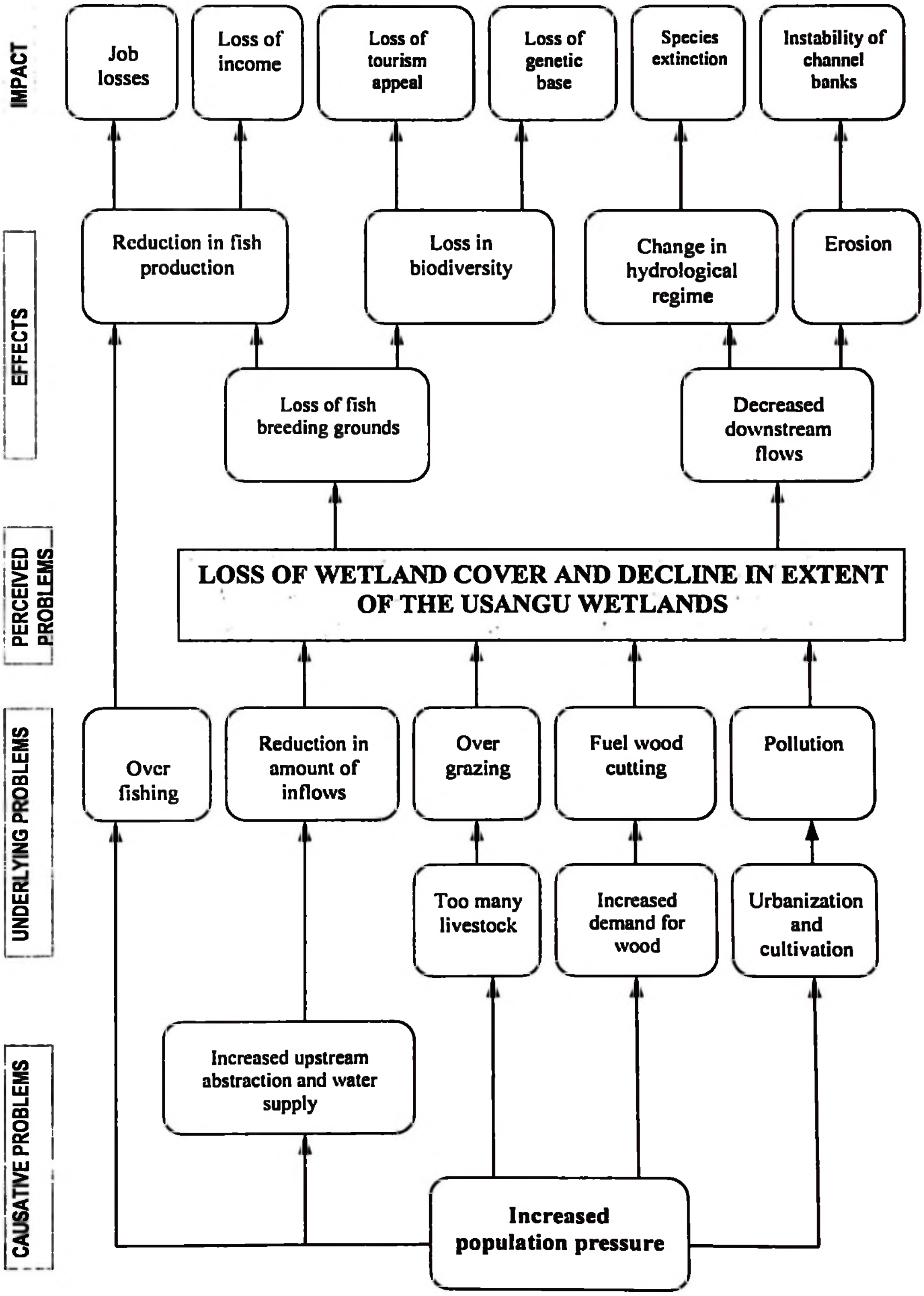


Figure 1.4: Problem tree analysis of wetlands degradation in the Usangu Plains

A sound wetland environmental management plan would require that the cause of the wetlands change as a result of alteration and depletion are well investigated and located. These would give an insight on the dynamics of the wetlands through a cause effect relationship which could inform appropriate remedial strategies in order to ensure sustainable management of the wetlands resources.

For effectiveness, remedial strategies should account for the water balance to understand the wetland response under varied flows conditions in order to estimate the water requirements (environmental flows) that could sustain the wetlands and other downstream demands. However, meeting water requirements would require balancing (proportioning) the available water resources among the competing demands. Also there is need to account for primary driving forces behind wetlands dynamics namely socio-economic, biophysical forces and natural disasters. This could be possible through proper and effective management and policy change aiming at sustainable use of the wetland resources.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Wetlands

2.1.1 Hydrology of wetlands

Wetlands create unique physiochemical conditions that make such an ecosystem different from both well-drained terrestrial systems and deepwater aquatic systems (Mitsch and Gosselink, 1993). Hydrologic conditions are very important in determining the structure and function of wetland ecosystems (Mitsch and Gosselink, 1993; Mihayo, 1993). Hydrologic pathways such as precipitation, surface runoff, groundwater, tides, and flooding rivers transport energy and nutrients to and from wetlands. Water depth, flow patterns, and duration and frequency of flooding, which are a result of all of the hydrologic inputs and outputs, influence the biochemistry of the soils and are major factors in the ultimate selection of the biota of wetlands (Mitsch and Gosselink, 1993). Gosselink and Turner (1978) indicated that water inputs are almost always the major source of nutrients to wetlands; water outflows often remove biotic and abiotic material from wetlands as well. These modifications of the physiochemical environment, in turn, have a direct impact on the biotic response in the wetland. When hydrologic conditions in wetlands change even slightly, the biota may respond with massive changes in species richness and ecosystem productivity (Mitsch and Gosselink, 1993). An important point about wetlands (Mitsch and Gosselink, 1993) is that their hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes.

2.1.2 Wetland soils

Wetland soils develop under anaerobic conditions (limited oxygen) and exhibit unique morphological and chemical properties that result from the presence of water for extended periods of time (Pataki and Cahill, 1997). Wetland soils are characterized by periodic inundation or saturation with water that leads to anaerobic conditions, reduction of Iron (Fe), Manganese (Mn) and other chemical elements and alteration of biogeochemical cycles. Wetland soils occupy the dynamic interface between terrestrial and aquatic ecosystems and, so, are uniquely positioned to intercept and transform pollutants from terrestrial landscapes. The physical properties of these soils are very important in determining the hydrological response within any catchment (McCartney, 1998) and in particular the wetlands. Schulze (1995, cited in McCartney, 1998) identified that it is the capacity of the soil to absorb, retain and redistribute water that is the prime control on the generation of storm flow, baseflow and peak discharge. A small difference in soil characteristics may have a pronounced effect on hydrological conditions and this is a typical character in areas dominated with clay soils

2.1.3 Wetlands vegetation

The hydrology of a wetland is largely responsible for the vegetation of the wetland, which in turn affects the value of the wetland to animals and people (Carter, 1999). Therefore, wetland vegetation types are generally adapted to particular water regimes; either too much or too little water can adversely affect all types of wetland vegetation. For example, a reduction in the level and duration of water may allow wetland vegetation to be invaded by upland or non-native species, changing vegetation composition and function. The duration and seasonality of flooding and (or) soil saturation, ground-water level, soil type, and drainage characteristics exert a strong influence on the number, type, and distribution of plants and plant communities in wetlands. Golet and Lowry (1987) showed that surface flooding and duration of saturation within the root zone, while not the only factors influencing plant growth, accounted for as much as 50 percent of the variation in growth of some plants.

Wetland vegetation influences the hydrology of a catchment by affecting both water storage and patterns of water movement. They influence hydrologic conditions by binding sediments to reduce erosion, by trapping sediment, by interrupting water flows and by building peat deposits (Gosselink, 1984). McCartney (1998) argued that storage in wetland is affected as a consequence of interception loss and transpiration. Furthermore McCartney (1998) added that movement patterns are affected by floristic modification of soil characteristics (in particular texture and organic matter content) and, where overland flow occurs, through resistance to flow caused by the presence of plant stems.

2.2 Hydrologic budget of wetlands

Understanding wetland hydrology requires balancing various components of the wetlands ecosystems processes. It is apparently realized that, to develop a water balance model, the components of water balance that include evapotranspiration, precipitation, surface runoff, infiltration and groundwater have to be determined. A wetland water budget tracks inflows; outflows and change in storage and can indicate the dominant hydrological processes and wetland type (Walton *et al.,* 1996).

2.2.1 Wetland hydro-period

The hydro-period (Figure 2.1) is the annual depth-duration curve that defines the rise and fall of the wetlands' surface and subsurface water. The hydro-period provides information about flooding depth, duration, and frequency that characterize the annual patterns of the wetlands and unique to each type of wetland (Mitsch and Gosselink 1993; Walton *et al.,* 1995). Mitsch and Gosselink (1993) called the hydro-period the "hydrologic signature of a wetland" because of its importance in controlling both the existence and composition of wetland plant communities. This control is exerted by eliminating species intolerant to extended inundation and indirectly by controlling the influence of fires.

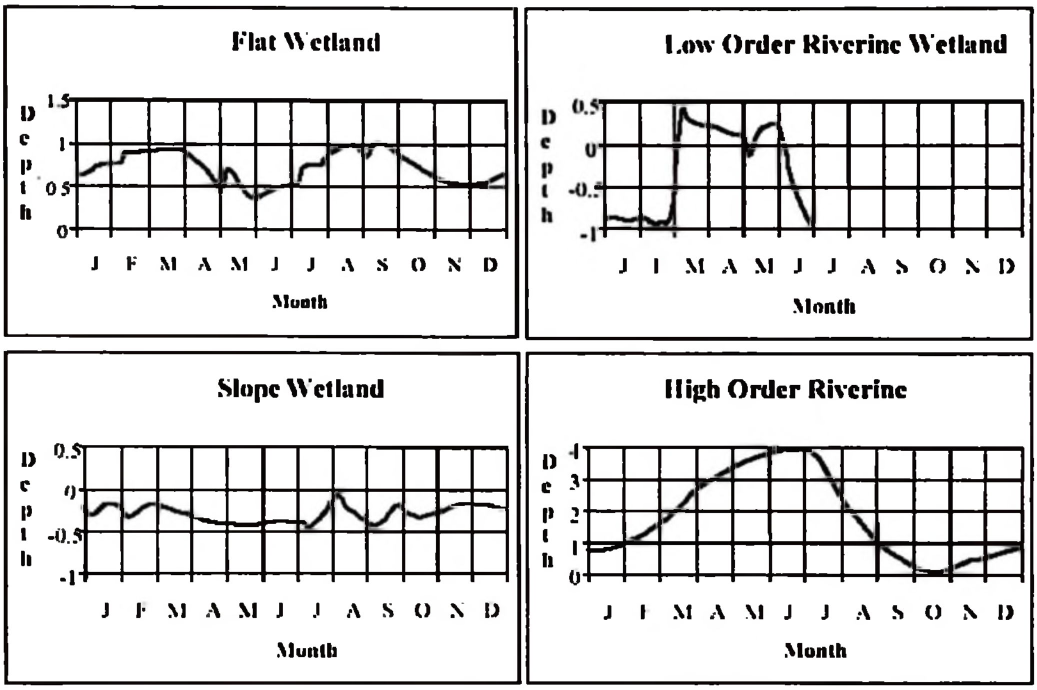


Figure 2.1: Examples of wetland hydro-period

Source: Mitsch and Gosselink (1993)

A relatively consistent hydro-period ensures stability of the wetland. Wetlands however are highly dynamic systems that interact with the ecosystem and change over time, making hydrologic conditions of these landforms difficult (Krause, 1999). Ecosystem considerations are important in wetland hydrology because a two-way relationship exists between the stability of wetland vegetation and hydrological stability (Heathwaite, 1995). The biotic components of wetlands (mainly vegetation) can control their water conditions through a variety of mechanisms, including interruption of water flow, peat building, sediment trapping, nutrient retention, water shading, and transpiration. Accumulation of sediments or organic peat can eventually decrease the frequency of flooding. For example, bogs can build peat to a point at which they are no longer influenced by the surface inflows (Mitsch and Gosselink, 1993).

2.2.2 General wetlands water balance equation

Mitsch and Gosselink (1993) summarized the hydro-period, or hydrologic state of a given wetland as being a result of the following factors: a) the balance between the inflows and outflows of water, b) surface contours of the landscape, and c) subsurface soil, geology, and groundwater conditions. The general balance between water storage and inflows and outflows (Mitsch and Gosselink, 1993) is expressed as:

$$\Delta V = P_n + S_i + G_i - ET - S_o - G_o \pm T \qquad [2.1]$$

Where, V is the volume of water storage in wetlands

ΔV is the change in volume of water storage in wetland

P_n is the net precipitation (excluding interception)

S_i is the surface freshwater inflows, including flooding streams (runoff)

G_i is the groundwater discharge to the wetland (inflows)

ET is the evapotranspiration from wetland

S_o is the surface water outflow

G_o is the groundwater recharge from the wetland (outflows)

T is the tidal inflow (+) or outflow (-)

The change in water depth can further be described as:

$$\Delta L = \frac{\Delta V}{A(L)} \qquad [2.2]$$

Where, L is the water level, including effective groundwater level;

ΔL is the change in water level; and

A(L) is the wetland area as a function of water level.

Water balance studies form the basis for understanding processes relating to soil water and soil chemistry, and nutrient, salt and energy balances that are dependent on water budgets (Harvey *et al.*, 1987; Harvey *et al.*, 1995; Harvey and Nuttle, 1995; Morris, 1995). To develop any water balance model, there is need to obtain data for or estimate the components of the water balance. These include precipitation, inflow, outflow and evaporation.

(i) Precipitation in wetlands

Precipitation is an important parameter in understanding the wetland water balance. Singh (1989a) presented a number of approaches that could be used in estimation of areal rainfall. However, rainfall over an area is highly varied and varies within year and from year to year. Raes (1996) recommended the use of statistical analysis for a long-term time series of rainfall data. Furthermore (Raes, 1996) argued that the analysis of long-term historical rainfall data forms the basis of most scientific understanding. Such studies assist in depicting trends, seasonality and periodicity within data. For example, SMUWC (2001b) performed trend analysis to determine if there were any long-term trends in annual rainfall in the Usangu area using annual flows of the Great Ruaha River. They concluded that there was a downward trend on dry season flows. Technological changes have led to new methods of analysing rainfall. Ngana (1994) used spectral analysis to determine if there were multiple cycles (any trends) in the annual rainfall in the Pugu and Kazimzumbwi coastal forests in Tanzania. The study revealed that cycles of 20 and 5 years were largely significant.

(ii) Evapotranspiration in wetlands

The significance of evapotranspiration (ET) in wetlands depends on climate. The more arid the climate, the more extreme this effect becomes (Hughes, 1998). Common methods of estimating potential evapotranspiration (PET) include empirical equations such as the Penman open water evaporation equation (de Leeuw *et al.*, 1991; Tyler, 1997), the Penman-Monteith potential evapotranspiration equation (Souch *et al.*, 1996 and 1998), Priestly-Taylor equation (Harvey *et al.*, 1995; Nuttle and Harvey 1995) or the Thornthwaite equation (Mitsch and Gosselink, 1993). Others include estimation using indirect methods based on water losses, such as atmometers, evaporation pans and lysimeters. Ward and Robinson (2000) recommended lysimeters as being the most desirable given the inaccuracies in the first two devices. However, lysimeters are very costly making them not widely used. The use of pan evaporation measurements in wetlands studies requires applying 'appropriate' pan and crop factors (Hughes, 1998). This is because the pan factors are highly variable and need calibrations. Furthermore they are highly sensitive to local environmental conditions (Smith, 1991). Though that has been revealed, most researches have concentrated on commercial crops and dry-land vegetation types and very little work has been done on crop factors for wetland vegetation (Hughes, 1998). Researches on aquatic plants so far suggest that standing water evapotranspiration may exceed open water evaporation. For example, a study by Acreman *et al.*, (2003) showed that because of high wetness and often dense vegetation, evapotranspiration from wetlands was higher than, for example agricultural land. The indication could be that the pan or crop factor is greater than 1 (Hughes, 1998). Boyd (1987) (cited in Hughes, 1998:2-15) found crop factors ranging from 1.17 to 1.58 for a range of aquatic plant species and reported values from the literature of up to 2.5 for *Typha latifolia*. Also crop factor is seasonally variable during the year in many locations, due to changes in the growth rates of wetland plants (Hughes, 1998). The South Florida Water Management Model (SFWMM) (SFWMD, 1997) has used monthly crop or vegetation coefficients for a wide range of wetland vegetation types to estimate actual evapotranspiration (AET) from ET calculated using the Penman-Monteith equation. For mangroves, the SFWMM seasonal crop coefficient varied from 0.69 to 1.0. Kite and Droogers (2000) compared eight different methods of estimating actual evaporation and transpiration using a common database. At the end of their study they concluded that, there was no ideal method, all had their advantages and disadvantages. However, Gerla (1992) and Rushton (1996), cited by Hughes (1998) reported that the observations of diurnal groundwater fluctuations could be used to estimate evapotranspiration and such methods have been used with some success in freshwater wetlands.

(iii) Surface runoff – inflows and outflows

Another component of the wetland water balance is the surface runoff. Surface runoff from a drainage basin into a wetland is difficult to estimate without a great deal of data (Mitsch and Gosselink, 1993). The direct runoff component of stream flow refers to rainfall during a storm that causes an immediate increase in stream flow. In other words, surface inflows into wetlands comprise a system of rivers that empty their water into wetlands. The inflow estimates are best obtained from point discharge measurements closest to the wetlands periphery as these give the net balance from the catchment upstream. In such cases, stage measurements are converted into discharge readings using a rating curve. However, for some wetlands formed within relatively flat surfaces of the floodplains, monitoring of the outflows is very difficult in the wet season as the water become spread over the wetlands and the neighbouring environment with no defined outlet channel.

(iv) Groundwater flows

Groundwater is one of the most important components of wetland hydrology, both for quantitative and qualitative purposes, but probably is also one of the most difficult to quantify (Carter, 1986; LaBaugh, 1986). Groundwater can be the dominant component of the water budget of a wetland (Cey *et al.*, 1998; Winter, 1999; Bendjoudi *et al.*, 2002) or only a small portion of it (Mitsch and Gosselink, 1993; Gilman, 1994) but, whatever its quantitative contribution, groundwater input is often important for the physical and chemical quality of wetlands (Devito and Dillon, 1993; Hayashi and Rosenberry, 2002). Although groundwater behaviour is considered to be less variable than that of the hydrological systems (Hunt *et al.*, 1997), it may be difficult to collect all the data necessary for the calculation of groundwater inflow to and outflow from wetlands (Weng *et al.*, 2003). Combining field studies and hydrological modelling generally helps to test the hypothesis about the functioning of a wetland as well as quantifying the importance of groundwater in the ecosystem (Hunt *et al.*, 1996; Morrison *et al.*, 1999; Gasca-Tucker and Acreman, 2000). One of the field studies is the use of nested wells and piezometers to measure the groundwater inflows and outflows. Hughes (1998) used piezometers to determine the groundwater flows by measuring the water levels. SMUWC (2001b) documents the use of lysimeters in determining deep percolation. However, this is not an easy process and requires a lot of resources.

The flow of groundwater into, through, and out of a wetland normally is described by Darcy's law (Freeze and Cherry, 1979). Darcy's Law describes groundwater flow through a porous medium as having a linear relationship with the hydraulic head gradient:

$$Q = -K\frac{dh}{dl}A \qquad [2.3]$$

Where, Q is the volumetric flow rate (L^3T^{-1}) across a cross section of area A (L^2),

K is the hydraulic conductivity of the soil (LT^{-1}),

dh/dl is the hydraulic gradient perpendicular to the cross section,

dh is the change in hydraulic head (L) over a distance dl (L),

Darcy's law can be applied to both saturated and unsaturated flow as long as the decrease in K with decreasing soil moisture content (relative permeability) can be defined (Freeze and Cherry, 1979). Despite the importance of groundwater flows in the budgets of many wetlands, there is poor understanding of groundwater hydraulics in wetlands (Mitsch and Gosselink, 1986) particularly in those with organic soils. The general form of the governing partial-differential equation describing groundwater flow under time varying conditions in a heterogeneous and anisotropic aquifer (McDonald and Harbaugh, 1988) is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad [2.4]$$

where, K_{xx}, K_{yy}, and K_{zz} are the values of hydraulic conductivity along x, y and z coordinate axes assumed to be parallel to the major axes of hydraulic conductivity [L/T];

h is the potentiometric head [L]

W is the volumetric flux per unit volume representing sources and /or sinks of water, with W<0.0 for flow out of the groundwater system, and W>0.0 for flow in [T^{-1}]

Ss is the specific storage of the porous material [L^{-1}]; and

T is time [T]

Most groundwater studies apply Equation 2.4, sometimes incorporating a few modifications to model the groundwater flow and interactions between surface water and groundwater. Mitsch and Gosselink (1986) discussed the possibilities of interactions that groundwater inflows result when the surface water (or groundwater) level of a wetland is lower than the water table of the surrounding land, and that when the water level in a wetland is higher than the water table of its surroundings, groundwater will flow out of the wetland. Several situations (Mitsch and Gosselink, 1986) in which wetlands and surrounding groundwater are hydrologically connected are shown in the Figure 2.3:

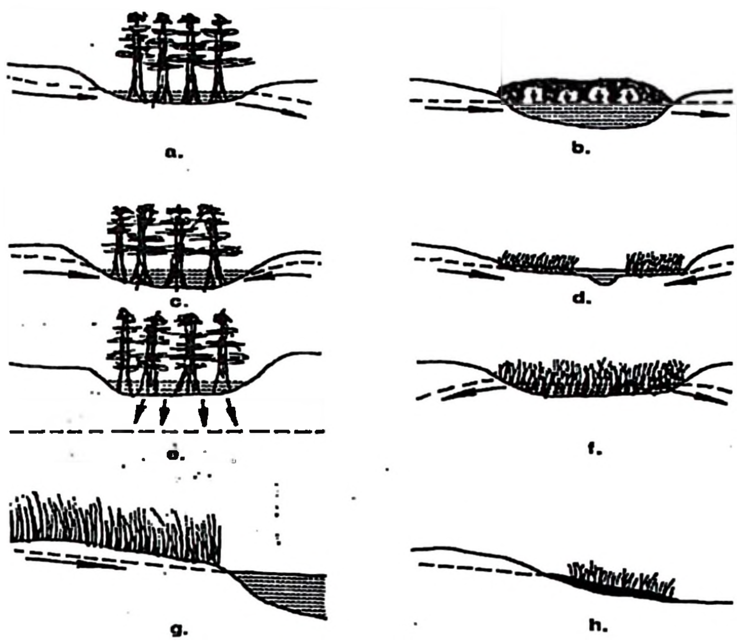


Figure 2.2: Possible groundwater interchanges with wetlands

a) both inflows and outflows of groundwater through swamp, b) underflow of raised bog, c) swamp as groundwater depression wetland, d) marsh a groundwater depression wetland, e) perched swamp or surface water depression wetland, f) marsh as groundwater source, g) groundwater flow through salt marsh or riparian wetland, and h) groundwater seep wetland or groundwater slope wetland. (Some terminology is after Novitzki, 1979; adopted from Mitsch and Gosselink, 1986).

2.3 Groundwater models and wetlands

Among different groundwater models available, MODFLOW has emerged as the *de facto* standard code for aquifer simulation and is widely used (Anderson and Woessner, 1992; Sun and Zheng, 1999; Bradford and Acreman, 2003). MODFLOW has been applied to numerous systems in many different geologic settings for a variety of reasons including developing a better understanding of the groundwater flow system (Barone, 2000); evaluation of management strategies to overcome a problem of groundwater withdrawals and water logging (Reynold and Spruill, 1995); to determine the effects of increased water withdrawal (Kashaigili *et al.*, 2003). In groundwater modelling, most groundwater flow models incorporate wetland systems as general head boundary nodes (Merritt, 1995), and sometimes simulated as constant head nodes, or lake stage packages (Restrepo *et al.*, 1998). However, recent studies have shown that MODFLOW could be used to simulate wetlands independently (Wilsnack *et al.*, 2002; Bradford and Acreman, 2003).

Most groundwater and surface water flow models have been developed independently (Restrepo *et al.*, 1998). Interaction between subsurface flow and surface flow in wetlands has not yet been simulated with an integrated model (Restrepo *et al.*, 1992; Swain and Wexler, 1993). Landscape models have been used to simulate wetlands condition; however these models generally do not have a rigorous physical basis (Restrepo *et al.*, 1998). Although reliable calibrations can be achieved by this type of model for carefully defined physical conditions (Restrepo *et al.*, 1998), the reliability is questionable under varied physical conditions. The simulation of wetland hydrodynamics needs to give fundamental consideration to the physics of surface flow processes. Restrepo *et al.* (1998) have indicated that the ability to accurately simulate surface water movement in wetlands and slough channels, along with its interaction with groundwater, is very important for many projects. As such, groundwater flow models may be used to simulate the interactions process. Wilsnack *et al.* (2002) used a two-dimensional MODFLOW Wetland package to develop a regional groundwater flow model for simulating regional wetland hydrology within the Everglades, US. The simulated water levels were in agreement with observed levels within 0.15m (Wilsnack *et al.*, 2002). Bradford and Acreman (2003) applied MODFLOW to in-field water table variations in the wet coastal grassland in Pevensey Levels. The study revealed that rainfall and evaporation were the most important factors influencing the water table fluctuations and in-field wetness in wet grasslands with low permeability clay soils while the field ditches had little influence in the field water regime.

While that has been revealed, literature on groundwater studies in the Usangu Plains is limited. The only documented study is the CCKK (1982), which was carried out as part of the water master plans for Iringa, Ruvuma and Mbeya Regions. The study assessed the availability of surface water and groundwater with attention directed to water supply for villages and livestock.

2.4 Detection of land use/ cover change in wetlands

Change in land use/cover could modify flow regime in the downstream by either increasing flows or decreasing flows for a certain period of time. Therefore understanding the linkage between land use/cover changes and changes in flow in the downstream is vital for sustainable catchment and environmental water management. The subsequent subsections review some of the methods for change detection of particular relevance to wetlands.

2.4.1 Remote sensing technology and GIS

Remote Sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lillesand and Kiefer, 1987). The term "remote sensing" first emerged in the 1950s (de Sherbinin and Giri, 2001). The history of remote sensing, however, dates back to as early as 1827 when Nicephore Niepce took the first picture of nature (Estes, 1999). Since then, the advancement of technology continued with the use of a captive balloon in 1858, pigeons in 1903, low altitude aircraft during World War-1, and high altitude aircraft in 1950s to take aerial photographs. The satellite remote sensing era began when TIROS-1, the first meteorological satellite, was launched in 1960 (de Sherbinin and Giri, 2001). During the same period, high spatial resolution military intelligence satellites were launched by the United States (Corona) and the former USSR (KH), though these data have found their way into the public domain only recently (de Sherbinin and Giri, 2001). Nduwamungu (2001) in his example pointed that reading is a remote sensing process, i.e., as you read these words you are employing remote sensing.

Remote sensing basically involves two processes namely data acquisition and data analysis. In remote sensing, earth resources data are acquired using various electromagnetic energy sensor systems, which are operated from airborne (e.g. aircraft, balloon) and space borne platforms (e.g. satellites and space stations). The gathered data are then converted into useful information using various viewing and interpretation devices for visual analysis and using computer modules for digital image analysis (Lillesand and Kiefer, 1987; Richards, 1993). In the whole process, it is worthwhile to note the human-machine interactions in the conversion of remote sensed data into useful information (Hoffer, 1994 cited in Nduwamungu, 2001).

In remote sensing, sensors measure the emitted or reflected electromagnetic radiation, or spectral characteristics, from a target object. These are of two types namely passive and active sensors. Passive sensors (i.e. multispectral sensor) record energy that is naturally reflected or emitted from a target. In contrast, active sensors supply their own source of energy, directing it at the target in order to measure the returned energy (Brandon and Bottomley, 1999).

A multispectral sensor unlike others acquires multiple images of the same target object at different wavelengths (bands). Each band measures unique spectral characteristics about the target (Brandon and Bottomley, 1999). A spectral band is a data set collected by the sensor with information from discrete portions of the electromagnetic spectrum. The electromagnetic (EM) spectrum is a range of electromagnetic radiation ranging from cosmic waves to radio waves. Multispectral sensors focus on ranges on the EM spectrum where radiation penetrates the air with little or no loss by absorption of the target. Remote sensors on space platforms are programmed to operate in these windows and make measurements using detectors tuned to these specific wavelength frequencies, which pass through the atmosphere. Spectral reflectance characteristics of common earth surface materials are located within the visible and near to mid-infrared range (Richards, 1986).

In most contemporary land use studies, which employ remote sensing imagery from multispectral sensors, the foremost task is the observation of spectral characteristics of measured electromagnetic radiation from a target or landscape. Analysts develop signatures based upon the detected energy's measurement and position in the electromagnetic spectrum. A signature is a set of statistics that defines the spectral characteristic of a target phenomenon or training-sites. Image analysts determine the measurement of signature separability by determining quantitatively the relation between class signatures. Signatures are refined by improved ground-truth and accuracy assessment analysis. By utilizing the developed signatures in mulitspectral classification and thematic mapping, the analyst generates new data for analysis (ERDAS, 1999).

Today, remote sensing image data of the Earth's surface acquired by spacecraft platforms is readily available in a digital format. Digital remote sensing systems convert electromagnetic energy (color, light, heat, etc) to a digital form. Spatially, the data is composed of discrete picture elements, or pixels, and radiometrically it is quantised into discrete brightness levels (ERDAS, 1999). The great advantage of having data available digitally is that it can be processed by computer either for machine assisted information extraction or for the enhancement by an image interpreter.

Resolution is an important term commonly used to describe remotely sensed imagery. However, there are four distinct types of resolution that must be considered. These four types of resolution are spatial, spectral, radiometric, and temporal. These resolution characteristics help to describe the functionality of both remote sensing sensors and remotely sensed data. Their descriptions could be found in ERDAS, Earth Resources Data Analysis System, Field Guide (1999). Spectral resolution is the number of frequency bands and the width of those bands. Radiometric resolution is the sensitivity of detectors to record the variations of reflectance. Temporal resolution is the age of the data and the frequency the data can be collected. Remote sensing has become an important tool applicable to developing and understanding the global, physical processes affecting the earth.

2.4.2 Change detection

The goal of change detection is to discern those areas on digital images that depict change features of interest (e.g. forest clearing or land cover/land use change) between two or more image dates (Hayes and Sader, 1999). With rapid changes in land cover occurring over large areas, remote sensing technology has become an essential tool for monitoring (Sader *et al.*, 1999). The remote and inaccessible nature of many places (i.e. tropical forest regions, large inundated wetlands) limits the feasibility of ground-based inventory and monitoring methods for extensive land areas (Hayes and Sader, 1999). Initiatives to monitor land cover and land use change are increasingly reliant on information derived from remotely sensed data. Numerous change detection techniques are available which achieve various levels of success (Kaufmann and Seto, 2001) and details on various methods are provided in (Singh, 1989b; Fung, 1990; Lambin and Strahler, 1994; Muchoney and Haack, 1994; Jensen, 1996; Coppin and Bauer, 1996; Gopal and Woodcock, 1996; Dai and Khorram, 1999). The method used depends largely on the landscape of the study area, the types of land-cover changes, and the temporal and spatial resolution of the data. However, there is no consensus regarding the 'best' technique (Kaufmann and Seto, 2001). Despite that, the post-classification comparison technique is widely used in detecting the land cover change (Wickware and Howarth, 1981).

2.4.3 Multi-spectral classification of wetlands

Historically Landsat MSS, Landsat TM, and SPOT satellite systems have been used to study wetlands (Lunetta and Balogh, 1999; Shepherd *et al.*, 1999; Shaikh *et al.*, 2001). Other studies have included AVHRR, IRS, JERS-1, ERS-1, SIR-C and RADARSAT (Alsdorf *et al.*, 2001; *Chopra et al.*, 2001). There has been some research done on wetlands using radar data (Rio and Lozano-García, 2000; Alsdorf *et al.*, 2001) as well as LIDAR (MacKinnon, 2001) but the majority has been concentrated on Landsat TM, MSS, SPOT, and airborne CIR photos. As far as classification of these images is concerned, most of the earliest work included visual interpretation of aerial photographs (Suguraman *et al.*, 2004). Unsupervised classification or clustering is the most commonly used digital classification to map wetlands and the Maximum Likelihood algorithm with a supervised method (Özemi, 2000). Low wetland accuracy percentages usually accompany these classification methods (30 – 60% accuracies). Several researchers increased the accuracy with other methods, for example, using multi-temporal and ancillary data along with various GIS models and non-parametric classifiers such as rule-based classifiers (using multi-spectral imagery) (Özemi, 2000). Other work has been done using multi-sensor assessment (Töyrä *et al.*, 2001), neural networks (Özemi, 2000; Han *et al.*, 2003), hyperspectral data (Schmidt and Skidmore, 2003) and ancillary data

(Houhoulis and Michener, 2000). Ancillary data provides a practical solution to solve the problem of distinguishing between spectral similarities in wetlands, agricultural fields, and forests.

2.4.4 Previous land resource mapping and change studies in the Usangu Plains

A number of studies have been conducted in the Usangu Plains. However studies relevant to land resources and especially to land cover and land use are limited (SMUWC, 2001e). Some of the early studies on land resources include FAO (1961) which was directed towards identification of irrigation potential within the Rufiji Basin; Pratt and Gwynne (1977) focused on rangeland management, for livestock production. These studies group the Usangu Plains in eco-climate zone V (arid) based on a map at 1:5 000 000 for all East Africa. Rombulow-Pearse and Kamasho (1982) reported on land evaluation for selected commercial crops based on land systems analysis undertaken at 1:500 000 scale, and on interpretation of Landsat imagery supported by aerial photographs and fieldwork. CCKK (1982) characterized the land use and vegetation patterns. Agrar-Und Hydrotechnik GNBH, (1986) conducted a Regional Land-Resource Survey and produced maps and reports covering soils (soil association at 1:100 000), soil suitability (1:250 000), present land use/vegetation (1:250 000), land units (1:250 000), ward boundaries (1:250 000), and a road map (1:500 000). BACAS (1993) undertook a comparative analysis of aerial photographic maps of 1977 and 1992a in an 825-km^2 area of upland catchments and found about 15% loss for forest and miombo woodlands. Charnley (1994) presented the ecological changes in the Usangu Plains based on 1:50 000 topographic maps produced in 1963 and in 1982/83. The study reported an increase over the period in the size of the perennial swamp. However, the validity of the analysis was entirely dependent on consistency in air photo interpretation and vegetation type presentation on the maps of the two dates (SMUWC, 2001e). HTS (1997) mapped land cover and land use based on Landsat TM of 1996 and this was later succeeded and modified by SMUWC (2001e). SMUWC (2001e), on the other hand, did an extensive classification for the land uses and cover based on aerial photos and images, however not much was reported on the nature of the changes.

Despite the good work done in the past studies including the recent SMUWC (2001e), a knowledge gap remains on the understanding of the inter-linkages between changes in wetlands size in relation to intensification of human and other developmental activities in the area and their impact on the hydrology of the Usangu wetlands. An understanding of the linkages between the wetland changes and the human influence and impact on wetlands hydrology could form the basis for proper wetlands management.

2.5 Environmental flows for wetlands and rivers

2.5.1 Definition, concepts, importance and role of environmental flows

An environmental flow (EF) is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits (Dyson *et al.*, 2003; King *et al.*, 2002; Tharme and King, 1998). It is also referred to as an ecologically acceptable flow regime designed to maintain a river in an agreed or pre-determined state. Therefore, EF is a compromise between water resources development on one hand and river maintenance in a healthy or at least reasonable condition - on another.

Despite that, there are challenges on the actual estimation of EF values as there is hardly data on both understanding of and quantitative data on relationships between river flows and multiple components of river ecology.

From ecological point of view, the major criteria for determining EF should include the maintenance of both spatial and temporal patterns of river flow, i.e. the flow variability, which affects the structural and functional diversity of rivers and their floodplains, and which in turn influences the species diversity of the river (Bunn and Arthington, 2002; Knights, 2002; Hughes and Rood 2003). Thus EF should not only encompass the *amounts* of water needed but also *when and how* this water should be flowing in the river. All components of hydrological regime have certain ecological significance (Knights, 2002). High flows of different frequency are important for channel maintenance, bird breeding, wetland flooding and maintenance of riparian vegetation. Moderate flows may be critical for cycling of organic matter from river banks and for fish migration, while low flows of different magnitudes are important for algae control, water quality maintenance and the use of the river by local people. Therefore many elements of flow variability have to be maintained in a modified EF regime. The important implications for this are that; first it moves away from a "minimum flow attitude" to aquatic environment, and secondly it effectively considers that aquatic environment is also "held accountable" and valued similarly to other sectors – to allow informed tradeoffs to be made in water scarcity conditions (Smakhtin and Markandu, 2005).

There are two basic approaches to setting environmental flows; objective-based and scenario-based (Acreman and Dunbar, 2004). In objective-based environmental flows setting, the ecological and/or socio-economic objectives of the river are first established; then the river flow regime is defined such that it will meet these objectives. A good example is the Water Framework of the European Union (EC, 2000), which requires Member states to maintain at least "Good Ecological Status" (GES) in all bodies of surface water and groundwater, and also to prevent deterioration in the status of those water bodies. In the South Africa, rivers are first classified according to management objectives (Hughes, 2001), which may range from negligible to high degree of modification, then environmental flow requirements (EFR) are defined to achieve this objective (Table 2.1).

Table 2.1: Ecological management classes

Class	Description
A	Negligible modification from natural conditions. Negligible risk to sensitive species.
B	Slight modification from natural conditions. Slight risk to intolerant biota.
C	Moderate modification from natural conditions. Especially intolerant biota may be reduced in number and extent.
D	High degree of modification from natural conditions. Intolerant biota unlikely to be present.

Source: Hughes, 2001

In the scenario-based environmental flow setting, no objectives are pre-defined. Instead, the ecological and socio-economic implications for a river of different water management options (such as different allocations to direct use, such as irrigation or hydro-power production) are determined. This approach allows stakeholders to participate by assessing pros and cons of each option (Acreman *et al.*, 2005).

Environmental flows provide critical contributions to river health, economic development and poverty alleviation (Dyson *et al.*, 2003). It is a product of an environmental flow assessment (EFA) that seeks to assess how much of the original flow regime of a river should continue to flow to maintain the ecosystem. An environmental flow assessment produces one or more descriptions of possible future flow regimes for a river. For example the requirement may be stated as "a water depth of at least 50 cm is required throughout the year to provide adequate wetted perimeter for a particular fish species". Alternatively it may be more complex detailing a comprehensive flow regime that specifies magnitudes, timing and duration of low flow and floods at a number of temporal scales.

Worldwide there is growing awareness of the pivotal role of the flow regime as a key 'driver' of the ecology of rivers and their associated floodplain wetlands (Arthngton, *et al.*, 2004; Naiman *et al.*, 2002). Ecological processes related to flow and other factors govern the ecosystem goods and services that rivers provide to humans, such as flood attenuation, water purification, production of fish and other foods and marketable goods. Protecting and restoring river flow regimes and hence the ecosystems they support by providing environmental flows has become a major aspect of river basin management (Arthington *et al.*, 2004). In large part, recognition of the importance of flow and its interactions with other driving variables has stemmed from an increasing body of information describing the negative impacts to riverine ecosystems that are clearly attributable, either directly or indirectly, to the alteration of natural flow regimes (Bunn and Arthington, 2002; Rosenberg, *et al.*, 2000).

According to Arthington *et al.* (2004), environmental flow assessments are directed at two main types of management response to the potential and extant impacts of altered flow regimes. These are: a) a proactive response, intended to maintain the hydrological regimes of undeveloped rivers as close as possible to the un-regulated condition, or at least to offer some level of protection of natural river flows and ecosystem characteristics, and b) a reactive response, intended to restore certain characteristics of the pre-regulation flow regime and ecosystem in developed rivers with modified/regulated flow regimes. Both of these circumstances can be addressed using the environmental flow assessment methods currently available.

2.5.2 Methods for determination of environmental flows

Four basic groups of environmental flow methodologies are widely recognised, namely; (i) hydrological index methodology; (ii) hydraulic rating methodology; (iii) habitat simulation methodology and (iv) holistic methodology (Karim *et al.*, 1995; Tharme, 1996, 2003). Each method has advantages and disadvantages and the applicability of any method is in accordance to the task to be undertaken; e.g. scoping, river basin planning or detailed assessment (Acreman *et al.*, 2005). In some developed countries, there is a move towards hierarchical multi-tier EFA frameworks, driven by the availability or access to resources, including data, time, technical capacity and finances (Dyson *et al.* 2003). The two major tiers (Smakhtin and Markandu, 2005) include:

a) Detailed assessment, using primarily holistic methodologies, or methods based on habitat modeling (i.e., group: ii – iv), and

b) Desktop, rapid assessment, using primarily ecologically relevant hydrological characteristics (indices) or analysis of hydrological time series (i.e. group: i)

Methods from group (a) often adopt a whole-ecosystem view in assessing EF, whereby ecologically and/or socially important flow events are identified and an ecologically acceptable flow regime is defined by a multidisciplinary panel of experts (Smakhtin and Markandu, 2005). These methods include substantial amounts of field work and may take significant amounts of time (e.g. 2 to 3 years for a basin – due to the need for ecological data collection at certain times of the year and the mere size of the basin) and resources to complete for a single river basin (Arthington and Pusey, 2003; King *et al.* 2003). Unlike other methods in this group, habitat models primarily focus on fish and like other holistic methods are data intense are requires a lot of field work. Methods from group (b) - desktop EFA, are much more diverse, more suitable for initial, reconnaissance or planning-level assessments of EFR (Smakhtin and Markandu, 2005). They can take a form of a look-up table (e.g. Tennant, 1976; Matthews and Bao, 1991) or be based on the detailed analysis of hydrological time series (e.g. Richter *et al.*, 1997; Hughes and Hannart, 2003). The look-up tables take significant amount of time to develop, before they can be used, while the methods based on the time series naturally require either observed or simulated discharge time series (or both).

Regardless of the type of the EFA methods, all of them have been designed and/or applied in a developed country context (Smakhtin and Markandu, 2005). Distinct gaps in EF knowledge and practice are evident in current approaches to water resources management in almost all developing countries, most of which lack technical and institutional capacity to establish environmental water allocation practices (Tharme and Smakhtin, 2003). The existing EFA methods are either complex or resource-intensive (holistic approaches), or not tailor made for the specific conditions of a particular country, region or basin (desktop methods).

Therefore, any country embarking on national or regional policies for managing water resources that include environmental water needs have to examine the appropriateness of different methods for the context of the types of rivers they have, the institutional structures in place and legal and policy tools that have been established (Acreman *et al.*, 2005).

(i) Hydrology-based approaches

These represent the simplest set of techniques and mostly referred to as desktop methods. 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 (Davis and Hirji, 2003; Arthington *et al.*, 2004). Commonly, the EFR is represented as a proportion of flow (often termed the 'minimum flow', e.g. Q_{95} – the flow equalled 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 (Arthington *et al.*, 2004). 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 (Tharme, 1996; Arthington *et al.*, 1998; Tharme, 2003). The most used hydrological index methods include: a) the Tennant (or Montana) method, b) Flow duration curve analysis, and c) Range of variability approach.

The Tennant (1976) method, attempts to separate *a priori* the entire range of the Mean Annual Runoff (MAR) at a site of a river into several ecologically relevant ranges. The ranges correspond to different levels of aquatic habitat maintenance or degradation. A threshold of 10% of the MAR reserved for an aquatic ecosystem is considered to be the lowest limit for EF recommendations (corresponding to severe degradation of a system). Fair / good habitat conditions could be ensured if 35% of the MAR is allocated for environmental purposes. Allocations in the range of 60 to 100% of the MAR represent an environmental optimum. This technique is still widely used in North America (Tharme, 2003), but is somewhat outdated and is scientifically weak as a threshold selection (% of the MAR) is arbitrary and no flow variability is accounted for (Smakhtin and Markandu, 2005). However, it is important to note from this method that a 10% of the MAR may be considered the lowest and highly undesirable threshold for EF allocations and that at least some 30% of the total natural MAR may need to be retained in the river throughout the basin to ensure fair conditions of riverine ecosystems (Smakhtin and Markandu, 2005).

The Range of Variability Approach (RVA) (Richter *et al.*, 1997) aims at protecting a range of flows in a river. The approach identifies 32 hydrological parameters, which jointly reflect different aspects of flow variability (magnitude, frequency, duration and timing of flows). These are estimated from a natural daily flow time series at a site of interest. The approach suggests that in a modified (ecologically acceptable) flow regime, all 32 parameters should be maintained within the limits of their natural variability. For each parameter, a threshold of 1 standard deviation (SD) from the mean is suggested as a default arbitrary limit for setting EF targets in the absence of other supporting ecological information. However, despite the relatively advanced nature of the RVA, the number of parameters used in it is too large for the level of subjectivity associated with their selection (Smakhtin and Markandu, 2005). In addition, many parameters are either likely to be correlated with each other, or there is little difference between their values. Smakhtin and Shilpakar (2005) justified and illustrated the simplification of this technique through a significant reduction of the number of parameters.

In flow duration curve (FDC) analysis, naturalised or present-day historical flow records are analysed over specific durations to produce naturalised flows duration curves displaying the relationship between the range of discharges and the percentage of time each of them is equalled or exceeded. For example in some cases the 95 percentile flow (Q_{95}) may be set as the minimum environmental flow. This is the flow that is exceeded 95% of the time (Pyrce, 2004). If rules for determining percentage of allowable abstractions at other flow percentiles at FDC are provided, an entire target environmental FDC can be derived. The output figures are based largely on professional judgment of specialists, since critical levels have not been defined directly by scientific studies at present. Any such figures are open to revision, but with no clear alternative, this provides a pragmatic way forward.

The most advanced and currently existing hydrology-based desktop EFA method has been developed by Hughes and Münster (2000) and further refined by Hughes and Hannart (2003). It is known as the Desktop Reserve Model (DRM). The Desktop Reserve Model emerged from the results of many comprehensive assessments of ecological reserve of South African rivers. The "ecological reserve" for rivers is effectively a South African term for "environmental flows". Quantifying ecological reserve involves determining the volumes and flow rates that will sustain a river in a predetermined condition. The latter is known as "environmental management class (or category) – EMC" (Hughes and Hannart, 2003) and is related to the extent to which this condition deviates from the natural (Smakhtin and Shilpakar, 2005). There are four main environmental management classes (A-D) where class A rivers are largely natural and class D rivers are largely modified where there is a large loss of natural habitat, biota and basic ecosystem functioning (Hughes, 2001).

The DRM originates from the Building Block Methodology (BBM) (King and Louw, 1998; Hughes, 2001; Hughes and Hannart, 2003). "Building Blocks" (BBs) are environmental flows, which jointly comprise the ecologically acceptable, modified flow regime. The major BBs are low flows (baseflows), small increases in flow (freshes) and larger high flows, which are required for river channel maintenance

(Smakhtin and Shilpakar, 2005). BBs are defined for each of the 12 calendar months and differ between "normal years" and "drought years." The first are referred to as "maintenance requirements" and the second as "drought requirements" (Hughes, 2001; Hughes and Hannart, 2003). The set of BBs, therefore, includes maintenance low flows, maintenance high flows, drought low flows and drought high flows. The DRM uses similar BBs and was developed as a rapid, low confidence environmental flow assessment approach.

The frequency with which maintenance years occur are defined on the basis of the variability of the natural hydrological regime, while it is also necessary to provide some idea of the frequency with which drought flows occur. Maintenance years may be expected quite frequently (60–70% say) in wetter, more reliably flowing rivers, while they would be expected to occur much less frequently in semi-arid and arid rivers (20% or lower) (Hughes and Hannart, 2003). It is further assumed that flows that exceed maintenance values are required and that the variability of flows (from drought to greater than maintenance) over time should reflect the natural variability of flows that would occur due to climatic variations. The final output from the BBM, as it is currently applied in South Africa, is therefore a table of flows for each month of the year for a range of percentage assurances. The flows can be expressed as volumes ($m^3 \times 10^6$) or as monthly mean flow rates (m^3s^{-1}). The assurance values are assumed to be equivalent to flow duration curve percentage points. If a flow had occurred naturally, which has been equalled or exceeded 70% of the time in the natural flow regime, then the IFR would be the BBM flow for the same month with a 70% assurance (Hughes and Hannart, 2003).

The major assumption of the DRM, which emerged from the analysis of comprehensive Ecological Reserve estimates, is that the rivers with more stable flow regimes (a higher proportion of their flow occurs as baseflow) may be expected to have relatively higher low-flow requirements in normal years ("maintenance lowflow requirements" in Ecological Reserve terminology). Rivers with more variable flow regimes would be expected, from the purely hydrological perspective, to have relatively lower maintenance low-flow requirements and/or lower levels of assurance associated with them. The consequence of these assumptions is that the long-term mean environmental requirement would be lower for rivers with more variable flow regimes. The DRM, therefore, explicitly introduced the principle of "assurance of supply" for "environmental water demand."

Smakhtin and Markandu (2005) pointed on the suitability of the DRM approach for EFA that the underlying concepts of the DRM are attractive and, to an extent, ecologically justified, as they emerge from the results of comprehensive assessments, which involve a variety of ecological disciplines. However highlighted on one stumbling block for its applications in other countries that, regional DRM parameters have been estimated on the basis of South African case studies, but are not generally available for other areas. This implies that its application requires some modification (calibration) of parameters. Symphorian *et al.*, (2002) used DRM to study reservoir operation for environmental water releases in Zimbabwe. Smakhtin *et al.*, (2006) illustrated the DRM application in Nepal, while Smakhtin *et al.* (2004) have used the principles behind the DRM in their global assessment of IFR. One additional advantage of the DRM is that it is originally based on monthly flow data which are more readily available or accessible in developing countries like Tanzania.

(ii) 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 (Arthington *et al.*, 2004). 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 decreases in 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 (Arthington *et al.*, 2004). These relatively low-resolution hydraulic techniques have been superseded by more advanced habitat modelling tools, or assimilated into holistic methodologies (Tharme, 1996; Jowett, 1997; Arthington and Zalucki, 1998; Tharme, 2003).

(iii) Habitat simulation 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 (Arthington *et al.*, 2004). 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 (Arthington *et al.*, 2004). 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 (Groshens and Orth, 1994). The resultants outputs, in the form of habitat-discharge curve for specific biota, or extended as habitat time and exceedence series, are used to derive optimum environmental flows (Arthington *et al.*, 2004). The habitat simulation-modelling package PHABSIM (Milhous *et al.*, 1989; Stalnaker *et al.*, 1994), housed within the In-stream Flow Incremental Methodology (IFIM), is the prominent modelling platform of this type. The relative strengths and limitations of such methodologies are described in King and Tharme (1994); Tharme (1996); Arthington and Zalucki (1998) and Pusey (1998).

(iv) Holistic methodologies

Holistic methodologies aim to address the water requirements of the entire "riverine ecosystem" (Arthington *et al.*, 1992) rather than the needs of only a few taxa (usually fish or invertebrates). 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 (Arthington *et al.*, 1992; King and Tharme, 1994). 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) (Arthington *et al.*, 2004). Ecosystem components that are commonly considered in holistic assessments include geomorphology, hydraulic habitat, water quality, riparian and aquatic vegetation, macro invertebrates, fish and other vertebrates with some dependency upon the river/riparian ecosystem (i.e. amphibians, reptiles, birds, mammals) (Arthington *et al.*, 2004). Each of these components can be evaluated using a range of field and desktop techniques (Tharme, 1996; Arthington and Zalucki, 1998; Tharme, 2003) and their flow requirements are then incorporated into EFA recommendations. These approaches have been described (Arthington *et al.* 1998) as either 'bottom-up' methods (designed to 'construct' a modified flow regime by adding flow components to a baseline of zero flows), or 'top-down' methods (addressing the question, "how much can we modify a river's flow regime before the aquatic ecosystem begins to noticeably change or become seriously degraded?").

The South African Building Block Methodology (BBM) (King and Tharme, 1994; King and Louw, 1998; King *et al.*, 2002) was the first structured approach of this type. It began as a bottom-up method, more recently incorporating the Flow Stress-Response Method (O'Keeffe and Hughes, 2002). In this modified form, the BBM is legally required for intermediate and comprehensive determinations of the South African Ecological Reserve (DWAF, 1999 a). Other essentially bottom-up methodologies include 'expert' and 'scientific panel' methods developed and applied in Australia (Cottingham *et al.,* 2002). There are several so-called 'top-down' methods. Examples of top-down methods are the Benchmarking Methodology (Brizga *et al.,* 2002) used routinely in Queensland (Australia) at the planning stage of new developments to assess the environmental impacts likely to result from future water resource developments and DRIFT - Downstream Response to Imposed Flow Transformations (King *et al*., 2003), a scenario-based approach that also predicts the probable ecological impacts of various scenarios of flow regime change. An important thing about DRIFT is that it links ecological aspects of ecosystems to livelihoods.

2.5.3 Environmental flows studies in Tanzania

The status of environmental flow studies in Tanzania at present may be characterized as being at its infancy. Generally, there is limited information on environmental flows studies. Conservation of nature and natural resources, including appropriate allocation of water to maintain aquatic ecosystems, is seen as a crucial element for sustainable development in Tanzania. The most common assessment is the Environmental Impact Assessments (EIA) normally undertaken on some projects. Nevertheless, EIA is not a legal requirement (Acreman *et al.*, 2005). Despite that the new institutional and legal framework for water resources provides for the environmental flows.

The National Water Policy (NAWAPO, 2002) recognises the importance of determining and allocating water for the environment. The policy covers strategic assessment of water resources. NAWAPO (2002) states that "water for the environment to protect ecosystems that underpin our water resources, now and in the future will attain second priority and will be reserved" (the first priority is for basic human needs). In addition, to strengthen the profile of environmental issues the National Environment Management Council (NEMC) has been placed within the Vice Presidents office, rather than within the Ministry of Natural Resources and Tourism. However, the capacity of Tanzania in the environmental field remains weak and institutional strengthening is required to ensure that the Water Policy is implemented effectively (Acreman *et al.*, 2005).

In building capacity, the first national workshop on Environmental flows was held at VETA Mbeya in 2003; supported by the Bank Netherlands Water Partnership Program (BNWPP) for the World Bank projects in Tanzania to build national capacity to undertake environmental flow assessments. The first phase of the work focused on identification of specific issues of water management and freshwater ecosystems in Tanzania and how environmental flow assessment could help. It recommended a 10 point plan for capacity building, which was supported by participants at a workshop on environmental flows that included government departments, universities, agencies and NGOs (Acreman and King, 2002). In 2005, the second environmental flows workshop was conducted at the Sokoine University of Agriculture. In addition to the two training workshops, a postgraduate programme in the Department of Water Resources Engineering, University of Dar es Salaam has started a course in Integrated Water Resources Management (IWRM) with a module on environmental flows. However, the programme still depends to a large extent on outside mentors (Kashaigili *et al.*, 2005 a).

A practical allocation for environmental flows is for the Kihansi ecosystem where in 1998, scientists from the University of Dar es Salaam discovered a small (1 cm) endemic toad whose habitat is created by the spray from the waterfalls (Acreman *et al.*, 2005). An environmental flow of 1.9 m^3s^{-1} is being released from the Dam (but still insufficient) to the falls, to ensure the environment for the Kihansi Spray Toad (the endemic toad). Test releases of 6-8 m^3s^{-1} are planned. Agreement on an acceptable flow release and on maintenance of any mitigation measures has not yet been reached. Another initiative on environmental flows assessment has started in the Pangani River basin, supported by IUCN.

2.5.4 Synthesis of the literature reviews

Wetlands hydrology

Wetlands are complex ecosystems. Many scholars have tried to study the hydrology of wetlands but surprisingly most of their findings differed in many aspects. The noted differences among different scholars connote the level of complexity in wetlands hydrology studies. Therefore wetlands under different hydrological settings have their peculiar characteristics which can not be generalized/ replicated in other areas. Because of that, a need for continued research to characterize the wetlands hydrology is indispensable given the complexity in wetland management.

Changes in land use and cover

Land use and cover change is a complex phenomena and the complexity mounts more when dealing with ecosystems which are dynamic in nature like wetlands. A review of literature identified the various approaches employed in assessing the changes in wetlands and other areas using different approaches. The importance of remote sensing in wetland studies has gained a wider recognition by most scholars. This is because of their abilities to capture information over a wider area of which some are in remote areas.

Environmental flows

Different methods and considerations have been highlighted through this review. It is clear from the literature review that there exists different methods and considerations for the determination of environmental flows. However, the choice of any from the existing methods is governed by data availability and level of assessment. For rapid EF assessment, methods which depend on river flow data are very important.

Generally, the EFA concept is still very new and evolving in most developing countries and most of the available methods were developed for temperate climates (i.e. Tenant, 1976) and can not be easily adopted for use in arid and semi-arid areas unless calibrated to suite the climate.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 The study area

3.1.1 Location and size

The Usangu Plains are located in the south west of Tanzania (Figure 1). They lie between longitudes 33°00'E and 35°00'E, and latitudes 8°00'S and 9°30'S, covering an area of approximately 15 560 km^2. They are located within the Great Ruaha River catchment (GRRC) which has an area of about 68 000 km^2. The GRRC is located within the Rufiji River Basin (the largest basin in Tanzania) which covers an area of about 177 000 km^2. The Plains, which lie at an average elevation of 1100 m above mean sea level (amsl), are surrounded by the Poroto, Kipengere and the Chunya mountains, with elevations up to 3000 m amsl. The Usangu wetlands are located at the centre of the Usangu Plains. They comprise the Western and Eastern wetlands - joined by a narrow band of land along the Great Ruaha River at Nyaluhanga. A large part of the Eastern wetland is located in the Usangu Game Reserve, which covers an area of about 4148 km^2. The Western wetland contains the Ifushiro swamp in the southern part.

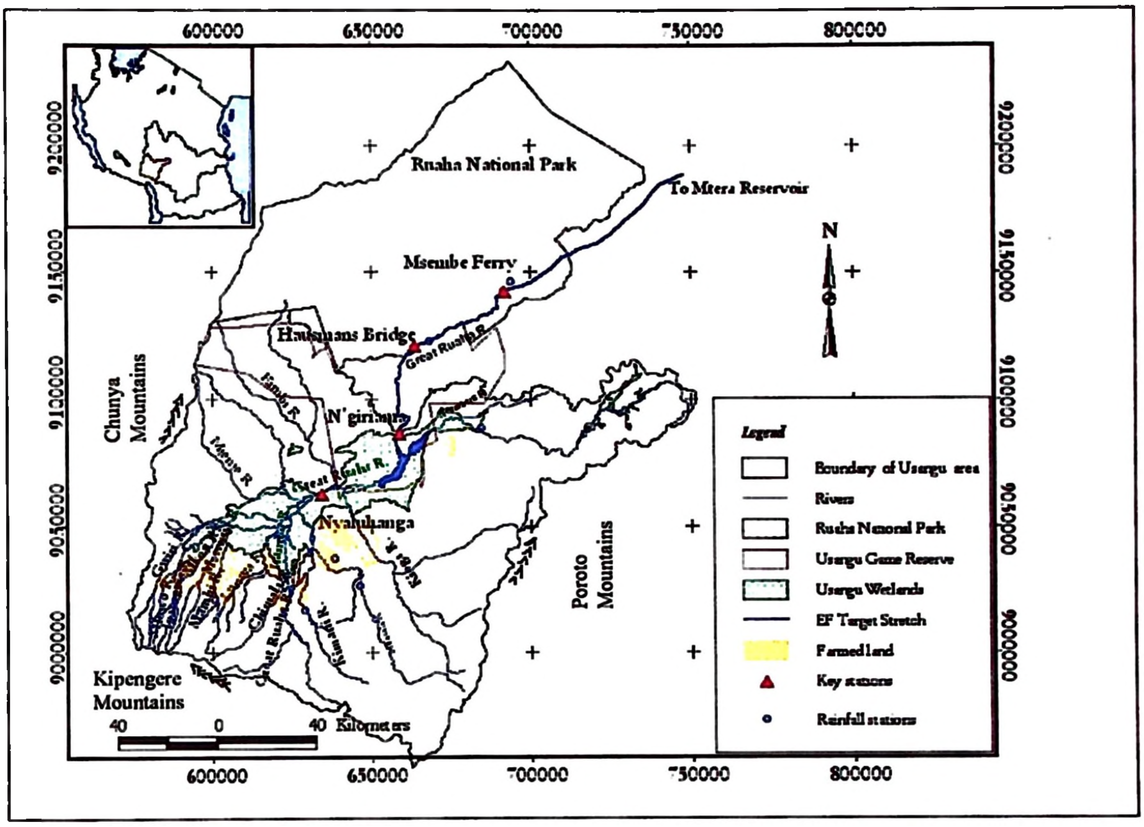


Figure 3.1: Map of Tanzania showing location of the study area

3.1.2 Geomorphology

The study area is characterised by two distinct landscapes namely the highlands and lowlands/plains (CCKK, 1982; SMUWC, 2001a). Details on these are presented in Table 3.1 and Figure 3.2. The highlands include all areas above 1100 m amsl. This includes escarpment foothills between about 1060 and 1200 m amsl. Topographically, the foothills belong to the plains. However, in terms of soil, vegetation and land use they are similar to the highlands. The highlands consist of the erosional surfaces, while the lowlands are a depositional basin. The highlands contain the high plateau surface at altitudes typically above 2500 m amsl; and occur only in the south of the study area. The plateau forms part of the Gondwana surface

(CCKK, 1982), dominated by granites and gneisses, with occurrences of shales and schists. These are the source of the major rivers draining the Usangu Plains. A distinct escarpment generally edges the high plateau. The escarpment rises from about 2300 to 2600 m amsl.

Below the escarpment are the low plateaus. The low plateau occupies those areas between about 1200 up to about 1800 m amsl in the south-west and in the north, and north-east from about 1100 to 1500 m amsl. According to the CCKK (1982), this constitutes the African surface, a smooth pediplain. The surface also occupies the extreme north of the Usangu, the eastern part, extending into Ruaha National Park. The low plateau is characterised by undulating to rolling topography, granitic rocks, sandy soils, and miombo vegetation (SMUWC, 2001a).

The northwestern and central lowlands are dry and flat plains, which is a natural sedimentation sub-catchment and part of the East African Rift Valley. The plains are characterised by a large number of seasonal and few permanent swamps. There are only minor variations in altitude, ranging from about 700 m amsl at the Mtera Dam to about 1100 m amsl at the southern part of the Usangu Plains. Generally, rolling to dissected Upper Plateaus, they form part of the Southern Highlands, to the southeast, south and west surrounds the Usangu Plains.

Table 3.1: Geomorphological units of the study area

Unit	*Erosion surface (CCKK)*	*Locations*	*Elevation (m)*	*Topography*	*Soils*	*Vegetation*	*Land use*	*Area (km²/%)*
UPLAND UNITS								
High plateau	Gondwana surface	Kitulo Gofio Kipengere	2300-2960 (mostly>2500)	Rolling hills	Granitic Ash	Open grassland	Grazing; cultivation of potatoes and pyrethrum	658.4 3.2%
Intermediate plateau (west)		Tukuyu Matamba Akondo Njombe	1800-2300	Rolling hills	Basaltic Granitic?	Dominantly cultivated Miombo + cultivation	Cultivation Cultivation	7510 36.1%
Intermediate plateau (east)		Ndembera	1400-1800	Rolling hills	Granitic	Miombo & cultivation	Cultivation	
High escarpment			2100-2600	Steep hills	Granitic?	Open grassland	Pastoralism	
Low plateau	African surface	Luwango Wanging'ombe	1200-1800 (W) 1100-1500 (E)	Undulating	Granitic	Dominantly cultivated; remnant miombo	Cultivation	4220 20.3%
Intermediate escarpment			1200-1800	Very steep	Granitic	Miombo woodland	Hunting and gathering	
N/A	Post-African surface							400 1.9%
Foothills and northern sand hills			1060-1200	Rolling	Sands Granitic	Miombo; mixed Acacia vegetation at lower altitudes	Hunting and gathering	1274 6.1%
LOWLAND UNITS								
Alluvial fans		Utengule Mbarali Ikoga	1030-1140	Very gently sloping	sands to clays	Acacia woodland; extensively cleared	Cultivation (rainfed & irrigated); pastoralism	3232 15.5%
Fan sand hills			1100-1200	Rolling	sands	Miombo woodland	Pastoralism	138 0.7%
Northern clay plain			1100-1150	Level	cracking clays	Cultivation	Cultivation	39 0.2%

Source: SMUWC (2001b)

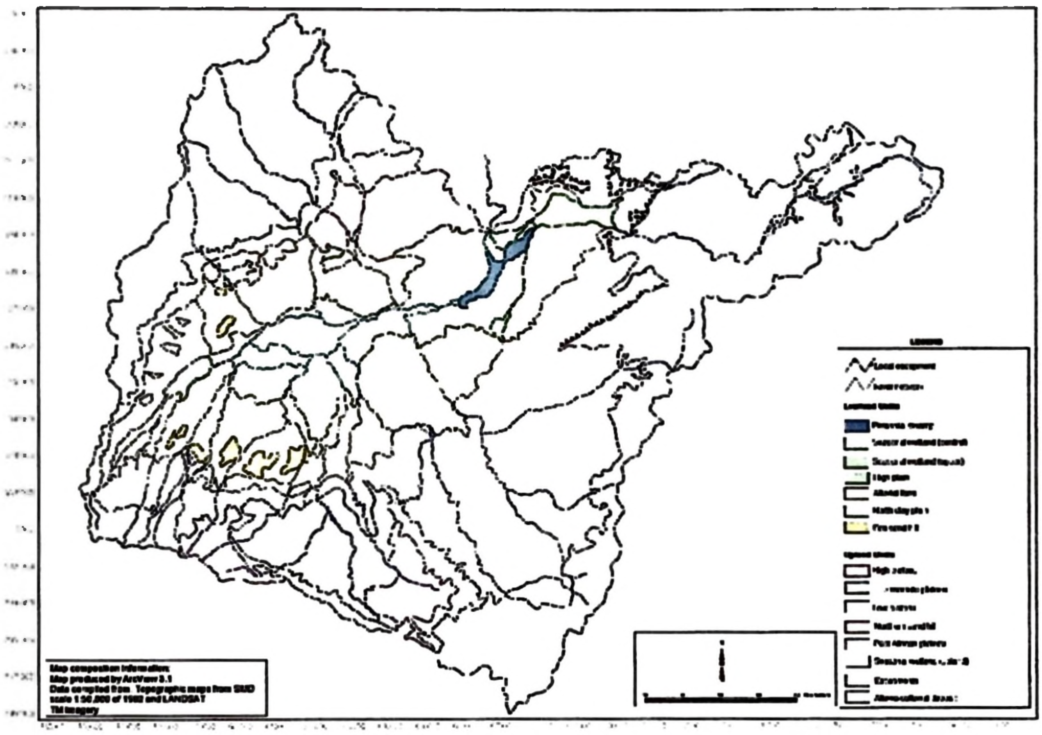


Figure 3.2: Geomorphological zones of the Usangu area

Modified from (SMUWC, 2001b)

3.1.3 Climate

The climate is largely controlled by the movement of air-masses associated with the Inter-Tropical Convergence Zone. The rainfall regime in the catchment is unimodal with a single rainy season from November through May, and hardly any rainfall during the rest of the year. The rainfall is irregular, highly localised, spatially varied and strongly correlated with altitude. In the highlands, the dry season is shorter as the rainy season tends to continue until June. The heaviest rainfall occurs in December to January or March to April. The mean monthly rainfall for selected four weather stations in the study area is presented in Figure 3.3.

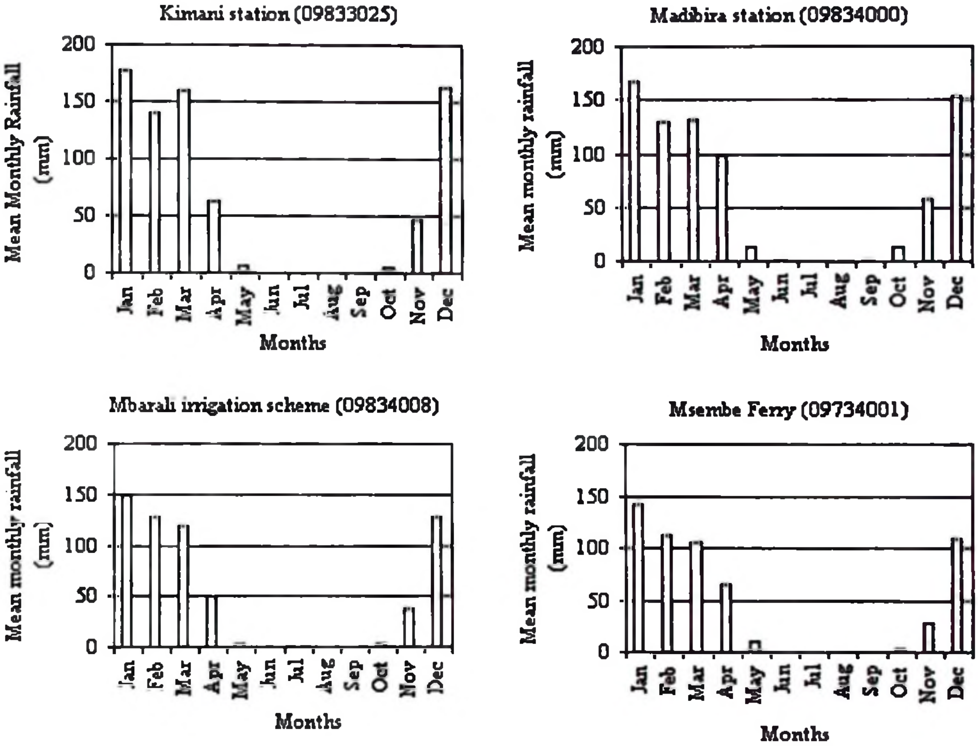


Figure 3.3: Mean monthly rainfall for selected stations in the study area

The Kipengere range, the Poroto Mountains in the Southern part of the catchment and the highlands in Kilolo Divisions (next to the Udzungwa Escarpment) in the Eastern part of the catchment receive the highest annual rainfall, about 1400 – 1600 mm. The annual rainfall decreases towards the North-western part of the catchment, and is only about 500 mm per annum at Mtera. Rainfall in wet and dry years may be 40 – 60% higher and lower, respectively, than the corresponding mean annual rainfall (DANIDA/World Bank, 1995).

The mean annual temperature varies from about 18^{0}C in the highlands to about 28^{0}C in the lowlands and drier parts of the Plains. Minimum and maximum average monthly temperatures vary from 5^0C to 13^0C and 22^0C to 27^0C, respectively in the highlands and from 15^0C to 24^0C and 28^0C to 34^0C, respectively in the lowlands. Most of the lower part of the study area, comprising the Usangu Plains and the Ruaha National Park areas is semi arid or semi-arid to sub-humid, whereas the highest part of the catchment is humid with a sub-humid belt in between. Mean annual potential evaporation is 1900 mm (SMUWC, 2001c; Yawson, 2003).

3.1.3 Drainage Pattern

The Usangu Plains are drained by the Great Ruaha River, which exits at a point called NG'iriama. At this location, a rock outcrop acts as a natural dam controlling flow from the Eastern wetland. Major tributaries to the Great Ruaha River, with confluences on the Plains, are the Mbarali, Kimani, Chimala and Ndembera (Figure 3.4). These rivers have their sources in the highlands, and account for 85% of the total discharge from the Plains. Other smaller rivers include the Umrobo, Mkoji, Lunwa, Mlomboji, Ipatagwa, Mambi, Kioga, Mjenje, Kimbi, Itambo and Mswiswi. Most of these smaller rivers have their sources in lower rainfall areas and are ephemeral. The major water supplier to the Eastern wetland is the Great Ruaha River, which flows from the Western wetland through the constriction at Nyaluhanga. The only other significant inflow into the Eastern wetland is the Ndembera River, which discharges into it from the north-east (Figure 1). Downstream of the Eastern wetland, the Great Ruaha River flows through the Ruaha National Park, and it is joined by the Little Ruaha and Kisigo rivers into the Mtera reservoir. From the Mtera reservoir, the GRR is joined by Lukosi River into the Kidatu reservoir. The Great Ruaha River discharges 56% of its runoff to Mtera, while the Little Ruaha and Kisigo Rivers discharge an additional 18% and 26% respectively. Downstream of the Kidatu plant, the GRR joins another major feeder river (the Kilombero), to form the Rufiji River. The long term (i.e., 1958-2004) mean annual runoff (MAR) for the catchment up to Msembe Ferry gauging station, located 80 km downstream of NG'iriama (Figure 3.1), is 2,443 Mm^3 (i.e., 77.4 m^3s^{-1}).

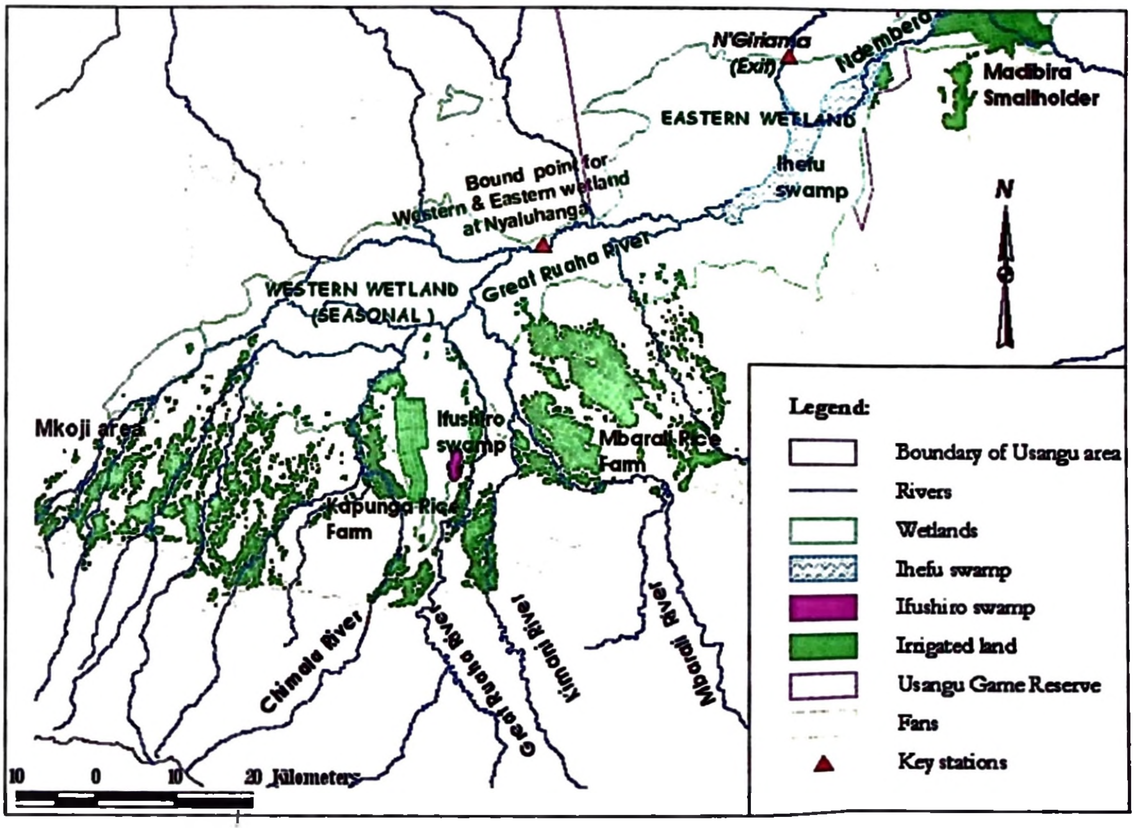


Figure 3.4: Drainage patterns and land use in the Usangu Plains

3.1.4 Geology and soils

The major part of the GRRC is underlaid by a basement complex of precambrian rocks dominated by gneiss and granite (Figure 3.5). However, the Usangu Plains and the Pawaga Plains between the confluence of the Little Ruaha and the Great Ruaha rivers and down to the Mtera reservoir are partly lacustrine and partly alluvial deposits. In the south western part of the catchment, in the Poroto Mountains the parent material is volcanic ash deposit originating from the Rungwe-Mbozi volcanic complex (DANIDA/World Bank, 1995).

In the higher rainfall areas most of the soils are deep weathered and highly leached red and yellow soils with high iron and aluminium concentrations (Ferralsols). In the highly dissected parts the soils are however shallow and rocky. Most of the soils are well-drained but of low inherent fertility. Many of them still have relatively high organic matter content and a good soil structure. Thus many of these soils are still relatively resistant to soil erosion.

In the drier part of the study area, between the flat plains and the highlands the soils are shallow having a relatively poor structure, which makes them susceptible to soil erosion. In the Usangu Plains a variety of soil textural classes can be found according to the variation in sedimentation conditions prevailing when the deposition took place. Alluvial clay and clay loams soils with up to 70% clay occupy the greatest part of the existing paddy producing area. These soils are generally of high fertility (CFTC, 1978). Many of the soils in Usangu Plains are poorly drained and are classified as vertisols.

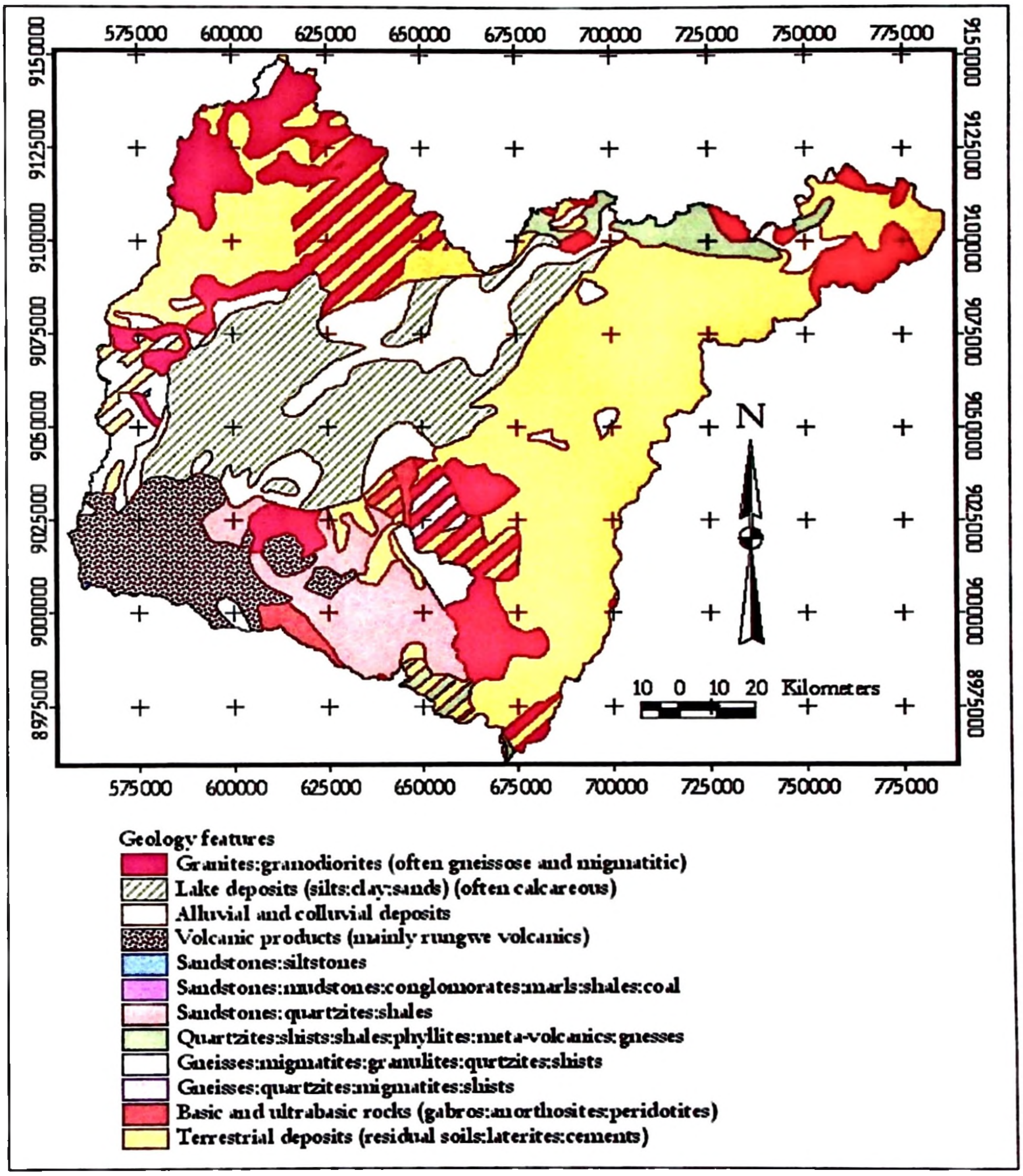


Figure 3.5: Geology of Usangu area

Source: SMUWC (2001e) geology shapefiles

3.1.5 Land cover

There is a distinct change in vegetation from the highlands to the lowlands. Above 2000 m amsl, remnant montane humid forest gives way to afro-alpine vegetation and, between 2000 m amsl and 1100 m amsl, Miombo woodland dominates (SMUWC, 2001a). Below 1100 m amsl, two broad areas are delineated by different vegetation composition and characteristics: i) the fans and ii) the Usangu wetlands. The fans are alluvial deposits spreading from the base of the mountains onto the plains. Natural vegetation comprises thorny woodland and/or wooded grassland. However, the fans are fertile and many agricultural activities are concentrated in this area. As a result, significant areas have been cleared and replaced by cultivation or secondary thorn bush. The vegetation of the lower fans naturally grades into bush mixed with open grassland. The Western wetland comprises seasonally flooded areas, which are not contiguous but broken into a number of independent wetlands. The Eastern wetland comprises seasonally flooded grassland and a perennial swamp, known locally as *mbuga* and *ihefu*, respectively.

3.1.6 Land use

Cultivation is the major activity in the study area. Over the past 30 years, there has been a rapid expansion in the irrigated area. From 1970 to 2002, the irrigated area increased from approximately 10 000 ha to about 45 000 ha (SMUWC, 2001 e). Irrigated agriculture is located on the middle and lower parts of the alluvial fans, primarily on the southern margins of the Usangu wetlands (Figure 3.4). The irrigation comprises large state-owned rice farms, as well as smallholder irrigation. It is estimated that approximately 30 000 households are involved in irrigation. However, a major part of the catchment consists of almost unutilised land and the Ruaha National Park covers most of the central part of the GRRC. The RNP has a high diversity of wildlife, both terrestrial and aquatic (including birds and reptiles) and supports approximately between 6000 and 8000 elephants. Pastoral activities dominate a large part of the Plains especially around the wetland.

The major food crops grown in Usangu Plains include rice, maize, sorghum, and beans. Other crops include onions, tomatoes, sugarcane, vegetables and fruits (mainly citrus, mangoes and pawpaw). Irrigated crops include paddy, maize, beans, cassava, sweet potato, sugar cane, onions, and vegetables. Paddy is the major crop under irrigation and is normally grown during the wet season, on the lower alluvial fans. Maize and dry season irrigated crops (such as beans, vegetables and fruits) are grown on the upper alluvial fans and foothills, where the soils are sandy loams.

The area under paddy in Usangu depends on the river flows and rainfall in each sub-catchment. The maximum irrigated land under paddy amounts to about 42 000 ha, during a normal-to-wet year when average weather conditions are favourable, and when irrigation is essentially supplemental (SMUWC, 2001 e). In dry years the area under irrigation is comparably smaller: the core irrigated area is 24 500 ha, of which rice occupies 22 000 ha and a non-rice crop 2500 ha. During bad years, both rice and non-rice crops are irrigated using mostly river flows resulting into some land being left idle.

Dry season irrigation plots are usually very small (about 0.1 - 0.2 ha). Land for rain-fed agriculture in Usangu varies from one year to another, and is between 50 000 ha to 65 000 ha depending on the amount and distribution of rainfall (SMUWC, 2001 d, e).

3.2 Data Collection

3.2.1 Socio-economic data

To understand the occurrence of major events and past changes in the Usangu wetlands including people's perceptions on the wetlands, a social survey was conducted to collect information on the changes that people had experienced in the past as well as understanding how the wetlands are being utilized. The methods used for data collection included Participatory Rural Appraisal (PRA), focus group discussions with key informants and household surveys using a questionnaire (Appendix D). These were mainly conducted in three representative villages neighbouring the Ifushiro wetland as shown in Figure 3.6. The household information was collected from a random sample of 120 households, 40 people from each village. The type of data collected included access to land, originality (if immigrant or resident), historical changes and crops grown in wetlands.

The household information collected through questionnaires was transcribed onto SPSS spread sheet, a statistical package, to generate summary statistics. The results were summarised in tables and graphs.

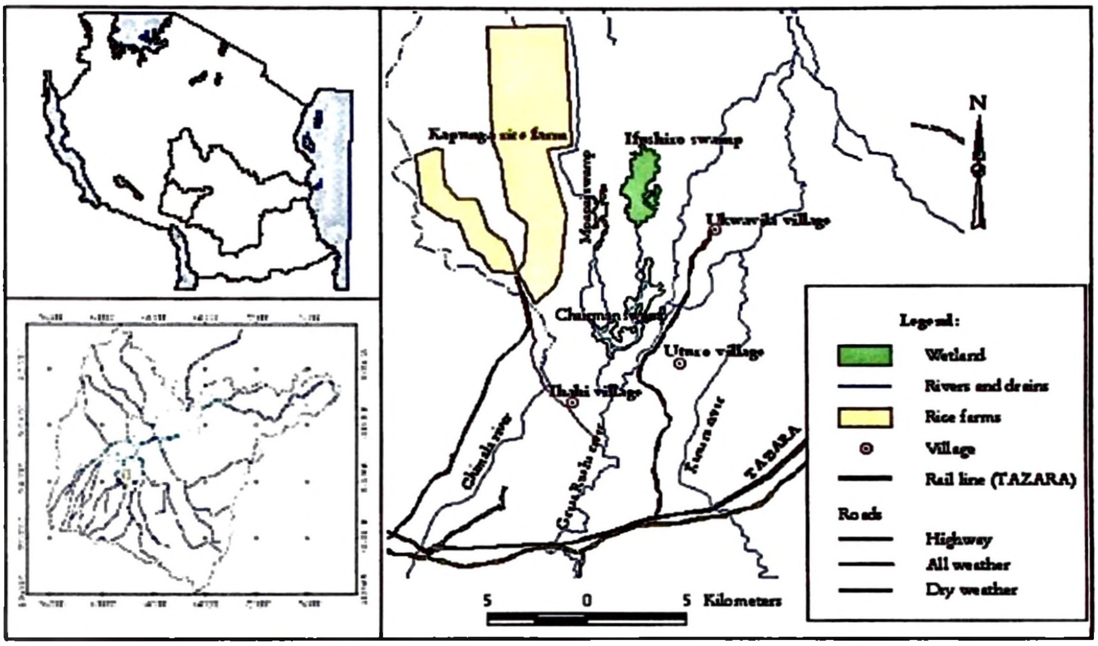


Figure 3.6: Location of the surveyed villages

3.2.2 Remotely sensed data, processing and change detection

To understand the dynamics of wetlands area and land use/ cover changes with time as well as the relationships between changes and flow regime response downstream of the Eastern wetland, analysis of remotely sensed data (satellite images) was done and involved the following:

(i) Image selection and acquisition

In consideration of cloud cover, the seasonality and phenological effects (e.g., Jensen, 1996), images listed in Table 3.2 were selected for image processing. The target was images acquired during the dry season (especially August-November) with minimum cloud cover and those acquired in the wet season especially April to June. For wet season it was however not possible to get the targeted images. For example, no good image is available in the wet season in 1973, 1991 and 1994. As a consequence, only images acquired in 1984 and 2000 in the wet season were used. The analyses considered three time frames or "windows": pre-1973, 1974-1985 and post-1985. These windows corresponded approximately to different levels of human intervention in the GRR catchment and their descriptions are presented in Table 3.2.

Table 3.2: Landsat images used in the analysis of land-cover change

Image	Path/Row	Date of acquisition	Season	Cloud cover (%)
Landsat MSS⁺	181/66	4th September 1973	Dry	0
Landsat TM*	169/66	15th June 1984	Wet	11
Landsat TM	169/66	3rd September 1984	Dry	0
Landsat TM	169/66	22nd August 1991	Dry	0
Landsat TM	169/66	14th August 1994	Dry	1
Landsat ETM+	169/66	26th May 2000	Wet	8
Landsat ETM+	169/66	7th September 2000	Dry	10

⁺ MSS = Multi spectral scanner
* TM = thematic mapper
ETM+ = Enhanced thematic mapper plus

(ii) Image Processing

Image processing involved three stages. These were: image pre-processing, image rectification/georeferencing, and image enhancement.

Image pre-processing

The methods for the images analysis required the use of both visual and digital image processing. The steps involved are summarized in Figure 3.7. Prior to image processing, images were extracted from the full scenes using ERDAS Imagine Software, Version 8.3.1 to sub-scenes followed by rectification.

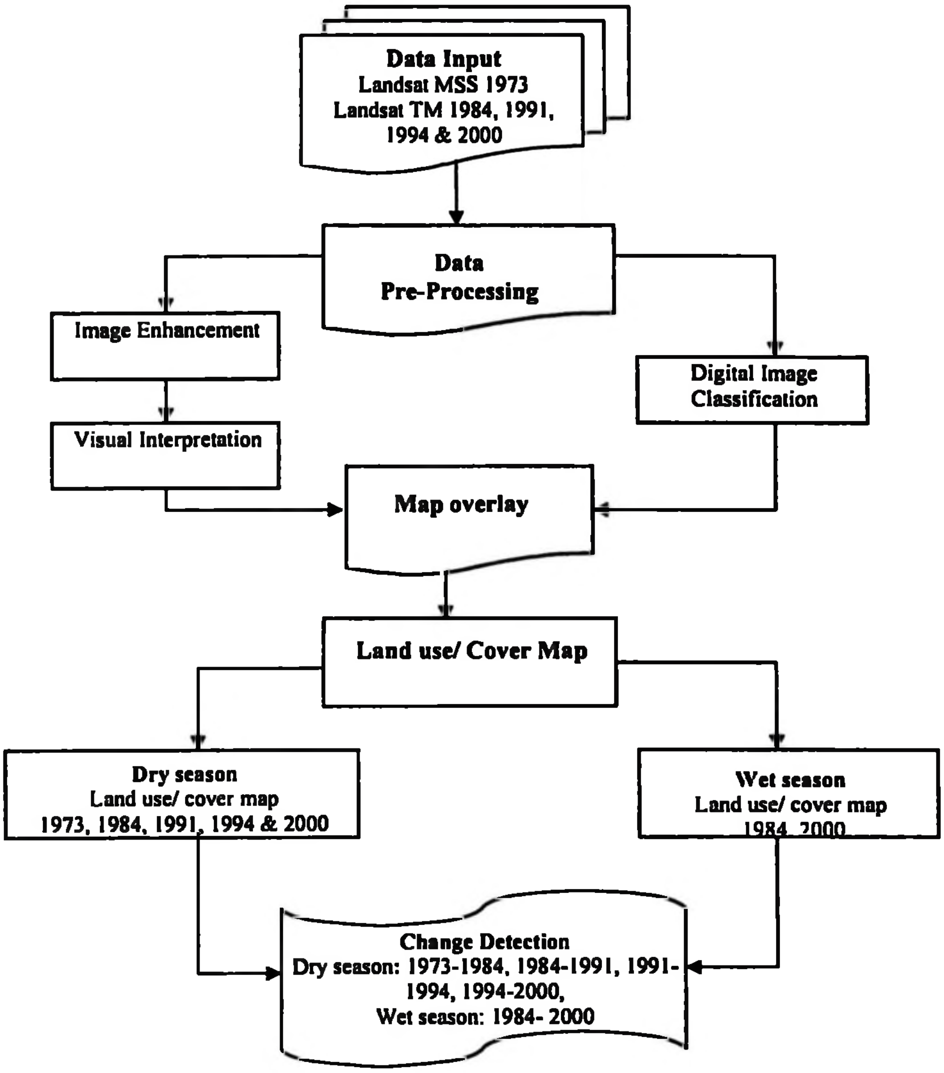


Figure 3.7: The image analysis flow chart

Image rectification/georeferencing

Image rectification was performed in order to correct image data for distortions or degradation resulting from the image acquisition process. To ensure accurate identification of temporal changes and geometric compatibility with other sources of information, the images were geo-coded to the co-ordinate and mapping system of the national topographic maps, i.e. UTM coordinate zone 36 South, Spheroid Clarke 1880, Datum Arc 1960, based on a previous georeferenced Landsat TM image of 14th August 1994. Since the images had already been corrected for radiometric distortions and available as geo-cover datasets with no apparent noise, the created sub-scenes were only subjected to geometric correction.

Radiometric distortion refers to the distortion of the relative distribution of brightness over an image in a given band in relation to the ground scene (Richards, 1993). It also applies to the distortion of the relative brightness of a single pixel from band to band compared with the spectral reflectance character of the corresponding site on the ground. Radiometric distortions may result either from a scattering effect of the atmosphere on radiation or from instrumentation errors. They are characterized by an incorrect intensity distribution, spatial frequency filtering of the scene data, blemishes in the imagery, banding of the images data. These distortions are caused by camera or scanner shading effects, detector gain variations, atmospheric and sensor induced filtering, sensor imperfections and sensor detector gain errors.

Geometric correction allows compensating for various distortions introduced by several factors including: earth rotation effects, panoramic distortions (wide field of view of some sensors), curvature of the earth, atmospheric refraction, relief displacement, variations in platform altitude, attitude and velocity and panoramic effects related to the imagery geometry (Lillesand and Kiefer, 1987; Richards, 1993). For those which needed rectification, image to image rectification was carried out with an overall RMS-error of less than 1.5 pixel. Image rectification was undertaken using 1st order Polynomial transformation and nearest-neighbourhood interpolation. The 1st order transformation can be represented as follows (ERDAS, 1994; 1997):

$$Y_O = a_1 + a_2 x_i + a_3 y_i \quad [3.1]$$

$$X_O = b_1 + b_2 x_i + b_3 y_i \quad [3.2]$$

Where: X_0 and Y_0 are the rectified coordinates (output)

x_i and y_i are source coordinates (input GCP coordinates)

$a_1, a_2, a_3; b_1, b_2, b_3$ are the transformation matrix coefficients or mapping polynomial coefficients.

According to Richards (1993), in order to estimate the transformation matrix coefficients, one should select enough, well defined and spatially small features that can be easily identified on both the map and the image. These points are called ground control points (GCP). Once selected, the GCPs are then registered and used to estimate the polynomial coefficients by substitution in the mapping polynomial equations. In this study image-identifiable points (the GCPs - normally taken at the river bends, roads intersections, bridges, etc.) were selected and matched to both the images and then digitised onscreen. At least thirty points per subset were collected. The GCPs were then used to project the uncorrected imagery to a UTM coordinate system. Each GCP was ordered by the residual error it contributed to the polynomial fit. Points with high error were discarded before registration. Image fit was considered acceptable if the root mean square error (RMS) was < 15 m or one half-pixel wide (RMS = 0.5). Overall, RMS errors of less than 0.5 pixel were achieved for each transformation.

To examine how well images were rectified, temporal images were overlaid on the same window and zoomed in to various features at multiple locations around the scenes. The "swipe" command within the ERDAS Imagine software aided checking the conformity of the co-registration.

Image enhancement

In order to reinforce the visual interpretability of images, a colour composite (Landsat TM bands 4 5 3) was prepared and its contrast was stretched using a Gaussian distribution function. Furthermore, a 3 x 3 high pass filter was applied to the colour composite to further enhance visual interpretability of linear features, e.g. rivers, and patterns such as cultivation. All image processing was carried out using ERDAS Image Software Version 8.3.1.

(iii) Preliminary image classification

Within the scope of this study, image classification is defined as the extraction of differentiated land use/cover categories, from remotely sensed satellite data. Supervised, using Maximum Likelihood Classifier (MLC), remote sensing classification methodologies were utilized to create a base map for ground truthing. Supervised classification process involved selection of training sites on the image, which represent specific land classes to be mapped. Training sites are sites of pixels that represent what is recognized as a discernable pattern, or potential land cover class (ERDAS, 1999). The training sites were generated by on-screen digitizing of selected areas for each land cover class derived from colour composite. Training was an iterative process, whereby the selected training pixels were evaluated by performing an estimated classification (ALARM command). Based on the inspection of alarm results, training samples were refined until a satisfactory result was obtained.

(iv) Ground truthing

Ground truthing was done in order to verify and modify land covers described in the preliminary image interpretation. Before going to the field, to implement ground truthing, preliminary image classification was performed to roughly identify vegetation types (section 3.2.2 (iii)). Sets of hard copies of colour composite images, with overlays of roads and UTM co-ordinates, were produced using image acquired on 7th September 2000 and used as base maps during ground truthing. A hand-held GPS was used to locate sampled land cover observations. This was done at the peak of the dry season to ease access to impassable areas during wet seasons. Recognisable features were recorded and circled on the map and their respective position recorded. During the ground truthing, the following major land cover classes were identified: closed woodland, open woodland, vegetated swamp, closed bush land, open bush land, bushed grassland, open bush land, cultivated land and bare land. Local communities were involved to give some information on land cover and particularly land cover changes in their communities.

(v) Preparation of land cover maps

Generally, two different mapping approaches for obtaining thematic classes from satellite data are possible: i) fully automated digital classification, ii) semi-automated classification utilising visual image interpretation with ensuing digitisation of the mapping results (Gross and Häusler, 1998). Digital image classification involves the numerical manipulation of image data. It is the process in which pixels with like values are grouped into classes based on predetermined decision rules and statistical probability theory. The objective of digital image classification is to produce thematic classes that resemble or can be related to actual land cover types on the earth's surface. The advantage of digital image classification is that it can provide efficient, consistent and repeatable routines for mapping large areas. It does require however human intervention to manage the process and assign real land cover types to pixel classes.

In this study, both approaches were used (unsupervised classification and visual image interpretation). The unsupervised image classification-using ISODATA algorithm in ERDAS imagine software was performed with the following parameters: 20 classes, convergence threshold of 0.999, 30 maximum iterations and skip factor of 1. From this, twenty thematic classes were formulated. The misclassified classes were corrected by visual interpretation aided by ground truth information. Similar classes were digitised, recoded and overlaid into respective classes.

Visual interpretation involved use of image characteristics such as pattern, texture, and colours to translate image data into land covers. The enhanced image colour composite was used in this operation. Visual image interpretation was considered to be feasible in this study for the following reasons:

- the knowledge of local experts can be integrated during interpretation.

- during ground truthing, it was found that land use pattern in the Usangu plains is very heterogeneous. For example, a non-uniform mixture of crops and field sizes characterizes cultivation. This makes discrimination of the cover using digital image classification very unreliable, resulting in mixed pixels. Thus, due to spectral and spatial heterogeneity of the covers, visual interpretation was considered to be more reliable technique to extract the covers so as to increase the accuracy of classification.

(vi) Change detection analysis

Change detection is a very common and powerful application of satellite based remote sensing. Change detection analysis entails finding the type, amount and location of land use changes that are taking place (Yeh *et al.*, 1996). Various algorithms are available for change detection analysis. They can be grouped into two categories namely a) Pixel-to-pixel comparison of multi-temporal images before image classification, and b) Post-classification comparison. Details on these methods can be found in various literature (e.g., Singh, 1989b; Jensen, 1996; ERDAS, 1999). In this study, a post-classification comparison method was used to assess land use and cover changes. The method has been found to be the most suitable for detecting land cover change (Weismiller *et al.*, 1977; Wickware and Howarth, 1981). The approach identifies changes by comparing independently classified multi-date images on pixel-by-pixel basis using a change detection matrix (Singh, 1989b; Jensen, 1996; Yuan and Elvidge, 1998). The matrix analysis produces a thematic layer that contains a separate class for every coincidence of classes in multi-date dataset. Although, the use of a change detection matrix provides detailed *from-to* information on the nature of change, mis-classification and mis-registration that may be present in each classified image may affect the accuracy of the results. Therefore accurate classifications are imperative to ensure precise change detection results (Foody, 2001).

(vii) Estimation of cover rate of change

The estimation for the rate of change for the different covers was computed based on the following formulae (Kashaigili *et al.*, 2004):

$$\%\ Change_{year\ x} = \frac{Area_{year\ x} - Area_{year\ x+t}}{Area_{year\ x}} x\ 100\ \% \quad [3.3]$$

$$\%\ Annual\ rate\ of\ change = \frac{Area_{year\ x} - Area_{year\ x+t}}{Area_{year\ x}\ x\ t_{years}} x\ 100\% \quad [3.4]$$

Where: $Area_{year\ x}$ = area of cover i at the first date,

$Area_{year\ x+t}$ = area of cover i at the second date, and

t_{years} = period in years between the first and second scene acquisition dates

3.2.3 Land use/cover change and flow regime downstream of wetland

Land use/cover change affects the water yield (total runoff) and flow regimes (i.e., the seasonal distribution of stream flow or runoff). Increased understanding between these two interactions is vital to ensure the sustainability of wetlands and river resources. To gain an understanding, a time series of flow data, obtained from the Msembe Ferry gauging station was used to investigate temporal changes in the flow regime downstream of the wetland. This station has operated from 1963 to date. The record was extended back to 1958 using data measured at Haussman's Bridge, a flow gauging station, located approximately 50km upstream of Msembe Ferry. This station operated between 1958 and 1988. The intervening catchment (4,200 km^2) is predominantly forest. There are no major abstractions between the two sites, but tributaries contribute to the flow at Msembe Ferry, particularly in the wet season. Using the period when both stations were operating (i.e., 1963 to 1988) a simple regression relationship was developed between the flows measured at the two stations (SMUWC, 2001d):

$$Q_{Msembe}(t) = A.Q_{Haussman}(t-b) \qquad [3.5]$$

Where: Q_{Msembe} = daily flow at Msembe Ferry

$Q_{Haussman}$ = daily flow at Haussman's Bridge

A = constant derived by linear regression

t = time interval (days)

b = lag time in days

The regression was done separately for the low flow season and for the high flow season. In both cases, the constant "b" was found to be zero. The constant "A" was determined to be 0.9217 and 1.0046 in the low flow and high flow season respectively (SMUWC, 2001 d). By interpolating to fill short periods of missing data, a complete daily flow record was derived for Msembe Ferry from 1st January 1958 to 31st December 2004. Long-term trends in river flows at Msembe station and rainfall over the Usangu Plains were analysed using conventional techniques of moving averages and linear regression. The student t-test (Helsel and Hirsch, 1993) was applied to test the significance of the slope of the trend-lines. The rainfall time series over the Usangu Plains was derived by combining data from rain gauges located on the Plains (Table 3.3). Daily rainfall was calculated as the numeric mean of the rainfall recorded at each gauge. Annual and seasonal flow duration curves were developed for the three windows using the Galway Flow Forecasting software (NUI, 2002). From flow duration curve (FDC) (i.e., a cumulative frequency distribution that show the percent of time that a specified discharge is equalled or exceeded during a period of interest), indices of flows were extracted and compared for the different time periods. To investigate the frequency of occurrence of low flow events, the ARIDA software (Fry *et al.*, 2001) was used.

Table 3.3: Rainfall stations used for estimation of rainfall for the Plains

Station name	Easting	Northing	Date of start of record	Status
NG'iriama	667427	9091296	1 Dec 98	Stopped 2002
Upagama Primary School	638232	9071732	1 Dec 98	Stopped 2002
Ikoga Primary School	677933	9070103	1 Dec 98	Stopped 2002
Madibira	701500	9091900	Restarted 1 Sep 99	Indeterminate
Mbarali	642200	9042800	1 Jan 58	Continuous

3.2.4 Ifushiro wetland study

The Ifushiro wetland is a surface water dependant wetland that gets water from the Great Ruaha River (Figure 3.6). Surface water and subsurface water levels in the wetlands were investigated to understand the interactions processes.

(i) Surface data collection and processing

Intensive monitoring of the Ifushiro wetland began at the beginning of January 2003 and continued until the end of March 2005. This section describes the instrumentation in and around the wetland, the monitoring conducted and the methods used in analysing the surface data collected. Figure 3.8 shows the location of monitoring sites at the Ifushiro wetland.

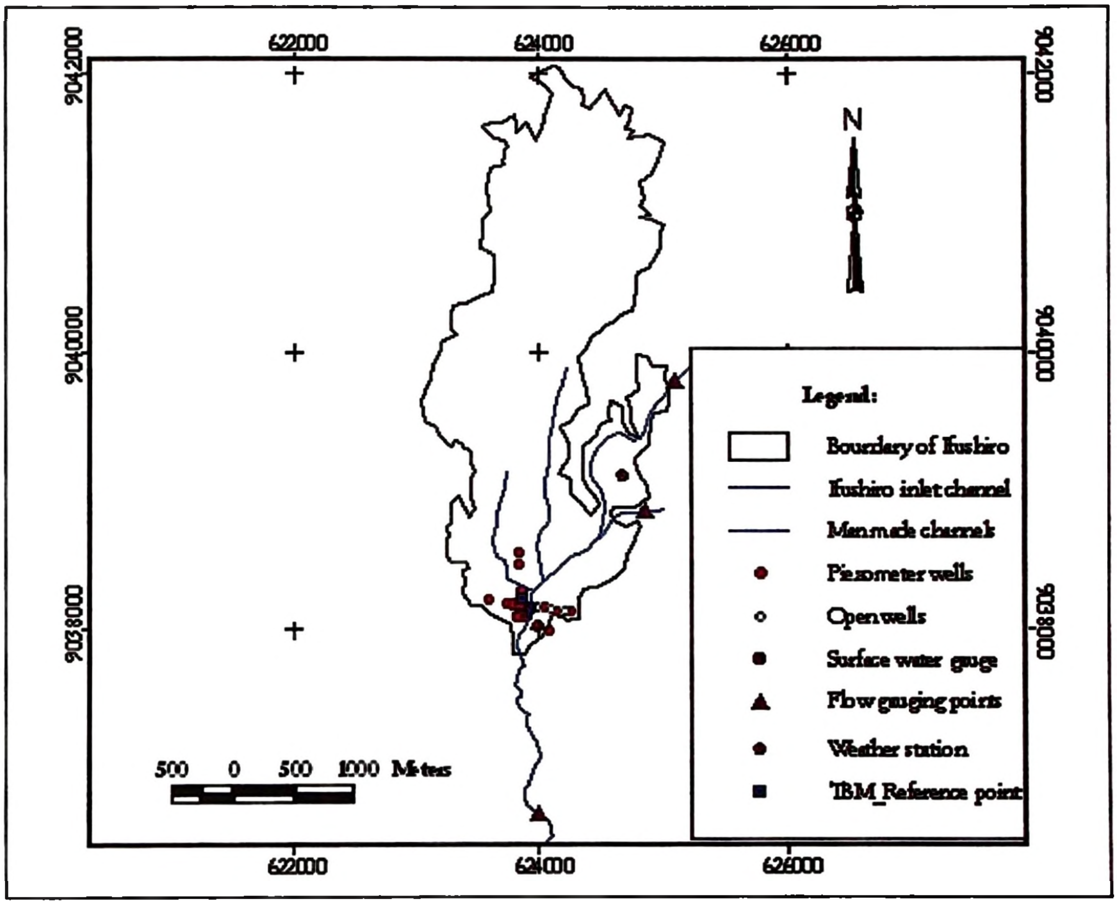


Figure 3.8: Location of monitoring sites at the *Ifushiro* wetland

Rainfall and evaporation

A rain gauge and Class A pan were established at the *Ifushiro* wetland at the beginning of April 2003. The rain gauge was used to collect the amount of rainfall received while the Class A pan was used to determine the amount of water evaporated from the wetland (Pan Evaporation). The collection of rainfall and evaporation data was done daily at 9.00 am starting from 01/04/2003 until 31/03/2005.

Potential evaporation estimation

Although the Penman equation is almost the *de facto* standard, in this study, daily Class A-pan evaporation (E_{pan}) was selected as a reference potential evaporation (E_r). The principal reason for collecting Potential Evaporation (PE) data in the current study was to serve as a guide in estimating actual evaporation when determining hydrological fluxes within the wetland. Other reasons included: a) a class A-pan (with diameter of 1200 mm and a depth of 254 mm) was readily available, and b) it is commonly used as a reference for PE, and relationships with maximum evaporation both from crops and to natural water body evaporation have been well documented (e.g. Doorenbos and Pruitt, 1977). It has also been found to correlate fairly well with pond and lake evaporation and evapotranspiration from a well watered vegetation provided periods of about two weeks to a month are used. However, although the correlations may be good, the regression equation constants (equation 3.6) change significantly with type of pan, type of vegetation, time of year and region. Kohler (1952) noted that pan evaporation rates are higher than for lakes and reservoirs, and recommended pan evaporation rates to be reduced by 30% when applied to open water within a wetland.

$$E_{lake} = P_p * E_{pan} \qquad [3.6]$$

where P_p = Pan factor or coefficient.

Flows

The Ifushiro wetland is ungauged both upstream and downstream. To gain an insight on the amount of water entering the wetland and leaving the wetland as surface runoff, water level staff gauges were installed. Also in order to understand the dynamic response of the water levels within the wetland, a water level staff gauge was installed inside the wetland. Standard procedures (USGS, 1982) for the installation of manual water level gauges including the selection of gauging site were followed.

Water levels, rating equation development and derivation of flows

Water levels collection

Measurement of water levels at the installed gauges commenced in January 2003. Readings from the installed gauges was done daily by a gauge reader. To improve the quality of data collected and efficiency, gauge readers were trained at site on how to read and book the data.

Rating equation

Discharge rating equations relate the observed/ or measured discharge to the stage. The derivation of flows from water levels requires development of a relationship between measured water levels and discharge (i.e., rating equation). This was facilitated by performing current meter measurements to obtain enough data points at different water levels and discharges to enable the derivation of the rating equation. However, during high flow periods, direct flow measurements using a current meter was not possible instead surface velocity approach was used. In this case, a relatively straight stretch of 20 meter close to the monitoring stations, identified by poles at one side of the bank was selected. Dry sticks were used as floats and these were thrown at the center of the channel just upstream of the initial observation point, and using a stop watch, the time taken by the float to travel a 20 meter stretch was recorded. The surface velocity was computed as distance of travel (i.e. 20 m) divided by the time taken by the floater to cover the distance. The procedure was repeated three times and the average surface velocity computed. This was then multiplied by a correction factor of 0.8 (Calvert, 2003) to obtain the mean velocity for the channel section. The cross-sectional areas corresponding to the depth of water read from the gauge at the time of measurement were determined using trapezoidal rule (Whittaker and Robinson, 1967). Knowing the area and average velocity, the discharge was computed as:

$$Q = V \times A \qquad [3.7]$$

where, Q is discharge in m^3s^{-1},

V is velocity in ms^{-1}, and

A is area in m^2

In this study, discharge measurement was done once a month and sometimes twice or three times depending on the river flow condition. The observed discharge and stage points were fitted with power function to develop the rating equation (Table 3.4). The rating curves were then used to transform the mean daily water levels to mean daily discharges for the period January 2003 to March 2005.

Table 3.4: Summary of rating equations at the Ifushiro wetland

Station ID	Rating equation	Range of water levels covered (m)	R^2	Comments
IF_G1	$Q = 7.9682\, h^{1.828}$	0 - 0.5	90.6	Inlet point
IF_G2	$Q = 0.226\, h^{1.039}$	0 – 0.6	83.7	Outlet point
IF_G3	$Q = 7.743\, h^{3.6545}$	0 – 0.5	97.9	Outlet point

It is important to note that a range of water levels covered using current meter were between zero and 0.5 m. During period of high flows, the channels attained higher water levels, approximately 1 m and at that time it was very difficult to do discharge measurements using a current meter. Instead surface velocity approach was used. According to (Marsh-McBirney, 2005) discharge measurements made with floats should be considered good estimates only as accuracy will range from approximately 10% to 25%. This can be a source of error for flows at greater depths estimated from the developed rating curves. But, since the target was the dry season, these were captured without greater certainty.

(ii) Subsurface data collection and processing

Instrumentation was installed in the wetland to obtain information on subsurface hydrological processes and hydrological fluxes change within the wetland.

Installations of wells

Site selection and soil profile characterization

Piezometers and monitoring wells were used to determine the depth of shallow water tables, and groundwater table elevations. The installation of wells followed the standard procedure as outlined by (Sprecher, 1993). Prior to installation, a site for the installation and monitoring of the piezometer wells was selected. Site selection for the monitoring wells were chosen based on a series of factors such as ease of access, hydrologic conditions, soil and geology type, and landscape setting. Furthermore it was decided that wells should be widely distributed to both sides of the main inlet channel to the wetland. Considering the above conditions, the site in the southern part of the main inlet channel (Figure 3.8) was chosen. Along a transect, small hand-dug test pits were dug and log of the test pit recorded following standard USDA-NRCS (2002) soil morphology description procedure. An important note is that it was necessary to have the soil profile described and evaluated before installation of the wells in order to identify strata that can alter vertical and horizontal water flows. The profile description included horizon depths and information about texture, induration (firm or hard), redoximorphic features, and roots, so that significant differences in permeability can be inferred. Once potential aquitard horizons had been identified in the soil, appropriate lengths and depths of well screen was determined.

Several soil characteristics may indicate that vertical water flow is impeded and that perched water tables exist. Thus, the main issues that were observed included the following: a) sudden change from many roots to few or no roots, b) sudden change in sand or clay content, c) sudden change in ease of excavation, d) sudden change in water content, such as presence of saturated soil horizons immediately above soil horizons that are dry or barely moist and e) redoximorphic features at any of the distinct boundaries listed above. The summary for the soil survey is presented in Appendix 1.

Installation of shallow monitoring wells and piezometers

Twenty-five wells were installed and used in monitoring water levels during the study period. The installations involved making holes into the ground using a hand bucket auger of a diameter of 0.0762m (Figure 3.9). The wells were made from 25 mm perforated polyvinyl chloride (PVC) pipe, and were installed to varying depths, up to 2.0 m. Prior to insertion of the slotted PVC pipe, a 0.051 m thickness of sand passing a 20-mesh screen but retained by 40-mesh screen (20-40 sand grade) was placed in the bottom of the hole. The slotted PVC pipe with a perforated cap at the bottom was inserted into the well followed by tamped sand (sand pack) to a depth of 0.152 m above and below screens. A bentonite clay seal of 0.305 m was provided on top of the sand filter to prevent water flow along the side of the pipe from the ground surface and through channels leading to the pipe. On top of the bentonite clay seal, excavated soil was backfilled followed by a concrete protection pad at the surface after inserting the casing with an extension of 1.00 meter above the ground surface (Figure 3.10). The casing was provided with a screw cap to avoid water from entering the well. After installation, all the wells including the gauge for measuring water levels in the wetland were surveyed to a common datum using a dumpy level. To check for clogging, water in the wells was pumped out using a hand pump (triddle pump) and monitored how quickly water levels returned to the pre-pumped level. If the well was dry, the pipe was filled with water and rate of outflow monitored. In principle, water levels in wells should return at approximately the same rate as they would in freshly dug holes without any pipe. This test was repeated regularly especially before the start of the rainy season and after the rainy season and sometimes when the readings from wells showed inconsistent pattern. It is important to note that a well can plug (i.e. well screens blocked) due to bacterial growth as well as slumping of dispersive soil.

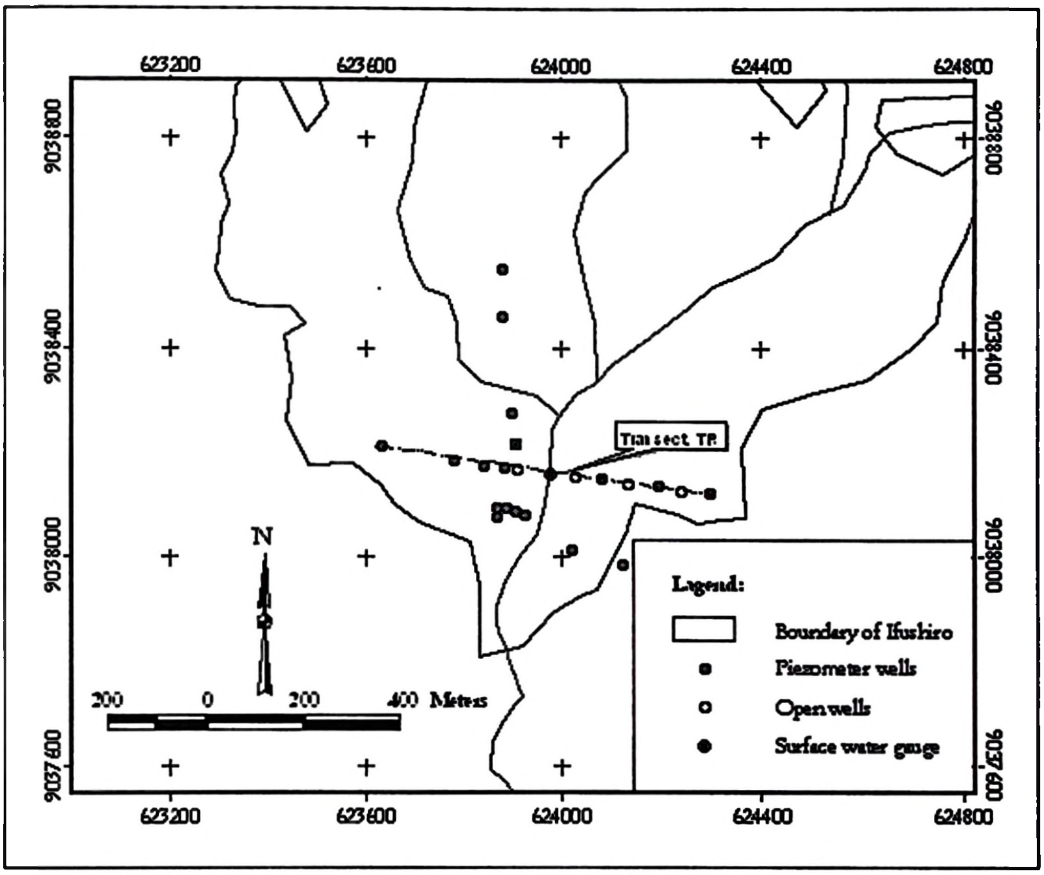


Figure 3.9: A well transect at *Ifushiro* wetland

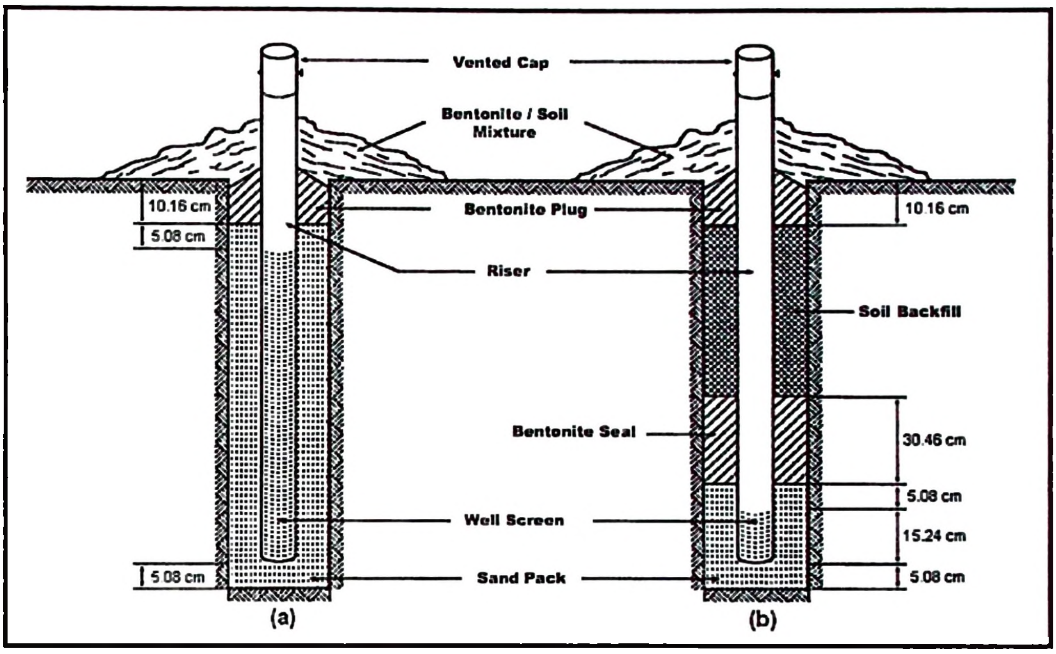


Figure 3.10: Schematic diagram of installed monitoring well and Piezometer. (a) Shallow monitoring well, (b) Piezometer

Note: The screen allows water entry into the sides of the pipe. In shallow monitoring wells the screen extends from the bottom of the pipe to within 6 inches (0.152 m) of the ground surface. In piezometers, the screen in the perforated end of the pipe, usually 6-12 inches (0.152 - 0.305 m).

Measurement of water levels in wells

Measurement was done daily from the top of the riser (casing pipe) to the water surface in the pipe using a manual dipper (steel tape). The water-levels were measured relative to the top of the well riser, and then converted to depth below datum so that the variation in the water table could be determined along the transect (Figure 3.9).

Estimation of hydraulic conductivity

To determine lateral subsurface fluxes in the wetland, estimates of soil saturated hydraulic conductivity were done. The slug test approach as suggested by Bouwer and Rice (1976) was used for the determination of saturated soil hydraulic conductivity.

The slug test consists of measuring the static water level (head) in the well, then introducing a near instantaneous change in water level, and measuring the change in water level over time until the water level returns to the original static level. The instantaneous change in head can be achieved by adding or removing a volume of water or solid into the well. A test that is initiated with a sudden rise in water level is known as a slug test, slug-in test, or falling-head test. A test that involves a sudden drop in water level is referred to as a slug-out test, bailer test, or rising-head test (Butler, 1997).

Since the diameter of the pvc pipe was small (i.e., 25 mm), the methodology adopted was to use a metal slug of known volume to produce rises and falls in the water-level within the wells. The metal slug (attached to a rope) was dropped into the well to cause a rise in the water table. The water-levels were then measured (using a manual dipper) until they fell back to their equilibrium position. Removing the metal slug resulted in a drop in the water-table, and measurements of the rising water-level were made until the levels once again returned to their equilibrium position.

For each test, saturated hydraulic conductivity (K_{sat}) was computed using the equations developed by Bouwer and Rice (1976). The following description of the test theory is based on Bouwer (1989). The expression used to compute hydraulic conductivity is shown in Equation 3.8:

$$Ksat = \frac{r_c^2 \ln(R_e / r_w)}{2L_e} \frac{1}{t} \ln \frac{y_o}{y_t} \qquad [3.8]$$

where: *Ksat* is the saturated hydraulic conductivity of the aquifer around the well

r_c is the radius of the casing where the water-level is measured

L_e is the length of the screened, perforated or otherwise open section of well

y_0 is the vertical difference between the water-level inside the well and the static watertable outside the well at time *0*

y_t is the vertical difference between the water-level inside the well and the static watertable outside the well at time *t*

R_e is the effective radial distance over which y is dissipated. Bouwer and Rice (1976) developed empirical relationships from electrical-analogue simulations to determine R_e for various system geometries

r_w is the radial distance from the centre of the well to the undisturbed portion of the aquifer (i.e. the radial distance to the normal *Ksat* of the aquifer, taking into account the region disturbed by drilling and the presence of any gravel and or sand packs)

Since *y* and *t* are the only variables in Equation 3.8, a plot of *ln* (y_t) versus *t* must be a straight line (McCartney, 1998). Thus, instead of calculating *Ksat* on the basis of two measurements of *y* and *t* (i.e. y_o at t = 0 and y_t at t) a number of measurements at various times were made and $[\ln(y_o/y_t)]/t$ determined as the best-fitting line through the *y* versus *t* points plotted on a semi-logarithmic scale. As the test progresses, the drawdown round the well becomes increasingly significant. For large values of *t* and small values of *y*, the points on the *y* versus *t* plot tend to deviate from the straight-line. Only the straight-line portion of the data points is used to evaluate $[\ln(y_o/y_t)]/t$ for calculation of saturated hydraulic conductivity (McCartney, 1998).

The Bouwer and Rice (1976) method estimates hydraulic conductivity of the aquifer near the screen. The following assumptions apply (Halford and Kuniansky, 2002):

- A volume of water is injected into, or is discharged from, the well instantaneously at t = 0.
- The well is of finite diameter and may partially penetrate the aquifer.

The Bouwer and Rice (1976) method applies to any diameter of borehole. The larger r_w and L_e, the larger the portion of the aquifer on which *Ksat* is determined (McCartney, 1998). In the current study, the holes augered for the piezometers were just 50 mm in diameter (i.e. R_e is 0.025 m) and the PVC pipe used to line the holes was 25 mm in diameter (i.e. r_c is 0.0125 m).

The field data were analysed using a spreadsheet computer package developed by Halford and Kuniansky (2002)

(iii) Modelling the Ifushiro wetland using MODFLOW

Understanding the changes that occurring in the wetlands requires knowledge of how surface water levels related to adjacent aquifer systems. This required complex three dimensional analyses to derive time-varying water table elevations over the irregular shaped area with partially-penetrating channels as line sinks (or line sources in the dry season) with variable stage and in hydraulic continuity with the underlying strata.

In this case Visual MODFLOW software (McDonald and Harbaugh, 1988) was applied to model the wetland processes.

Software selection and rationale

When developing a computer model, simplifying assumptions must be applied to permit practical solution of the inherent mathematical equations and to accommodate the data that are typically available. Since the assumptions and types of data required by each model can vary considerably, selection of the appropriate model is critical to the reliability of the modelling predictions. Modelling the flow of groundwater and the flow paths of constituents requires a mathematical system that can model the velocity and direction of groundwater flow. Several computer programs exist to solve these mathematical problems and Visual MODFLOW software has been found the best, applied widely and has become the most appropriate for many groundwater-related studies (Bradford and Acreman, 2003).

MODFLOW employs a block-centred approach and a modular structure consisting of a main program and a series of sub-routines grouped into packages. Each package includes specific features of a hydrological system, such as recharge or drains, and various methods to solve the linear equations (Anderson and Woessner, 1992). Visual MODFLOW is a sophisticated pre-processing/post-processing graphical user interface, which automatically creates the input files required by MODFLOW and downloads and interprets the outputs. This fully integrated modelling environment enhances model integrity by virtually eliminating errors associated with handling cumbersome data input files and output files. Besides ease of use, the application of a groundwater model, such as MODFLOW to in-field water regime studies has several potential benefits. For example, it can take account of spatial heterogeneities, vertical groundwater flow and any regional groundwater flow component (Anderson and Woessner, 1992). Whilst vertical leakage through clay sequences will occur at a low rate, and consequently will be a minor component at the field scale, the volume of leakage could be significant over the total area of a wetland. Irregular field boundaries and steep hydraulic gradients adjacent to a drain can be accommodated. However with a finite difference approach this may result in an excessive number of grid cells particularly with multiple layers. Recharge can be distributed areally and, although recharge is assumed to be instantaneous to the saturated zone, this is not necessarily a disadvantage where the depth to water table is shallow even in low permeability sequences. The Evapotranspiration Package in MODFLOW accommodates evapotranspiration from the soil. A maximum evapotranspiration rate is assigned to each cell when the water table equals an assigned head value (normally ground level) and ceases below a user-prescribed depth (extinction depth). The rate of evaporation is assumed to vary linearly between these two extremes, although the reduction in evaporation with depth is usually non-linear. Hence, the rate of evapotranspiration and extinction depth can be varied in each cell with time, in order to accommodate different rooting depths associated with different vegetation distributions. Another important feature of MODFLOW is the ability to represent a wide range of different drainage situations (drain, river or stream packages), including variable stage, different drain depths, geometry or configurations, bed permeabilities and to accommodate situations when the water table falls below the bed of the channel. The hydraulic conductivity of the bed of field drains penetrating a clay sequence can be assumed to equal that of the sequence.

Design of the *Ifushiro* model in MODFLOW

Model design includes all parameters that are used to develop a calibrated model (McDonald and Harbaugh, 1988). The input parameters include model grid size and spacing, layer elevations, boundary conditions, hydraulic conductivity/transmissivity, recharge, any additional model input, transient or steady state modelling, dispersion coefficients, degradation rate coefficients.

Finite difference grid

The model area is nearly rectangular with dimensions of approximately 2200 m x 4300 m (i.e., laying between coordinates 623000E, 9037800N and 625200E, 9042100N) long at the widest and longest points of the "active" model area, respectively. The primary finite difference grid for the model consists of 44 rows and 86 columns at the longest and widest regions of the "active" model area, respectively spaced at $\Delta x = \Delta y = 50$ m. Since MODFLOW allows refinery of grids to incorporate small features like wells and drain networks within the model domain, the primary grids were further refined by adding additional narrow rows and columns (Figure 3.11). Inactive cells (i.e. cells outside the model domain) were deleted to achieve the aquifer configuration after refining the grids.

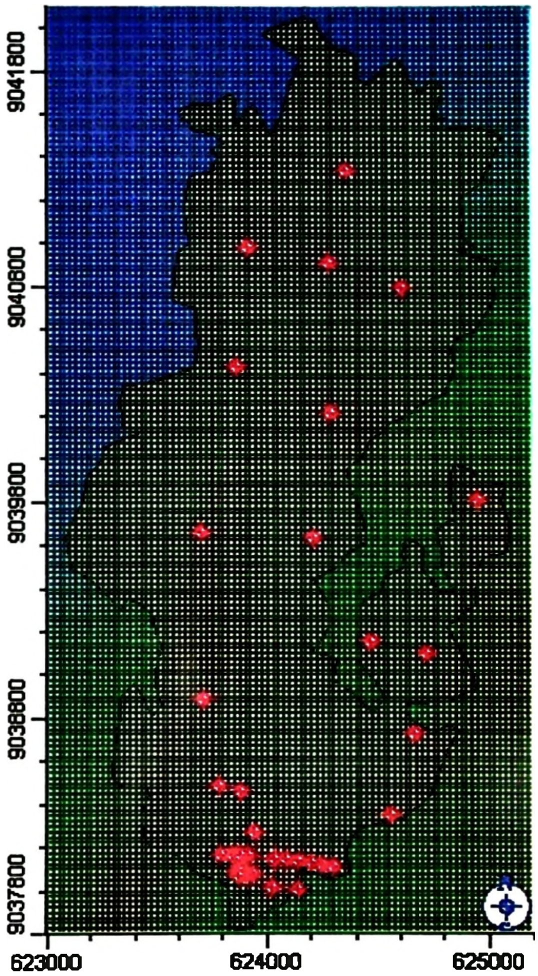


Figure 3.11: ***Ifushiro* model grid (the red points indicate the location of initial water level measurements)**

Boundary conditions

The side boundaries of the modelled flow region were taken as impermeable creating no flow boundary. The wetland was assumed to comprise of three layers: the surface clay (Layer 1), the peat layer (Layer 2) and the underlying sediments (Layer 3), consistent with layering observed from pits (Section 3.2.4 (ii)). Each layer was assumed to be homogeneous and isotropic and their vertical boundaries were determined from the well log data. The ground surface elevations at well locations and elevations at boundaries of layers were inserted into the SURFER6 software to create the surfaces (Figure 3.12) and then imported to MODFLOW.

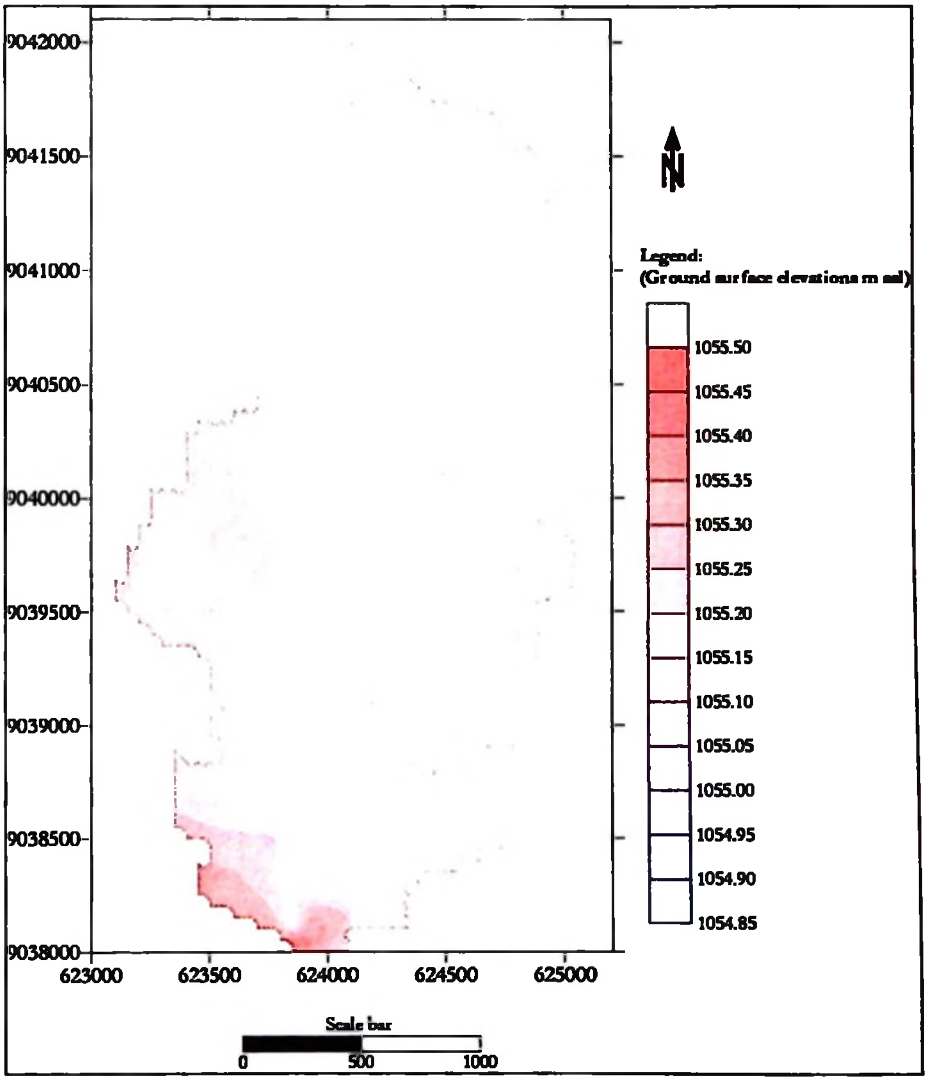


Figure 3.12: Distribution of ground surface elevation

The main inlet channel is typically 1.4 m in depth and 3 m wide while other channels inside the wetland are in the order of 0.4 m to 1 m depth and the width averaging to 1 m. These were represented as stage-controlled, head boundaries. The stage throughout the channel system within the model domain was considered uniform at any one time. As the channels generally penetrate to the peat layer, the permeability of the channel bed sediments was considered to be the same as that of the peat layer. The two ponds, one located close to the weather station and the other located in the north-western part of the *Ifushiro* area were treated as constant head boundaries.

Hydraulic conductivity, storage coefficient and hydraulic conductance

The hydraulic conductivity of the top (L1) and second layer (L2) was taken from published information. A typical K-value of 0.024 md^{-1} reported by Armstrong (1993) for an alluvial clay soil characterized by slow permeability was initially adopted. The second layer was considered to contain peat materials. These deposits are often anisotropic due to compaction and secondary permeability features and often show a correspondingly wide range in hydraulic conductivity. However, a K value of 1 m d^{-1} is considered typical of peat soils (Armstrong, 1993) and this was adopted initially for the peat layer. The horizontal permeability of peat deposits is often much greater than the vertical permeability and, as the peat layer is discontinuous and thin, it would have a very low transmissivity (Bradford and Acreman, 2003).

The third layer (L3) was assumed to be 8 m thick and to consist of sand loam soils as determined from well soil profile analysis. It was assumed to comprise of the hydraulic conductivity determined from slug test (section 3.2.4 above). The argument here is that since piezometer well screens extended largely to this layer, the rise and fall depended on the transmissive ability of this layer. Literature shows that such deposits are likely to have K values in the range of 0.1 to 10 md^{-1} (Anderson and Woessner, 1992), consistent with slug test results.

Storativity values for each layer were based on typical values given in the literature. Specific yield (S_y) values for alluvial deposits range from 1 to 10% (mean 6%) for clays and 10 to 30% for silty sands. Specific storage (S_s) values of 10^{-5} to 10^{-2} m^{-1} would be representative of the clay and 10^{-5} to 10^{-3} m^{-1} of the silty sand (Bradford and Acreman, 2003).

The hydraulic conductance, which defines the degree of interaction between the drain and the aquifer within the finite grid, was calculated using the following formula (Anderson and Woessner, 1992):

$$C = \frac{KLW}{M} \qquad [3.9]$$

Where, C is hydraulic conductance (m^2d^{-1})

K is hydraulic conductivity of the bed materials (m d^{-1})

L is length in a particular cell of the grid (m)

W is width of the drain (m)

M is thickness of the bed material (m)

The theory, which underlies the formula above, is based on one–dimensional Darcy's law where as true seepage into or out of river/drain is two-dimensional and comprises both saturated and unsaturated flow. The hydraulic conductivity was considered to be that of clay layer as it was found to be a dominant layer in most channel bed materials with an average thickness of 0.2 m, width of 0.5 in small channels and 1 m in main channel and a length of 10 m.

Recharge and evapotranspiration

In MODFLOW, recharge is normally estimated and entered as input values into the Recharge Package. For the initial calibration, rainfall data from the rain gauge at *Ifushiro* were used as recharge input values and applied uniformly over the model domain as 10-day mean daily values. The Evapotranspiration Package of MODFLOW was then used to simulate evaporative losses from shallow groundwater and soils. The initial input values were based on 10-day mean daily A-pan evaporation values and these were applied uniformly over the *Ifushiro* model area with an extinction depth of 1.0 m. When groundwater elevations were equal to land surface, the evapotranspiration rate was equal to the maximum rate. When depth to water in a cell was at the extinction depth, the evapotranspiration rate was zero. In between these depths, the evapotranspiration rate was linearly interpolated.

Calibration of *Ifushiro* model in MODFLOW

The model was run in time varying mode with a time step of 10 days. Initial groundwater heads corresponding to water levels recorded on 01/04/2003 were imported as surfaces to MODFLOW from SURFER6 Software (Figure 3.13).

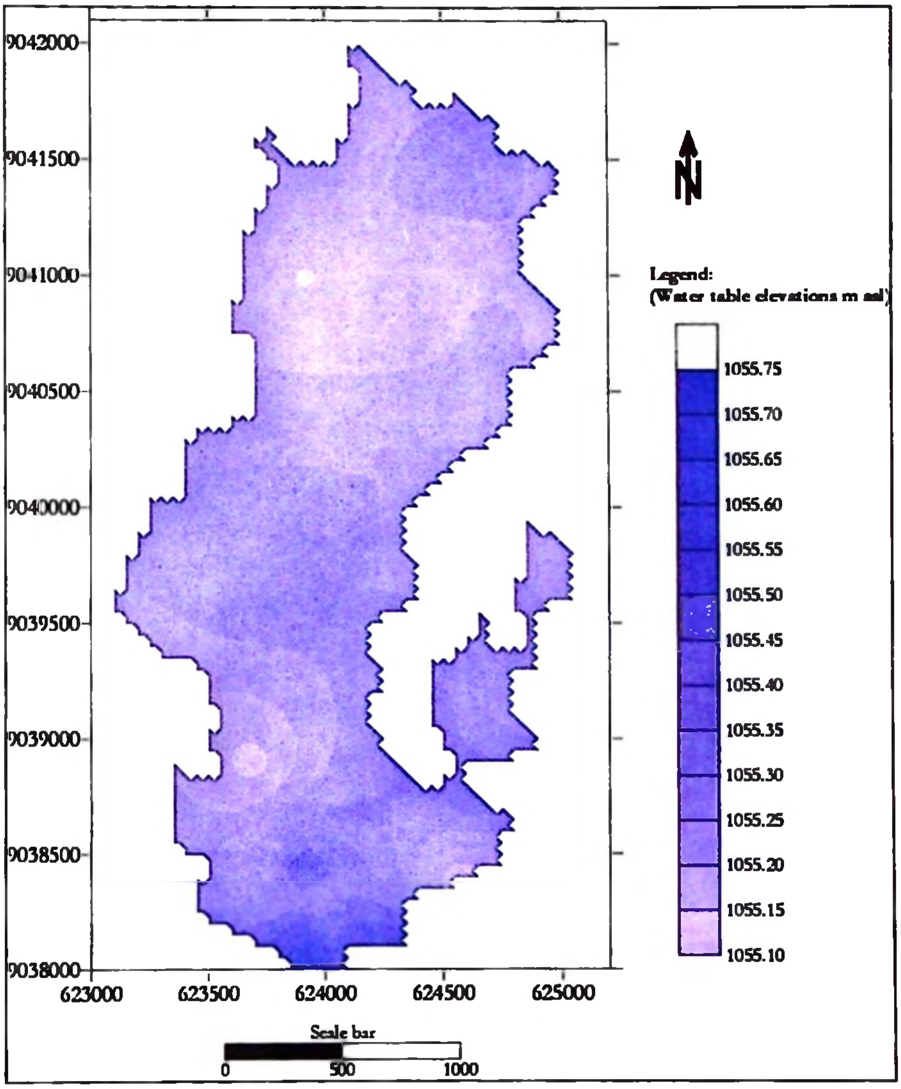


Figure 3.13: Initial water levels distributions (01/04/2003)

The period 01/04/2003 to 30/09/2004 was used for the calibration of the model as this period had the most detailed water level data. The results of the model calibration were expressed as water table contour maps and directions of groundwater movement together with mass water balances for the model domain and zonal water budgets for flow to drains/channels in the model domain at selected times.

The calibration was based mainly on water level hydrographs for wells located along the main transect. Traditional calibration measures (Anderson and Woessner, 1992) such as the mean error (ME), the mean absolute error (MAE) and the root mean square error (RMSE) that quantifies the average error in the calibration process were used. The mean error (ME) is the mean of the differences (residuals) between observed hydraulic heads (h_{obs}) and simulated hydraulic heads (h_{sim}):

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_{obs} - h_{sim})_i \qquad [3.10]$$

The MAE is the mean of the absolute value of the differences between measured hydraulic heads and simulated hydraulic heads:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|(h_{obs} - h_{sim})_i\right| \qquad [3.11]$$

The RMSE is the square root of the average of the squared differences between measured hydraulic heads and simulated hydraulic heads:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(h_{obs} - h_{sim})_i^2\right]^{0.5} \qquad [3.12]$$

where, i is serial number of observation wells

n is number of observation wells

$h_{obs,i}$ is observed head in i^{th} well

$h_{sim,i}$ is simulated head in i^{th} well

To minimize the residuals during calibration (i.e. the difference between calculated and observed/ measured hydraulic heads) input parameters were changed through trial and error. The RMSE was used as the basic measure of calibration for hydraulic heads. The RMSE is useful for describing the model error on an average basis but, as a single measure, it does not provide insight into spatial trends in the distribution of the residuals. Therefore, an examination of the distribution of residuals was necessary to determine if they are randomly distributed over the model grid and not spatially biased. Post plots of head residuals were used to check for spatial bias by indicating the magnitude and direction of mismatch between observed and simulated heads. Simulated head distributions were also compared to the head distributions developed from the field measurements (Figure 3.13). Scatter plots were used to determine if the head residuals were biased based on the magnitude of the observed head surface.

Sensitivity analyses

A sensitivity analysis was performed to determine the impact of changes in a calibrated parameter on the predictions of the calibrated model. A standard "one-off" sensitivity analysis was performed. This means that the hydraulic parameters or stresses were adjusted from their calibrated "base case" values one by one while all other hydraulic parameters were unperturbed. In this case, parameters were systematically increased or decreased from their calibrated values while the change in head was recorded. Four simulations were completed for each parameter varied, where the input parameters were varied according to:

$$\text{Sensitivity value} = (\textit{calibrated value})(\textit{factor}) \qquad [3.13]$$

And the factors were 0.8, 0.9, 1.1, and 1.2.

3.2.5 Development of hydrological model for the Eastern wetland

The flows downstream of the Usangu wetlands are dependent on the hydrological balance of the Eastern wetland. One of the primary objectives of this study was to estimate the inflows required to generate desired downstream flows. One of the challenges in doing this is the fact that inflows, in the perennial rivers, have only been monitored in a few years. Therefore, a spreadsheet model was developed to simulate the water budget of the wetland and compute the inflows over the period 1958 to 2004.

(i) Model development

The Eastern wetland was conceptualized as a reservoir (Figure 3.14) and the general water budget equation (Equation 3.14) was used:

$$Q_{in} = E + Q_{out} - P \pm \Delta S \qquad [3.14]$$

where: ΔS is change in water stored within the wetland

Q_{in} is the total inflow to the wetland including contributions from groundwater

Q_{out} is the total outflow from the wetland at the NG'iriama exit

P is rainfall falling directly onto the wetland (a function of wetland surface area)

E is evapotranspiration from the wetland (a function of wetland surface area)

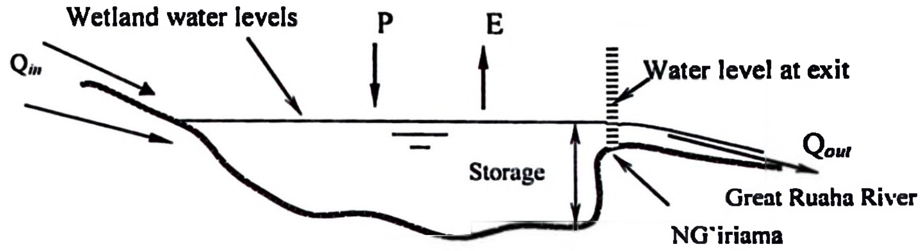
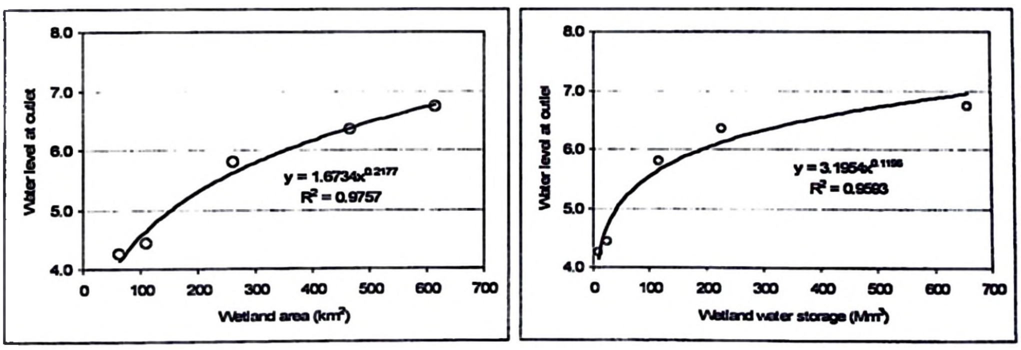


Figure 3.14: Conceptualization of the Eastern wetland as a simple reservoir

The water budget equation (Equation 3.14) was programmed in excel and was run on monthly time step.

(ii) Stage-area and stage storage relationship

A key assumption of the model is that wetland storage; area and outflow are all a function of water level at the outlet (i.e., at the rock sill at NG'iriama). Water elevation-area and water elevation-storage relationships derived during the SMUWC study (SMUWC, 2001d) were fitted with power functions to enable the wetland area and the storage to be calculated from water levels at NG'iriama (Figure 3.15).



(a) (b)

Figure 3:15: a) Water elevation- wetland area curve and b) Water elevation-wetland storage curve (developed from data in SMUWC, 2001b)

(iii) Derivation of outflows

The outflow from the wetland is dependent solely on the water elevation at the NG'iriama outlet. From measured water levels and discharge measurements, a rating equation was developed to convert levels measured at the outlet to discharge (SMUWC, 2001d), when h ≥ 4.3 m:

$$Q = 5.449(h - 4.3)^{3.375} \quad [3.15]$$

where: h is the water level measured to a local datum at the outlet. On this scale the rock sill is at 4.30 m (= 1009.525 m amsl). For water-levels lower than this there is no flow from the wetland.

Measured water levels were available at NG'iriama for the period 20/10/98 to 30/10/02. To extend the water-level series, it was assumed that the flow at NG'iriama was the same as that at Haussman's Bridge, located 30 km downstream of the outlet as there are no major abstractions or tributary inflows between the two locations. The flow record at Haussman's Bridge was extended from 1988 to 2004 using the Msembe Ferry flow record and Equation 3.5. The flow at Haussman's Bridge was assumed to equal the flow from the wetland and the NG'iriama rating (Equation 3.15) was applied in reverse to compute the time series of water level at the outlet. Thus a complete daily water-level record was derived for NG'iriama for the period 1958 to 2004. This provided the basis for calculating the wetland storage capacities and area.

(iv) Rainfall and evapotranspiration

Rainfall over the wetland was assumed to be the same as the rainfall over the Plains, and the data from the rain gauges in Table 3.3 was used. Potential evapotranspiration data derived at Dodoma meteorological station were used since data measured at this station was found to be representative of evaporation from the Usangu Plains (SMUWC, 2001c; Yawson, 2003). Evapotranspiration from the wetland surface was assumed to be at potential rates in all months. This is a simplification that makes no allowance for restrictions in evapotranspiration caused by water stress. For each simulation time step, the rainfall into, and the evapotranspiration from the wetland was computed by multiplying by the wetland area.

(v) Simulation of inflows

Having used the water-level information to compute outflows and evaporation, and taking rainfall over the wetland and the storage within it into account, the inflows were calculated as the unknown term in the water budget (Equation 3.14).

3.2.6 Environmental flows downstream of the Eastern wetland

Currently, there are more than 200 methods and approaches for estimating environmental flows (Tharme, 2003). Two approaches were considered in an attempt to determine "desired" dry season flows downstream of the Eastern wetland. In the Usangu Plains, where water is already over-allocated without any consideration of the environmental requirements, it is not reasonable to plan only environmentally favourable allocations. For this reason, the analyses conducted included consideration of current human abstractions as well as routing requirements. A number of alternative allocation scenarios were evaluated. For each, the wetland hydrological model was used to compute the inflows required to guarantee minimum dry season outflows.

Lack of data is often a constraint to estimating environmental flows. This is also true for the Great Ruaha River, where lack of requisite data and understanding of the linkages between different flow regimes and ecological impacts makes estimating flow requirements difficult. To compensate for the lack of ecological information, several methods of estimating environmental flows have been developed that are based solely on hydrological indices derived from historical flow data (Tharme, 2003). In this study the flow duration curve analysis (the most commonly used elsewhere in the world (Tharme, 2003; Pyrce, 2004)) and the Desktop Reserve Model (Hughes and Hannart, 2003) which was developed and widely used in Southern Africa were tried to evaluate the environmental flows. Analyses were based on the 1958-1973 (i.e., least modified) river flow data measured at Msembe Ferry.

The flow duration curve analysis

The "design" low flow range of a flow duration curve is generally in the Q_{70} to Q_{99} (i.e., flow exceeded 70% and 90% of the time) range (Smakhtin, 2001). The Q_{95} and Q_{90} are frequently used as indicators of low flow and have been widely used to set minimum environmental flows (i.e., Smakhtin, 2001; Tharme, 2003; Pyrce, 2004). From the flow duration curve for the pre-1974 period, low flow percentiles were extracted.

The Desktop Reserve Model

The Southern Africa Desktop Reserve Model (DRM) was selected and used to estimate the environmental flows for the Great Ruaha River. This was selected in consideration of the fact that it is a widely used tool in Southern Africa (i.e., South Africa, Lesotho, Swaziland and Zimbabwe) and ensures variability of flow which is important for ecology. The Desktop Reserve Model involves some process on data preparations and separations to different categories (i.e., high flow, low flows, drought flows). To clarify on these processes, a more descriptive methodology on the approach is provided in the following subsections.

Preparation of input data

The desktop reserve model (DRM) (Hughes and Hannart, 2003) uses historical observed or naturalized monthly flow data in the assessment of environmental flows. The historical river flow data for Msembe corresponding to the near-natural (least modified) flows was aggregated to create monthly flow time series for the 1958 to 1973 period.

Defining environmental management class

Environmental water requirement aim to maintain an ecosystem in, or upgrade it to, some prescribed or negotiated condition/ status also referred to as 'desired future state', 'environmental management class (EMC)'/ 'ecological management category', 'level of environmental protection (e.g. Durban *et al.*, 1998, DWAF, 1997). This study used the term 'environmental management class' (EMC). The information collected from the Ruaha National Park on the river condition and the present water situation was used in deciding the EMC category for the Great Ruaha River from Table 3.5. In that respect, the GRR was categorised as C/D.

Table 3.5: Environmental management classes (EMC)

EMC	Ecological description	Management perspective
A: Natural	Pristine condition or minor modification of in-stream and riparian habitat.	Protected rivers and basins. Reserves and national parks. No new water projects (dams, diversions etc.) allowed.
B: Slightly modified	Largely intact biodiversity and habitats despite water resources development and/or basin modifications.	Water supply schemes or irrigation development present and / or allowed.
C: Moderately modified	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present.	Multiple disturbances associated with the need for socio-economic development, e.g. dams, diversions, habitat modification and reduced water quality
D: Largely modified	Large changes in natural habitat, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitat modification and water quality degradation
E: Seriously modified	Habitat diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem.	High human population density and extensive water resources exploitation.
F: Critically modified	Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitat and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow pattern, river habitats etc (if still possible / feasible). – to "move" a river to a higher management category.

Source: Modified from Smakhtin and Markandu, 2005

Determination of annual IFR component

The annual IFR components (low and high flow maintenance quantities and the high and low flow drought quantities) were computed internally by the DRM software from the time series of monthly flows at Msembe. The description of the methods/approach used is contained in (Hughes *et al.*, 1998).

Flow variability index

Flow variability plays a major role in determining environmental flow requirements. Within the model two measures of hydrological variability are used. The first is a representation of long-term variability of wet and dry season flows and is based on calculating the coefficient of variation (CV) for all monthly flows for each calendar month. The average CVs for the three main months of both the wet and the dry season are then calculated and the final, CV-Index, is the sum of these two season averages (Hughes and Hannart, 2003). A limitation of the model is that in computing CV-Index, the model assumes that the primary dry season months are June to August and wet season months are January to March, as occurs over much of South Africa. Within the model this cannot be altered. However, for the Great Ruaha the key months were February to April and September to November for the wet and dry seasons respectively. To ensure that the model computed a flow variability index much closer to reality, and since it was dominated by the wet season months, the input time series of flows was shifted by one month (i.e., January became February etc.). The model output was then corrected to ensure that the results applied to the appropriate months.

Index of base flow

The index of base flow (BFI) represents the proportion of total flow that can be considered to occur as baseflow (i.e. baseflow index - BFI). Rivers with high BFI are less variable than those with low BFI values. The model computed the BFI from the monthly flows time series. The computed BFI was then compared to the one obtained from daily flows. The BFI computed from daily flows was used as a check to correct the computed BFI from the DRM. The model parameters that determined BFI (Figure 16) using the monthly flow data were modified (by trial and error) until the model computed BFI closely matched that obtained from the daily data.

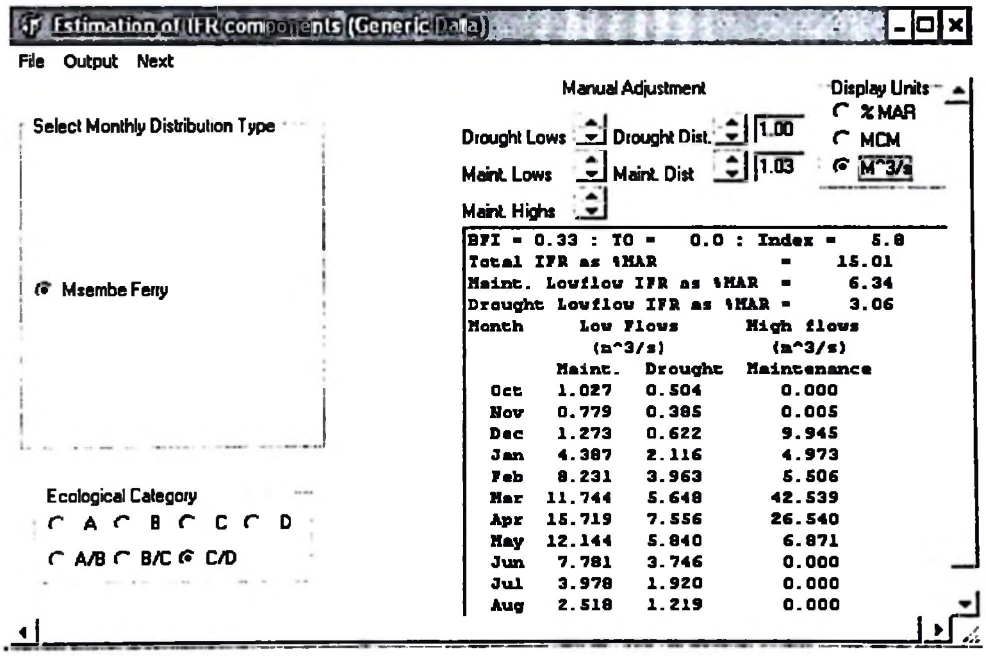


Figure 3.16: Illustration on manual adjustment of monthly values during calibration

Establishing the Assurance Rules

The DRM generated a modified time series of flow requirements that was assessed and revised through a calibration process. The model analysed the % of time that the recommended flows are equalled or exceeded (i.e. a flow duration curve analysis), which was thought of as expressions of the assurance with which certain target flows were achieved. The reserve rules were defined at 10, 20, 30, 40, 50, 60, 70, 80, 90 and 99%. These were then used to generate a representative time series of required flows.

Modification of reserve rule curves

The window that displays the rules graphically (Figure 3.17) includes an option to toggle between the months of the year and to modify the five parameters that are applicable to each month. These five parameters were the low and high flow shape factors, the lower and upper time shifts and the low flow maximum value. These were changed to ensure the graphical representation of the rule curves changed and their shape matched with the shape of the natural flow duration curve for that specific month.

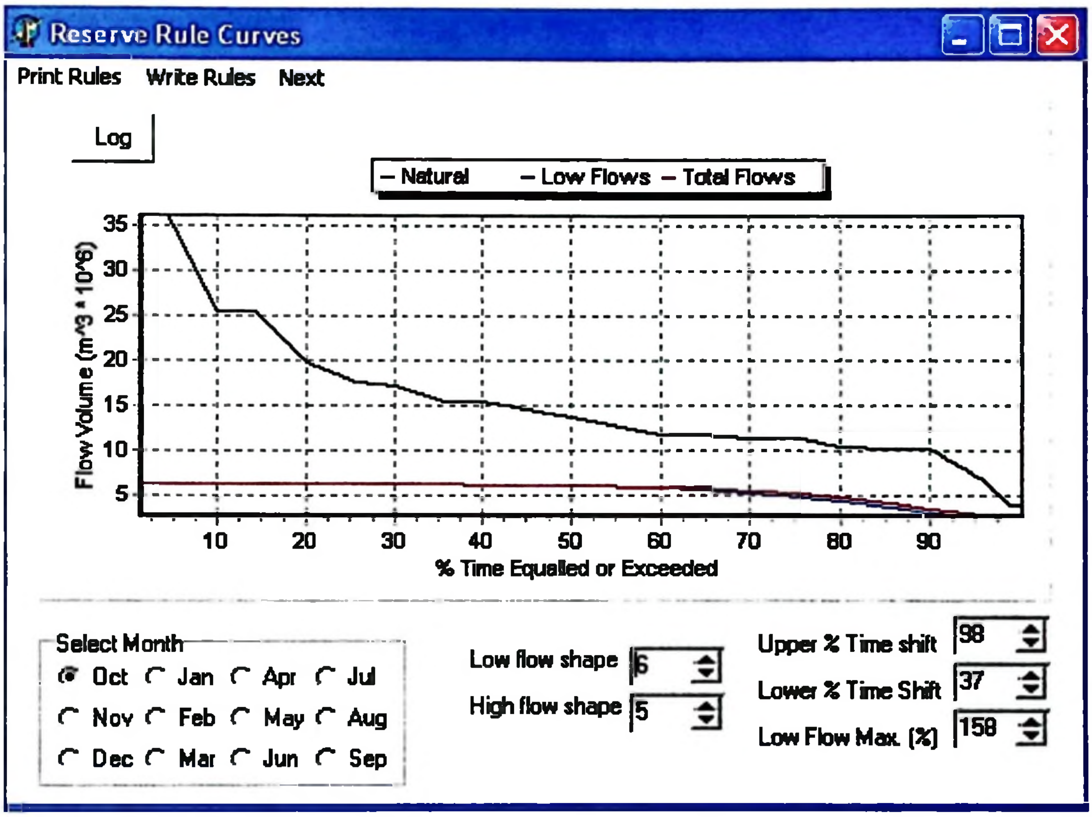


Figure 3.17: Capture of the reserve rule curve for October during calibration

Simulating continuous monthly time series of modified (environmental) flows

The final stage after parameter modification (calibration) was to generate a modified time series of the same length as the natural time series. This was carried out by using the calendar month duration curves of the natural time series and the assurance rule curves. The programs step through the natural time series, identifying the duration curve percentage point value of each month and generating the modified (IFR) flow as the monthly discharge volume equivalent to the same percentage point on the assurance curve for the same calendar month.

The FDC curve generated from assurance curves represented an environmental FDC for any EMC, and only gave a summary of environmental flow regime acceptable for chosen EMC. The curve however did not reflect the actual flow sequence. At the same time, once such environmental FDC was determined as described above, it was also possible to convert it into the actual environmental monthly flow time series. The spatial interpolation procedure described in detail by Hughes and Smakhtin (1996) was used for this purpose. The underlying principle in this technique was that flows occurring simultaneously at sites in reasonably close proximity to each other corresponded to similar percentage points on their respective FDCs.

The site at which streamflow time series was generated was called a *destination site*. The site with available time series, which was used for generation, was called a *source site*. In essence, the procedure was to transfer the streamflow time series from the location where the data was available to the destination site. In the context of this study, the destination FDC was the one representing the IFR sequence to be generated, while the source FDC and time series were those representing the reference natural flow regime.

For each month, the procedure: i) identified the percentage point position of the source site's streamflow on the source site's period-of-record FDC, and ii) read off the monthly flow value for the equivalent percentage point from the destination site's FDC (Figure 3.18).

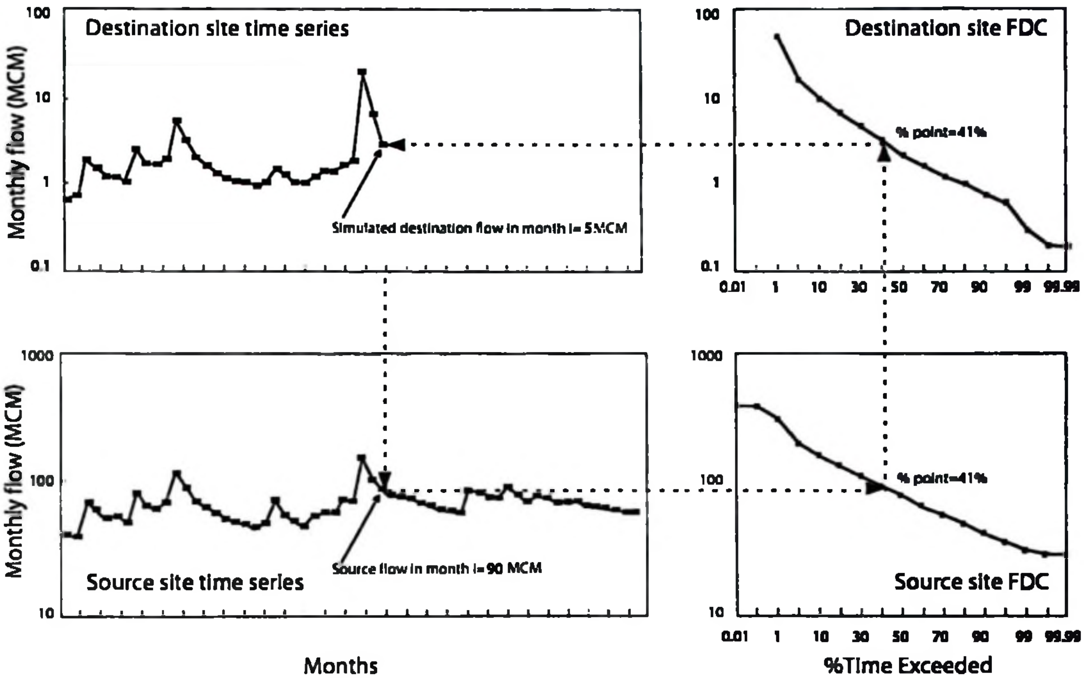


Figure 3.18: The illustration of the spatial interpolation procedure used to generate a complete monthly time series of IFR from the established assurance rule curves for a given EMC

Source: Modified from Smakhtin and Shilpakar (2005)

Limitation and accuracy of IFR estimates using DRM

It is important to recognize that the DRM parameters have been regionalized for South Africa only - based on past experience of IFR determinations, where there has been a considerable amount of input from ecologists and geomorphologists. Extrapolation to other areas, like Tanzania (Great Ruaha River) is expected to produce uncertain IFR estimates. However, in the absence of such input, it had to be assumed that relationships between hydrological variability and annual requirements for the Great Ruaha River are the same as for Dolomites in South African rivers which had the same monthly distribution pattern for both low and high flows. Some other parameters of the DRM (baseflow separation parameters, the seasonal distribution parameters, etc) were inferred from the available natural monthly flow time series. It is reasonably certain that parameter values that determine the annual volumes on the basis of the hydrological variability index need to be modified for Great Ruaha River from original South African values, used in this study. There is, however, no scientific ground upon which to base any such changes at present.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Dynamics of wetlands in the Usangu Plains

4.1.1 Distribution of land cover classes

Table 4.1 presents the distribution of land cover classes in the Usangu Plains for a subset study area (wetland area and neighbouring areas) for different years, while Table 4.2 presents a comparison in areas for the vegetated swamp cover of the Eastern wetland for wet and dry season in response of annual rainfall.

Table 4.1: Distribution of major land covers classes in the dry season for the subset area

Image aquisition Year	Land cover class	Area (ha)	% cover area of subset area (316 976 ha)
1973	VS	15 425	4.9
	CLB	12 116	3.8
	CW	33 164	10.5
	OW	136 893	43.2
	Other covers	119 381	37.7
1984	VS	26 975	8.5
	CLB	31 855	10.0
	CW	23 618	7.5
	OW	75 624	23.9
	Other covers	158 907	50.1
1991	VS	24 069	7.6
	CLB	67 926	21.4
	CW	10 570	3.3
	OW	103 891	32.8
	Other covers	110 524	34.9
1994	VS	20 895	6.6
	CLB	74 338	23.5
	CW	6489	2.0
	OW	82 148	25.9
	Other covers	133 109	42.0
2000	VS	8777	2.8
	CLB	87 433	27.6
	CW	9710	3.1
	OW	60 934	19.2
	Other covers	150125	47.4

Note: VS = vegetated swamp, CW = closed woodland, OW = open woodland and CLB = cultivation and bareland, other covers = closed bushland (CB), open bushland (OB), bushed grassland (BG)

Table 4.2: Comparison of wet and dry season vegetated swamp cover areas

Year	Annual Rainfall on the Plains (mm)	Wet season Vegetated Swamp (*Ihefu* area) (ha)	Dry season Vegetated Swamp (*Ihefu* area) (ha)
1973	696.4	na	11 960
1984	641.3	43 640	22 340
1991	519.2	na	20 410
1994	791.8	na	18 790
2000	403.0	31 810	8 290

na = not available

From Table 4.1, the VS, CW, OW represent a major portion of the wetlands in the Usangu Plains while CLB provides a direct indication of human modification. Other covers have been grouped together as "other covers". The information in Tables 4.1 and 4.2 depicts the different cover areas that were available for the three time frames or "windows" namely Pre-1974, 1974-1985 and post-1985 period. Therefore, in this discussion, the time frames/windows have been used more frequently than the actual image acquisition dates/years.

From Tables 4.1 and Figure 4.1 the cultivated land and bare land (CLB) have increased while closed woodland and open woodland generally declined up to 2000. The vegetated swamp cover, a major component of the Usangu wetland increased between 1973 and 1984 (Tables 4.1 and 4.2) but with a gradual decline up to 1994 and a sharp decline afterwards. Other covers (closed bushland, open bushland and bushed grassland) generally increased between 1973 and 2000.

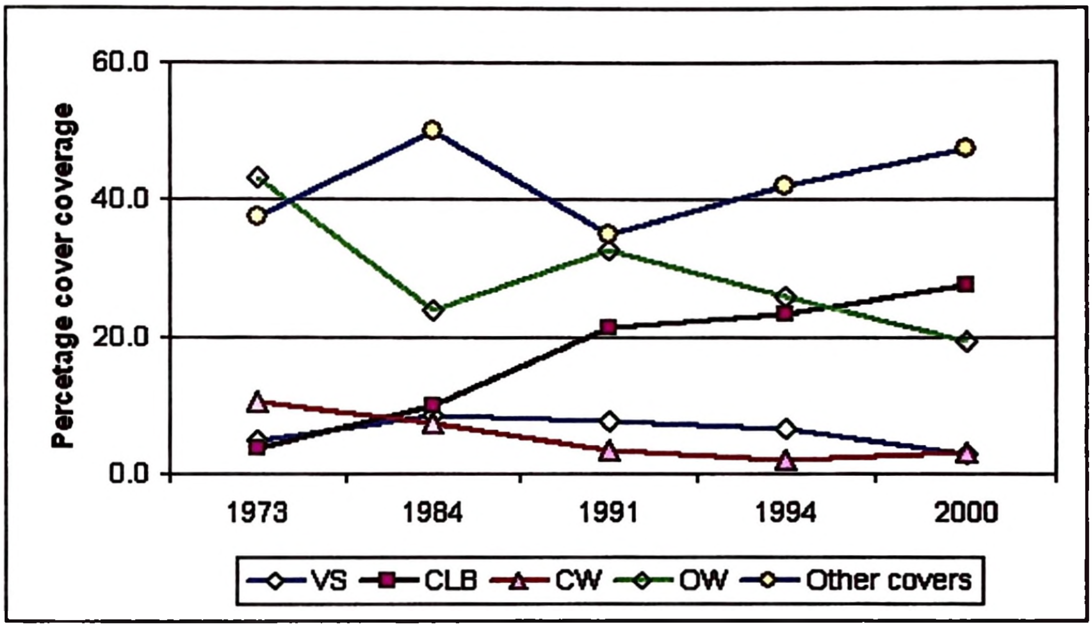


Figure 4.1: Cover coverage in percentage of the subset study area for different image acquisition dates (years)

The total area of vegetated swamp which occupied 15 455 ha (5% of the total geographical subset study area of 316 979 ha) in 1973, increased to 26 928 ha (8.5%) in 1984, indicating an increase in vegetated swamp area of about 3.5%, while in year 2000, the area covered by vegetated swamp decreased to 8778 ha (3% of the total subset area). While vegetated swamp cover increased in area between 1973 and 1984, and decreased afterwards, both closed and open woodland areas declined in areal extent. Closed woodland declined from 10.5% (of total areal cover in 1973) to 7.5% in 1984 and 3.1% in 2000. Open woodland declined from 43% in 1973 to 24% in 1984 and 19.2% in 2000. A simple analysis based on subtracting areas may often be misleading and in principle, should be supplemented by an analysis of change detection matrix (Mbilinyi, 2000). To examine in more detail how the land cover classes changed between 1973 and 1984, and between 1984 and 2000, the land cover transition matrices (change detection matrices) were calculated. For the period 1973 to 1984 the results are presented in Table 4.3 while for the period 1984 to 2000 are presented in Appendix B.

Table 4.3:Change detection matrix for the period 1973 to 1984 during the dry season

Cover 1973 (ha)	Cover in 1984 (ha) Dry season								Total
	CW	OW	CB	OB	BG	OG	CLB	VS	
CW	(7563)	4226	10583	2635	530	2992	1966	2669	33164
OW	8543	(40469)	48050	13320	10378	1455	13366	1311	136893
CB	3378	16732	(23367)	4696	3856	729	3951	430	57139
OB	1443	7749	9928	(2319)	1128	508	1183	468	24726
BG	1978	5167	5947	1281	(663)	210	724	129	16099
OG	674	1200	5460	2605	92	(2545)	206	8606	21388
CLB	0	0	685	519	443	7	(10450)	12	12116
VS	39	81	349	110	327	1236	8	(13303)	15455
Total	23618	75624	104370	27484	17417	9683	31855	26928	316979

(CW = closed woodland; OW = open woodland; CB = closed bushland; OB = open bushland; BG = bushed grassland; OG = open grassland. CLB = cultivation plus bare surface; VS = vegetated swamp)
Note: Numbers in brackets represent areas of no change during the period

The land cover transition matrix (Table 4.3) shows the area conversions between land-cover classes in 1973 and 1984. The numbers in brackets indicates the cover area which remained unchanged between 1973 and 1984, while others indicate the flow of covers or covers that changed to another cover category. It is important to note that all land cover categories changed but with varying magnitudes. For example, there was a transition from vegetated swamp cover to closed woodland, open woodland, closed bushland, open bushland, bushed grassland, open grassland and cultivation plus bareland.

4.1.2 Land use and cover changes between 1973-1984 and 1984-2000

The comparative analysis of the land uses and covers between 1973 and 1984, 1984 and 2000 identified the changes that took place for the different time horizons. The analysis indicated that the Usangu wetlands and neighbouring areas have undergone notable changes in terms of land cover area.

Table 4.4 summarises the net changes between 1973 and 1984, and between 1984 and 2000 and the estimates of the annual rate of change in terms of area and percentage annual rate of change during the period under consideration. Figures 4.2 and 4.3 are maps showing the changes in land cover between 1984 and 2000.

Table 4.4: Net area change between 1973 and 1984, 1984 and 2000 and percentage annual rate of change

Land cover classes	Net area change		Annual rate of change			
	1973-1984 (ha)	1984-2000 (ha)	1973-1984 (ha)	%	1984-2000 (ha)	%
VS	+11 550	-18 198	+1050	+6.8	-1137	-4.2
CLB	+19 739	+55 578	+1794	+14.8	+3474	+10.9
CW	-9546	-13 908	-868	-2.6	-869	-3.7
OW	-61 268	-14 691	-5570	-4.1	-918	-1.2
Other covers	+39 525	-8782	+3593	+3.0	-549	-0.3

Note: VS = vegetated swamp, CW = closed woodland, OW = open woodland and CLB = cultivation and bareland, other covers = closed bushland (CB), open bushland (OB), bushed grassland (BG)

Table 4.4 indicates that cultivation plus bare land cover class experienced the highest annual increase (+14.8% per year) between 1973 and 1984 and (+10.9% per year) between 1984 and 2000. The closed woodland and open woodland consistently declined between the two time horizons (i.e., -2.6% and -3.7% per year and -4.1% and -1.2% per year) between 1973 and 1984, and between 1984 and 2000 for closed and open woodland respectively. Other covers (closed bushland, open bushland, bushed grassland) increased by (+3.0% per year) between 1973 and 1984 and declined at -0.3% per year between 1984 and 2000. The vegetated swamp had the highest net decrease (-4.2% per year) between 1984 and 2000. In the former window it increased at a rate of +6.8% per year between 1973 and 1984. The increase in vegetated swamp cover between 1973 and 1984 as opposed to the period 1984 and 2000 was subjected to further analysis to identify its causes by analysing the inter-annual rainfall variability and the details are discussed in the following section.

4.1.3 Variations on detected changes and interpretations

Discrepancies or variations on results from change detection analysis are inevitable and these could impair the interpretability for the detected changes. In this study, some variations on the detected changes were noted. For instance, an increase in cover of vegetated swamp for the period between 1973 and 1984 had been detected which contravene the detected decline in area coverage after 1984. Nevertheless, it is highly acknowledged that ecosystems dynamic response is non-linear and depends on many drivers/factors but the most prominent is the variation in rainfall pattern and distribution. A linear trend analysis on annual rainfall data in the Usangu plains for the period 1973 to 1984 revealed that there was not statistically significant increase in rainfall amount between 1973 and 1984 at the 95% confidence level. Instead rainfall decreased (section 4.2.2 and 4.2.3).

Likewise, no significant change on temporal distribution of rainfall was revealed. Therefore, it is unlikely that the apparent increase in vegetated swamp area between 1973 and 1984 can be attributed to an increase in rainfall. It is possible that the change variations were due to plant phenological effects and spectral resolutions as discussed hereunder.

The different plant phenological effects are related to the season to which an image is acquired on the ground by the satellite. Studies have shown that the dry period is the most desirable period for image change analysis.

As noted by Burns and Joyce (1981), selecting the driest period of the year for change analysis will enhance spectral separability and yet minimize spectral similarity due to excessive wetness prevailing during other periods of the year. The wet season spectral separability, which is responsible for class assignment, becomes somewhat difficult and may result into misclassification of some of the classes, which results into under-or over-classification. But this is unlikely to be a source of variation as images used for this study were obtained in the dry season (Table 3.2) though at different dates. As highlighted above, the variation could also be caused by the use of images with different spatial resolution as revealed by some studies. For example, a study by Zhou *et al.*, (2004 a) on detecting and modelling land use change using multi temporal and multi-sensor imagery concluded that poor classification results were found in association with lower spatial resolution, demonstrated by the higher fluctuation of area statistics results. More details on influence of spatial resolution on change detection could be found in (Zhou *et al.*, 2004 b; Benson and MacKenzie, 1995; Frohn, 1998). Therefore, it is possible that the apparent increase in vegetated swamp cover area between 1973 and 1984 is an artefact of the different resolutions of the two images (i.e., Landsat MSS of 1973 had 79m x 79m while Landsat TM of 2000 had 30m x 30m).

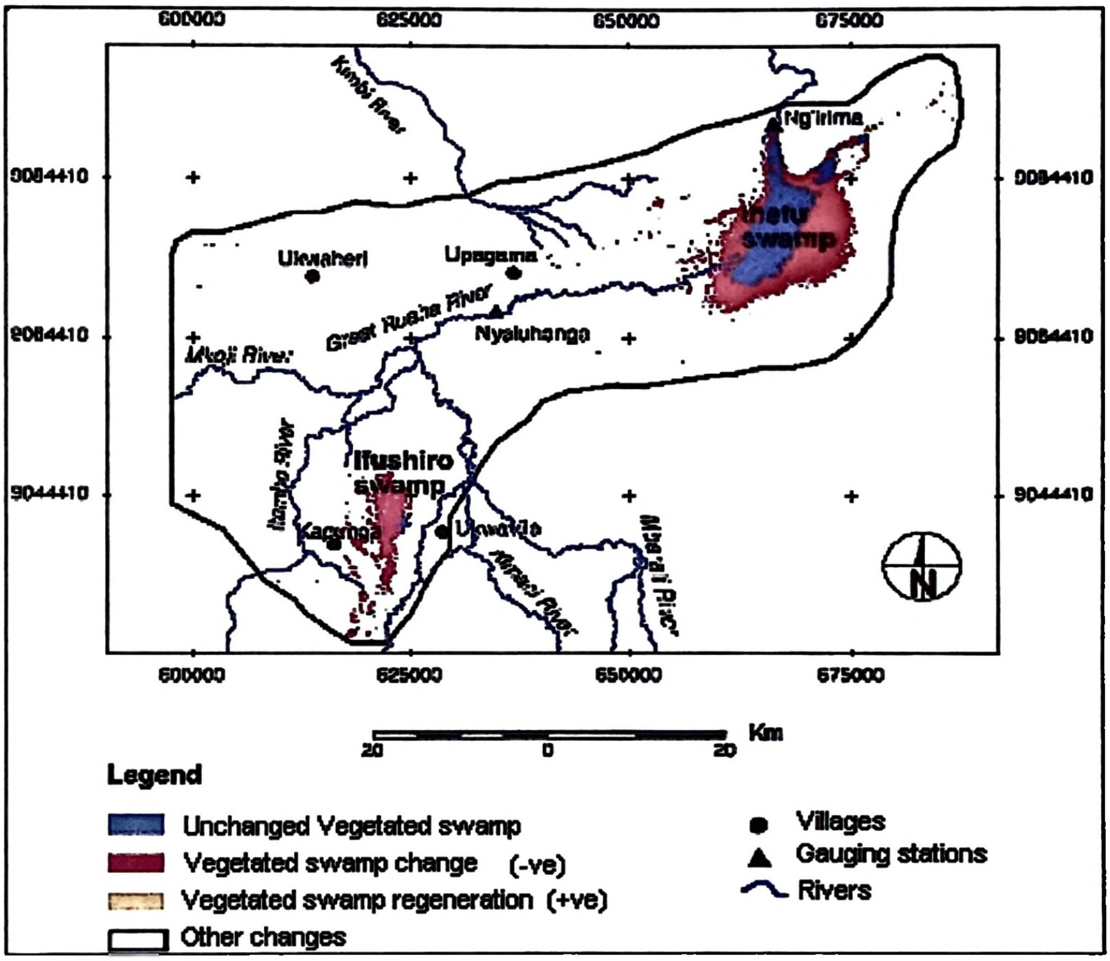


Figure 4.2: Dry season land cover change for vegetated swamp from 1984 to 2000

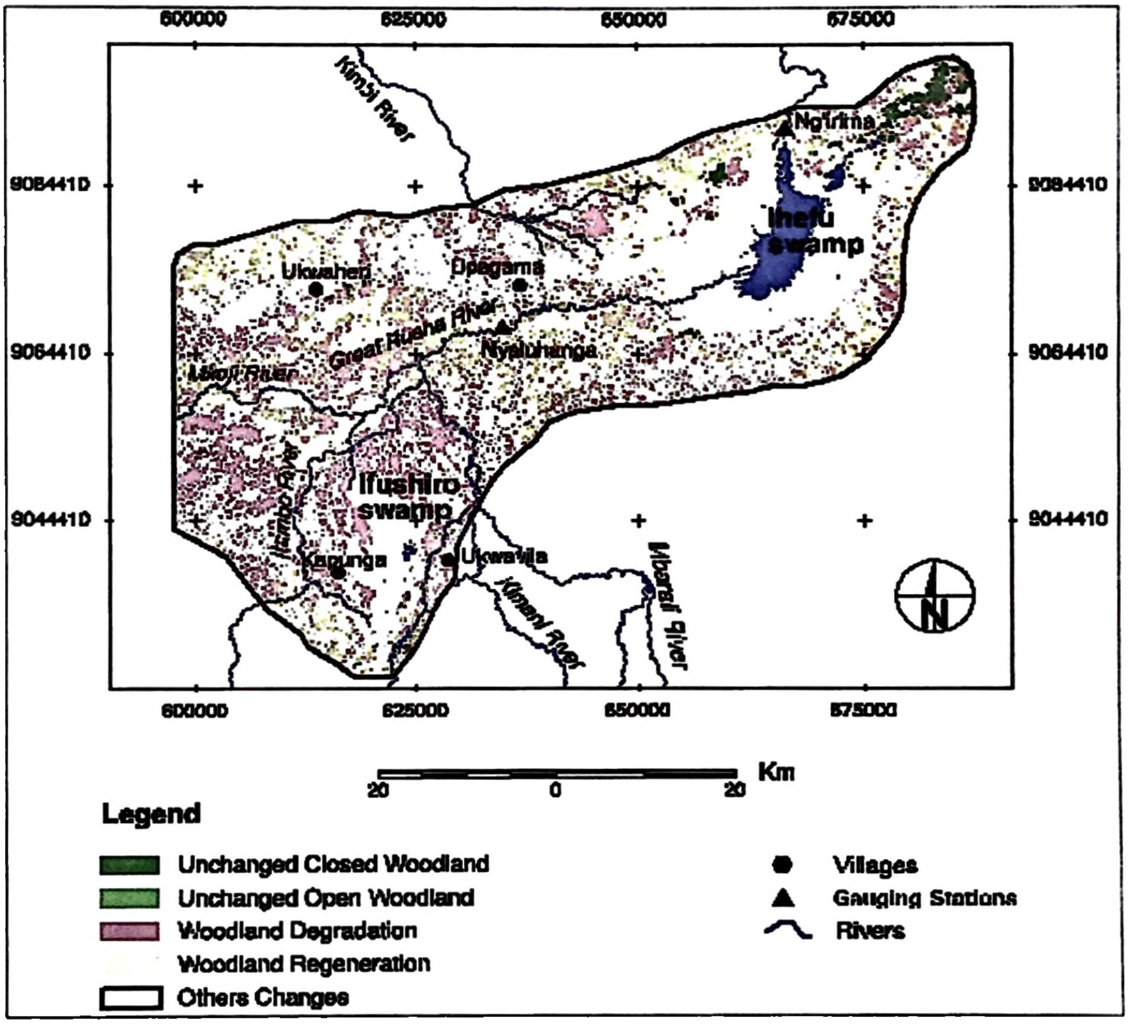


Figure 4.3: Dry season land cover change for woodland from 1984 to 2000

4.1.4 Linking detected changes to causes

i) Changes due to human population and immigration

There is a close link between ecosystem change and the increased anthropogenic activities. The increase in anthropogenic activities reflects an increased population. Figure 4.4 presents the population dynamics in Mbarali district where the Usangu wetlands are located.

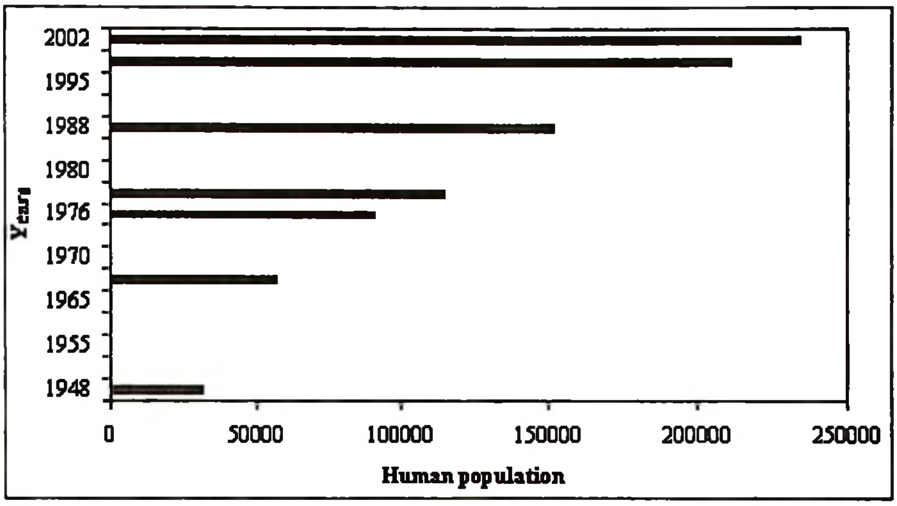


Figure 4.4: Population dynamics in the Mbarali District

Sources: Tanzania Population and housing census website and SMUWC (2001a)

The growth in population reflects increased human socio-economic activities (i.e., expansion in agriculture, timber, woodworks, etc). The review of literature showed that the Usangu Plains had undergone different phases of development and as earlier discussed. The phases could be broken into three time horizons. The pre-1974 was regarded as a near-natural period with moderate human interventions. The major interventions during this period were the introduction of irrigated agriculture by people from Baluchistan in the 1940s and the construction of the Mbarali rice farm (3 200 ha) in 1972. At the end of this window, the population in Usangu was approximately 90 000 and the irrigated area was about 12 000 ha. The 1974-1985 window was a period characterized by rapid increase in both population and irrigated area. At the end of the window, irrigated area was about 26 000 ha and the population was estimated at 150 000. This represented 67% increase in population and a 117% increase in the area under irrigation over a period of 12 years.

The post-1985 (i.e., 1985-2000) window was characterized by increased water abstraction as a result of continued population growth, increased irrigation and increased pastoral activities. Increased catchment degradation, expanded markets and increased conflict (over limited water resources) also characterized it (SMUWC, 2001 a). During this period, the Kapunga rice farm (3 000 ha) was commissioned abstracting water from the Great Ruaha River. Other new irrigation schemes commissioned in this period included: Kimani (6 000 ha), Madibira (3 000 ha), Majengo (800 ha), Mswiswi (800 ha), Motombaya (800 ha), Ipatagwa (700 ha), Meta Lunwa (1 200 ha) and Chimala (3 000 ha).

Land cover clearance which involved tree felling was one of the activities associated with expansions in agriculture. The results (Table 4.1 and Figure 4.1) showed that, expansion of agricultural activities was associated with conversion of closed and open woodland to other forms of land cover (refer to Appendix B). From interviews with farmers and ground-truthing, it was ascertained that most woodland and bushland areas were found cleared for agriculture. Also felling of trees for economic timber production was found to be a dominant activity in villages close to forests.

The developments that took place after 1984 involved draining of the wetlands. This phenomenon was confirmed by interviews with key informants around Kapunga, who also reported that the present-day *Ifushiro* wetland and the Kapunga areas previously supported huge forests as well as other natural vegetation but presently, all have been cleared. The rise in population and the associated changes were accelerated by an influx of immigrants.

To gain an understanding on the reasons for the immigration to the Usangu Plains, different reasons were given. More than half of the immigrant households reported to have migrated to the sample villages before 1989. High immigration fluxes were reported to have occurred between 1968 and 1971, in 1984, early and late 1990s and in 2000. When asked to rank the reasons of their migration to the Usangu Plains, most of the immigrant respondents (53% in Ihahi; 48% in Ukwavila and 30% in Uturo) pointed out the fertility of the land, and suitable grazing land for livestock (35%, 45% and 38% respectively) as the major reasons (Table 4.5). Other factors (e.g., migration due to marriage and employment/official) were given less weight, representing only about 3% in Ihahi; 5% in Ukavila and 10% in Uturo villages.

Table 4.5: Respondents on major reasons for migration into the Usangu

	Ihahi		Ukwavila		Uturo	
Reasons	Frequency	Percent	Frequency	Percent	Frequency	Percent
Soil fertility	21	53	19	48	12	30
Availability of grazing land and pasture	14	35	18	45	15	38
Migration due to marriage	4	10	1	3	9	23
Employment/ official transfer	1	3	2	5	4	10
Total	40	100	40	100	40	100

Source: Own survey, (2003 - 2004)

It was also revealed that about 40% of the interviewed households in the sample villages were immigrants from other areas. The majority are the Sukuma agropastoralists originating from Shinyanga, Mwanza and Tabora regions (41%). Other immigrants originate from the Lower GRR catchment in Iringa region and other areas in Mbeya region.

ii) Changes due to economic development and increased poverty at local level

In the Usangu Plains, the detected changes in cover were related to the change in economic development as a result of infrastructure development, and the increased poverty. This is evident from the general understanding of the Usangu area and the interviews with key informants. At the village level, land use/ cover change was highly related to the percentage of population living under poverty. Lambin *et al.* (2001) related this to agricultural intensification, and argued that small-holders have no choice but to increase inputs and/or cropping frequency to eke out a living on decreasing per capita land area, and with increasing competition (*land scarcity* driver).

On the infrastructure side, some large-scale water control projects were initiated. For example, over the past 15 years there have been a series of programmes aimed at improving smallholder irrigation (FAO, 1983; World Bank, 1996). In principle these programmes aimed to improve the "efficiency" of water use and thereby increase water availability downstream (Franks *et al.*, 2004). They tended to focus on irrigation infrastructure and in particular on the construction of concrete intake works and other system modifications. However, recent work has raised doubts, both about the theoretical basis for such programmes and its actual outcomes (Lankford and Gillingham, 2001). Practically, the physical improvements to the system were intended to give greater water control to farmers, particularly at the head of the systems, and the farmers responded by taking more water, rather than less (Franks *et al.*, 2004). The result has been to decrease river flows downstream. In addition, such development has led to a rapid and remarkable transformation in the Usangu through change in land use to paddy fields.

iii) Changes due to inadequate institutional arrangement

Fragmented and uncoordinated institutions accelerate the land use and cover changes. For example, presently, there is no specific legal and policy framework regarding wetlands, but wetland-related issues are touched upon in a variety of laws, policies and strategies, due to the inherent cross-sectoral character of wetlands issues. The policy and legal framework surrounding wetlands can be roughly divided into policies and laws of a sectoral nature (Wildlife, Fisheries, Agriculture and Livestock, Forest and Minerals) and those of a more general and cross-sectoral nature (Water, Environment and Land). Thus there is no single legislation covering the use, development, management or conservation of wetlands. This was also revealed from the respondents, where over 90% of the respondents reported to have not been aware of the environmental policies and the governing laws.

4.2 Flow regime downstream of the Eastern wetland

4.2.1 Annual rainfall and discharge for the Great Ruaha River

Figure 4.5 shows the time series of annual rainfall over the Usangu Plains, while Figures 4.6 and 4.7 show the time series of annual flows and dry season flows in the Great Ruaha River as recorded at Msembe Ferry station respectively. Figure 4.8 presents the annual rainfall over the high catchment and the Usangu Plains for the period 1973 to 1984. Visually, the annual rainfall over the Usangu Plains and the annual flows at the Msembe station do not clearly depict any increasing or decreasing pattern unlike the dry season flows (Figure 4.7) which shows a declining pattern, much occurring from early 1990s.

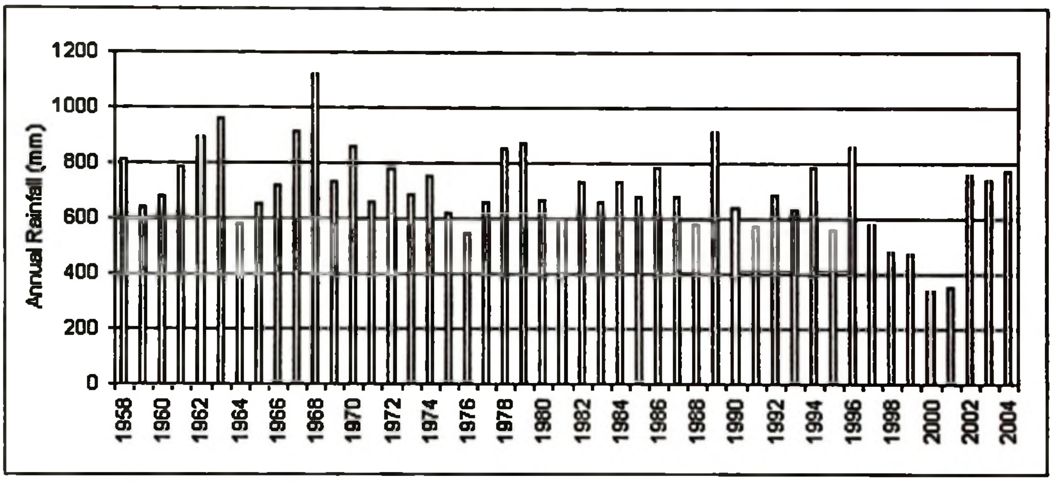


Figure 4.5: **Annual rainfall over the Usangu Plains (1958-2004)**

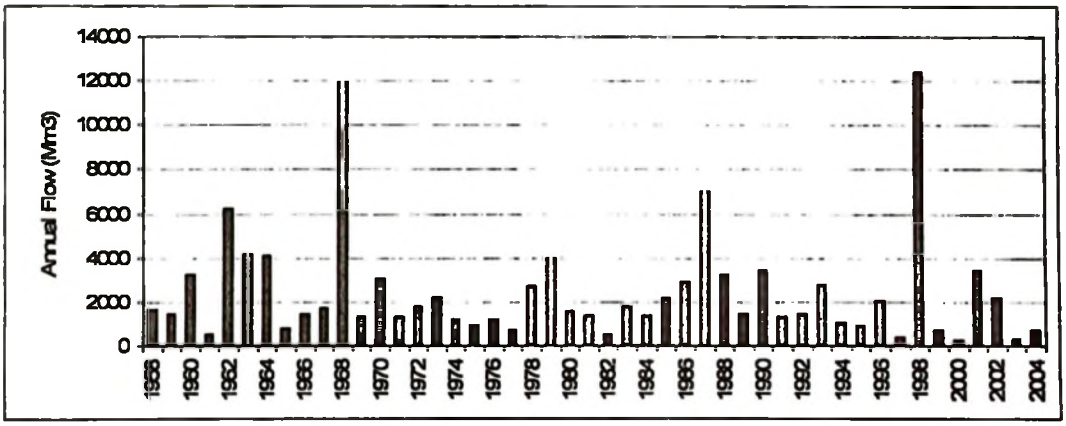


Figure 4.6: **Annual flows in the GRR at Msembe Ferry (1958-2004)**

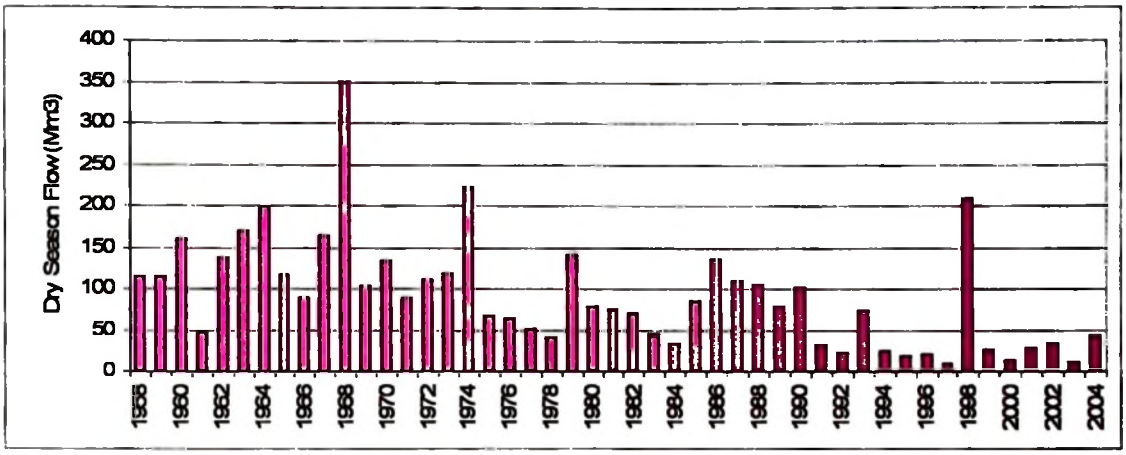


Figure 4.7: Dry season flows (July to November) in the Great Ruaha River at Msembe Ferry (1958-2004)

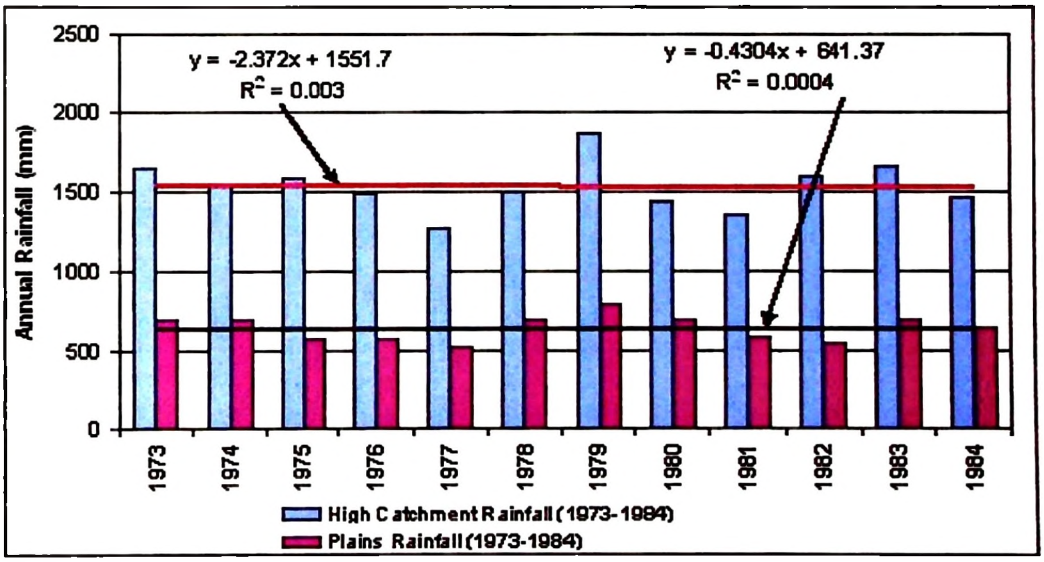


Figure 4.8: Annual rainfall over the high catchment and the Usangu Plains (1973-1985)

4.2.2 Statistical trend analysis on rainfall and flows

Table 4.6 presents results of trend analysis on rainfall over the Usangu Plains and selected stations in the high catchment while Table 4.7 presents results of trend analysis on annual and dry season flows at Msembe Ferry. The results (Table 4.6) indicated that there is no significant decreasing or increasing trend in the annual rainfall in the high catchment but with the significant decreasing trend in annual rainfall over the Usangu Plains for the period 1958 to 2004 at the 95% level of significance. However, considering the period 1973 to 1984 there is no significant trends on the annual rainfall over the Plains.

The results (Table 4.7) indicated that there is no significant decreasing or increasing trend in the annual river flows for the Great Ruaha River downstream of the Usangu wetlands at the 95% level of significance. However, a significant downward trend in dry season flows has been depicted. The perennial rivers (Great Ruaha River at Salimwani and Mbarali River at Igawa) which contribute a large quantity of flow to the Usangu Plains and the most important rivers in the dry season indicated a no significant trend in annual flows.

The results concluded the fact that the amount of flows generated from high catchment has not statistically changed. Therefore if any change might have occurs in the high catchment could not have contributed to decreased dry season flows in the Plains. It is there the changes in land use and land cover in the Usangu Plains which contributed to decreased dry season flows.

Table 4.6: Summary of statistical trends in annual rainfall at some stations in the high catchment and in the Plains

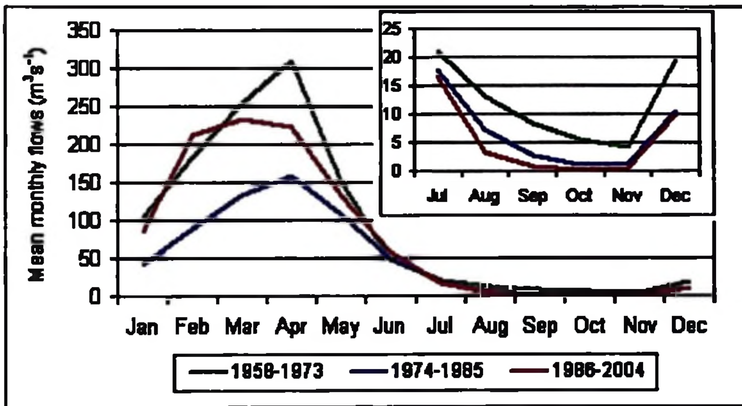
Description of parameter	Start year	End year	No. of years	Mean Annual Rainfall (mm)	Slope of trend line (mm/year)	t-statistics	t-critical	Remarks
High catchment								
Annual rainfall at Mbeya Maji	1961	2003	43	943.580	-3.198	-1.540	2.019	Not a significant decreasing trend
Annual Rainfall at Tanganyika Wattle	1928	2003	76	1103.470	2.079	1.893	1.993	Not a significant increasing trend
Annual rainfall at Ichenga Agriculture	1958	2001	44	1343.040	-4.456	-1.668	2.018	Not a significant decreasing trend
Annual rainfall at Mbeya Met.	1956	1999	44	973.070	2.541	0.986	2.018	Not a significant decreasing trend
Areal annual rainfall (1973-1984)	1973	1984	12	1536.3	-2.372	0.381	2.228	Not a significant decreasing trend
Usangu Plains								
Annual rainfall over the Usangu Plains	1958	2004	47	701.470	-4.456	-3.020	2.016	Significant decreasing trend
Annual Rainfall over the Plains (1973-1984)	1973	1984	12	699.200	2.592	0.676	2.228	Not a significant increasing trend

Table 4.7: Summary of statistical trends in annual and dry season river flow at Msembe Ferry, annual flow for Great Ruaha River at Salimwani and Mbarali River at Igawa

Description of parameter	Start year	End year	No. of years	Slope of trend line	t-statistics	t-critical	Remarks
Annual river flow at Msembe	1958	2004	47	-18.890	-0.546	2.016	Not a significant trend
Dry season flow at Msembe	1958	2004	47	-2.730	-4.480	2.016	Significant decreasing trend
Annual flow for Great Ruaha River at Salimwani	1955	2004	50	20.702	0.910	2.013	Not a significant trend
Annual flow for Mbarali river at Igawa	1955	2004	50	-9.974	-0.709	2.013	Not a significant trend

4.2.3 Mean annual runoff and mean monthly flows for GRR

To discern seasonal changes within the annual cycle, changes in flow regimes were investigated. Figure 4.9 shows variations in flow regimes, based on mean monthly flow at Msembe Ferry for each of the three windows. As revealed in Figure 4.9, there is a slight change in peaking for the post-1985 period. It is possible that, this has contributed to attainment of higher flows earlier in February as compared to April for other periods.



	1958-1973	1974-1985	1986-2003
Jan	104.34	42.00	85.58
Feb	183.65	90.61	212.06
Mar	254.98	133.21	233.43
Apr	309.83	158.63	222.83
May	151.47	108.13	133.79
Jun	47.59	48.97	57.34
Jul	21.20	17.91	16.76
Aug	13.07	7.25	3.25
Sep	8.34	2.84	0.81
Oct	5.50	1.09	0.26
Nov	4.14	1.46	0.57
Dec	19.42	10.42	9.93
MAR	93.0	51.62	80.48

Figure 4.9: Mean monthly flow at Msembe Ferry

This highlights the fact that there has not been a decrease across the full spectrum of the flow regime. In fact between 1974 and 1985 overall flows were lower (MAR was 51.6 m^3s^{-1}) than in either of the other two windows (i.e. MAR was 93 m^3s^{-1} and 80.5 m^3s^{-1} for pre-1974 and post-1985 windows respectively), but throughout this period the Great Ruaha River continued to flow in the dry season.

Table 4.8 gives the variations in mean monthly flow calculated for 1974-1985 and 1986-2003 periods compared to those during the pre-1974 period, in terms of both percentage of flow and depth (mm). Table 4.9 presents the coefficient of variation in monthly rainfall over the Usangu Plains.

Table 4.8: Variation in mean monthly flow

Period	Feb.-April (high flow)	April (high flow)	Sept.-Nov. (low flow)	Jul.-Dec. (low flow)	Annual total
1974-1985	-38.6% (-15.0 mm)	-39.6% (-37.2 mm)	-69.7% (-1.7 mm)	-42.9% (-3.7 mm)	-37.8% (-54.7 mm)
1986-2003	-29.3% (-11.4 mm)	-12.8% (-12.0 mm)	-94.4% (-2.2 mm)	-56.4% (-4.9 mm)	-16.5% (-23.9 mm)

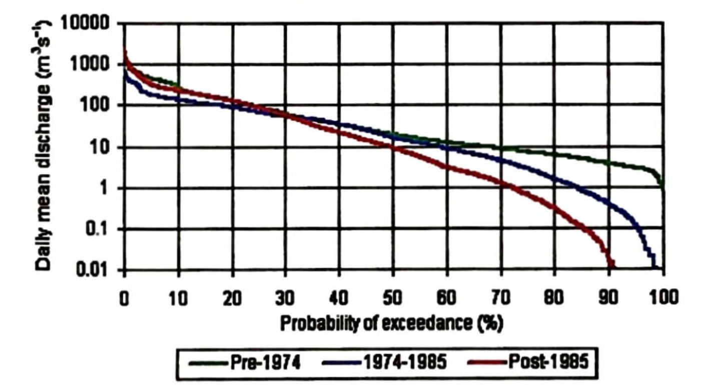
Table 4.9: Wet season mean monthly rainfall over the Usangu Plains

Month/Window	Pre-1974 (mm)	1974-1985 (mm)	Post-1985 (mm)	Mean (mm)	CV
November	36	40	43	39	9
December	143	145	111	133	15
January	160	136	145	147	8
February	155	103	120	126	21
March	134	123	149	135	10
April	54	61	55	57	7

Some studies (i.e., Elkaduwa and Sakthivadivel, 1998; Kiersch, 2000) have indicated the effect of land use/cover changes to be associated with high runoff generation due to reduced infiltration. Generally, change in land cover results into more runoff generation, for example a small amount of rainfall event results in an immediate runoff (i.e., flush runoff), however, this does not contribute significantly to flows in the dry season.

4.2.4 Flow duration curves for GRR

Figure 4.10 shows the flow duration curves of one day duration at Msembe Ferry drawn on a log scale to illustrate clearly the differences between low flows in the three different time periods. The flow duration curve (FDC) is cumulative frequency distribution that shows the percent of time that a specified discharge is equalled or exceeded during a period of interest. For example, Q_{95} is the mean daily flow that is exceeded 95% of the time. From Figure 4.10, the curves confirm the progressive and significant decline in flows lower than Q_{50}. Between the pre-1974 and post-1985 windows, Q_{95} and Q_{90} decreased from 2.84 m^3s^{-1} and 3.73 m^3s^{-1} to 0.0 m^3s^{-1} and 0.02 m^3s^{-1} respectively. The non-significant trend in annual flows can be attributed to the fact that wet season flows, which have not changed significantly, are much greater than dry season flows and hence dominate the analysis of the annual series.



	1958-1973	1974-1985	1986-2003
Q_{95}	2.84	0.11	0.0
Q_{90}	3.73	0.37	0.02
Q_{75}	7.09	2.77	0.65
Q_{50}	19.23	16.51	9.04
Q_{25}	91.28	68.09	86.68
Q_{10}	281.01	138.86	228.73
Q_{5}	445.09	181.50	325.79

Figure 4.10: Flow duration curves for the Great Ruaha River at Msembe Ferry

4.2.5 Frequency of occurrence of low flow events

The analysis for frequency of occurrence of low flow events for each time window revealed an increasing frequency and extension of low flow periods between the pre-1974 and post-1985 windows (Table 4.10). Between 1958 and 1973 there was not a single day with zero flow and the return period of a minimum one-day duration flow of 0.84 m^3s^{-1} was approximately 30 years. Between 1974 and 1985 short periods of zero flow occurred and a zero flow of one-day duration had a return period of approximately 4 years. Post-1985, zero flows of one-day duration occurred in all years and zero flow for durations of 60 days and greater were common.

Table 4.10: Comparison of minimum flows (m^3s^{-1}) for different durations for each of the time windows

	Duration			
Window	1-day	10-day	30-day	60-day
1958-1973	0.84	0.89	1.04	1.34
1974-1985	0.00	0.00	0.01	0.11
1986-2004	0.00	0.00	0.00	0.00

The results of the analyses of flow at Msembe Ferry, confirm the progressive decrease in dry season flows in the Great Ruaha River since 1958. They indicate that changes to the hydrological balance have occurred upstream in the Usangu catchment, which is associated with the increased change in land use and covers.

4.2.6 Linkage between land use/cover and flow regimes changes

There is a clear linkage between land use/cover changes and the changes in hydrological regime for the Great Ruaha River. According to Kiersch (2000), the impacts of land use practices on surface water can be two fold: (i) on the overall water availability or the mean annual runoff, and (ii) on the seasonal distribution of water availability. With regard to the latter, impacts on peak flows and impacts on dry season flows are of importance. A clear correlation existed between the detected changes and the change in hydrological regime of the Great Ruaha River. For example, there was a clear correlation between the decrease in average dry season flow at Msembe Ferry and the increase in total irrigated area within the Usangu area (Figure 4.11). This was to be expected, because though not extensively used for irrigation, it was due to the continued diversion of water to irrigation areas during the dry season, which was a major factor in reduced inflows to the wetland.

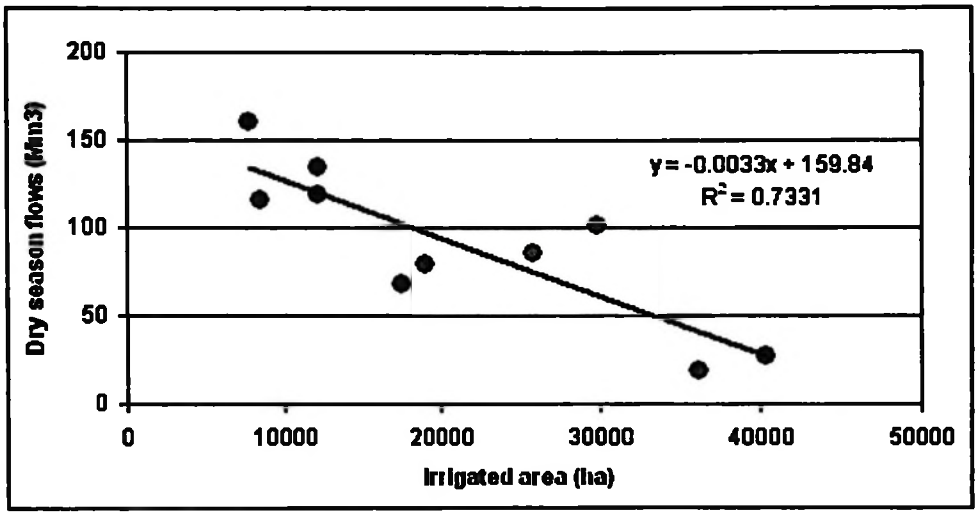


Figure 4.11: Comparison of dry season flow at Msembe Ferry and irrigated area in the Usangu Plains

Source: (SMUWC, 2001b); this study

Comparatively, the post-1985 period has experienced more changes in dry season flows, which were linked to changes in base flow within the catchment.

4.2.7 Impacts of land use/cover changes on flow regime

It is important to note that the Usangu wetlands are maintained by the inflows from upstream areas and rainfall. Therefore any alteration in inflows may impact the general response of the wetland. The increase in the size of the vegetated swamp in 1984 was not justified by the increased inputs of rainfall and inflows. The analysis for inter-annual variability of rainfall indicated a non-significant shift in rainfall months for the pre-1974 and 1974-1984 and neither did the rainfall in 1984. Therefore, as it had been pointed out before (refer section 4.2.2), the increase in area under vegetated swamp between 1973 and 1984 is an artefact of the differences in spatial resolution in images used for the two dates. However, the decrease in vegetated swamp between 1984 and 2000 may be associated with the change in land use and increased human activities in the area. As previously discussed, the period was associated with various interventions including establishment of both large and small-scale rice irrigation schemes. The expansions in agricultural activities are reflected on the increased land use transformations and the increased water abstractions for irrigation upstream of the wetland. The detected decrease in woodland areas reflected the increased timber logging activities and forest clearance for agriculture. The deforested woodland areas were mainly replaced by shifting cultivation and home gardens. This is still practised in Usangu and is one of the characteristic of the farming systems of the Usangu Plains. Also the land clearing for the establishment of large schemes, e.g., the Kapunga rice irrigation farm, caused deforestation. This was also revealed during interviews with locals who had stayed in the area for a long period of time.

These land use changes, particularly the conversion of natural forests (woodland) for the post-1985 period must be responsible for the increased runoff generation process during the post-1985 as revealed by the analysis. Increase in storm runoff is mainly due to the reduced infiltration rate when forest is converted to other land uses (Kiersch, 2000; Allan, 2004). These changes in runoff generation are in agreement with the state of knowledge that reducing forest cover results into an increase in the water yield. However the sustenance of baseflow (groundwater) in the dry season becomes more questionable especially in the arid and semi-arid areas (Kiersch, 2000; Allan, 2004). In the post-1985, the woodland cover decreased to 22.3 percent of the study area (refer section 4.1.2); however, the changes in flow regimes were on the higher side as compared to the 1974-1985 period despite the decreased rainfall amount. The observed reduction in dry season flow after 1985 during low flow periods is accompanied by increased storm runoff during high rainfall months compared to that observed with the high percentage of forest cover. Such phenomena might be due to reduced infiltration as explained by Bruijuzeel (1990) cited in Elkaduwa and Sakthivadivel (1998) that if infiltration opportunities after forest removal have decreased to the extent that the increase in amounts of water leaving the area as storm runoff exceeds the gain in base flow associated with decreased evapotranspiration, then the result is diminished dry season flow.

Therefore in comparison with the pre-1974 period which had substantial woodland cover, the significant deviation of flow regimes during the post-1985 (as well as during the 1974-1985) is a clear indication that the present management of agricultural land uses has failed to sustain the flow regimes closer to its initial existing conditions with substantial forest and wetland covers. Studies in other countries (e.g. Asia) have also shown the influence of land use changes on runoff generation (e.g. Madduma, 1997; Elkaduwa and Sakthivadivel, 1998). It is apparently clear that, land use and cover changes impact the flow regimes and have implications on the sustenance of dry season river flows. The major land use changes during the study period were the reduction in forested area, area of the vegetated swamp and increase in cultivated and bare land.

4.2.8 Implications of changed flow regimes

The modification of the land use and cover results in changes in time distribution of runoff with the reduction in low flows and an increase in high flows. The major impacts include the shrinkage of the Eastern wetland and decreased dry season flows downstream of the wetlands through the Ruaha National Park. Other impacts include decreased water availability for domestic uses. During the FDG and interviews it was revealed that in the dry season, women and children had to spend more time searching for water. Some had to walk up to 20 km to locate sources (Kashaigili and Rajabu, 2003). Therefore, the reduced low flows are reflected in reduced dependency on a reliable supply of good quality water downstream during periods of less rainfall. The cessation of flows also adversely impacts on the fragile ecosystem of the Ruaha National Park. It has caused significant mortality of fish and hippopotami. For example, in the dry season of 2003, 5,000 fishes and 49 hippos died following the drying up of the GRR (Gladys, Ecologist for the Ruaha National Park. Pers. Comm.). It also disrupted the lives of many animals that depended on the river for drinking water, causing changes in their behaviour and leading to outbreaks of disease such as Anthrax. For example, the fresh oyster beds are have become extinct. the endemic fishes for the Ruaha River are now extinct, and the White Crowned Plover, whose only breeding ground in Tanzania is on the Great Ruaha River, is now severely threatened by lack of success in breeding (Sue, FORS, Pers. Comm.)

The change in river channel morphology experienced in the Usangu Plains is attributable to land use changes. This has resulted from the disturbance to the land forms, without appropriate soil conservation measures and seems to have aggravated the sediment supply into streams, sometimes with landslides resulting from the indiscriminate removal of the toe-support. The dominant cultivation practices involve those along the river banks and these compounds to the problem of sediment generation and destabilization of river banks. Also, poor fishing practices that involve construction of barriers across the river channel reduces sediment flushing because of reduced velocity of flow, enhancing sediment deposition and this contribute to changes in river courses.

4.3 The Ifushiro wetland hydrology and interactions

The Ifushiro wetland gets water from the Great Ruaha River and is located upstream of the Eastern wetland. It was studied to evaluate its contribution to downstream flows in the dry season as well as understanding the interactions between surface water and groundwater in the wetland. Beliefs with respect to this wetland are that the Ifushiro wetland acts as sink for much of the water flowing onto it from the GRR especially in the dry season and that it acts as a water scarcity multiplier for downstream. However, no study has ever tried to investigate the quantities of inflows and outflows from the wetland as well as its interactive processes between groundwater and surface water. Therefore, the results presented in this section characterise the flow mechanisms of the wetland and the interactive processes between surface water and groundwater for this wetland.

4.3.1 Rainfall and evaporation within the Ifushiro wetland

Figure 4.12 presents the mean daily rainfall and Class A-pan evaporation. The results indicate that rainfall around the Ifushiro wetland is unimodal and is received between November and April. The mean annual rainfall for the 2003 hydrological year (HY) (i.e., 1st November 2003 to 31st October 2004) is 417.6mm.

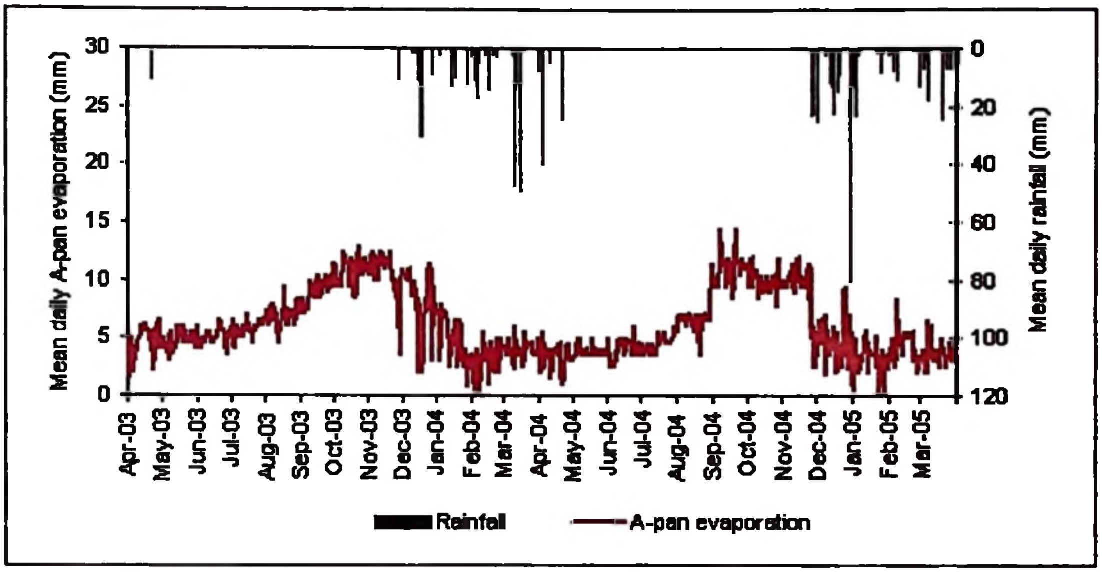


Figure 4.12: Variations in mean daily rainfall and A-pan evaporation at the Ifushiro wetland (March 2003 to March 2005)

Table 4.11 presents the monthly A-pan evaporation at the Ifushiro wetland. The results show that the highest evaporation rates occur between September and November. The annual pan evaporation for the 2003 hydrological year is 2234 mm and this equates to annual potential evapotranspiration of 1564 mm using a pan-factor of 0.7. According to Kohler (1952) pan evaporation rates should be reduced by 30% when applied to open water within a wetland.

Table 4.11: Monthly rainfall and monthly class A-pan evaporation around the *Ifushiro* wetland

	Monthly	
	Rainfall	A-pan evaporation
Apr-03	11.9	135.4
May-03	0.0	142.0
Jun-03	0.0	151.0
Jul-03	0.0	176.0
Aug-03	0.0	212.0
Sep-03	0.0	272.0
Oct-03	0.0	337.5
Nov-03	10.5	320.0
Dec-03	92.9	257.4
Jan-04	42.8	146.8
Feb-04	80.9	87.4
Mar-04	114.1	121.6
Apr-04	76.4	103.9
May-04	0.0	118.0
Jun-04	0.0	117.5
Jul-04	0.0	140.0
Aug-04	0.0	197.0
Sep-04	0.0	331.0
Oct-04	0.0	311.5
Nov-04	45.0	283.5
Dec-04	189.3	150.8
Jan-05	64.2	97.2
Feb-05	36.5	119.0
Mar-05	77.8	114.8

4.3.2 Inflow and outflow at the Ifushiro wetland

Figure 4.13 presents the mean daily inflows and combined outflow time series. The results show that there is a big difference between the observed inflows and outflows from the Ifushiro wetland. A bigger difference is experienced in the wet season.

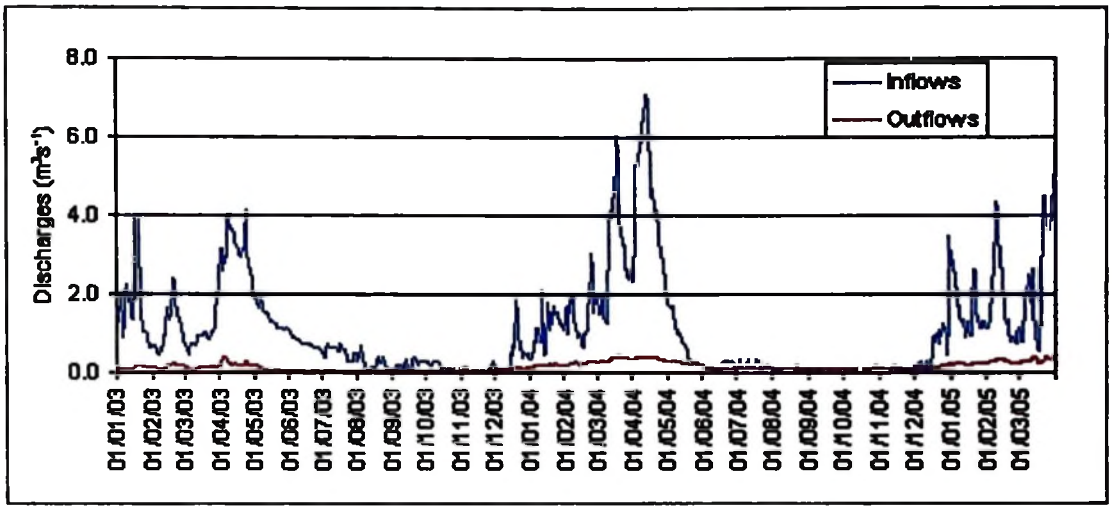


Figure 4.13: Mean daily inflows and outflows at Ifushiro wetland (01/01/2003 to 31/03/2005)

Figure 4.14 presents the mean monthly inflows and outflows for the 2003 hydrological year. There is big difference (Figure 4.14) between monthly inflows and outflows in the wet season compared to the dry season. The big difference is experienced during the rising limb of the hydrograph and is highest April.

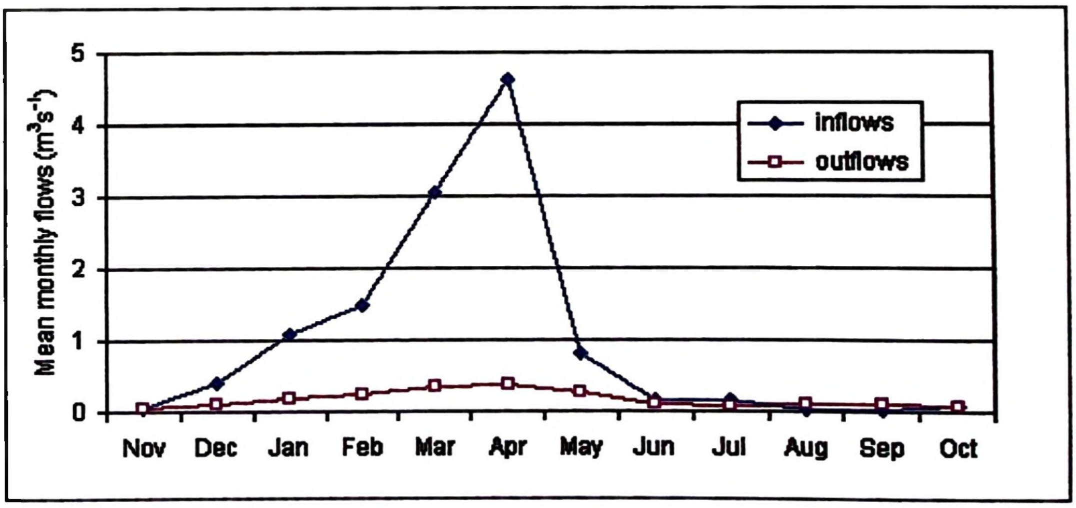


Figure 4.14: Mean monthly inflow and outflow from Ifushiro wetland for HY2003

Table 4.12 presents the flow statistics for Ifushiro wetland. For the HY2003, the annual inflow volume was 31.38 Mm^3 while the outflow was only 5.52 Mm^3 indicating a difference of 25.86 Mm^3 between the inflows and outflows. As revealed in Figures 4.13 and 4.14 and in Table 4.12, there is a big differencc between the inflows and outflows.

Table 4.12: Flow statistics for HY 2003

Parameter	HY2003
Annual inflow volume (Mm^3)	31.38
Annul outflow volume (Mm^3)	5.52
Daily mean inflow (m^3s^{-1})	1.04
Maximum daily mean inflow (m^3s^{-1})	7.12
Minimum daily mean inflow (m^3s^{-1})	0.0018
Low flow inflow (July-November) (Mm^3)	3.27
Low flow outflow (July-November) (Mm^3)	0.81 (2.46) ‡
Daily mean low flow inflow (m^3s^{-1})	0.25
Daily mean low flow outflow (m^3s^{-1})	0.06

‡ Numbers in bracket indicate the difference between inflows and outflows in the dry season

The observed difference is likely due to flows that bypassed the gauges in the wet season. The hydrometric monitoring at Ifushiro has shown that during the wet season, the Ifushiro wetland floods and there is no particular defined channel for collecting the outflow from the wetland. This is normally occurring between January and May each year. The dry season (Table 4.12) have indicated a large difference between inflows and outflows (i.e. 2.46 Mm^3), which is about 300%. This could be attributed to evaporative loss as revealed from the water balance analysis in section 4.3.5.

4.3.3 Dynamics of groundwater levels at the Ifushiro wetland

Figure 4.15 shows the groundwater levels fluctuations in four piezometer wells, two taken from each side of the main inlet channel (refer Figure 3.9). From Figure 4.15, the groundwater levels in wells responded dynamically with time and the fluctuations are highly correlated with rainfall. It is also interesting to note a correlation between groundwater fluctuations in the wells and water level observations in the wetlands represented by WL. Almost all the wells had the same response pattern with minor variations.

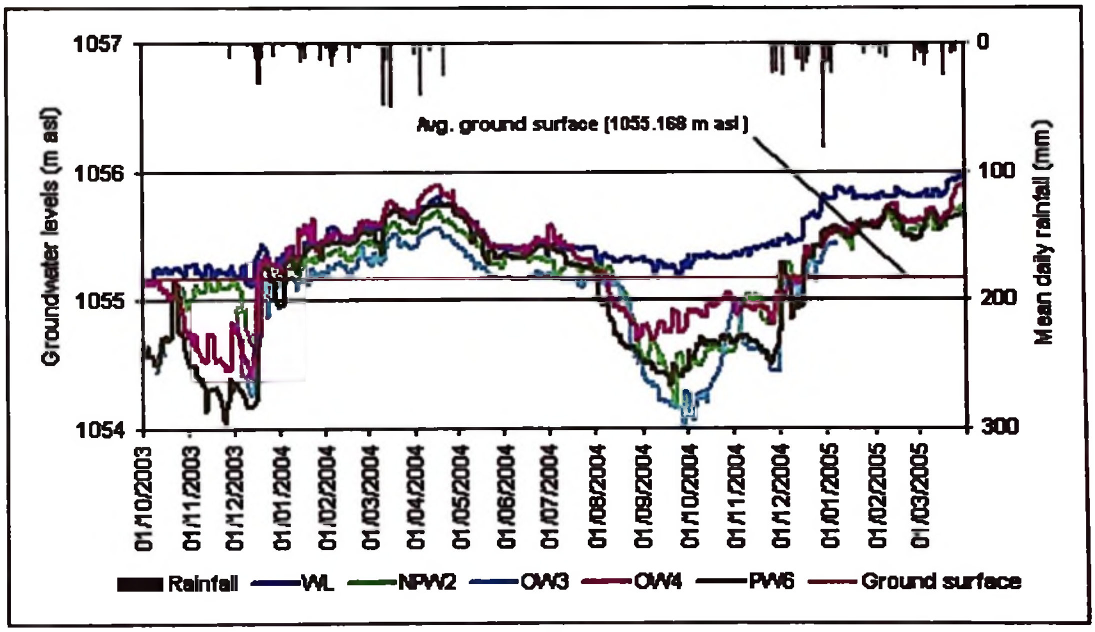


Figure 4.15: Comparison of groundwater fluctuations in some well and surface water levels in the *Ifushiro* wetland

The differences were attributed to differences in soil properties and other external influences. The external influences included upstream water diversions from the inlet channels for dry season cropping, and channel blockages especially in the dry season which causes overtopping of the channel banks and spread of water in the wetland causing water to pond on the ground surface. Since all these occasions are non-natural, they create an imbalance in subsurface flows. Though the process of infiltration is beyond the scope of this study, it is possible that water infiltrated slowly from the ponded surface to argument the groundwater table and this was revealed from the readings in the wells. Also, draining of water from the wetland in the dry season for cultivation in the downstream of the Ifushiro wetland contributed to lowering the groundwater table which affect the wetland hydro-periods.

The hydro-period of a wetland depends upon the length of time that water is present in the wetland. Protection of wetland plant and animal communities depends on controlling the wetland's hydro-period. Considering the ground surface as a reference level, Figure 4.15 shows that the water table was above the ground surface for 216 days (red horizontal line) (i.e., from 15/12/2003 to 16/08/2004). The rise in groundwater level above the ground surface was in response to the rains, which start in November till May and sometimes June. After the rainy season, the water table is maintained at the surface by the inflows until a time when the outflows and evaporative losses surpass the inflows.

Towards the peak of the dry season (October-November), the water table declines to approximately 1.2 metres below the ground level. The fall in ground water levels results into drying of some of the wells. This was experienced in wells located away from the main inlet channel. For example, well P5 dried from 01/11/2003 to 27/11/2003, and water levels rose after the onset of rains from 28/11/2003.

4.3.4 Hydraulic conductivity

Table 4.13 presents a summary of the results of hydraulic conductivity. The test was conducted in the dry season when water in the wells was at the lowest levels.

Table 4.13: Summary of hydraulic conductivity results

Well ID	Mean Ksat (md^{-1})					
	Falling head (slug in)	No. of tests	Standard deviation	Raising head (slug out)	No. tests	standard Deviation
NP1	0.168	2	0.004	0.176	3	0.005
NP2	0.194	3	0.014	0.211	2	0.018
NP4	0.121	3	0.012	0.137	3	0.011
P5	0.201	1	-	0.200	2	0.024
P10	0.206	3	0.027	0.177	1	-
P14	0.116	2	0.019	0.119	2	0.018
P15	0.145	3	0.017	0.162	4	0.039

Table 4.13 presents results of hydraulic conductivities derived from slug tests (Bouwer and Rice, 1976). The results indicate a high degree of variability in hydraulic conductivity within proximity for the different wells. This could be attributed to the soil composition and formation mechanism inside the wetland, which is mainly a result of deposition of the eroded materials from the uplands. Further more, Table 4.13 shows that there was a considerable difference in the results obtained from a falling water-level test (i.e. when the metal cylinder was added to the well) and a rising water-level test (i.e. when the metal cylinder was removed from the well). However, it is important to note that the Bouwer and Rice (1976) technique was developed for slug tests in which there is a rising water level in the borehole. Although the technique can be applied to falling water levels, the results are only strictly applicable if the equilibrium water-level is above the screened or

open section of the well (Bouwer, 1989). However, this was not possible to achieve in the current study therefore the rising head (i.e. slug out) results are more reliable.

4.3.5 MODFLOW simulation results for the Ifushiro wetland

i) Calibration

Figure 4.16 shows the hydrographs of calculated water levels in comparison to observed (decadal) water levels for the selected five wells, while Figure 4.17 presents a scatter-plot of simulated and observed water levels at the end of the calibration period (t = 550 days). The model fit criteria, root mean square error, RMSE = 0.233 (mean error -0.091, mean absolute error 0.183) were obtained at the end of transient calibration (t = 550 days) indicating that the calculated and observed water levels were in good agreement. However, the model underestimates the water levels in the dry season but with reasonable correspondence to observed water levels in the wet season. The uncertainty in head measurements can be the result of measurement errors, scale errors, averaging errors among various input parameters, both spatial and temporal. Additional errors could be due to combining multiple lithologies into a single grid block representing one simulated head.

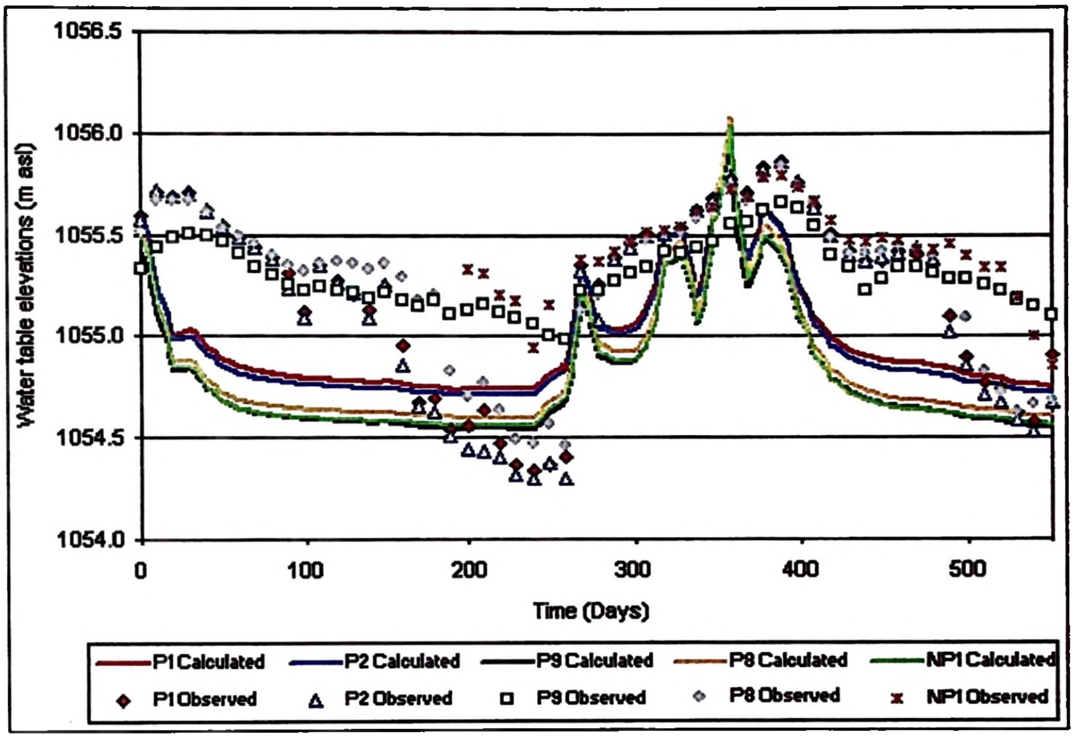


Figure 4.16: Calibration (estimated) against observed water level fluctuations, April 2003 to September 2004

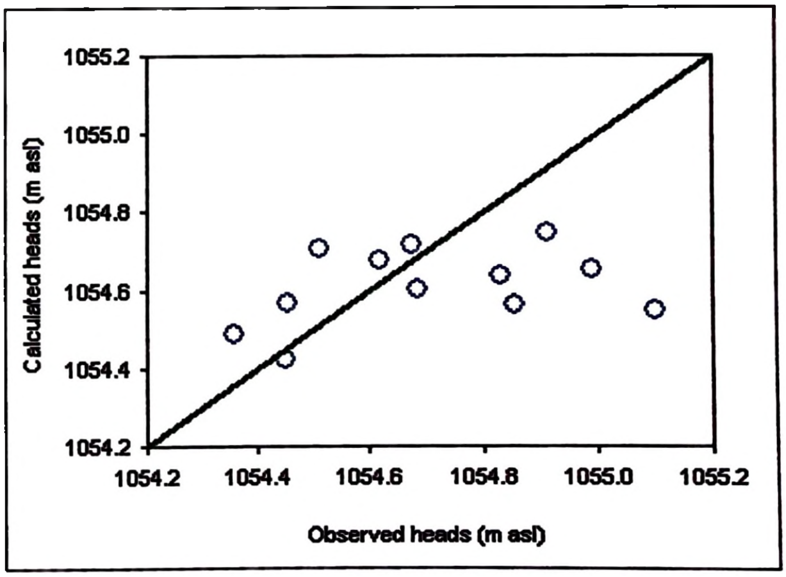


Figure 4.17: Scatter plot of simulated (calculated) and measured (observed) water level for different wells (t = 550 days)
(Mean error, ME = -0.091, Mean absolute error, MAE = 0.183, Root mean square error, RMSE = 0.233)

ii) Sensitivity analysis

The sensitivity analysis revealed that the Ifushiro wetland is very sensitive to changes in hydraulic conductivity and recharge rate while sensitivity to other parameters is smaller. The change in hydraulic conductivity values was found to have more influence on the hydraulic heads. Stream conductance was also found important in controlling the movement of water between the stream and the aquifer.

iii) Groundwater flows

Figure 4.18 presents the ground water level configurations and flow paths for low (t = 220 days) water level conditions, while Figure 4.19 show the spatial distribution of water level elevations.

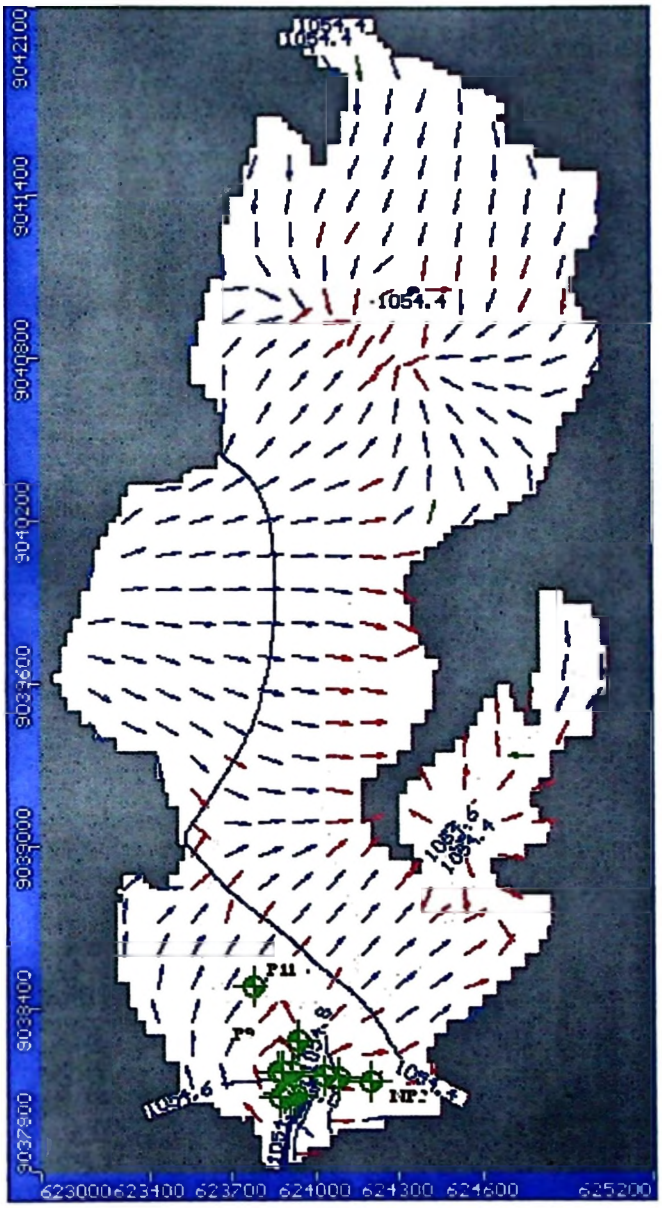


Figure 4.18: Low (dry season, t = 220 days) water table configuration and directions of groundwater flow for model domain

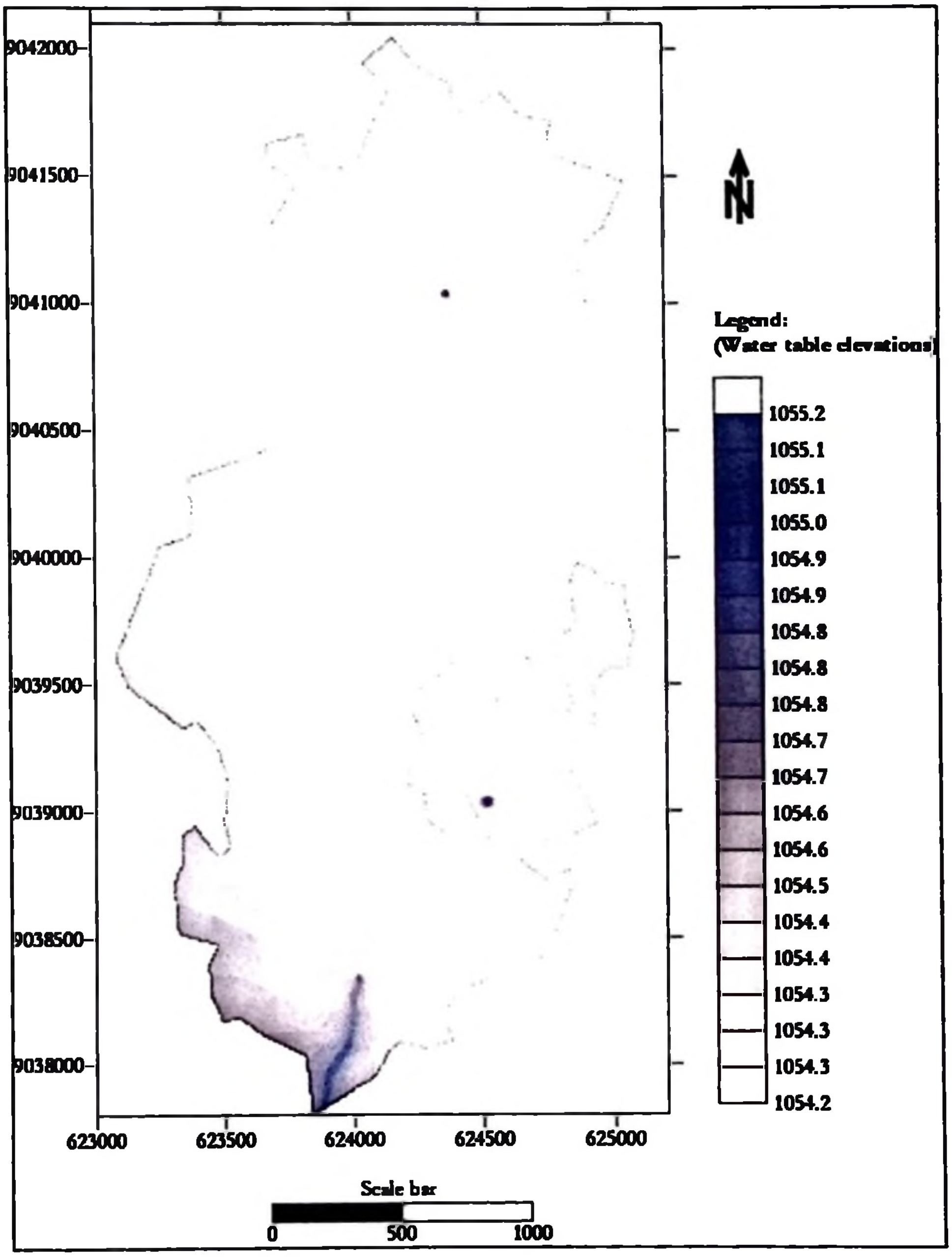


Figure 4.19: Low (dry season, t = 220 days) spatial distribution of water table elevations

Figure 4.20 presents the ground water level configurations and flow paths for high (t = 370 days) water level conditions, while Figure 4.21 shows the spatial distribution of water level elevations

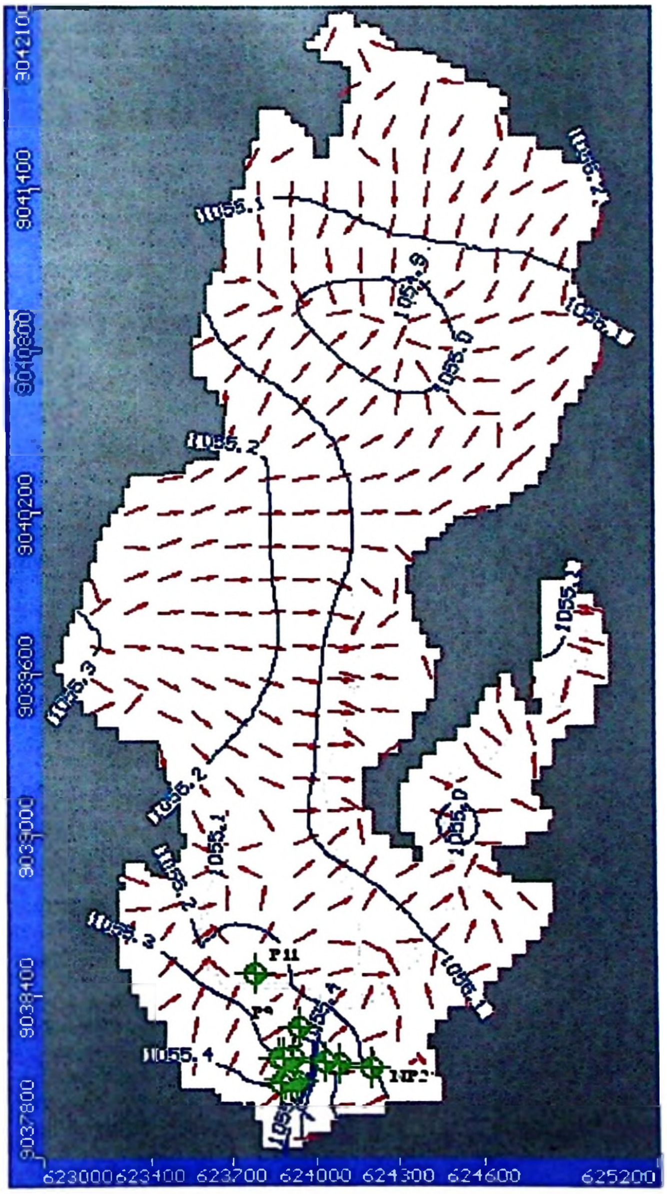


Figure 4.20: High (wet season, t = 370 days) water table configuration and directions of groundwater flow

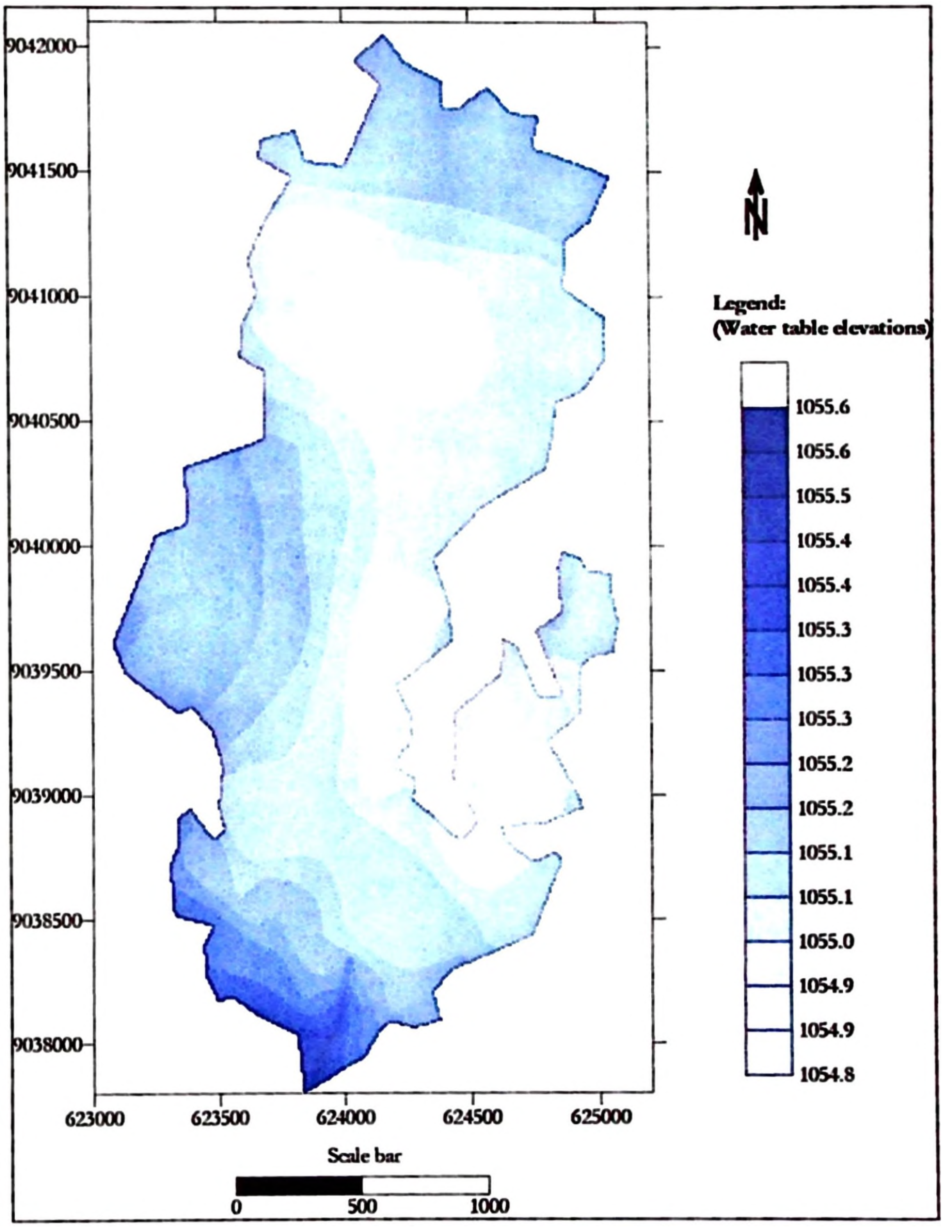


Figure 4.21: High (wet season, t = 370 days) spatial distribution water table elevations

The pattern is similar for both times with flow moving towards the eastern side and the depression in the northern side near the pool inside the Ifushiro wetland. The role of main inlet channel in controlling the water level distribution in neighboring areas is revealed but this takes place to some few meters (within 300 m) from the course. Cross-sections show an upward movement of groundwater in the dry season and downward movement in the wet season. However, the water table was found to be higher than the drains in the wet season and lower in the dry season. The constant head boundary influenced the water table distribution. It acted as water sources in the dry season and supplied water to the neighboring areas (Figures 4.18 and 4.19).

Figure 4.22 presents the drawdown distribution (i.e. water level drops with reference to ground surface) meter below ground level (m bgl) in the dry season (t = 220 days). The drawdown ranged between zero and 1.2 m bgl and generally increased from the eastern to western side of the *Ifushiro* modeled area except for areas closer to the point sources (i.e. the constant head boundaries – the pools and main inlet channel). The increased decline in water levels towards the western side could be attributable to drainage of the Ifushiro wetland for cultivation in the dry season apart from topographical arrangement. The channels draining water from the *Ifushiro* wetland are located in the eastern side and are used for supplying water to crop fields in the dry season.

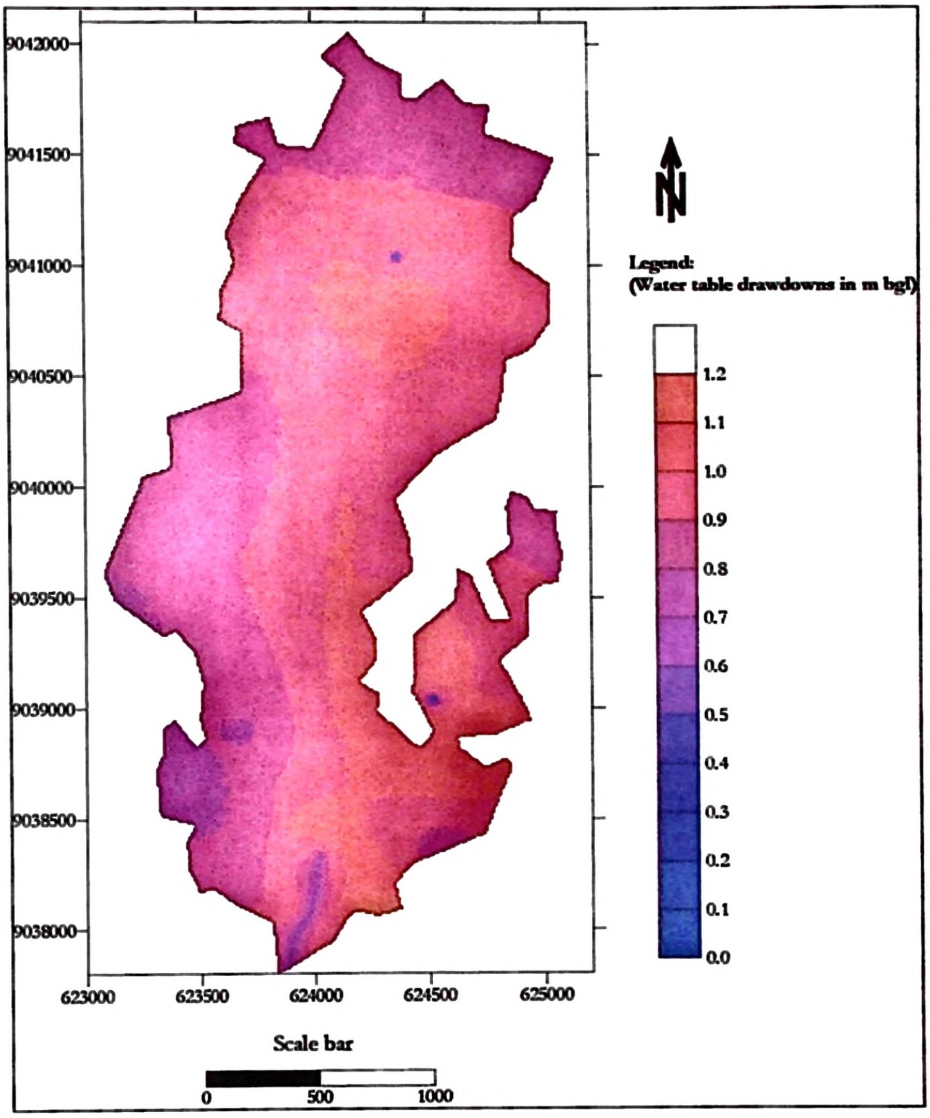


Figure 4.22: Spatial distribution of water table drawdown (m bgl) in the dry season (t = 220 days)

iii) Cumulative mass balance

The cumulative mass balance at the end of the calibration period (t = 550 days) is given in Table 4.14. The results demonstrate the importance of rainfall and evaporation in the water balance compared to the drains and constant head boundaries. Rainfall accounted for 65.6% of the total inflow volumes while evaporation accounted for 77.5% of the total outflow volumes. This finding corroborates other studies on wetlands done elsewhere which reported that evapotranspiration is a major water loss in wetlands (Bradford and Acreman, 2003; McCartney, 1998).

Table 4.14: Cumulative mass balance (m^3) at t = 550 days

	IN	% of total	OUT	% of total
Storage	838086	32.0	578834	22.13
Constant head	16717	0.6	1021	0.04
Drains	-	-	7149	0.27
River leakage	44582	1.7	1149	0.04
Recharge	1716261	65.6	-	0.00
Evapotranspiration	-		2027493	77.51
Total	2615646		2615646	

4.3.6 Summary

The study revealed a large difference between inflow and outflow from the *Ifushiro* wetland. Much of this was attributed to evaporation losses especially in the dry season. During the wet season, gauges at outflow points were bypassed by water as the whole wetland flooded. Therefore, the difference between inflow and outflow was not very well reflected unlike the dry season when water was contained in defined channels. This was due to the topographic alignment, which was relatively flat and water found its way out of the wetland. Considering the dry season, the amount of inflows and outflows were very minimal and most of the water was lost through evaporation and some was used for dry season cultivation downstream of the *Ifushiro* wetland. The implication of this is that it is impossible to have contribution of *Ifushiro* wetland outflows to augment flows in the Eastern wetland in the downstream during the dry season.

It has been revealed that rainfall and evaporation had the most influence on water table fluctuations. This reveals the close relationship that also exists between surface water and ground water table response. However, there was only limited lateral movement of water from the channels and constant head boundaries. These acted as hydraulic boundaries and their influence on the water table configuration extended only a short distance.

4.4 Wetland hydrology of the Eastern wetland

4.4.1 Comparison of simulated and observed wetland area

The hydrologic model was used to simulate hydrological fluxes for the period 1958 to 2004. Wetland areas simulated by the model were compared to the "observed" areas derived from Landsat images and from aerial surveys combined with GPS ground measurements of the wetland perimeter (SMUWC, 2001b).

Table 4.15 presents a comparison between observed and simulated wetland area for the Eastern wetland. The "observed" represent the area delineated from remotely sensed images and aerial photos while simulated areas are the estimated areas from the wetland hydrologic model.

Table 4.15: Comparison of "observed" and simulated wetland area

Source	Date	"Observed" wetland area km²	Model simulated area * km²	Difference km²	Percentage error
L	04th September 1973	120	202	+82	+68
L	15th June 1984	436	217	-219	-50
L	03rd September 1984	211	137	-74	-35
L	22nd August 1991	204	136	-68	-33
L	14th August 1994	188	154	-34	-18
S	21st November 1998	111	90	-21	-19
S	21st January 1999	64	79	-15	-23
S	02nd May 1999	611	436	-175	-29
S	12th May 1999	465	365	-100	-22
S	11th May 2000	217	267	+50	+23
S	26th May 2000	318	243	-75	-24
L	07th September 2000	79	108	+29	+37
S	07th November 2000	27	75	+48	+178

* data from daily model for exact date of the "observed" area
S = SMUWC (2001b) – areal estimates derived from satellite observations, aerial photographs and GPS fixing of wetland perimeter
L = Landsat images

Figure 4.23 presents a comparison between the observed and simulated area with the fitted linear trend line. The criteria of fitness (Figure 4.23) between the observed and simulated wetland areas is about 75% (R^2 = 75.25%), which shows that model simulated areas and observed areas are comparable.

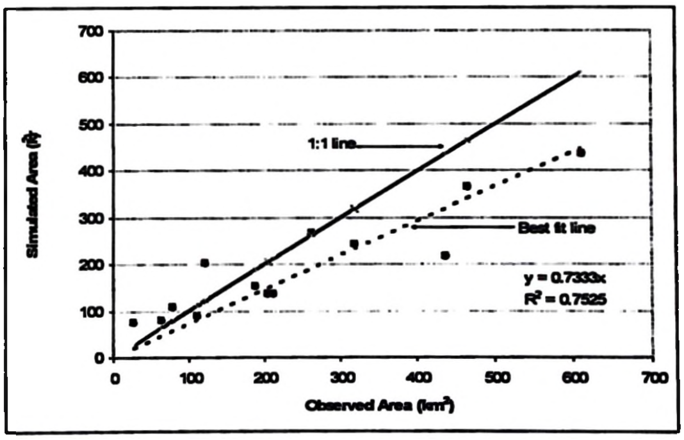


Figure 4.23: Comparison of observed and simulated wetland area

Considering Table 4.15 and Figure 4.23, it is clear that there may be considerable errors in the "observed" areas. Nonetheless, they are at least indicative of the wetland area and so provide a useful check on the model performance. The results suggest that the model tends to underestimate the wetland area, especially in the wet season, and simulates lower variability than occurs in reality. It is possible that the tendency to underestimate the wetland area is a consequence of the assumption that evapotranspiration was always at potential rates or it may be that the model is overestimating wet season outflow. However, overall there is reasonable correspondence between observed and simulated values, particularly in the dry season, which was of most concern to the current study.

4.4.2 Water budget of the Eastern wetland

Figure 4.24 shows simulated water levels at the NG'iriama outlet. It illustrates the decline in levels and increase in periods below the level of the rock sill from the 1990s onwards.

Figure 4.25 presents simulated mean monthly inflow and outflow from the wetland for the 1958-1973 window (i.e., the most natural period). This illustrates the effect of wetland attenuation on flows and indicates that there is approximately a 4 to 6 weeks time lag between inflows to, and outflows from, the wetland.

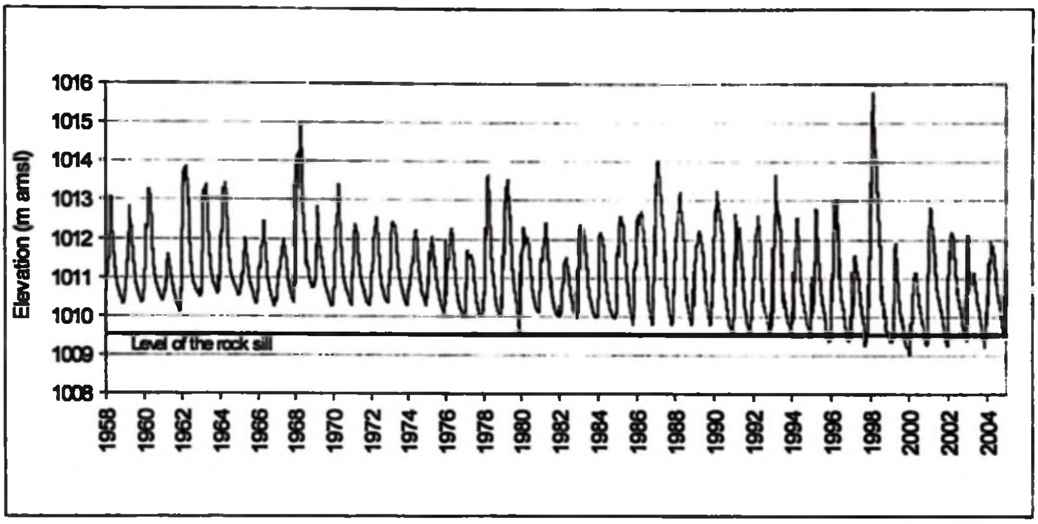


Figure 4.24: Simulated water levels at NG'iriama for the period 1958 to 2004

Source: Modified from SMUWC (2001b)

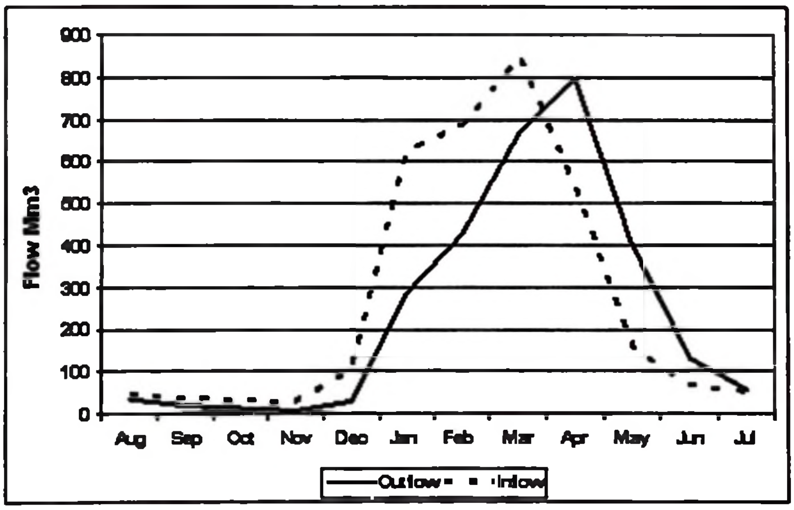


Figure 4.25: Simulated mean monthly inflow and outflow from the Eastern wetland (1958-1973)

For the 1958 to 1973 window, the average annual influx to the wetland (i.e., rainfall + inflow) was 3,881 Mm^3. However, there was considerable inter-annual variability. The minimum influx was 1,320 Mm^3 in 1961 and the maximum was 14,424 Mm^3 in

1968 (i.e., an *El Nino* year). Although rainfall was measured on the plains and a lot of inflow was generated in the highlands, rainfall and inflow were well correlated (Figure 4.26). On average, rainfall was 13% (i.e., 491 Mm^3) of total annual influx to the wetland. Of the total inflow, on average 22% (i.e., 835 Mm^3) was evapotranspiration and 78% (i.e. 3,045 Mm^3)[1] was flows from the wetland at NG'iriama.

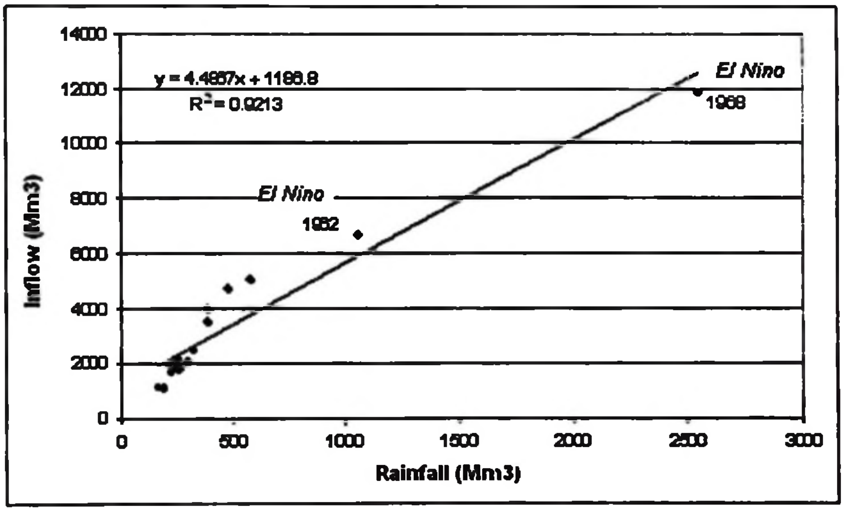


Figure 4.26: Comparison of rainfall in the plains and inflow to the Eastern wetland (Mm^3)

As would be expected, there was high correlation between the simulated maximum area of the wetland each year and the total annual influx of water into the wetland (Figure 4.27).

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[1] Note: this compares well with the estimated average annual flow at Msembe Ferry over the same period which was 2,934 Mm^3.

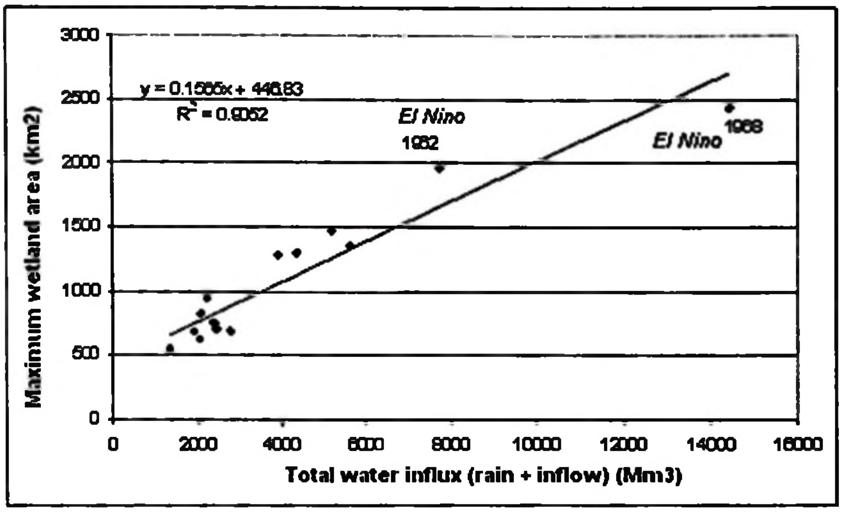


Figure 4.27: Relationship between annual maximum wetland area and total annual influx of water (i.e. rainfall + inflow) (Mm^3)

The scatter in points can be attributed to the fact that in any given year the maximum areal extent of the wetland will also be partly affected by the temporal distribution of rainfall and flow within the year.

The simulated annual water budget of the wetland varied considerably between the three time windows (Table 4.16). These results corroborate the flow analyses, presented above, that the second window was drier than either the first or the third window. During the second window average annual outflow from the wetland was considerably less than it was in the post-1985 period. However, dry season outflows from the wetland did not cease. This confirms that it is not declines in inflow *per se*, but rather decreases in inflows in critical periods, which resulted in the cessation of dry season outflows in the post-1985 window.

Table 4.16: Simulated average annual water budget for the three time windows

Period	Rainfall onto wetland (Mm³)	Inflow to wetland (Mm³)	Outflow from wetland (Mm³)	Evaporation from wetland (Mm³)
1958-1973	491	3390	3045	835
1974-1985	251	2096	1731	608
1986-2004	319	2920	2531	720

4.4.3 Simulated water fluxes and change in the area

Comparison of the model results for the three windows enabled temporal changes in the wetland area and water budget to be evaluated. Between the pre-1974 and the post-1985 windows the average area of the wetland in the wet season did not change significantly. However, the dry season minimum area (occurring in October) decreased by about 40% from an average of 160km^2 to 93 km^2 (Table 4.17; Figure 4.28).

Table 4.17: Simulated mean monthly wetland area (km^2) for each of the time windows

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958-1973	547	725	885	687	409	283	225	197	176	160	158	249
1974-1985	380	488	642	607	434	288	207	169	144	129	139	226
1986-2004	490	659	744	646	427	253	170	134	114	93	107	188

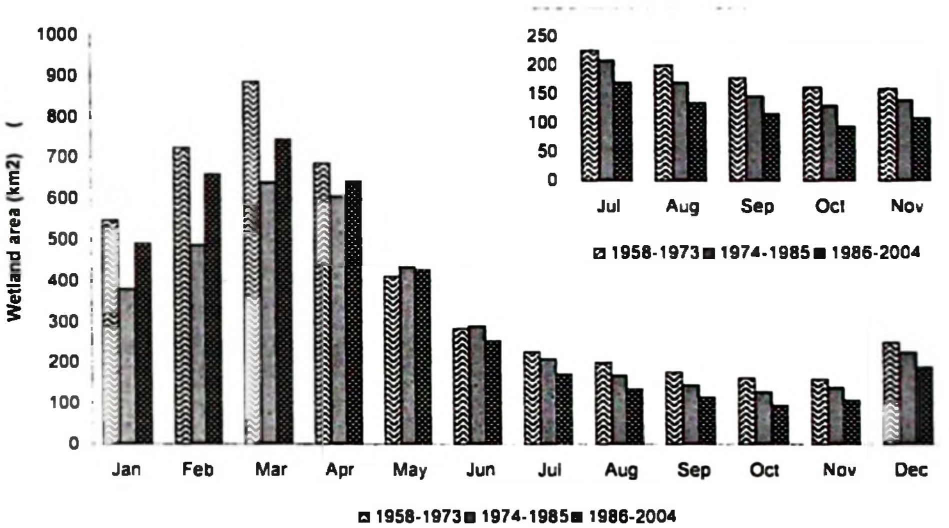


Figure 4.28: Simulated mean monthly area of the Eastern wetland, (insert is the dry season magnified)

Between the pre-1974 and the 1974-1985 and then the post-1985 windows, there was a progressive decrease in the average minimum dry season inflows to the Eastern wetland. Average flow in October decreased from 32.1 Mm^3 to 18.6 Mm^3 to 9.2 Mm^3 respectively for the three windows. Similar declines occurred in August and September (Table 4.18; Figure 4.29). Over the entire period there was a total decrease in the simulated dry season inflows of approximately 70%.

Table 4.18: Simulated mean monthly inflows (Mm^3) for each of the time windows

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958-1973	626.1	685.8	849.6	536.1	158.4	67.7	50.9	48.4	36.8	32.1	31.7	102.8
1974-1985	234.1	359.0	605.2	433.0	212.8	63.1	26.2	24.5	18.8	18.6	26.0	74.5
1986-2004	542.5	741.2	761.8	485.4	197.4	45.6	20.0	12.2	11.8	9.2	22.3	78.7

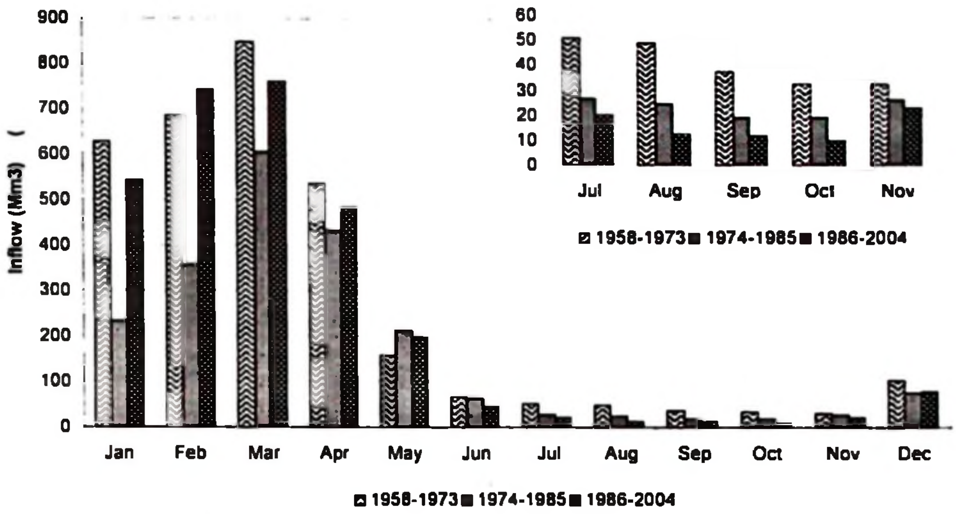


Figure 4.29: Simulated mean monthly inflows to the Eastern wetland (insert is the dry season magnified)

The average minimum dry season wetland "storage", occurring in October. decreased from 58 Mm^3 to 40 Mm^3 to 24 Mm^3 in the pre-1974. 1974-1985 and post-1985 windows respectively (Table 4.19). Overall this represented a 60% decrease in the minimum dry season storage.

Table 4.19: Simulated mean monthly wetland storage (Mm^3) for each of the time windows

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958-1973	485	730	927	583	251	140	98	80	67	58	57	129
1974-1985	225	331	543	462	270	140	84	61	48	40	46	99
1986-2004	422	632	723	533	279	118	62	42	33	24	32	83

Simulated wet season outflows from the wetland varied between the time windows. For example, there was no clear trend over time and hence no trend in annual data. because the wet season flows dominated the annual flow series. In contrast there was a steady decline in the outflows during the dry season. In the post-1985 window, the average minimum dry season outflows, which occurred in October/November declined to just 0.3 Mm^3 - 0.6 Mm^3 and were just 2-6% of the values they were in pre-1974 window (Table 4.19; Figure 4.30).

Table 4.20: Simulated mean monthly wetland outflow (Mm^3) for each of the time windows

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1958-1973	287.8	426.3	668.9	797.8	402.7	130.5	57.1	35.1	21.7	14.3	10.2	30.3
1974-1985	92.0	231.8	374.7	456.4	331.5	142.1	48.5	18.9	7.7	3.6	3.6	20.0
1986-2004	202.0	506.7	635.3	587.8	367.8	154.7	43.5	8.3	1.9	0.3	0.6	22.8

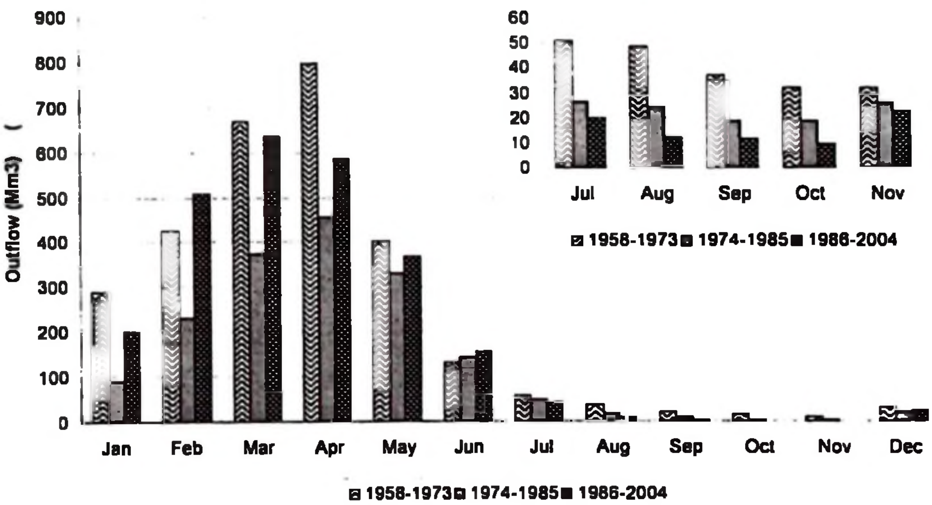


Figure 4.30: Simulated mean monthly outflow from the Eastern wetland (insert is the dry season magnified)

Between 1998 and 2003, flows were measured on the perennial rivers flowing into the wetland, upstream of the abstractions on the plains. Dry season results are summarized and compared to the simulated dry season inflows to the Eastern wetland in Table 4.21. The results indicate that, between 1998 and 2003, average dry season flows in the perennial rivers totalled 112.6 Mm^3, but only 56.3 Mm^3 flowed into the Eastern wetland. The difference suggests that on average a total of 56.3 Mm^3 (i.e. 50%) of dry season flows was abstracted for human use. This compares well with the total of 47.6 Mm^3 derived independently from the sectoral dry season water use estimates (Kashaigili, *et al.* 2005 b) and equates to an average dry season abstraction of 4.25 m^3s^{-1}. The greatest reduction in flow occurs in October because the greatest demand for irrigation water, when the paddy fields are flooded prior to planting, coincides with the period of lowest flows.

Table 4.21: Comparison of average monthly dry season flows (m^3s^{-1}) for perennial rivers and simulated inflows to the Eastern Wetland (1998-2003)

Sub- catchment	Average monthly flows (m^3s^{-1})					
	July	August	September	October	November	Average
Great Ruaha	3.64	2.86	2.41	2.31	2.29	2.70
Mbarali	5.00	3.93	3.09	2.39	2.68	3.42
Kimani	1.46	1.11	0.90	0.76	0.74	0.99
Ndembera	2.50	1.50	1.00	1.00	0.90	1.38
Current water available at gauging stations before abstractions in the Plains	12.59 (33.7)	9.40 25.2)	7.40 (19.2)	6.47 (17.3)	6.62 (17.2)	8.50 (112.6)
Simulated total inflow to the Eastern wetland (1998-2003)	4.58 (12.3)	4.51 (12.1)	4.81 (12.5)	2.80 (7.5)	4.58 (11.9)	4.26 (56.3)

Nos. in brackets is flow converted to Mm^3.

The model results indicate a large decrease in dry season inflows to the Eastern wetland. This, in conjunction with the decrease in rainfall over the Usangu Plains, has resulted in a shrinking of the perennial swamp, a decrease in water stored within the wetland and a marked decline in the dry season outflow from the wetland.

4.5 Maintaining environmental flows downstream of the Eastern wetland

A number of approaches to estimating environmental flows were considered in an attempt to determine "desired" dry season flows during the critical low flow period downstream of the Eastern wetland. In the Usangu Plains, water is already over-allocated without any consideration of the environmental requirements. It is therefore not reasonable to plan only environmentally favourable allocations. For this reason, the analyses conducted included consideration of current human abstractions as well as routing requirements. A number of alternative allocation scenarios were evaluated.

4.5.1 Estimates for environmental flows

Estimate from flow duration curve of natural flows

The Q_{95} derived from the flow duration curve (Figure 4.9) is $2.84m^3s^{-1}$. However, the low flow analysis (section 4.2.5) indicated that even in the pre-1974 period flows lower than this occurred every year. Consequently, there is no doubt that the ecology of the river and its surroundings will have adapted to dry season flows lower than $2.84m^3s^{-1}$.

Estimate using desktop reserve model

Table 4.22 presents results from the Desktop Reserve Model. It is clear from Table 4.22 that the IFR constitutes 21.6% of MAR equivalent to 635.3 Mm^3.

Table 4.22: Summary output from the desktop reserve model applied to the Great Ruaha at Msembe Ferry, based on 1958-1973 monthly flow series

Annual Flows (Mm³ or index values)			
MAR	= 2936.30	Total Environmental flow	= 635.30 (21.6%MAR)
S.D.	=2932.16	Maintenance Low flow	= 465.44 (15.9%MAR)
CV	= 0.99	Drought Low flow	= 293.26 (10.0% MAR)
BFI	= 0.89	Maintenance High flow	= 169.86 (5.8%MAR)
CV (SON + FMA) Index	= 1.54		

	Observed flow (Mm³)			Environmental flow requirement (Mm³)			
				Low flows		High-flows	Total Flows
Month	Mean	SD	CV	Maintenance	Drought	Maintenance	Maintenance
Jan	279.452	536.153	1.919	35.57	13.33	37.15	72.72
Feb	451.068	505.184	1.12	67.55	22.43	18.58	86.12
Mar	682.947	705.617	1.033	106.02	72.57	86.05	192.1
Apr	803.089	777 042	0.968	131.22	93.15	18.58	149.80
May	405.689	318.063	0.784	71.75	50.69	2.30	74.05
Jun	123.363	72.367	0.587	22.05	15.69	0	22.05
Jul	56.774	25.68	0.452	10.12	7.22	0	10.12
Aug	35.002	19.179	0.548	6.22	4.45	0	6.22
Sep	21.618	10.842	0.502	3.82	2.75	0	3.82
Oct	14.729	7.644	0.519	2.58	1.87	0	2.58
Nov	10.808	5.974	0.553	1.87	1.37	0	1.87
Dec	51.762	109.609	2.118	6.67	4.77	7.21	13.88

The maintenance low flow corresponds to 15.9% MAR (i.e. 465.44 Mm³) and the drought low flow 10% (i.e. 293.26 Mm³) while the maintenance high flow corresponds to 5.8% of MAR (i.e 169.86 Mm³). The present ecological status for the Great Ruaha River was considered to be transitional between category C and D, indicating a range from a moderate to highly modified change in natural habitat and biota. It is important to note that each category (A-D) is linked to a level of utilisation of the river as a resource. Therefore, the higher the EMC, the more water will need to be allocated for ecosystem maintenance or conservation and more flow variability will need to be preserved. DWAF (1999 c) has indicated that, IFRs for what could be category B rivers (largely unmodified) have encompassed as much as

70% of the MAR, whilst those for critically modified rivers have encompassed as little as 5% of the MAR. Critically modified rivers are the ones where realistically there is little chance of enhancing the natural functioning of the river. For example, the Great Ruaha River, and IFRs for such rivers tend to represent a small percentage of the MAR. As such, little motivation can be provided for most kinds of river-maintenance flows.

Figure 4.31 presents the monthly natural flow time series and the corresponding modified flow (IFR) time series on a semi-log scale. The environmental flow time series depicts the natural variability of the natural time series.

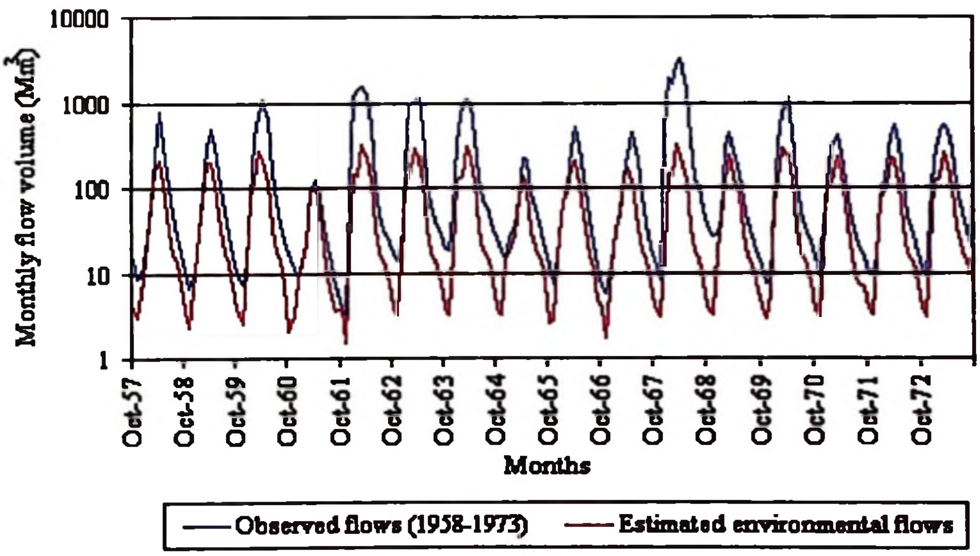


Figure 4.31: Monthly observed flow and estimated environmental flow time series for the Great Ruaha at Msembe station (1958-1973) (note log scale on the y-axis).

Figure 4.32 presents a comparison between the monthly natural flow volumes and the corresponding monthly low flow maintenance volumes. Table 4.23 presents the environmental flows for different months and the corresponding chances of exceedance and return periods (1.1 to 1:5 years).

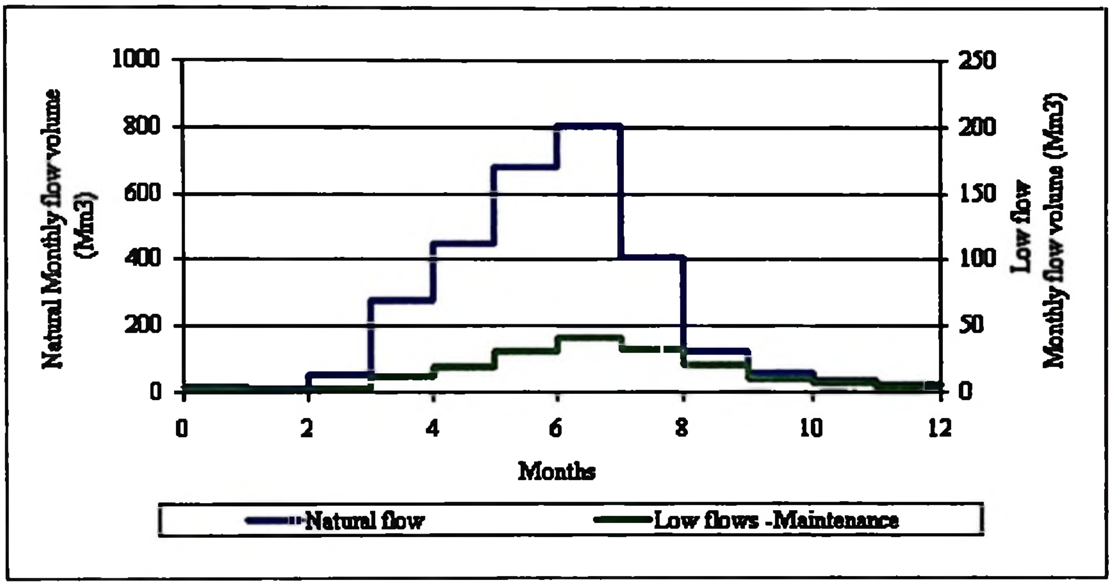


Figure 4.32: Comparison between natural flow volume and monthly low-flows maintenance volume (1958-1973)

Table 4.23: Environmental flow requirements (m^3s^{-1}) at Msembe for different return periods, for management category C/D

Chance of exceedance	Return Period (years)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.99	1	5.0	8.4	31.1	36.1	21.3	7.0	3.4	1.9	1.4	0.8	0.6	1.9
0.50	2	18.8	36.2	64.7	70.7	43.3	13.0	6.8	5.3	2.9	1.6	1.2	3.4
0.30	3	21.5	37.9	66.1	72.9	44.3	13.2	6.9	5.4	3.0	1.6	1.2	3.5
0.20	5	22.0	37.9	66.4	73.2	44.4	13.2	6.9	5.4	3.0	1.6	1.2	3.6

It is clear from Table 4.23 that for a one year return period flow, there is less than 1 m^3s^{-1} of water for the October and November months. For the Great Ruaha River, October and November are the most critical dry months. From Table 4.23 the absolute minimum flow (i.e. exceeded every year) at Msembe is about 0.54 m^3s^{-1}. In this case, considering the present water competition in the catchment, one would recommend 99% assurance level for this critical period to ensure some flows during the critical periods in the dry season. However, such a recommendation would be a function of the routing requirement through the wetland and the available water resources.

4.5.2 Scenarios and environmental water requirements

Realising the need to balance environmental water requirements and livelihoods issues under the prevailing surface water conditions, four possible flow scenarios were formulated. In each case the wetland model was used to compute the inflows to the Eastern wetland required to maintain the specified environmental flows in the downstream. The scenarios were:

i) Ensuring a dry season outflow of 2.84 m^3s^{-1} (i.e. corresponding to the "natural" Q_{95})

The Q_{95} as derived from the flow duration curve is 2.84 m^3s^{-1}. The corresponding average dry season inflow required to maintaining this outflow was estimated to be 12.2 m^3s^{-1}. This corresponds closely to average dry season inflows simulated for the pre-1974 (Table 4.21) but is significantly greater than the perennial river flows measured upstream of the off-takes on the Plains between 1998 and 2003. This indicates that abstractions upstream of the Plains are reducing flows on the perennial rivers. Given current demand for water in the catchment it would be very difficult to achieve this flow.

ii) Ensuring a dry season outflow of 1.65 m^3s^{-1} (T = 5 years derived from DRM for critical period)

The flow during the critical dry season period for a return period (T = 5 years) as derived from the Desktop Reserve Model is 1.65 m^3s^{-1}. The corresponding average dry season inflow required to maintain this outflow was estimated to be 9.98 m^3s^{-1}. This is slightly higher than the average dry season flow in the perennial rivers, upstream of the abstractions on the Plains (Table 4.21). Similar to the first scenario, given the present water conditions in the catchment it would be very difficult to achieve this flow.

iii) Ensuring a dry season outflow of 1 m^3s^{-1} (T = 2 years derived from DRM for most critical period)

The flow during the critical dry season period for a return period (T = 2 years) as derived from the Desktop Reserve Model is 1 m^3s^{-1}. This is also a scenario preferred by the Ruaha National Park warden and the Friends of Ruaha Society that dry seasons flow of 1.0 m^3s^{-1} should be ensured. This was proposed, on the basis of "expert judgement" (Gladys, Ecologist for the Ruaha National Park, Pers. Comm.) through an evaluation of the likely ecological impact of such a flow within the Park. The corresponding average dry season inflow required to maintain this outflow was estimated to be 8.59 m^3s^{-1}; approximately the average dry season flow in the perennial rivers, upstream of the abstractions on the Plains (Table 4.21). However, allocating all this water for environmental needs would leave nothing for irrigation and other livelihood support activities.

iv) Ensuring a dry season outflow of 0.5 m^3s^{-1} (i.e. T = 1 year)

The absolute minimum dry season flow required to maintaining conditions (i.e., temperature and dilution requirements) suitable for wildlife in the dry season pools and the river in the Ruaha National Park was judged to be 0.5 m^3s^{-1} (Gladys, Ecologist for the Ruaha National Park, Personal Communication). This is approximately equal to the critical dry season flow of 0.54 m^3s^{-1} for a return period (T = 1 year) in November as derived from the Desktop Reserve Model. The corresponding average dry season inflow required to maintaining this outflow was estimated to be 7.0 m^3s^{-1}. This is approximately 3.25 m^3s^{-1} greater than the current average dry season inflows (Table 4.21). To maintain this average inflow would require the available dry season surface water resource to be divided in the ratio of 80% for the environment (i.e., 7.0 m^3s^{-1}) and 20% for anthropogenic water needs (i.e., 1.50 m^3s^{-1}). In absolute terms this would require current dry season abstractions to be reduced from approximately 4.25 m^3s^{-1} to about 1.50 m^3s^{-1} (i.e., a 65% reduction).

4.5.3 Options for maintenance of environmental flows

The analyses conducted in this study indicated that, in order to maintain absolute minimum desired flows downstream of the Eastern wetland (i.e., 0.5 m^3s^{-1}), it would require a 65% reduction in current dry season abstractions from the perennial rivers. Some reduction in abstraction may be possible through improved water use efficiency. Currently demand management is being implemented through a program of gate closure on the irrigation schemes. By reducing water diversions at the end of the wet season (i.e. March/April) it was hoped to "top-up" the wetland storage sufficiently to ensure the maintenance of dry season flows. However, to date the program has not prevented the drying up of the Great Ruaha River. The current study has shown a lag of 4-6 weeks between inflows and outflows. This suggests that it is maintenance of flows throughout the dry season, not storage within the wetland *per se*, which is critical to sustaining the downstream river flows.

Increased use of groundwater is another possible approach to reducing surface water abstractions. No detailed survey of groundwater sources has been conducted, but it has been estimated that annual groundwater inflow, combined with inflow from the ephemeral rivers, may be of the order of 29-36 Mm^3 (SMUWC, 2001b). Currently many of the villages rely on water supplied by the irrigation canals and this means that diversions have to be maintained throughout the dry season. even at those locations where irrigation is minimal or non-existent. Since much of the water diverted is "lost" through seepage and evaporation, significant water saving might be possible if alternative options for domestic supply could be found. Replacing domestic supply with groundwater sources would enable some off-takes to be closed completely in the dry season. However, groundwater distribution, which is likely to be closely associated with permeable deposits and paleo-river channels (SMUWC, 2001b), may be very variable and not located close to where the water is needed. Furthermore, since groundwater flows contribute to maintaining the wetland during the dry season, the impact of significant dry season groundwater abstraction (e.g., if groundwater was used for irrigation) on low flows is not clear.

To ensure an outflow of 0.5 m^3s^{-1} an average dry season inflow of 7 m^3s^{-1} to the Eastern wetland must be guaranteed. There is clearly significant potential for dry season water saving in the Usangu catchment. However, given the current importance of the river abstractions for dry season livelihood needs (i.e. irrigation, water supply and others), it is very difficult to see how, under existing circumstances, the reductions required to attain these inflows could be attained. Consequently, it is necessary to consider alternative management scenarios.

4.5.4 Management of the wetlands

The difference between the relatively large inflows and small outflows from the wetland is attributed to evapotranspiration from within the Eastern wetland and the surrounding grassland. Clearly, although many benefits are derived from the wetland, much water is lost in the wetland, and in relation to downstream water requirements, can be considered a "scarcity multiplier" (i.e. reducing outflows because evaporation in the wetland). Given the current difficulty reducing dry season abstractions, the likely possible trade-off that might be considered is that between the wetland itself and the Ruaha National Park. This trade-off can be expressed in terms of evaporation in the wetland versus uses in the Park and the downstream hydropower dams; or in terms of benefits for fisheries, livestock and biodiversity in the wetland, versus wildlife conservation and energy generation. The trade-off can be expressed as decision over the size of the permanent wetland as presented in the following statement:

EITHER

A larger wetland evaporating all the incoming water. All ecological benefits of the inflow are attained by the wetland and there is no exit flow.

OR

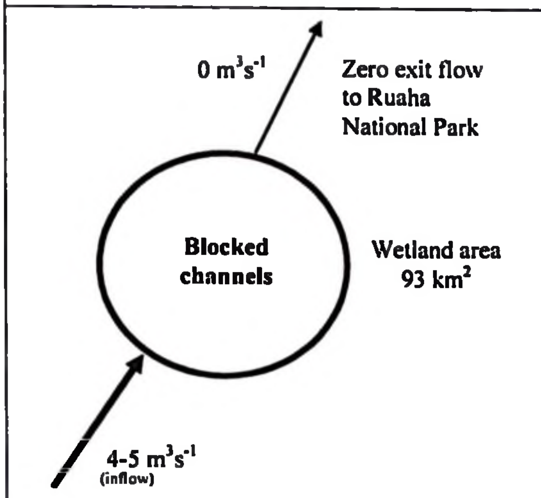
A smaller permanent wetland evaporating most of the inflow but allowing an exit flow of about 0.5 m^3s^{-1} to the Ruaha National Park during low flow period. The ecological benefits of the inflow are shared between the wetland and the Ruaha National Park.

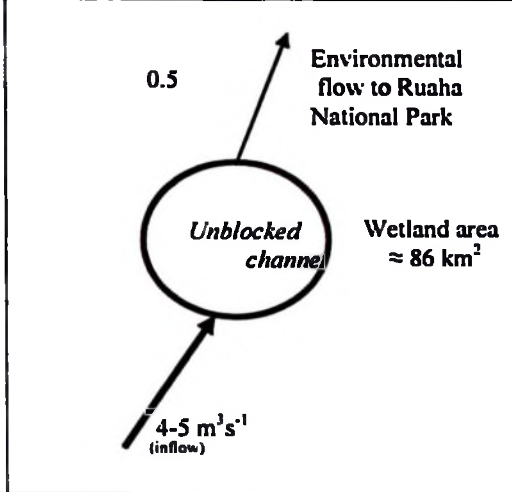
Figure 4.33 is a schematic representation of these two possible management options. If the second option is preferred, the objective becomes to manage the wetland in a way that, despite the limited current inflows, retains as far as possible the benefits provided by the wetland but simultaneously ensuring a flow from the wetland to the Park. Such a strategy can only be achieved if evapotranspiration from the wetland is reduced. This in turn requires active management of water within the wetland, specifically better control of flows within it.

If flows through the wetland were increased so that inflowing water reached the outlet more rapidly, evapotranspiration would be reduced and downstream flows could be maintained. Currently there is no defined channel extending all the way from Nyaluhanga to NG'iriama and, within the wetland, water moves as sheet flow through reed beds, at all but the lowest flows. More rapid flows could be achieved by ensuring that major pools within the wetland are linked by channels and the major channels are kept clear of reeds and other aquatic vegetation[2].

Before the expulsion of fishers from the wetland, the local people were very effective at blocking and unblocking channels. If a plan could be endorsed to allow fishers to return to the reserve, they could be encouraged to keep channels open, especially if the practice resulted in improved fisheries. Otherwise mechanical and perhaps even chemical removal of reeds, and/or dredging of channels, might have to be considered.

[2] Despite the increased irrigation, fertiliser use within the catchment is low and there is no evidence of enhanced reed growth arising as a consequence of greater nutrient inputs (SMUWC, 2001c)

<table>
<tr>
<th>Un-managed tradeoff, zero flow to Ruaha National Park</th>
<th>Managed tradeoff, small environmental flow to Ruaha National Park</th>
</tr>
<tr>
<td>


</td>
<td>


</td>
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<td>
Currently, the Ihefu wetland is in an "unmanaged" scenario because livestock keepers and fisher folk have been excluded. Although supposedly natural, the channels have been blocked in the past by livestock keeping and fishing activities.

Inflow to the wetland spreads and this generates greater evapotranspiration loss. Although the inflow is now greater than before year 2001, (because of canal regulation by RBWO), the average dry season flow of about 4-5 m^3s^{-1} is insufficient to generate 'spill' at the outlet. Consequently the Ruaha National Park is left without water for several months.

The situation may not improve because:

No one is allowed in the area (although there is some discussion of fisher folk being allowed to return)
No use of wetland resources is allowed
No human action is occurring on the wetland

</td>
<td>
In an alternative 'managed scenario' the wetland is more carefully managed. All stakeholders (RBWO, Ruaha National Park, Mbarali, Usangu Safaris Ltd, livestock keepers and fisher folk) agree to a community management plan, where livestock keepers are not excluded but numbers are decreased. Fisher folk are not excluded but their number and use of resources is "controlled" or self-regulated. Active management of water flows results in reduced evapotranspiration.

The situation may improve because:

Negotiated uses of wetland is promoted
"Controlled" use of wetland resources is allowed
The wetland is managed in order to ensure minimum flows of 0.5 m^3s^{-1} at the outlet.

</td>
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Figure 4.33: Possible management scenarios for the wetlands

Alternative options

To maintain flows downstream of NG'iriama, a number of engineering alternatives could also be considered. These include:

- Raising the sill level at the outlet, by constructing a low (i.e. 0.5 to 1.0 m) weir across the rock lip at NG'iriama (i.e., crest level between 1010.0 m amsl and 1010.5 m amsl). Such a structure would increase the size of the perennial swamp and effectively transform the wetland into an inter-seasonal reservoir by increasing the volume of water "stored" in the swamp at the end of the wet season. Although evapotranspiration losses would also be significantly increased, if flow through the weir was regulated via an adjustable sluice gate, downstream flows could be controlled to ensure that minimum flow requirements were met. To minimize changes to wet season flows from the wetland, the weir would have to be designed such that it is overtopped during periods of high flows.
- Construction of a pipe to transfer a portion of the inflow at Nyaluhanga directly to NG'iriama. This would reduce both the permanent size of the wetland and evapotranspiration from it. Providing current inflows to the wetland are maintained in the future, it would ensure that minimum flow requirements downstream of the outlet could be attained.
- Construction of a dam on the Ndembera River to store water for controlled inflows to the north-eastern end of the wetland. Preliminary studies for construction of such a dam have been conducted as part of the feasibility studies of the Madibira Rice project in 1985 by Halcrow and Partners. However, the dam was not built, largely because the cost made it uneconomic. Certainly building a dam is an expensive option and it could be difficult to justify construction solely for the purpose of maintaining dry

season flows. If the dam was built for multiple purposes. careful management would be required to ensure that environmental flows did not lose out to other demands.

The ecological impacts of these measures would need to be carefully assessed through detailed environmental impact assessment. Detailed surveys of the wetland geometry as well as hydraulic analyses, would be required to determine likely changes to the areal extent of the permanent swamp and hence consequences for the seasonal wetland. The implications for fisheries and grazing, as well as other livelihood activities in the area. would have to be carefully evaluated. Participation of local people in the decision-making process would be essential for any intervention to be successful and sustainable.

CHAPTER FIVE

1.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and conclusions

5.1.1 Land use and cover change dynamics

Analyses of the images showed changes in land use and cover between the different dates and seasons. The analysis indicated that the study area had undergone notable changes in terms of land use and land cover. However, it is not clear whether the changes had been continuous or varied from year to year. The analysis considered both seasons (wet and dry), but it was impossible to obtain the corresponding wet season images for some years.

The dry season analysis revealed a steady increase in cultivation and bareland area. Between 1973 and 1984 the cultivated plus bareland experienced the highest annual increase (+14.8% per year) and (+10.9% per year) between 1984 and 2000. The closed woodland and open woodland consistently declined between the two time horizons (i.e., -2.6% and -3.7% per year and -4.1% and -1.2% per year) between 1973 and 1984, and between 1984 and 2000 for closed and open woodland respectively. Other covers (closed bushland, open bushland, bushed grassland) increased by (+3.0% per year) between 1973 and 1984 and declined at -0.3% per year between 1984 and 2000. While vegetated swamp had the highest net decrease (-4.2% per year) between 1984 and 2000 in the former window it increased at a rate of +6.8% per year between 1973 and 1984.

5.1.2 Flow regime change and its link to land use and cover changes

The flow regime for the Great Ruaha River has changed as a result of increased human interventions which have led to modification of land covers. The modifications of natural vegetation cover as well as soil conditions led to modified runoff production and consequently to changing flow regimes. Major changes observed in recent years are related to such modifications.

The inflows that used to maintain the wetland decreased because of intensification in agricultural activities and river flow regulations in the upstream. Since the maintenance of downstream flows depends on the inflows into the Eastern wetland, the decreased inflows led to cessation of outflows at the exit of the wetlands which led to drying of the Great Ruaha River. In this case the inflows into the Eastern wetland were insufficient to surpass the evaporative loss in the wetland. Unlike the dry season, because of changes in land use and cover, more runoff is generated in the wet season but not sustained during the dry season. This indicates an impact of changes on the base flows which are responsible for dry season maintenance.

The analysis for mean monthly flows considered in three time periods (i.e. pre-1974, 1974-1985 and 1986-2003) indicated variations during the peak. For the case of 1986-2003, it was skewed to the left but relatively flat from February to April as compared to the former periods. Unlike the latter period, the former periods, the peak flow was attained in April. The observed variations are attributed to land use and land cover changes. Because of that, there is earlier attainment of higher flow in the post-1986 periods in February as compared to April for other periods. The trend analysis on mean annual runoff did not reveal any significant trend at 95% level of confidence but a declining trend in low flows has been detected. The analysis for Flow Duration Curves and frequency analysis for low flows confirmed a decline in low flows.

The trend analysis on high catchment annual rainfall for some key stations did not reveal any significant trend likewise for the perennial rivers (Great Ruaha River and Mbarali River). This concluded the fact that it was the changes in land use and land cover in the Usangu Plains which contributed to reduced dry season flows in the Great Ruaha River downstream of the wetland.

5.1.3 Hydrology of *Ifushiro* wetland and dry season flows

A spatially distributed, groundwater flow model, Visual MODFLOW provided information on the timing, extent and duration of the water table intersection with the ground surface for different seasons. Variations in other features, such as evapotranspiration from different vegetation distributions within the wetland, could also be accommodated but the depth of standing groundwater should be interpolated from contour information. Such models would benefit management studies of wetland. The Ifushiro wetland study revealed a direct dependency on surface water. The water table fluctuations corresponded with the surface water supply (i.e., rainfall and water levels in the pools and channels inside the wetland). The water budget was dominated by evapotranspirative losses, which accounted for 77% of the total outflows. Analysis for inflows, outflows and the water budget concluded that the Ifushiro wetland did not contribute to downstream flows in the dry season.

5.1.4 Eastern wetland hydrological model and simulations

The model performance was evaluated through a comparison between the observed wetland areas from remotely sensed images and aerial photos. Overall, the model showed good correspondence between observed and simulated values (R^2 =0.75), but with underestimation of wetland areas. It is possible that the tendency to underestimate the wetland area is a consequence of the assumption that evapotranspiration was always at potential rates or it may be that the model is overestimating wet season outflow.

Application of the model to evaluate the inflows and outflows revealed that there was approximately a 4 to 6 weeks lag between inflows to, and outflows from, the wetland, indicating the effect of wetland attenuation on flows. For the pre-1974 window, the average annual influx to the wetland (i.e., rainfall + inflow) was 3,881 Mm^3. The minimum influx was 1,320 Mm^3 in 1961 and the maximum was 14,424 Mm^3 in 1968 (i.e., an *El Nino* year). Although rainfall is measured on the plains and a lot of inflow is generated in the highlands, rainfall and inflow are well correlated. On average, rainfall equalled 13% (i.e., 491 Mm^3) of total annual influx to the wetland. Of the total inflow, on average 22% (i.e., 835 Mm^3) was evapotranspired and 78% (i.e. 3,045 Mm^3) was outflow from the wetland at NG'iriama. The simulated annual water budget of the wetland showed that the second window (1974-1985) average annual outflow from the wetland was considerably less than it was in the post-1985 period. However, dry season outflows from the wetland did not cease. This confirmed the fact that it was the decline in inflows during critical period (July-

November) which resulted in the cessation of dry season outflows in the post-1985 window.

The assessment for temporal change in the wetland area and water budget between the pre-1974 and the post-1985 revealed a significant change in average area of the wetland in the wet season. However, the dry season minimum area (occurring in October) decreased by about 40% from an average of 160km^2 to 93 km^2. The water budget indicated a progressive decrease in the average minimum dry season inflows to the Eastern wetland. Average flow in October decreased from 32.1 Mm^3 to 18.6 Mm^3 to 9.2 Mm^3 respectively. Over the entire period there was a total decrease in the simulated dry season inflows of approximately 70%. The average minimum dry season wetland "storage", decreased from 58 Mm^3 to 40 Mm^3 to 24 Mm^3 in the pre-1974, 1974-1985 and post-1985 windows respectively. Overall this represented a 60% decrease in the minimum dry season storage.

Simulated wet season outflows from the wetland varied between the time windows. However, there was no clear trend over time and hence no trend in annual data, because the wet season flows dominated the annual flow series. In contrast there was a steady decline in the outflows in the dry season. In the post-1985 window, the average minimum dry season outflows, which occurred in October/November declined to 0.3 Mm^3 - 0.6 Mm^3 and were just 2-6% of the values they were in pre-1974 window.

The model results indicated a large decrease in dry season inflows to the Eastern wetland. This, in conjunction with the decrease in rainfall over the Usangu Plains, resulted in shrinking of the perennial swamp, a decrease in water stored within the wetland and a marked decline in the dry season outflow from the wetland.

5.1.5 Environmental flows and management

The different estimates for environmental flows were derived using hydrological approaches. The wetland model enabled calculation of the inflows required to maintain specified discharges during the critical low flow period, taking into account the available surface water in the perennial rivers and abstractions for anthropogenic water demands. Evaluation of different estimates using the wetland model and consultations with stakeholders revealed that a 0.5 m^3s^{-1} was the most likely flow required during the critical dry season. Nevertheless, this being the average value it did not account for flow variability which is very important for ecology. But recognizing the fact that it is the flow required during the critical period of low flow, with almost a constant horizontal slope and occasional variability, it is certainly that the value is acceptable. To maintain a flow of 0.5 m^3s^{-1}, as the minimum required flow for maintenance of fish habitat and the current ecology of the Ruaha National Park, an average dry season inflow of approximately 7.0 m^3s^{-1} into the Eastern wetland in the dry season is required. Although significant opportunities exist to increase local water use efficiency, and hence inflows into the wetland, given current levels of diversion it will be very difficult to "release" sufficient water to ensure the desired 0.5 m^3s^{-1}. Consequently, a pragmatic approach is to consider alternative options that manage water within the wetland to either reduce evaporation or increase water storage. However, all the suggested alternatives would have ecological, as well as socio-economic consequences, which need to be carefully assessed through environmental impact assessments and discussion with all stakeholders.

5.2 Recommendations

The following recommendations are proposed:

(a) An integrated management of land and water is vital for the sustainability of the wetlands resources in the Usangu Plains. Sustainable wetlands management strategies should be formulated together with the land use plans. A well placed and coordinated institutional arrangement for wetlands management that links to catchment management is urgently required to reconcile agricultural production and the environment in a more rational manner.

(b) Community based wetlands management has become a global concern and this is essentially a move from resource "management *against* and *for* the people" to "management *with* and *by* the people. Involving of local communities in the management of the Usangu wetlands should be considered for the sustainability of the wetlands resources. However, this would require proper environmental impact assessment.

(c) Proper monitoring of the inflows and outflows from the Eastern wetland, and rainfall in the Usangu Plains is necessary. Currently, flow data at the Msembe Ferry located downstream of the Eastern wetland in the Ruaha National Park was regressed backward and used in modelling the wetland processes. This technique is liable to errors that impair the accuracy of the modelling processes and the estimates. The Ndembera River (input point near exit) is not monitored daily and the Chimala river course is at present not well defined in the Plains. They need to be well monitored.

(d) Groundwater is one component of the wetland water balance. At present, this component is not well known. In the previous studies this component was considered negligible. In this study it was accounted for in the inflow term. However, such oversimplification is a source of errors in the model estimates. Therefore, to gain more confidence on the results from the simulation model, the groundwater component for the Eastern wetland need be thoroughly studied.

(e) Further holistic (more detailed) study should be conducted to re-evaluate the environmental flows considering other aspects of ecological and socio-economic importance through stakeholder involvement. Therefore, ecological monitoring at specific environmental flow sites (EFS) including survey of cross sections at EFS is necessary.

(f) This study has demonstrated the value of combining different research analyses and the role of a relatively simple model to provide a credible scientific basis to underpin decisions relating to environmental water allocations. The wetland model is simple and could be used to assist decision-makers in evaluating water allocation for the environment and in understanding the hydrological functioning of the wetland. While application of wetland model shall be encouraged, a concerted action is needed to collect more information through aerial surveys for different seasons to generate more data points so as to improve the model performance.

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Glossary of terms

Actual evapotranspiration: is the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration.

Aquifer: a rock formation that store groundwater water.

Aquitard: a geologic formation that is not permeable enough to yield significant quantities of water to wells, but on a regional scale can contribute significant water to the underlying or overlaying aquifer.

Evapotranspiration: combined loss of water to the atmosphere via the processes of evaporation and transpiration.

Heterogeneous: material property that varies with the location within the material.

High-gradient riverine wetlands: occur along stream channels in or near headwater areas (generally, stream orders 1-3). They are typically very small, and occupy banks and sites where sediment has accumulated behind logs and other obstructions. These wetlands often are very important components of the overall aquatic food web.

Homogeneous material: homogeneous if its hydrologic properties are identical everywhere.

Hydraulic conductivity: factor of proportionality in Darcy's equation relating flow velocity to hydraulic gradient having units of length per unit of time. A property of the porous medium and the fluid (water content of the medium.

Hydraulic gradient: slope of the water table or potentiometric surface. The change is static head per unit of distance in a given direction. If not specified, the direction generally is understood to be that of the maximum rate of decrease in head.

Hydraulic head: Height that water in an aquifer can raise itself above an (arbitrary) reference level (or datum). When a borehole is drilled into an aquifer, the level at which the water stands in the borehole (measured with reference to a horizontal datum such as sea level) is, for most purposes, the hydraulic head of water in the aquifer. This term defines how much energy water possesses. Ground water possesses energy mainly by virtue of its elevation (elevation head) and of its pressure (pressure head).

Isotropic: Having the same properties in all directions. Obtained by combining the Greek iso, meaning alike or same, and tropos, meaning turning.

Low-gradient riverine wetlands: occur within the 5-year floodplain of alluvial streams (usually 7th order or higher). They include a wide variety of community types, and have important functions related to habitat as well as sediment and water storage.

Monitoring well: allow penetration of water through perforations along most of the length of the pipe below ground. Therefore, the water level in a monitoring well reflects the composite water pressure integrated over the long, perforated portion of the pipe.

Observation well: non-pumping well used primarily for observing the elevation of the water table or the piezometric pressure; also to obtain water-quality samples.

Piezometer wells: allow penetration of water only at the bottom of the pipe, either directly into the bottom or along a short length of perforation near the bottom.

Consequently, the water level in a piezometer reflects the water pressure only at the bottom of the pipe.

Piezometric surface: surface defined by a pressure head and position (elevation above a standard datum, such as sea level). For an unconfined aquifer, it is equal to the elevation of the water table. For a confined aquifer, it is equal to the elevation to which water would rise in a well penetrating and open to the aquifer. This term is now replaced by potentiometric surface.

Potential evapotranspiration: amount of water that evaporates or is transpired from a saturated surface, or is a measure of the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming no control on water supply.

Redoximorphic features, or mottling, is identified by the presence of oxidized and reduced states of iron in the same ped. In more highly weathered soils, it is identified as concentrations and depletions of iron. *Iron concentrations* occur as bright (red or yellow) spots in a reduced (gray) matrix. *Iron depletions* occur as reduced (gray) spots in an oxidized (red or yellow) matrix.

Riverine: wetlands occurring in topographic valleys adjacent to stream channels ranging from ephemeral or intermittent headwater streams, to perennial higher order streams. Surface and shallow subsurface water movement is from the valley sides toward the stream channel, from the stream channel toward the adjacent floodplain and downstream during overbank events. Water levels in riverine wetlands rise and fall as a result of runoff from valley sides, groundwater discharge, and overbank flow.

Slope/Flat: Slope and flat wetlands occur on hill or valley slopes ranging from steep to slight. The movement of surface and shallow subsurface water is perpendicular to topographic contour lines. Slope and flat wetlands are distinguished from the riverine wetland class by the lack of a defined channel with observable features of bed and bank. The distinction between slope and flat is subjective, but slope wetlands become flat wetlands when the slope is so slight or gradual that for all intents and purposes the wetland functions as if it were in a topographic flat area. Slope and flat wetlands may be isolated, or periodically connected to other wetland classes or surface waters.

Slough: a hollow filled with mud, or a swamp, marsh, or muddy backwater, or a small sluggish creek in a marsh or tidal flat. During dry periods, it is often the area left with standing water.

Specific storage: volume of water released from or taken into storage per unit volume of the porous medium per unit change in head. It is the three-dimensional equivalent of storage coefficient or storativity, and is equal to storativity divided by aquifer saturated thickness.

Storativity or Storage coefficient: volume of water released per unit area of aquifer and per unit drop in head. Storage coefficient is a function of the compressive qualities of water and matrix structures of the porous material. A confined aquifer's ability to store water is measured by its storage coefficient. Storativity is a more general term encompassing both or either storage coefficient and/or specific yield.

Taxa: a classification or group of organisms (ie, kingdom, phylum, class, order, family, genus, species), or the named classification unit to which individuals or sets of species are assigned, such as species, genus and order.

APPENDICES

Appendix A: Soil survey

1. Introduction

A reconnaissance survey of the soil at the Ifushiro wetland was conducted. This involved the 25 augered holes for the installation of piezometer and monitoring wells to depths ranging between 1.5 and 2 m. Descriptions of the soil profile characteristics were made for each hole, using the method suggested in Landon (1984) cited in McCartney (1998). The description of the soil profile includes information on soil horizons, distinguished on the basis of colour and texture. Soil texture was determined by feel, soil colour using Munsell colour charts and the presence of roots and gravel was noted. An estimate of soil drainage class was made from the morphological characteristics of the soil profile. Table A1 gives definitions of the six drainage classes (McCartney (1998). Figure A1 presents the soil profile (summarized) along the transect A-B.

Table A1: Drainage class and water regime related to profile morphology (after Landon, 1984 cited in McCartney, 1998)

Soil drainage class	Key to field identification
Well drained (excessive)	Coarse-textured soils with small available water capacity and only saturated after heavy rain. Surplus water is removed very rapidly. Any water table is well below the solum.
Well drained	Soil is rarely saturated in any horizon within 90 cm of the surface. Mottling is usually absent throughout the profile.
Moderately well drained	Some part of the soil in the upper 90 cm is saturated for short periods after heavy rain but no horizon within 50 cm of the surface remains saturated for more than one month in the year.

	Colours typical of well drained soils on similar material are usually dominant but may be slightly lower in chroma, especially on ped faces and faint to distinct ochreous or grey mottling may occur below 50 cm.
Imperfectly drained	Some part of the soil in the upper 50 cm is saturated for several months but not for most of the year. Subsurface horizon colours are commonly lower in chroma and/or yellower in hue than those of well drained soils on similar materials. Greyish to ochreous or grey mottling is usually distinct by 50 cm and may be prominent below this depth. There is rarely any gleying in the upper 25 cm.
Poorly drained	The soil is saturated for at least half the year in the upper 50 cm but the upper 25 cm is usually unsaturated during most of the growing season. The profiles normally show strong gleying. A horizons are usually darker and/or greyer than those of well drained soils on similar materials and contain rusty mottles. Grey colours are prominent on ped faces in fissured clayey soils or in the matrix of weakly structured soils.
Very poorly drained	Some part of the soil is saturated at less than 25 cm for at least half the year. Some part of the soil within the upper 60 cm is permanently saturated. The profiles usually have peaty or humose surface horizons and the subsurface horizon colours have low (near neutral) chroma and yellowish to bluish hues.

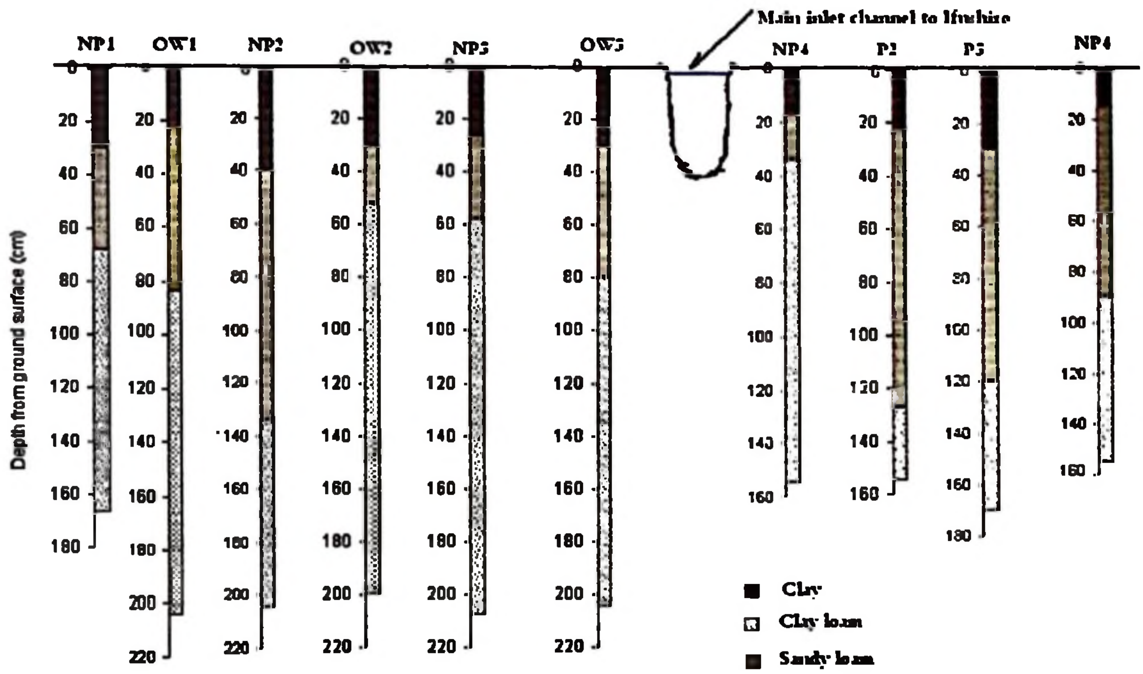


Figure A1: Soil profile along transect A-B on both sides of the main inlet channel

A2 Soil profile descriptions

Profile descriptions from the soil pits and the holes augered for wells are presented in this section.

Soil profile - at P1

Depth (cm)	Field Description
0-32	Slightly moist organic clay; very dark grey (10YR 3/1) when dry and black (10YR 2/1) when moist; strong fine sub angular blocky structure; friable; many roots; gradual transition to:
32-43	Slightly moist clay; grey (10YR 5/1) when dry and dull reddish brown (5YR 4/4) when moist; strong fine sub angular blocky structure; firm wet; hard when dry; few fine roots; sharp transition to:
43-90	Slightly moist clay; grey (10YR 5/1) when dry and dull reddish brown (5YR 4/4) when moist; strong very fine sub angular blocky; firm when wet; hard when dry; no roots; water table at 54 cm; gradual transition to:

80-150	Sandy clay loam; darkish/reddish brown (5YR 4/6) when dry and light brownish grey (5YR 7/1) when moist; very strong, very fine sub angular blocky; no roots.

Soil drainage class: poorly drained

Soil profile - at P2

Depth (cm)	Field Description
0-22	Slightly moist organic clay; very dark grey (10YR 3/1) when dry and deep black (10YR 2/1) when moist; strong very fine sub angular blocky structure; friable; many roots; gradual transition to:
22-40	Slightly moist clay; grey (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; strong fine sub angular blocky structure; friable when wet; hard when dry; few fine roots; sharp transition to:
40-96	Slightly moist clay; grey (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; strong, very fine sub angular blocky; friable when wet; hard when dry; no roots; water table at 67 cm; gradual transition to:
96-127	Clay loam; darkish/reddish brown (5YR 4/6) when dry and reddish brownish grey (5YR 4/5) when moist; firm, very fine sub angular blocky; no roots.
127-150	Sandy clay loam; reddish brown (5YR 4/6) when dry and light brownish grey (7.5YR 7/1) when moist; friable, very fine sub angular blocky; no roots.

Soil drainage class: poorly drained

Soil profile - at P3

Depth (cm)	Field Description
0-30	Slightly moist organic clay; very dark grey (10YR 3/1) when dry and deep black (10YR 1.7/1) when moist; strong fine sub angular blocky structure; friable; many roots; gradual transition to:
30-50	Slightly moist clay; grey (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; moderate fine sub angular blocky structure; firm when wet; hard when dry; few roots; sharp transition to:

50-120	Slightly moist clay; grey (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; strong, very fine sub angular blocky; firm when wet; hard when dry; no roots; water table at 52 cm; gradual transition to:
120-142	Slightly moist clay loam; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/4) when moist; strong fine sub angular blocky; firm when wet; hard when dry; no roots; gradual transition to:
142-170	Most Clay; greyish (10YR 4/3) when dry and reddish brownish grey (5YR 4/5) when moist; firm, very fine sub angular blocky; no roots.

Soil drainage class: poorly drained

Soil profile - at P4

Depth (cm)	Field Description
0-24	Slightly moist organic clay; very dark grey (10YR 3/1) when dry and deep black (10YR 1.7/1) when moist; strong very fine sub angular blocky structure; firm; many fine roots; gradual transition to:
24-49	Slightly moist clay loam; greyish (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; strong fine sub angular blocky structure; firm when wet; hard when dry; few roots; gradual transition to:
49-78	Slightly moist silty clay loam; grey (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; moderate medium sub angular blocky; friable when wet; hard when dry; few roots; gradual transition to:
78-97	Moist clay; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/4) when moist; strong very fine sub angular blocky; firm when wet; hard when dry; no roots; gradual transition to:
97-145	Moist sandy clay; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/4) when moist; weak fine sub angular blocky; friable when wet; hard when dry; no roots; gradual transition to:
145-160	Moist clay loam, Slightly moist clay loam; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/4) when moist; moderate fine sub angular blocky; firm when wet; hard when dry; no roots.

Soil drainage class: poorly drained

Soil profile - at P5

Depth (cm)	Field Description
0-22	Slightly moist organic clay; very dark grey (10YR 3/1) when dry and deep black (10YR 1.7/1) when moist; strong very fine sub angular blocky structure; firm; many fine roots; gradual transition to:
22-45	Slightly moist clay loam; greyish (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; strong fine sub angular blocky structure; firm when wet; hard when dry; few roots; gradual transition to:
45-78	Slightly moist silty clay loam; grey (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; moderate medium sub angular blocky; friable when wet; hard when dry; few roots; gradual transition to:
78-99	Moist clay; grey (10YR 5/1) when dry and dark reddish brown (10YR 4/6) when moist; strong very fine sub angular blocky; firm when wet; hard when dry; no roots; gradual transition to:
99-141	Moist sandy clay; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/6) when moist; weak fine sub angular blocky; friable when wet; hard when dry; no roots; gradual transition to:
141-160	Moist clay loam; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/4) when moist; moderate fine sub angular blocky; firm when wet; hard when dry; no roots.

Soil drainage class: poorly drained

Soil profile - at P6

Depth (cm)	Field Description
0-14	Slightly moist organic clay; very dark grey (10YR 3/1) when dry and deep black grey (10YR 3/1) when moist; strong very fine sub angular blocky structure; firm; many fine roots; gradual transition to:
14-26	Slightly moist clay loam; greyish (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; strong fine sub angular blocky structure; firm when wet; hard when dry; few roots; gradual transition to:

26-60	Slightly moist silt clay loam; grey (10YR 5/1) when dry and reddish brown (5YR 4/6) when moist; moderate medium sub angular blocky; friable when wet; hard when dry; few roots; gradual transition to:
60-100	Moist clay; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/4) when moist; strong very fine sub angular blocky; firm when wet; hard when dry; no roots; gradual transition to:
100-142	Moist sandy clay; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/6) when moist; weak fine sub angular blocky; friable when wet; hard when dry; no roots; gradual transition to:
142-160	Moist clay loam, Slightly moist clay loam; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/6) when moist; moderate fine sub angular blocky; firm when wet; hard when dry; no roots.

Soil drainage class: poorly drained

Soil profile - at P7

Depth (cm)	Field Description
0-14	Dry organic clay; very dark grey (10YR 3/1) when dry and deep black (10YR 3/1) when moist; strong very fine sub angular blocky structure; friable; many fine roots; gradual transition to:
14-26	Silt clay; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; strong fine sub angular blocky structure; very friable when wet; hard when dry; few roots; gradual transition to:
26-60	Silt clay; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; moderate medium sub angular blocky; very friable when wet; hard when dry; few roots; gradual transition to:
60-84	Slightly moist clay; greyish (10YR 5/1) when dry and dark orange (7.5YR 7/3) when moist; strong fine sub angular blocky; firm when wet; hard when dry; no roots; water table at 61 cm; gradual transition to:
84-99	Moist clay; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/4) when moist; strong fine sub angular blocky; sticky when wet; hard when dry; no roots; gradual transition to:

99-135	Moist silt clay; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/6) when moist; strong fine sub angular blocky; sticky when wet; hard when dry; no roots; gradual transition to:
135-150	Moist clay; grey (10YR 5/1) when dry and dark reddish brown (5YR 4/6) when moist; moderate fine sub angular blocky; sticky when wet; hard when dry; no roots.

Soil drainage class: poorly drained

Soil profile - at P8

Depth (cm)	Field Description
0-38	Dry organic clay; very dark grey (10YR 3/1) when dry and brownish grey (10YR 2/1) when moist; strong fine sub angular blocky structure; firm; many roots; gradual transition to:
38-60	Slightly moist clay; greyish (10YR 5/1) when dry and blackish (7.5YR 3/1) when moist; strong, very fine sub angular blocky structure; firm when wet; hard when dry; few roots; gradual transition to:
60-87	Slightly moist clay; grey (10YR 5/1) when dry and reddish brown (10YR 4/6) when moist; strong, fine sub angular blocky; firm when wet; hard when dry; no roots; gradual transition to:
87-99	Slight moist clay loam; greyish (10YR 5/1) when dry and dark reddish brown (5YR 4/6) when moist; strong, fine sub angular blocky; firm when wet; hard when dry; no roots; gradual transition to:
99-132	Moist clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; very strong, very fine sub angular blocky; friable when wet; hard when dry; no roots.
132-150	Moist silt clay; greyish (10YR 5/1) when dry and dark brownish (10YR 3/1) when moist; moderate fine sub angular blocky; friable when wet; hard when dry; no roots.

Soil drainage class: poorly drained

Soil profile - at P9

Depth (cm)	Field Description
0-28	Dry organic clay; very brownish (10YR 3/1) when dry and dark reddish brown (5YR 4/6) when moist; moderate, very fine, sub angular blocky structure; firm; many roots; gradual transition to:
28-32	Slightly moist clay loam; greyish (10YR 5/1) when dry and dark reddish brown (5YR 4/4) when moist; moderate, fine sub angular blocky structure; friable when wet; hard when dry; few roots; gradual transition to:
32-137	Moist sandy clay; greyish (10YR 5/1) when dry and reddish brown (10YR 4/6) when moist; weak, medium, angular blocky; very friable; no roots; water table at around 47 cm; gradual transition to:
137-150	Moist sandy clay loam; greyish (10YR 5/1) when dry and dark reddish brownish (5YR 4/4) when moist; moderate fine sub angular blocky; firm when wet; hard when dry; no roots.

Soil drainage class: poorly drained

Soil profile - at NP1

Depth (cm)	Field Description
0-26	Dry organic clay; greyish (10YR 3/1) when dry and blackish (10YR 2/1) when moist; brown mottling, strong very fine sub angular blocky structure; firm; many roots; gradual transition to:
26-58	Dry sandy clay; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist mixed with yellowish and black mottling; moderate, fine sub angular, blocky structure; firm when wet; hard when dry; few roots; gradual transition to:
58-107	Slightly sandy clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist mixed with yellowish and black mottling; moderate, fine sub angular, blocky structure; firm when wet; hard when dry; no roots; gradual transition to:
107-137	Moist sandy loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; weak, very fine sub angular blocky; friable; no roots; water table at 117 cm; gradual transition to:

137-164	Moist sandy clay; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; moderate, fine sub angular blocky; friable; no roots; gradual transition to:
164-200	Moist clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; strong, fine sub angular blocky; hard both wet ahd dry; no roots.

Soil drainage class: poorly drained

Soil profile - at NP2

Depth (cm)	Field Description
0-40	Dry organic clay; greyish (10YR 3/1) when dry and blackish (10YR 2/1) when moist; strong, very fine sub angular blocky structure; hard; many fine roots; gradual transition to:
40-82	Dry clay; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; strong, fine sub angular, blocky structure; firm when wet; hard when dry; few roots; gradual transition to:
82-134	Slightly clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist mixed with yellowish and black mottling; moderate, medium, sub angular, blocky structure; firm when wet; hard when dry; no roots; gradual transition to:
134-170	Moist sandy clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; moderate, very fine sub angular blocky; firm; no roots; gradual transition to:
170-200	Moist clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; weak, fine sub angular blocky; friable; no roots.

Soil drainage class: poorly drained

90-130	Moist sandy loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; strong, very fine sub angular blocky; firm; no roots; water table at 130 cm; gradual transition to:
130-155	Moist sandy loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; weak, fine sub angular blocky; friable; no roots.

Soil drainage class: poorly drained

Soil profile - at OW1

Depth (cm)	Field Description
0-30	Dry organic black clay; dark grey (10YR 3/1) when dry and blackish (10YR 2/1) when moist; strong, very fine sub angular blocky structure; firm; many fine roots; gradual transition to:
30-80	Moist clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; mixed with yellowish mottling; strong, very fine sub angular, blocky structure; very firm when wet; hard when dry; few roots; water table at 81 cm; gradual transition to:
80-160	Slightly moist sandy clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; mixed with yellowish and black mottling; moderate to weak, medium, sub angular, blocky structure; friable when wet and dry; no roots; gradual transition to:
160-205	Moist sandy loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; moderate, fine sub angular blocky; firm; no roots.

Soil drainage class: well drained

Soil profile - at OW2

Depth (cm)	Field Description
0-30	Dry organic black clay; dark grey (10YR 3/1) when dry and blackish (10YR 2/1) when moist; strong, very fine sub angular blocky structure; very firm; many fine roots; gradual transition to:
30-52	Slightly moist clay; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; strong, fine sub angular, blocky structure; firm when wet; hard when dry; very few roots; gradual transition to:

52-147	Moist sandy; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; weak, medium, sub angular, blocky structure; friable when wet and dry; no roots; water table at 80 cm; gradual transition to:
147-200	Moist sandy clay loam; greyish (10YR 5/1) when dry and brownish and yellowish (10YR 8/6) when moist; moderate, fine sub angular blocky; friable; no roots.

Soil drainage class: well drained

Soil profile - at OW3

Depth (cm)	Field Description
0-22	Dry organic black clay; dark grey (10YR 3/1) when dry and blackish (10YR 2/1) when moist; strong, very fine sub angular blocky structure; very firm; many fine roots; gradual transition to:
22-83	Slightly moist clay; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; mixed with yellowish and reddish mottling; strong, fine sub angular, blocky structure; very firm when wet; hard when dry; very few roots; gradual transition to:
83-127	Wet sandy; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; weak, medium, sub angular, blocky structure; friable when wet and dry; no roots; gradual transition to:
127-200	Wet sandy clay loam; greyish (10YR 5/1) when dry and brownish and yellowish (10YR 8/6) when moist; moderate, fine sub angular blocky; firm; no roots.

Soil drainage class: well drained

Soil profile - at OW4

Depth (cm)	Field Description
0-17	Dry organic black clay; dark grey (10YR 3/1) when dry and blackish (10YR 2/1) when moist; strong, very fine sub angular blocky structure; very firm; many fine roots; gradual transition to:
17-34	Dry clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; mixed with yellowish and reddish mottling; strong,

fine sub angular, blocky structure; very firm when wet; hard when dry; very few roots; gradual transition to:

34-73	Moist sandy loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1) when moist; moderate, medium, sub angular, blocky structure; friable when wet and dry; no roots; gradual transition to:
73-90	Wet clay loam; greyish (10YR 5/1) when dry and brownish (10YR 3/1)) when moist; weak, medium, sub angular, blocky structure; firm when wet and dry; no roots; water table at 87 cm; gradual transition to:
90-155	Wet sandy loam; greyish (10YR 5/1) when dry and brownish and yellowish (10YR 8/6) when moist; weak, fine sub angular blocky; firm; no roots.

Soil drainage class: well drained

Appendix B: Change Detection Matrices

B1: Change detection matrix for the period 1984 to 2000 during the dry season

Cover 1984 (ha)	Cover 2000 (ha) Dry season										
	CW	OW	CB	OB	BG	OG	CLB	VS	KRF	TTC	Total
CW	4080	5306	3031	2256	1164	1579	4446	151	1285	320	23618
OW	3772	17684	12818	11494	4613	3420	21018	48	329	428	75624
CB	6256	33426	18474	14053	4728	10538	14683	221	1475	517	104370
OB	1861	6713	6340	3909	1817	2264	4218	25	134	202	27484
BG	571	2432	5371	663	1759	395	6103	28	31	63	17417
OG	1252	1394	632	667	163	3610	354	280	1331	2	9683
CLB	0	0	5029	608	2399	836	22953	4	10	16	31854
VS	0	0	1093	1112	195	15839	150	8020	518	1	26928
Total	17792	66954	52788	34762	16838	38482	73924	8778	5113	1549	316979

(CW = closed woodland; OW = open woodland; CB = closed bushland; OB = open bushland; BG = bushed grassland; OG = open grassland, CLB = cultivation plus bare surface; VS = vegetated swamp; KRF = Kapunga rice farms; TTC = tail & top end cultivation)

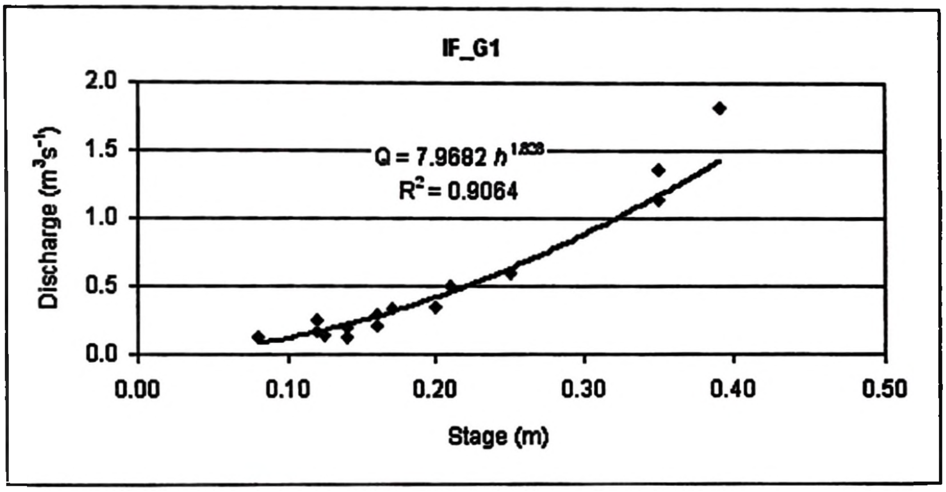
B2: Change detection matrix for the period 1984 to 2000 during the wet season

Cover 1984 (ha)	Cover 2000 (ha) Wet season										
	CW	OW	CB	OB	BG	OG	CLB	VS	KRF	TTC	Total
CW	1590	5395	1710	1939	2870	2511	3843	3324	1280	365	24826
OW	6139	21643	7130	7976	9568	5387	19635	1843	332	515	80170
CB	9760	32872	13985	11070	15289	6457	23506	2223	504	756	116423
OB	840	5176	910	470	1134	882	1215	418	249	118	11413
BG	839	3081	1047	1455	1297	920	1628	471	1	0	10739
OG	622	773	358	17	687	261	414	85	0	0	3217
CLB	0	0	224	177	651	735	7437	11	0	2	9237
VS	2545	7033	1496	1205	2268	6188	1804	35591	2783	39	60954
Total	22335	75974	26859	24310	33764	23342	59483	43966	5150	1795	316979

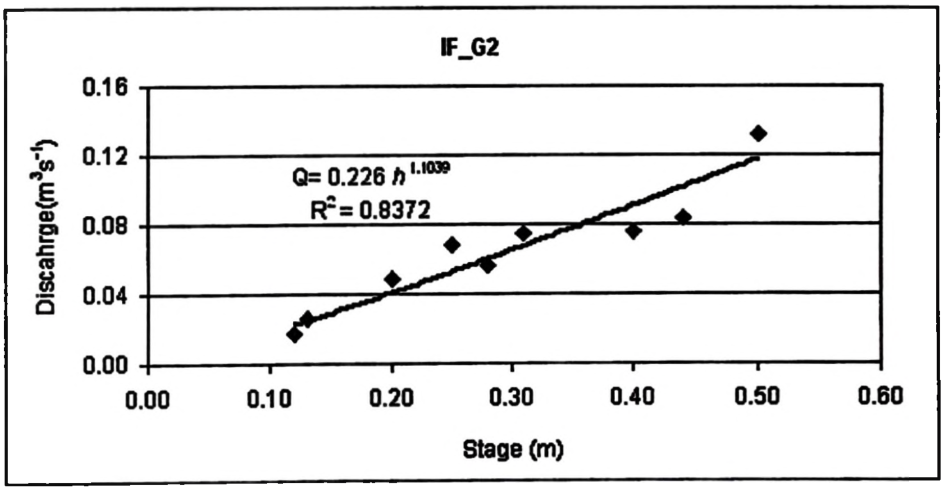
(CW = closed woodland; OW = open woodland; CB = closed bushland; OB = open bushland; BG = bushed grassland; OG = open grassland, CLB = cultivation plus bare surface; VS = vegetated swamp; KRF = Kapunga rice farms; TTC = tail & top end cultivation)

Appendix C: Derived rating curves at Ifushiro wetland

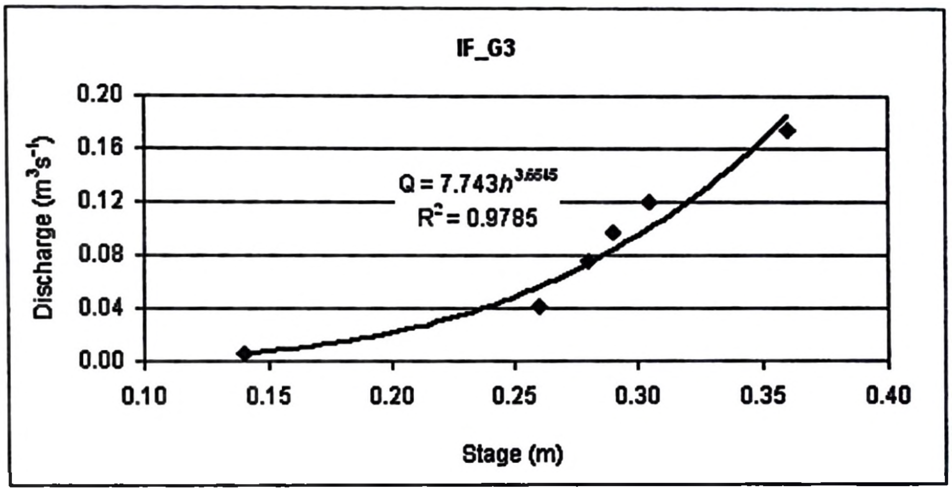
C1: Rating curve at the main inlet channel to Ifushiro wetland



C2: Rating curve at the first outlet from Ifushiro wetland



C3: Rating curve at the second outlet from Ifushiro wetland



APPENDIX D: Questionnaire

A QUESTIONNAIRE TO WETLANDS USERS

A: General Information

Date	
Name of cluster/ Sub Village	
Name of the village	
Name of District	
Interviewee number	

B: Interviewee information

Gender		Age	Originality		Marriage status		Education	
1=Female			Region		1= Married		1=Not been to school	
					2= Not married		2=Primary school	
2=Female			District		3= Widowed		3=Secondary School	
					4= Divorced		4=College (Not University)	
Working status and type (Occupation)					5= Separated		5=University	

C. Research information

1. When did you establish in this area? (State year) ☐☐☐☐

2. Which reasons made you to establish in this area? ( )
   1. Fertility of the soil
   2. Availability of grazing land and pasture
   3. Migration due to marriage
   4. Close to my working place
   5. Other reasons, (please specify)

   ....

3(a). Do you own some plot(s)? ( )
   1. YES
   2. NO

3(b). If YES, how did you acquire the plots?
   1. Through buying
   2. Through a friend/relative (free of charge)
   3. In heritance

4. Official procedure
5. Other reasons, please mention..

3(c). If NO, how did you get access to land? ( )
1. I am employed here
2. I have rented the place
3. Other reasons, please mention
....

4. What is the size of your plot(s)? ( )
1. Less than one hectare or acre
2. Between one and five hectare or acre
3. Between six and ten hectare or acre
4. Over ten hectare or acre (please specify)

5. How was this area looking like at the first time of your establishment? ( )

1. Natural with bushes, tall grasses, animals, trees and birds
2. Natural with bushes, tall grasses, animals and trees
3. Natural with trees, tall grasses and birds
4. Natural with tall grasses and trees
5. Village settlement
6. Already developed for agriculture
7. All of the above
8. Others (please specify)
....

6. What can you say about the coverage of the wetlands/swamp/valley bottom; is it still the same as to when you first established here? ( )
1. It is decreased in size
2. It has expanded
3. No change
4. Others (please specify)
....

7. How would you describe the level of encroachment since you first established here? ( )
1. High
2. Moderate
3. Low

4. Others (please specify)
....

8. What do you think is the major activity in this area?

1. Rain fed agriculture
2. Irrigated agriculture ( )
3. Fishing
4. Livestock (cattle keeping)
5. Others (please specify)
....

9. Do you cultivate some crops?
1. YES
2. NO ( )

10. If YES, which type of cultivation are you practising?
1. Irrigated agriculture
2. Rain fed agriculture
3. Others (please specify) ( )
....

11. If irrigation is one of your activities, where do you get water?
1. River
2. Always available from wetland ( )
3. Canal
4. Groundwater well
5. Others (please specify) ....
If it is river or canal, please give the name and the distance from the main source...

12. Which crops are grown in this area during dry season? (Please put a tick)

a) Rice ☐
b) Maize ☐
c) Irish potatoes ☐
d) Beans ☐
e) Groundnuts ☐
f) Field peas ☐
g) Cowpeas ☐
h) Sunflower ☐
i) Simsim ☐
j) Cassava ☐
k) Sugarcane ☐
l) Yams ☐
m) Onions ☐
n) Wheat ☐
o) Sorghum ☐
p) Millet ☐
q) Round Potatoes ☐
r) Tomatoes ☐
s) Sweet potatoes ☐
t) Fruits (specify) [ ]

u) Vegetables (specify) [ ]
v) Others (Please specify) [ ]

13(a). Do you use industrial fertilizers or pesticides?
1. YES
2. NO ( )

13(b). If YES, please mention the type of fertiliser and pesticides you are using
a) ....
b) ....
c) ....

13(c). How often you apply fertilizer?
1. More frequently
2. Moderate
3. Others (please specify)
....

14(a). On average, how many households were occupying this area originally?
[ ]

14(b). Is the number of household (population) in the area increasing or decreasing?
1. Decreasing
2. Increasing ( )

15. Why do you think people have established themselves in this area?
1. Lack of land in other area
2. Fertility of the land conducive for cultivation
3. Availability of water
4. Good pasture for cattle grazing ( )
5. Others (please specify)
....

16(a). Do you think your activities are affecting wetlands?
1. YES
2. NO ( )

16(b). If YES, how?, and If No, why do you think so?
a) ....
b) ....
c) ....

17. Which activities do you think affect the wetland/swamp most?
1. Agriculture

2. Settlement
3. Cattle grazing ( )
4. Others (please specify) ....

18. Why do you think so and how? (Please explain)
a) ....
b) ....

19. What problems and constraints you are facing since you established in this area?
a) ....
b) ....
c) ....

20(a). Have you noticed any changes that are directly related to the utilization of this wetland area?
1. YES
2. NO ( )

20(b). If YES, what are the changes? (please list)
a) ....
b) ....
c) ....

21. How do you perceive this area of aquatic nature?
1. It need be transformed
2. It is a waste land ( )
3. It is useful, be conserved
4. Others (please explain)
....

22. Why do you think so? Please explain
a) ....
b) ....

23(a). Do you think it is wise to leave this area without any use?
1. YES
2. NO ( )

23(b). Please explain why you think so
a) ....
b) ....

23(c). How do you perceive the idea of leaving this wetland untouched?
....
....

24(a). Have you ever received any directives/ instructions from the government on the wise use of this area?

1. YES
2. NO ( )

24(b). If YES, which instructions/ or advices were given?

a) ....
a) ....
b) ....

24(c). When was the directives/instructions/ given? (Please state the year and mode of instructions, i.e., workshop, seminar, individual discussions, etc.

[ ]

25. What could you advice your government on the wise use of the wetlands for their continual existence?

a) ....
b) ....
c) ....

THE END

!! THANK YOU !!