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APPENDICES

LIST OF ACRONYMS

DFID	Department for International Development
DOS	Directorate of Overseas Surveys
FAO	Food and Agriculture Organisation
GIS	Geographical Information System
GoT	Government of Tanzania
HIMA	Hifadhi ya Mazingira
MATI	Ministry of Agriculture Training Institute
MOW	Ministry of Water
NAFCO	National Agriculture and Food Corporation
RBMSIIP	River Basin Management and Smallholder Irrigation Improvement Project
RBWO	Rufiji Basin Water Office
RUBADA	Rufiji Basin Development Authority
SMUWC	Sustainable Management of Usangu Wetlands and their Catchments
TANAPA	Tanzania National Parks Authority
TANESCO	Tanzania Electricity Supply Company
UNDP	United Nations Development Programme
WREP	Water Resources Engineering programme

1 INTRODUCTION

1.1 General

This report presents the findings of the hydrology and water resources programme of the project 'Sustainable Management of the Usangu Wetland and its Catchment' (SMUWC). The report forms Supporting Report No. 7 of the final report of the project. There are a number of other supporting reports which focus on particular aspects of the water resources work carried out by the SMUWC project. The other reports are:

- Supporting Report No. 8 Irrigation water management.
- Supporting Report No. 9 Community irrigation management.
- Supporting Report No 10 Irrigation efficiency study
- Supporting Report No. 11 Usangu basin modelling study.
- Supporting Report No. 12 Groundwater.
- Supporting Report No. 13 Water quality assessment.
- Supporting Report No. 14 Environmental functions of the Usangu wetland.
- Supporting Report No. 18 Subcatchment Resource Management Programme.

All raw hydrological data collected by SMUWC have been collated into a single volume. That document (Hydrometric monitoring data, March 2001) is not referred to further in this document.

This report draws on the above supporting reports, bringing the investigations together to present an understanding of: the functioning of the hydrological and water quality system in Usangu, how water is used in the basin, and the impacts that exploitation has downstream on water availability. The report also suggests some possible objectives for water management in Usangu that could be considered for inclusion in the overall management strategy for the basin. The report reviews some of the options that are available to achieve those objectives. While the consultant has investigated the water resources of the basin as thoroughly as possible, neither the list of objectives or of options should be considered final, and other possibilities may be added as discussion takes place.

The Government of Tanzania, with assistance from the SMUWC project, is in the process of identifying an overall strategy for the management of natural resources in Usangu. A strategy for the management of water resources will be a key component of the overall environmental management strategy for the basin. The Government, together with other stakeholders, must select the most appropriate options to form the basis of the strategy on water management. It is hoped that the supporting reports will become a source of reference on the water resources of Usangu and that they will contribute to the development of a sustainable strategy on water for the benefit of people living the basin and downstream.

1.2 Background

Water is the key resource in Usangu in that without it other resources, natural and human, cannot be sustained. A variety of stakeholder groups depend on water for drinking supplies, irrigation, livestock watering and hydropower generation. The Usangu wetlands owe their existence and nature to the balance between the inflow and outflow of water. The distribution of flora and fauna in and around the wetland is also largely controlled by water availability. The amount and timing of water in different parts of the basin controls the seasonal rhythm of life in Usangu.

The water resources of Usangu are under pressure from competing uses. Use of water by some is causing changes in the hydrology of the basin and in the availability of the resource to others both within the basin and downstream. This has resulted in social conflict between upstream and downstream users. The latter have economic and political power, and demand that upstream use of water be restricted. There are also issues over access to other resources such as land for livestock grazing, cultivation and wildlife.

The SMUWC project was designed in response to the need expressed by the Government of Tanzania for an integrated approach to natural resource management. The purpose of the SMUWC project is to establish a comprehensive basis for an integrated natural resource management strategy for the Usangu wetland and its catchment for the social, economic and environmental benefit of stakeholders, particularly the poor, and including downstream users. The intention is to assist the Government of Tanzania to develop and implement an integrated strategy to manage natural resources in Usangu, including water, land, livestock, wildlife and fisheries.

The formulation of appropriate strategies to manage the water resource depends on a sound understanding of the causes of problems of water availability in the catchment. The understanding that has been gained during the project is considerable, and it is still developing. It is now sufficient to form a basis for developing a strategy for improved management of water. This report identifies and reviews the potential options that will form the basis for a water resources strategy for Usangu. This, hopefully, will result in improved availability of the resource to all users and reduced competition.

The next section briefly reviews the water resources management sector in Tanzania and places the SMUWC project in this context.

1.3 Water resources management in Tanzania

The framework for integrated water resources management is laid out in the Water Utilisation (Control and Regulation) Act 42 of 1974, as amended by Act 10 of 1981. Water resources management involves the following functions: water resources development, water allocation, pollution control and environmental protection. The use of a river basin as a planning unit enables consideration of upstream and downstream demands, and attempts to satisfy them through a participatory process of water resource assessment, demand assessment and allocation of resources in a socially equitable manner that is economically efficient and environmentally acceptable.

RUBADA (Rufiji Basin Development Authority) was created by act of parliament in 1975. RUBADA's function was primarily to promote multi-sectoral water resources development (hydropower, irrigation, water supplies) throughout the Rufiji basin. RUBADA's role was not specifically to manage the water resources of the Rufiji basin. The responsibility for managing the water resources of the nation lies with the Ministry of Water (MOW).

Before the 1990s water was managed by MOW on the basis of administrative regions. Since the early 1990s the emphasis has changed to managing water resources on the basis of river basins. Tanzania has nine defined river basins of which the Rufiji river basin is one. The Rufiji basin covers an area of 174 800 km^2. A Rufiji Basin Water Office (RBWO) was established in Iringa in 1993, together with the Rufiji Basin Water Board which should comprise representatives from key stakeholder groups. However, seven out of ten board members are civil servants and not representative of users. Not all management functions are carried out by the RBWO. The RBWO has focused, owing to conflicts over water in the Great Ruaha basin, including Usangu, on allocation of water resources. Although the 1974 Act as amended by the 1981 Act provides for pollution control, there is no institution within MOW which has clear responsibilities for pollution control. The pollution control function mainly rests with the Regional Water Engineers who are supported by zonal water quality laboratories. There is no formal government agency responsible for coordination and management of environmental protection at river basin or regional level.

To strengthen river basin management the MOW is implementing the river basin management component of the River Basin Management and Smallholder Irrigation Improvement Project (RBMSIIP) in the Rufiji and Pangani basins. RBMSIIP began implementation in December 1996. The smallholder irrigation improvement component is being implemented by the Ministry of Agriculture and Cooperatives (MOAC). The project is intended to deal effectively with water management problems and improve the efficiency of smallholder irrigation.

The river basin management component of RBMSIIP treats water as a scarce resource and ensures that interlinkages between the needs of different users, such as irrigators, livestock owners, domestic supply users, hydropower generators and the needs of the environment, are taken into consideration in deciding water allocation and management principles. The project is promoting a participatory approach to planning and decision making which will involve all key stakeholder groups. It is also promoting improved analysis and understanding of hydrological and hydrogeological phenomena and their interaction with other natural resources and water users. Other objectives include the design of a more effective system for allocating resources which includes incentives for efficient and non-polluting use and the development of national water policies.

1.4 Objectives of the SMUWC water resources programme

SMUWC was designed as a parallel project to RBMSIIP in the Rufiji basin. SMUWC was to develop a detailed approach to formulation of a strategy to manage natural resources, among which water is a key resource, in an integrated way in the relatively small headwater basin of Usangu. Usangu's water resources, which include a wetland, are significant and are needed downstream. There are also competing demands upstream. It was intended that outputs from SMUWC would contribute to the wider aims of RBMSIIP and the development of approaches for the management of water and other natural resources that can be applied in other basins with wetlands in Tanzania.

The development of a strategy to manage water resources depends on gaining a good understanding of the nature and occurrence of the resources, and of the causes of issues and conflicts, before an approach to overcome the problems can be developed. Accordingly, a key output of the water programme is the understanding of the hydrological behaviour and water quality functions of the Usangu wetland and its catchment. The SMUWC water programme has comprised studies of the hydrology of the Usangu basin in order to analyse relationships between flows and water levels in different parts of the area.

The purpose of this report is to describe the work carried out under the SMUWC hydrology programme, to describe the current understanding of the causes of the hydrological issues in Usangu and to present options for the water management strategy for the basin.

Equally important is a good understanding of the demand for water and of the causes of competition over access to water. This is particularly necessary with respect to water use for irrigation. A second important element of the SMUWC water programme comprises studies of community management of irrigation in Usangu. These studies investigate the different types of irrigation in Usangu; how irrigators use and manage water. The studies also identify the causes of conflicts between water users. The study of community irrigation management is reported in Supporting Report No. 9.

1.5 The Usangu catchment

The Usangu catchment is defined by the boundary of the river basin that drains to N'Giriama where the Great Ruaha river exits from the Usangu Plains. The area covers some 20 800 km^2 of which 4 840 km^2 (23%) is in the alluvial plains below about 1 100 m asl. The remaining 77% of the catchment area lies in the 'high catchment' which ranges in altitude from about 1 100 m asl to over 2 000 m asl. The catchment of the Usangu wetland forms the headwaters of the Great Ruaha river, which itself is a major tributary of the Rufiji River. The project area is about 12% of the 174 800 km^2 area of the Rufiji basin.

The high catchment surrounds the plains. The highest ground lies on the shoulder of the rift valley around the south eastern, southern and south western margins of the plains. To the north of the plains the country is not as high. Highland areas receive between 1 000-2 000 mm of rain annually, while the plains receive around 700-800 mm. Rainfall is highly seasonal, occurring mainly between December and April. A long dry season occurs between May and November.

The Usangu basin comprises a number of water resource subsystems (Figure 1.1). The relatively wet high catchment on the southern and western boundary of the project area forms the source area for a number of perennial and seasonal rivers which flow into the Usangu Plains. The perennial rivers, the Great Ruaha, Kimani, Mbarali, Chimala and Ndembera Rivers, have their sources in high rainfall areas. Among these the Ndembera River is notable in that there is a seasonal wetland at relatively high elevation in its headwater region. Seasonal rivers, such as the Halali, Kimbi, and Kioga Rivers, have their sources at lower elevation in areas of lower rainfall.

The plains consist of alluvial fans, seasonally flooded open grassland or *mbuga* and perennial swamp. The soils of the *mbuga* and swamp are vertisols, which are deep cracking clay soils.

The alluvial fans slope toward the centre of the basin from the surrounding higher ground and form an almost continuous band around the margins of the central plain. They initially slope gently and then very gently towards the *mbuga*. The rivers cross the alluvial fans to the central plains. Owing to the erodible nature of the fan sediments and the large flood flows that may occur in the wet season, the courses of rivers are very unstable and many channel changes, both natural and man-made have occurred. Relatively small, individual wetlands, here called 'fan swamps', occur on the alluvial fans owing to the low slopes and indistinct natural drainage network. These may receive part or all the flow from perennial or seasonal rivers or irrigation schemes. Their nature and existence is controlled by the balance of drainage into and out of them, which can change over time depending on natural or man-made changes.

Irrigated agriculture is situated on the middle to lower parts of alluvial fans on the southern margin of the Usangu wetland. Rainfed cultivation, some using water harvesting techniques, exists on the upper parts of the fans where rainfall is slightly higher. The irrigation schemes consist of large state-owned rice farms and smallholder irrigation. A number of types of smallholder irrigation have been identified and details of these are presented in Supporting Report No. 9. Suffice to say that the irrigation supplements rainfall and depends on water diverted mainly from the perennial, but also the seasonal rivers.

Downstream, the central plains may be divided into the western plains and the eastern plains. The plains are divided by a constriction at Nyaluhanga. This constriction, essentially higher ground in the centre of the plains, may be due to a combination of a rise in the underlying basement rocks and the meeting of alluvial fans from the north and the south sides of the plains. The western plain is situated to the west of Nyaluhanga and the eastern plain is situated to the east. The western plain contains unflooded woodlands and seasonally flooded treed and grassland areas. The seasonally flooded areas may not be contiguous, but may be broken into a series of independent wetlands. These seasonally flooded areas form the Western Wetland.

The eastern plains extend up to the exit point of the wetland into the Great Ruaha river. In the centre of these plains lie the *mbuga*, a seasonally flooded grassland, and the *ihefu*, a perennial swamp containing aquatic vegetation. These perennially and seasonally flooded areas form the Eastern Wetland.

All the perennial rivers except the Ndembera, and several seasonal rivers, drain into the Western Wetland. The Mkoji and Mbarali Rivers act as 'collectors'; the Mkoji collects all drainage from the Chimala westward to the Chunya Escarpment. The Mbarali River collects the drainage from the southern highlands from the Great Ruaha river to the Mbarali River.

The main inflow to the Eastern Wetland is the Great Ruaha river flowing from the Western Wetland. The Ndembera River is the only other main inflow to the Eastern Wetland. The remaining inflows come mainly from the seasonal Kimbi and Kioga Rivers which enter the wetland approximately at the junction between the Western Wetland and the Eastern Wetland.

Water exits the Eastern Wetland at N'Giriama and forms the Great Ruaha river which flows northeastwards through the Ruaha National Park. The river is an important source of water for wildlife in the park. Downstream of the park, the river flows into the Mtera hydropower reservoir where it is used, with Kidatu hydropower reservoir, to generate electricity. Prior to 1995 the combination of the Mtera and Kidatu schemes represented 91% of Tanzania's installed hydropower generating capacity. After the Pangani Falls station was constructed that year, this proportion fell to 75%. There was a further reduction to 51% after the latest station at Lower Kihansi opened in the year 2000. However Mtera and Kidatu still play a very important role in the country's electricity supply, because their combined reservoirs form 79% of the water storage available in the Tanzania for hydropower production during the dry season.

1.6 Previous studies in Usangu

As indicated in Section 1.1, the water resources programme of the SMUWC project has focused on gaining an understanding of the hydrology and water resources of the basin and the causes of water problems in Usangu. This section describes previous hydrological work in Usangu, including studies which focus on the hydrological problems of Usangu. These contribute to the identification of water resources issues in Section 2.7.

The first hydrological studies of Usangu were carried out over the period 1955-1960 as part of the Rufiji Basin Survey (FAO, 1960a, 1960b). The hydrometric network in Usangu was initiated in this period when a number of important river gauging stations were installed. Regular measurements commenced of meteorological parameters, river flows, sediment transport, and some water quality data were collected. The raingauge network, which dated from the 1940s, was extended. Studies were made of rainfall using the record from 1940, the newly acquired runoff data, evaporation, sediment transport and water quality data, for the purpose of developing storage sites and irrigation. A water balance for Usangu was also developed. The early runoff records which were started by FAO are important to SMUWC's hydrological work because they allow us to understand the natural hydrological regime of Usangu rivers and the water balance of the Usangu Plains before the development of irrigation.

Hazelwood and Livingstone (1978) made a study of the development potential of the Usangu Plains. This study took place after the construction of Mbarali Rice Farm but before the growth of irrigation in Usangu. The study recognised that the availability of water in the perennial rivers draining the high catchment would constrain the expansion of irrigated cultivation. Using available river flow data, and making assumptions for cropping pattern and irrigation efficiency and no storage, they tentatively estimated that the maximum irrigable area would range from 35 000 ha to 71 000 ha. Hazelwood and Livingstone recognised that the development of irrigation would seriously deplete downstream flows and cause an impact on downstream users such as Mtera dam. However, at that stage it was not considered appropriate to consider downstream impacts.

Hydrological studies have been carried out as part of the water master plans for Iringa, Ruvuma and Mbeya Regions (CCKK, 1982). The studies assessed the availability of surface and groundwater in order to provide the Government of Tanzania with firm recommendations for the development of water resources over the period 1981 to 1991. Particular attention was paid to water supply for villages and livestock. Water resources for irrigation were not assessed. Although the studies provided the Ministry of Water with a comprehensive and up to date hydrological database, the analyses are presented at a regional scale which is too broad to be of significant use to SMUWC.

Hydrological studies have also been carried out as part of feasibility studies for specific irrigation projects in Usangu. These are Kimani Irrigation Project (WER Engineering Ltd, 1991, 1993), Madibira Rice Project (Halcrow, 1992) and Kapunga Rice Project (Agrar-und-Hydrotechnik, 1979; Halcrow, 1985). These studies have been oriented to obtaining design parameters for the construction of the schemes.

The Kimani scheme involves the improvement of an existing smallholder irrigation system which started in the 1940s. The Madibira scheme consists of the development of a new scheme for smallholders and the Kapunga scheme is partly run as a large scale state farm and partly by smallholders. The studies include analyses of the water resource available for diversion, crop water requirements, the estimation of the irrigable area, the estimation of floods and the need for and location of diversion weirs and river training works to make the courses of rivers more stable. All the studies have noted the natural tendency for rivers to change their courses during floods, often taking the course of irrigation furrows. The construction of the schemes, such as Kimani, Kapunga and Madibira, has nearly always involved the man-made diversion of rivers from their natural courses around the edges of the schemes.

Few of the engineering feasibility studies, however, consider impacts of irrigation development, such as the reduced flows available for downstream farmers, reduced inflow into the Usangu swamp and the possible implication for the water balance and outflow from the swamp. This tendency to ignore downstream impacts has led to the current upstream-downstream conflicts within and outside the basin.

Moirana and Nahonyo (1996) and Kikula *et al.* (1996) were perhaps the first studies to report water resources problems in Usangu. These problems involve reductions in the outflow of the Great Ruaha river from the Usangu Plains. Moirana and Nahonyo's report is a proposal to establish a game reserve covering 5000 km^2 of the Usangu Plains. They identify the Usangu wetland as being an important but fragile ecosystem which has been degraded by human encroachment, overstocking, farming, tree felling and uncontrolled hunting. They also identify the flow in the Great Ruaha river as having considerable economic importance. Kikula's report investigates possible ecological reasons for the fall in water levels in Mtera reservoir since 1989, based on mapping of land cover and vegetation in the Usangu Plains using satellite imagery, ground truth vegetation transects and discussions with residents.

Moirana and Nahonyo list the threats to the existence of the Usangu Plains. These include the following water-related factors:

- Excessive use of water resources for irrigation.
- Destruction of water catchment areas (by overstocking and deforestation).
- Disturbance of the natural water reservoir of the wetland.
- Lack of a comprehensive land use management plan for the area.

They also list the indicators of degradation on the Usangu Plains. These include the following hydrological indicators:

- High floods and complete cessation of flow in the dry season.
- Late discharge into the Great Ruaha river (displacement of over two months) observed in last four years.
- Reduced water retention capacity in catchments and in the swamps, particularly the *ihefu* swamp.
- Low water levels in the swamps and rivers.
- Increased water evaporation.

The Great Ruaha river is said to have been perennial with flow lasting all through the dry season (although it is known to have dried up naturally in 1954, a year of extreme drought in south western Tanzania). Flows towards the end of the dry season would typically be between 1 m^3/sec and 3 m^3/sec. It is reported, however, that flow in the Great Ruaha in recent years has ceased during the dry season and there is a delay of around three months after the onset of the wet season while the swamp fills until outflow starts in March. Low water levels in Mtera reservoir are attributed to irrigation schemes upstream.

Moirana and Nahonyo and Kikula *et al.* correctly attribute these changes in flow regime to reduced water availability to provide the flow. Moirana and Nahonyo suggest that the causes are persistent drought and human activities upstream. Kikula *et al.* found no evidence for decreasing rainfall, but focused on two groups, pastoralists and irrigators, as the causes of changes in the swamp and downstream flows.

Pastoralists' activities include vegetation clearing, trampling and overgrazing. According to Moirana and Nahonyo these have caused the soils to dry and have probably lowered the water table in some parts of the plains. It is argued that soils need to absorb a lot of water before they start producing runoff. Kikula explains that sealing of the soil surface by trampling can lead to reduced infiltration of rainfall and increased storm runoff, which causes gullying, and that both lead to lowering of the water table. This is said to have enabled the encroachment of bush in the Usangu swamp. Lowering of the water table is also said to have occurred due to the drainage of swamps and the construction of canals for irrigation schemes such as Kapunga.

In addition, according to Moirana and Nahonyo, removal of the grass cover by excessive numbers of livestock has resulted in increased exposure of surface water and an increase in water losses by evapotranspiration. A reconnaissance by plane of the Usangu Plains (reported in Moirana and Nahonyo, 1996) by the Friends of Ruaha Society (FORS) on 12 December 1995 indicated large herds of cattle grazing in the swamp and on the plains.

Activities of farmers and hunters are also blamed, such as uncontrolled burning and deforestation which lead to increased erosion. According to Moirana and Nahonyo, areas without forests get less rainfall than those with forests. Kikula suggests that silting of the Usangu wetland is occurring as a result of increased erosion around the plains and desilting of irrigation canals, causing a reduction in storage capacity.

Excessive use of water for irrigation is cited by Moirana and Nahonyo as a threat to the plains. The FORS reconnaissance observed all the flow in the Mbarali and Kimani rivers being diverted into the Mbarali and Kapunga rice schemes so that no flow was reaching the Usangu wetlands from these rivers at that time. Kikula *et al.* likewise highlight the large growth in irrigation and the uncontrolled diversion of river flows as being an important factor. The use of fertilisers by farmers is cited as a cause of increased growth of aquatic vegetation in the swamp.

Among the recommendations made by Moirana and Nahonyo are the following:

- Establish new stations to monitor the weather and water flow in the rivers upstream and downstream of the swamp.
- Monitor water and flood levels in the Usangu swamp at various points all year round, and use a GPS to mark the spatial extent of the swamp at different times of the year.
- Existing and future projects in the Usangu Plains should be subjected to Environmental Impact Assessments.
- Prepare a comprehensive land use management plan for the proposed game reserve.

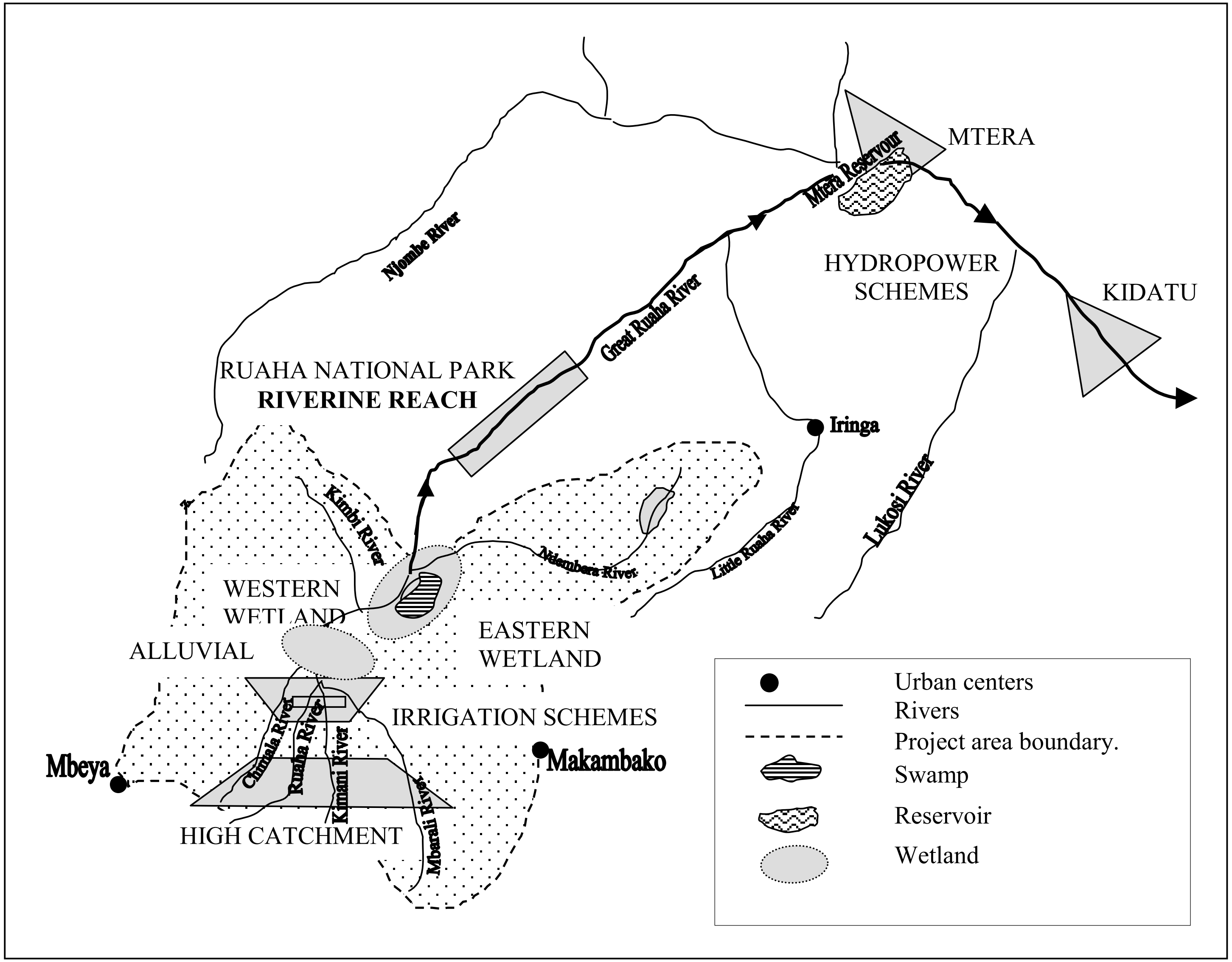
The reports by Moirana and Nahonyo and by Kikula *et al.* are notable in that they try to explain observed downstream impacts in terms of processes operating in the catchments upstream. Their weakness is the lack of data on irrigation diversions, residual flows in rivers, water levels in the swamp, the use of fertilisers, changes in vegetation growth, or the effect of livestock trampling and overgrazing, to prove or substantiate their interpretations of interlinkages between cause and effect. This would have enabled identification of the most important causal factors controlling changes in the swamp. They also fail to understand the nature of the *mbuga* vertisol soils and their considerable resilience. Both studies suggest the need for land and water management and an integrated approach. Whether management of land and water can reverse the observed trend in catchment degradation and decreasing outflow is questioned by Kikula *et al*.

Work under RBMSIIP has contributed to the analysis of flows downstream of Usangu, in order to explain the fall in reservoir water levels in Mtera. Danida/World Bank (1995) suspects that irrigation, because it causes a large evaporative loss, and evapotranspiration losses from the Usangu wetland, are together responsible for the low levels. However the study concluded that analysis of 30 years of inflow data to Mtera indicates no discernible decreasing trend, either for annual data or on the basis of rolling averages. They are therefore unable to link upstream activities, including irrigation, directly with decreasing water levels in Mtera. This is ascribed partly to unreliable data. Improvements to the hydrometric network and a specific study of the hydrological role of the Usangu swamp are recommended.

1.7 Structure of the report

This first section has provided the background to the hydrological and water resources problems in Usangu. Section 2 examines the demand for water in Usangu and identifies the main water resources issues in the basin. This serves as a basis for the description in Section 3 of the approach which has been taken by the SMUWC project to data collection and studies to gain an improved understanding of the hydrology and of the causes of the issues. The studies have led to the development of a number of ‘possible causes’ to explain the water resources problems. Section 4 describes the analysis of the possible causes and identifies those which contribute to causing the problems and those that do not. Having discussed the causes of problems in water resources availability in Section 4, Section 5 identifies the objectives of water resources management in Usangu and the options that are available to achieve those objectives. Each option is reviewed in some detail and it is from these that the Government of Tanzania should select the most appropriate options to form the basis of a water resources management strategy for Usangu.

Figure 1.1 Schematic map of the major water resources subsystems in Usangu



2 WATER RESOURCES DEMANDS AND MAJOR ISSUES

2.1 Introduction

Section 1 described the general background to the water resources problems in Usangu. Previous studies in Usangu were reviewed and the overall approach of SMUWC was outlined. This section examines firstly the demands for water in Usangu and downstream. Secondly, the major water resources issues are identified, together with the questions that faced SMUWC at the start of the project.

The water resources of Usangu are exploited both within the Usangu basin and downstream. Principal demands within the basin include those from:

- Wet and dry season irrigation.
- Livestock watering.
- Domestic supplies.
- Environment (aquatic ecology) of the Usangu wetland.

Principal uses of the Great Ruaha river downstream of Usangu are:

- Environmental (maintenance of the aquatic ecology, wildlife watering and aesthetic conditions for tourists along the Great Ruaha river through the Ruaha National Park).
- Hydropower generation by Mtera and Kidatu reservoirs.

The following sections estimate the demands for water within the basin and downstream.

2.2 Irrigation

2.2.1 Introduction

Irrigation using diverted river water is the greatest source of demand for water in Usangu. Demand for irrigation water exists in both the wet season and the dry season. Irrigated areas are situated on the middle to lower parts of the alluvial fans surrounding the southern margin of the wetland.

Demand during the wet season arises primarily from rice paddy, cultivated on the Usangu Plains by large-scale state owned schemes managed by National Agriculture and Food Corporation (NAFCO), such as Mbarali Rice Farm, and by smallholders.

Demand during the dry season arises partly from minor irrigation of non-rice crops (eg, maize and vegetables) but mostly from abstractions that meet net domestic needs, late-ripening rice, early planting of the next season's rice and watering of fields without crops in them. Some dry season irrigation of potatoes is reported to take place in the high catchment, but most dry season irrigation demand is located on the alluvial fans in the Usangu Plains.

Detailed studies of irrigation water management in Usangu have been carried out by the SMUWC project. These are reported in Supporting Report No. 8. Community management of irrigation has also been studied and this work is reported in Supporting Report No. 9.

2.2.2 Historical development

Irrigation has not always taken place in Usangu. Work carried out by SMUWC has tried to determine the historical development of rice cultivation and the present area irrigated. It originated in the 19th century, but only developed since the 1940s when the Baluchi people introduced paddy irrigation. The irrigated area expanded rapidly after the mid 1980s when market prices were liberalised.

Figure 2.1, derived from a combination of a literature survey, aerial photography interpretation and ground survey by the SMUWC Community Irrigation Specialist, shows the growth in the area of irrigated rice in the Usangu Plains.

2.2.3 Areas irrigated

The SMUWC project has found that the area irrigated is dynamic and complex, varying from year to year depending on the availability of water in the rivers for diversion. A core area of 20 000-24 000 ha is irrigated every year, including poor rainfall years. In years of above average rainfall more can be irrigated. It is estimated that during a good rainfall year the present total irrigated area in Usangu is 44 500 ha, of which 42 000 ha is wet season paddy (Figure 2.1) and dry season irrigation covers 2 500 ha (Supporting Report 10). Figure 2.1 shows that the total area under paddy is gradually increasing year by year. This growth will eventually be restricted by lack of river water available for diversion, rather than lack of commandable land. A number of past studies consider that approximately 43 000 to 68 500 ha is irrigable from both a 'suitable land'and 'maximum water ultilisation' perspective. The maximum irrigable area is therefore realistically set at 55 000 ha, which is the value determined by the community irrigation specialist during a survey in 1998/99.

2.2.4 Net irrigation demands

The terms net and gross irrigation demand are not used in this report in the conventional sense. Instead they are used to define believable lower and upper limits of real water use.

The net irrigation is an ideal minimum water demand occurring at the field level arising from evaporation, seepage, minimum domestic demand, minimum periods of cultivation and an ideal crop season length. In this scenario, conveyance and distribtuion losses are negligibleand return flows are zero.

Demand for wet season irrigation water begins in October and finishes in July. The net wet season irrigation demand for rice has been estimated by SMUWC based on the assumptions given in the 'net demand' column in Table 2.1. Important points to note are the division of rice into NAFCO and smallholder systems and that the starting date for cultivation is set at 1st December.

2.2.5 Gross irrigation demands

The gross irrigation is the maximum water demand occurring at the irrigation system level, arising from measurements and observations made about evaporation, seepange, variable domestic demand, commonly observed extended periods of cultivation and crop season lengths, and extended field wetting practices. This gross irrigation nonetheless represents a true demand lost from the river after accounting for a small proportion of return flows.

The parameters that determine the gross irrigation demand are given in Table 2.1 so that they may be compared to the same variable for net irrigation. For example, in the gross irrigation scenarios, cultivation begins in September. Other major differences are found in the crop factors and the amounts of water used to wet up fields and maintain standing water layers. For gross irrigation, the end of the rice cropping season carries on for longer, and is accompanied by wetting of harvested fields in order to maintain flows to tail end fields. This increases evaporation of water at a time when the net demands from smaller areas of tail-end rice are much less.

2.2.6 Non-rice irrigation demand

Non-rice crops are grown throughout the year and therefore establish a demand for water when rice cropping decreases during April to November. The net dry season irrigation demand for rice has been estimated by SMUWC based on the assumptions given in Table 2.2. Important assumptions to note are 2 500 ha of non-rice crops, a crop factor of 0.6 and a seepage rate of 0.25 mm/day.

Table 2.1 Main information and assumptions to determine the net and gross irrigation demand for rice

Item no.	Item	Net Demand	Gross demand	Comments
1.	Start of rice field preparation	1st Dec	1st Sept	Early planting (stretching of the season) due to high rice prices and constrained resources
2.	Main season crop factor	1.10	1.10	No change in crop factor.
3.	End of season crop factor	0.00	1.00	In the net demand scenario, irrigation ceases altogether before harvesting. In gross demand scenario, the standing water layer remains.
4.	Harvested field factor	0.0 (NA)	1.00	In the gross demand scenario, fields are watered after harvesting by error, or to supply tailend fields.
5.	Non-rice crop factor	0.6	0.6	This CF accounts for mixed cropping.
6.	Smallholder presaturation water	200 mm	250 mm	Smallholder water use (this depth has been estimated)
7.	NAFCO presaturation water	200 mm	650 mm	NAFCO water use is very high due to land prep and large fields (this depth has been measured)
8.	Duration of field wetting-up period in smallholder fields	10 days	10 days	Smallholders take about 7-10 days between first wetting and transplanting of rice.
9.	Duration of field wetting-up period in NAFCO fields	10 days	30 days	NAFCO allow fields to remain wet for a longer period (30 days) before transplanting due to method of land preparation
10.	Withholding of water period length at end of season	20 days	0 days	In the net demand scenario, irrigation is withheld for 20 days before harvesting. In the gross demand scenario, water is supplied to the fields until harvest.
11.	Deep percolation of water below the root zone, lost to groundwater for rice	2.5 mm/day	2.5 mm/day	No difference between net and gross demand scenarios
12.	Deep percolation, non-rice	0.25 mm/day	0.25 mm/day	No difference between net and gross demand scenarios
13.	Smallholder standing water layer	50 mm	100 mm	Ideal water depth is reckoned to be ankle-high (180 cm), whereas target depth should be 50 mm. Variability results in an average depth of 100 cm.
14.	NAFCO standing water	50 mm	220 mm	NAFCO water depth as recorded

Table 2.1 Main information and assumptions to determine the net and gross irrigation demand for rice (continued)

15.	'Growing period' season length	150 days	160 days	The gross demand scenario has an increased period to account for varieties mix and delayed ripening
16.	Field wetting period after harvesting has been completed	0 days	S-shaped area curve	Proportion of fields continued to be supplied depends on S-shaped curve properties 20 days. This differs in perennial and seasonal rivers.
17.	Attenuation factor	100%	85% wet 80% dry	Canal and vijaruba operating losses occur which add water demand but not to the area irrigated.
18.	Residual return flow to drains	0%	0%	Zero return flow to drains for most part of the year. Model is of demand and area expansion.
19.	Peak return flow rate to drains	0%	0%	Zero return flow to drains during wet season part of the year. Model is of demand and area expansion.
20.	Flow required for domestic uses	2.0 cumecs	Variable	Depends on season and sub-catchment. See tables below.
21.	Area of September nurseries and fields wetted up	0 ha	830 ha	In net scenario, nurseries are not started until December. Gross scenarios includes areas of nurseries for wetting up

Table 2.2 Information and assumptions to determine the net irrigation demand for non-rice crops

Area of irrigation 2 500 ha Taken to be one type of mixed cropping/intercropping of crops/crops at different growth stages, averaged together, runs throughout the year. Depth of water layer is ignored for non-rice crops Depth of presaturation is currently set at zero, but see different seepage rate, below Seepage rate 0.25 mm/day (estimated as being lower than seepage under rice as non-rice crops have no standing water layer) Effective rainfall, decadal value minus 10 mm Total offtake capacity is set at 45 cumecs Total proportion that can be abstracted is given as 70%

2.2.7 Impact of irrigation abstractions on river flows

Tables 2.3 to 2.6 summarise the calculated net wet season and dry season irrigation demands in relation to the estimated total flow available in the rivers for normal to wet and dry climatic scenarios. These tables show that net demands are smaller than gross demands, that impact differs in the wet and dry seasons, and that the irrigation impact relative to total available water is greater in dry years. For example, in Table 2.6 the impact of irrigation on river flows is 42% during the wet season and 64% during the dry season.

Table 2.3 Calculated net irrigation demands in Usangu for a normal to wet year

Period	Result
Wet season	
Total flow volume in rivers (Mm^3)	2134
Total net irrigation demand volume (Mm^3)	405
Net irrigation demand as % of river flow volume	19%
Dry season	
Total flow volume in rivers (Mm^3)	495
Total net irrigation demand volume (Mm^3)	67
Net irrigation demand as % of river flow volume	13%

Table 2.4 Calculated net irrigation demands in Usangu for a dry year

Period	Result
Wet season	
Total flow volume in rivers (Mm^3)	924
Total net irrigation demand volume (Mm^3)	308
Net irrigation demand as % of river flow volume	33%
Dry season	
Total flow volume in rivers (Mm^3)	261
Total net irrigation demand volume (Mm^3)	66.5
Net irrigation demand as % of river flow volume	25%

Table 2.5 Calculated gross irrigation demands in Usangu for a normal to wet year

Period	Result
Wet season	
Total flow volume in rivers (Mm^3)	2134
Total gross irrigation demand volume (Mm^3)	537
Net irrigation demand as % of river flow volume	25%
Dry season	
Total flow volume in rivers (Mm^3)	495
Total gross irrigation demand volume (Mm^3)	278
Net irrigation demand as % of river flow volume	56%

Table 2.6 Calculated gross irrigation demands in Usangu for a dry year

Period	Result
Wet season	
Total flow volume in rivers (Mm^3)	924
Total gross irrigation demand volume (Mm^3)	389
Net irrigation demand as % of river flow volume	42%
Dry season	
Total flow volume in rivers (Mm^3)	261
Total gross irrigation demand volume (Mm^3)	168
Net irrigation demand as % of river flow volume	64%

It should be noted that during the early part of the wet season, the rice water requirement arises primarily from the wetting up of land and the creation of the standing water layer rather than meeting crop evapotranspiration.

It is also important to note that at the end of the wet season there is substantial abstraction from the rivers as intake gates remain open to irrigate fields that still need water or are conveying water to tail-end fields.

A question which arises is 'are the quantities of water that are actually abstracted in each season related to the above calculated irrigation demand?' The above calculation uses mean historical data when rain and river flow begins to pick up in early December. Actual measurements of irrigation abstractions by SMUWC in a relatively dry November/December (end dry season/early wet season) in 1999 showed that a total of 34 m^3/sec were being abstracted from rivers in Usangu. This represented around 95-100% of the available flow in the rivers at that time. The FORS aerial survey on 12 December 1995 (Section 1.6) recorded that all the flow in the rivers Kimani and Mbarali was being abstracted, leaving the rivers dry downstream of the diversion points. Observations showed that all water was used in wetting up fields in preparation for rice. In other words, both the model and observations indicate that substantial amounts of water are taken out of the Usangu rivers to irrigate rice.

However, during the main part of the dry season a second question arises which is 'is all the water that is abstracted used for irrigation ?' The model above indicates that less than 20% of water is abstracted for net irrigation *of crops*, yet the gross demand model and observations show that the water is used to supply gross domestic demand and to wet up fields that do not have crops in them. Thus during periods of the dry season, rivers below abstraction points are dry or low in flow.

Regardless of whether the abstracted water was being used for irrigation or not, it can be concluded that under certain conditions abstraction of water through intakes results in a major use of water in Usangu, and therefore impacts on flows downstream of the irrigation intakes.

However, the key point that must be made is that this impact changes depending on the prevailing climate, and that therefore irrigation does not always cause major effects on downstream flows. Thus, during a normal to wet year, an annualised impact of less than 35% seems acceptable. Furthermore, during the wet season of normal years, the impacts of around 25% are even less. On the other hand, the 'danger' periods are dry seasons during all kinds of climatic conditions, and wet seasons during dry years.

2.3 Livestock watering

Livestock obtain water from three main sources: rivers, swamps and temporary ponds which form during the rains. The *ihefu* swamp is only one of the potential sources, and assumes importance mainly in the dry season. Supporting Report 4 on livestock discusses the water requirements of livestock in the project area and water demand. Table 2.7 below provides estimates of water demand in terms of the equivalent number of hectares of irrigated rice.

Table 2.7 Livestock water demand

Stock type	Unit demand (l/head/day)	Approximate livestock numbers[1]	Annual demand (Million m^3)	Equivalent number of hectares of rice[2]
Cattle	30	300 000	3.285	106
Sheep and goats	3	65 000	0.071	2
Donkeys	35	3 000	0.038	1
Total			**3.394**	**109**

1 Based on SMUWC surveys in the wet season and dry season of 1999 (Supporting Report 4)
2 Assumes an irrigation demand of 2 l/second/hectare for 6 months.

Table 2.7 indicates that the total livestock demand is equivalent to only 109 hectares of rice, indicating the very small demand in relation to irrigation. It is concluded that livestock demand for drinking water cannot contribute significantly to the losses of water which are occurring in Usangu. It has been argued by others (Section 1.4) that livestock affect the availability of water indirectly, for example, by trampling and overgrazing. This is discussed further in Sections 4.2.7 and 4.3.7.

2.4 Domestic water supplies

The development of domestic water supplies are the responsibilities of the District Water Department and the local communities. The operation and maintenance and overall management of the rural water schemes fall on the beneficiaries.

Mbarali District had a population of 152 882 in 1998 (1988 census) which is estimated to be about 215 015 today. The district has eight gravity piped schemes. Three of the schemes are old and are supplying water under their design capacity. Madibira water supply scheme, which is among the old ones, has only recently been rehabilitated by funds from the African Development Bank (constructing the Madibira smallholder irrigation scheme). The rest of the schemes have been constructed recently (1988-1999) with assistance from Danida.

The piped schemes serve a population of 118 794, while shallow wells equipped with handpumps serve a population of 20 139. The total population with improved water supply for the whole of Usangu is 138 933. Development of water supply schemes has mostly been donor-funded, although the villagers are expected to develop their water supplies through their own initiative. The drilling of a shallow tube well in Ukwaheri Village in July 1999 was funded by the British High Commission and the formation of a village water committee was facilitated by SMUWC.

The demand for water for domestic uses is a tiny proportion of the total use in Usangu. If it is assumed that the domestic demand is 33 litres per person per day (MOW design criteria), then the total amount required in Mbarali District is only 7 095 m^3/day (2.6 million m^3/year). This is equivalent to approximately 83 ha of irrigated rice. This is certainly too small to merit further consideration as a potential source of hydrological change in Usangu. However, it will form an important element in the future water resources management strategy, since a fundamental policy of the Government of Tanzania is to improve access to water for drinking and other domestic uses.

A survey of water demand was carried out in all villages in Mbarali and Kimani irrigation schemes in the dry season of 2000. This survey collected data on the demand for water for domestic use, livestock watering, brick making (an important dry season activity) and dry season irrigation, in relation to amounts of water diverted from the rivers Mbarali and Kimani. This survey was an initial task in the process of improving the management (saving) of water in the irrigation areas in order to improve the availability of water downstream (Section 5). The survey is reported in Appendix A.

2.5 Environmental demand from Usangu wetland

The Usangu wetland owes its nature and existence to the balance between inflows and outflows. The aquatic ecology and the functions of the wetland (provision of fisheries, grazing resources, wildlife and bird life) are all dependent on water. The surface area of the wetland expands and contracts according to the seasonal variation of inflowing water. Too much inflow, as in the *el niño* year of 1998, is not a problem for the wetland itself because there are no villages and few cultivated areas around the perimeter which are in danger of inundation. Any excess water overflows down the Great Ruaha river through the Ruaha National Park; however such flood flows can cause damage to infrastructure downstream.

Too little water, on the other hand, could pose problems for the long term sustainability of the wetland. A reduction of inflow during the wet season could lead to a reduction in the maximum perimeter of the seasonal wetland. This would lead to woody encroachment on those areas which are not regularly inundated, and consequently reduce the amount of grazing resources.

A reduction in inflow during the dry season might have more serious consequences. An aerial overflight of the Eastern Wetland in November 2000 showed that the perennial swamp had shrunk to just 27 km^2 at the end of the very dry year of 2000. This suggests that there is a distinct possibility that, if no remedial actions are taken, the perennial swamp could be lost entirely and it would turn into just a seasonal wetland. This would cause extreme changes to the wetland ecology, and complete loss of some of its functions, such as fisheries.

2.6 Downstream demands

2.6.1 Environmental and tourist demands in the Ruaha National Park

The Great Ruaha river flows through the Ruaha National Park and forms an important source of water, particularly in the dry season, for wildlife. Under natural conditions, the river is normally perennial, with flows lasting all the way through the dry season. This provides habitat for hippopotami, fish and other aquatic life, and aesthetic wildlife viewing conditions which are important factors affecting the attractiveness of the park for tourists. Flows at the end of most seasons, under natural conditions and based on the flow record at Msembe which dates from 1958, are typically low and are thought to lie in the range 1-3 m^3/sec. It should be recalled that the river occasionally dries up for natural reasons. For example, it is known to have dried up naturally in the severe drought of 1954.

It is very difficult to put a value on the demand for water by the wildlife and aquatic ecology along the river. In the absence of other information it may be argued that flows in the above range constitute the demand for water in the river through the park.

2.6.2 Hydropower generation

Mtera and Kidatu dams are located on the Great Ruaha river downstream of the Ruaha National Park. They require both inflows and management of releases and reservoir water levels in order to provide an optimum supply of electricity. Mtera has been the focus of studies carried out under RBMSIIP (eg World Bank/Danida, 1995) and is not the subject of detailed studies by SMUWC.

The catchment of the Great Ruaha river forms just 58% of the total area which drains to Mtera. Storage in Mtera is controlled mainly by the volume of the annual flood passing down all inflowing rivers and the reservoir operating policy. Storage is not greatly affected by dry season inflows which are very small in relation to the volume of the reservoir and evaporation rates from the reservoir surface.

The volume and timing of the annual flood in the Great Ruaha are therefore the parameters of most importance to TANESCO, the operator of Mtera and Kidatu.

2.7 Identification of major water resources issues

The main water resources issue has arisen as a result of the ceasing of outflow from Usangu into the Great Ruaha river during the dry season each year since 1994 (discussed by Moirana and Nahonyo (1996) and Kikula *et al.* (1996), Section 1.5). There are seasonal rivers which drain into the Great Ruaha between the exit from the Usangu wetland and Mtera, but the flows in these rivers are dependent on local rainfall and are sporadic and unreliable.

The drying up of the river has been reported particularly by TANAPA, the parks authority, and the residents of the Ruaha National Park as causing widespread mortality of fish and some hippopotami and creating unaesthetic conditions in remaining pools. Although the river is known to dry up naturally, the ceasing of flow each year since 1994 may be without precedent in living memory.

TANESCO reports that reservoir water levels in Mtera have been falling since about 1989. According to TANESCO this has severely affected Mtera's ability to generate power. National power rationing was necessary in 1992 and in 1994. TANESCO's perception is that inflows to Mtera have been decreasing in recent years due to a combination of climate change and upstream activities, and that this is responsible for the lowering of reservoir levels since 1989 (Kikula *et al.*, 1996).

To illustrate the drying up of the river flow in the dry season, Table 2.8 lists the dates on which outflow from the Usangu wetland ceased and then resumed, and the duration of the period of no flow in each case.

Table 2.8 Periods of no flow in Great Ruaha river in the Ruaha National Park[1]

Year	Date flow stopped	Date flow restarted	Period of no flow (days)
1993	Did not stop		0
1994	17 November	15 December	28
1995	20 October	15 December	56
1996	17 October	16 January 1997	91
1997	25 September	25 November	61
1998	18 November	19 January 1999	62
1999	21 September	10 January 2000	111
2000	16 September	22 November	67

[1] Stolberger Camp, Jongomeru, Ruaha National Park (UTM grid reference: 679147E 9127828N).

There is a tendency for dates on which flow stops to become earlier each year and the length of the periods with no flow have been getting longer. The river even dried up in the dry season of 1998, following a very wet season which has been associated with the *el niño* phenomenon. Figure 2.2 shows the annual sequence of average dry season (June-November) flows at Msembe. There is a clear trend of decreasing dry season flow in the Great Ruaha river.

To illustrate the possible reduction of inflows to Mtera, Figure 2.3 shows the sequence of average annual flows in only the Great Ruaha river at Msembe. There appears to be a slight downward trend in annual flows in this river. Statistical analysis has been carried out on this data and the trend has been found to be not statistically significant.

The drying up of the outflow from the Usangu wetland is a major problem for the aquatic ecology of the river through the Ruaha National Park. The fact that dry season flows in the downstream Great Ruaha river show a decreasing trend suggests that changes to the hydrological balance are occurring upstream in the Usangu basin and that these may involve changes to the Usangu wetland. Key questions that face the SMUWC project are therefore:

- What are the causes of this trend in reduced dry season flows?
- Can water resources in Usangu be managed so as to cause the outflow from the wetland into the Great Ruaha river to continue through most dry seasons ?

In addition to these 'upstream-downstream' issues, there are issues over access to water within the Usangu basin. Diversion of water from rivers for irrigation by upstream farmers has led to shortages for downstream farmers. Competition for water also exists between 'top end' and 'tail end' farmers on the same irrigation furrow. Problems of access for livestock to water in the irrigation schemes also exist and this has sometimes resulted in conflict between irrigators and livestock keepers.

The SMUWC water programme has consisted of two main components:

- Hydrological studies, which have focused on gaining an understanding of the hydrological functioning of the Usangu basin, the hydrological causes of the low flow problems and how the outflow into the Great Ruaha may be maintained throughout the dry season.
- Community irrigation management studies, which have focused on gaining an understanding of how communities in Usangu manage their local water resources for irrigation, the causes of conflicts and how these may be resolved for the benefit of the communities at the same time as enabling more water to reach the swamp for the purpose of maintaining outflow into the Great Ruaha river during the dry season.

This report deals with the hydrological studies carried out to date. Supporting Report 10 deals with the community irrigation studies.

The existence of competition and conflicts over water within the Usangu basin and the need for water downstream in the Ruaha National Park indicate the need for the management of the water resources of the river basin. The understanding gained by the hydrological studies and those of community management of irrigation will form the basis for a water resources management strategy which will form part of an integrated strategy to manage the natural resources of Usangu.

This section has examined the demands for water in Usangu and downstream. The major water resources issues have been identified together with the main questions that face the SMUWC water programme. The next section describes the approach taken by SMUWC and the data that have been collected in order to investigate the cause of the seasonal cessation of outflow from the Usangu wetland into the Great Ruaha river.

Figure 2.1 Growth of area under rice in Usangu Plains

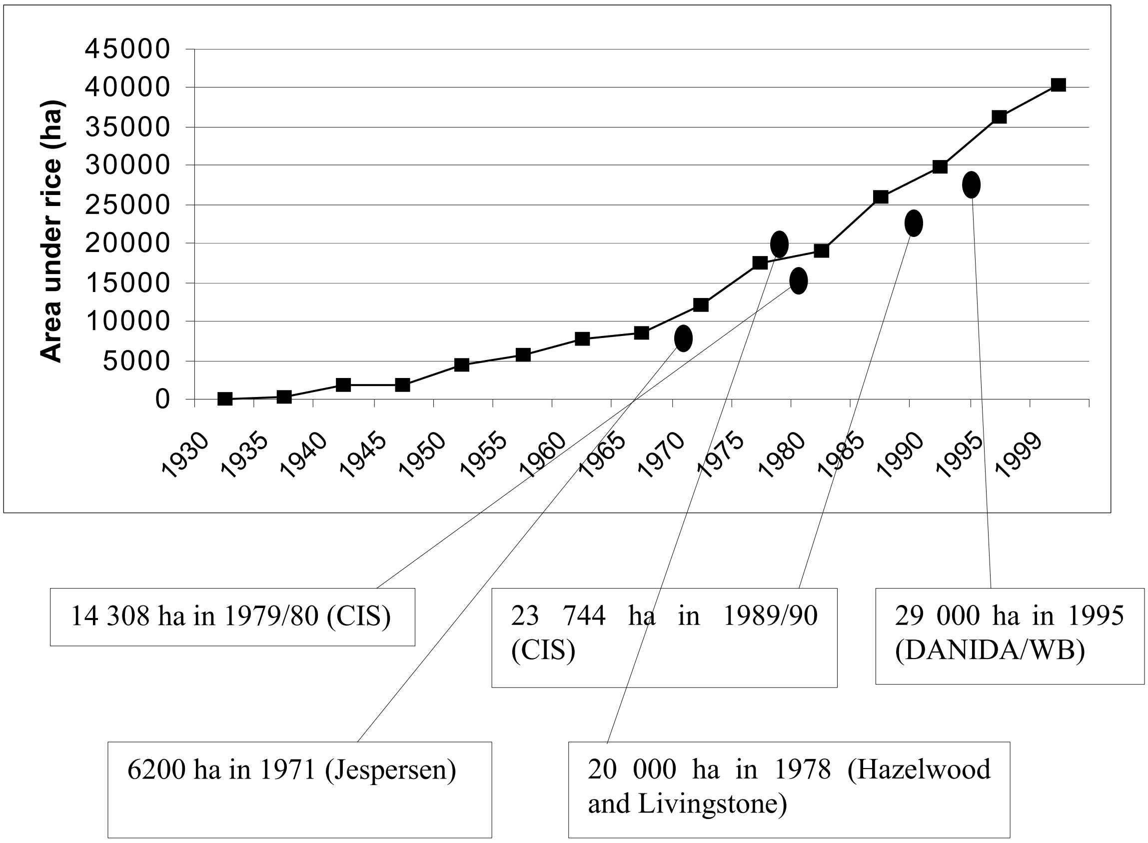


Figure 2.2 Average dry season flows (1 July-30 November) in the Great Ruaha river at Msembe

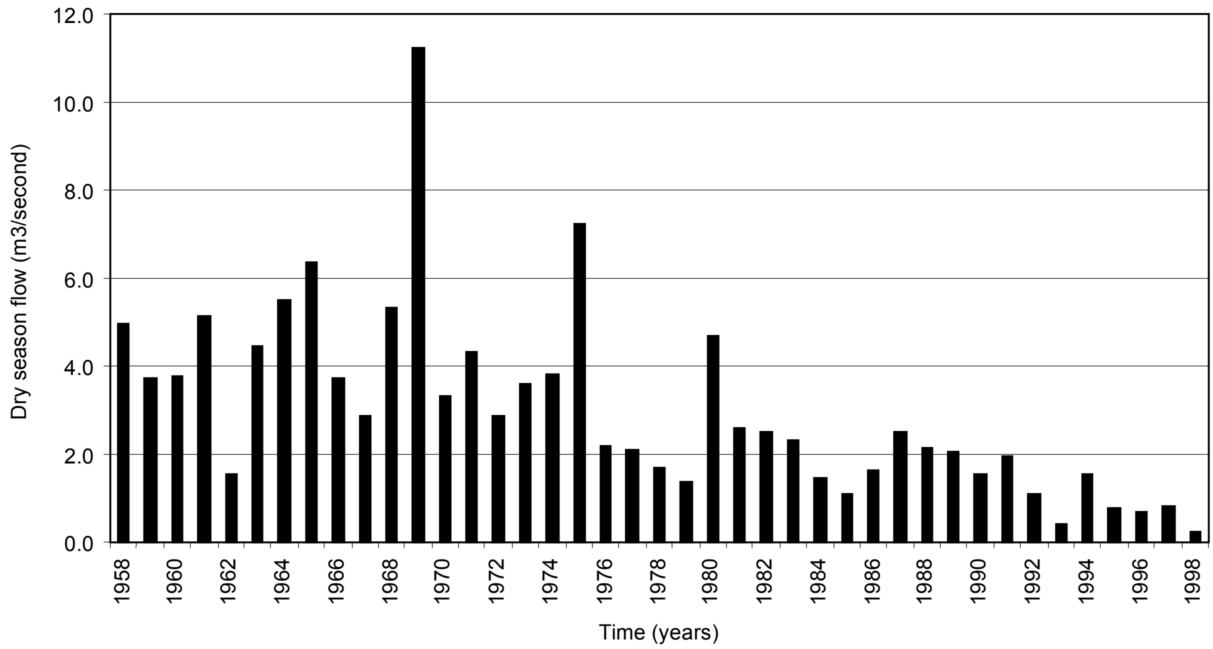
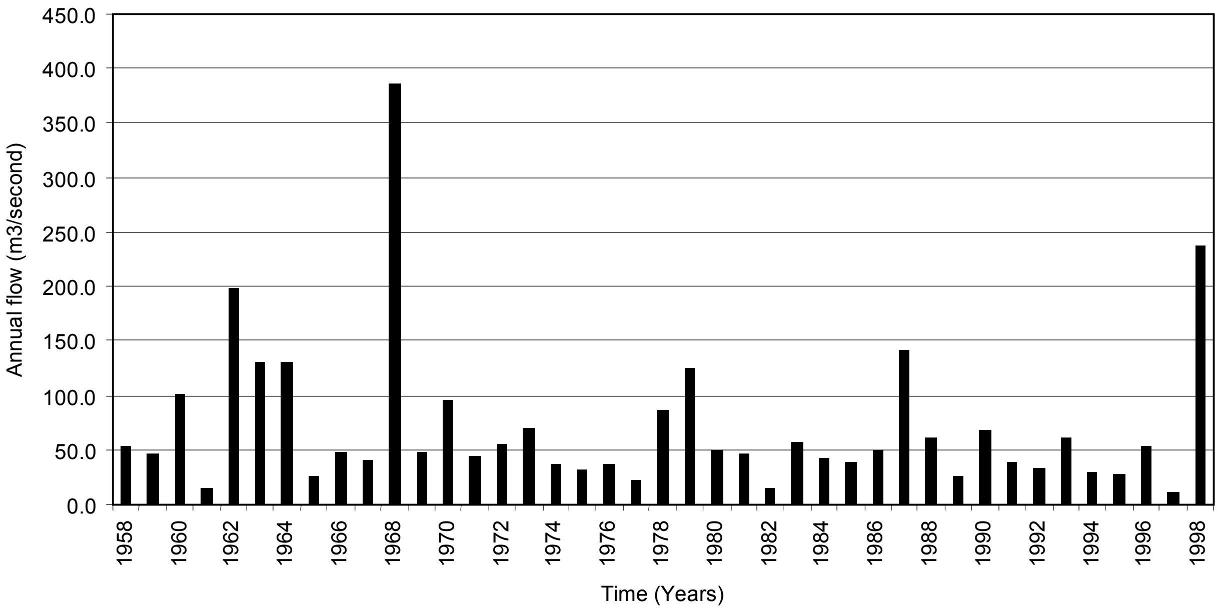


Figure 2.3 Average annual flows in the Great Ruaha River at Msembe



3 HYDROLOGICAL INFORMATION COLLECTION PROGRAMME

3.1 Introduction

The previous section provided estimates of the demands for water for different uses in and downstream of Usangu. It was seen that, within the Usangu basin, irrigation is by far the heaviest user of water. Livestock watering and domestic supplies are relatively insignificant demands. The environment also exerts a demand for water, principally for maintaining the aquatic habitat of the Usangu swamp and the aquatic habitat and wildlife viewing conditions in the Great Ruaha river downstream. The major water resource issue, the drying up of the Great Ruaha river each dry season since 1994, was also described. SMUWC's hydrological studies focussed on identifying and understanding the causes of this behaviour and identifying the management options to redress the situation. Options for water management are identified and reviewed in Section 5.

It will be recalled that the Usangu basin comprises the following four water resource subsystems (Section 1.3, Figure 1.1): the high catchment, alluvial fans, wetlands and riverine reach. The hydrological cycle controls the overall behaviour of each of these sub-systems. The main inputs are rainfall over the project area and flows produced on the high catchment. The outputs from the cycle are the downstream flows into Mtera Reservoir and the evaporation from the land and open water bodies in the project area. Temporary storage of water can occur in the wetlands and underground as groundwater.

This section presents SMUWC's approach to the problem, and describes the information that has been collected to date in order to gain an understanding of the hydrology and water resources of the basin and the causes of the cessation of outflow. The section is divided into subsections which describe the approach to estimate and measure each of the components of the hydrological cycle; rainfall, evaporation, river flow and groundwater. In each case sources of current and historical data are documented. This section also describes work carried out to:

- Gain an understanding of the hydrological behaviour of the Usangu wetland. The variation in the surface area and volume of water stored in the Eastern Wetland, and how this effects the amount leaving the wetland through the single outlet is explained. A water balance is given for each of the two years of the project period.
- Investigate the impact of irrigation on downstream flows.
- Develop a hydrological model of the whole basin which will be used to provide a theoretical simulation of the overall water balance of the network composed of the above four water resource subsystems, together with the impact on this water balance of irrigation abstractions.
- Gain an understanding of the water quality functions and the pollution potential of the Usangu swamp.

3.2 Rainfall

3.2.1 Introduction

Mean annual rainfall is one of the main factors that control the type and distribution of human activity occurring in the project area. It is not the only factor, other important parameters are geology, soils, slope and vegetation. The variation in mean annual rainfall is shown in Figure 3.1. This map was produced as one of the outputs from the Water Master Plan for Mbeya, Iringa and Ruvuma, prepared in 1982 for the Ministry of Water by Danish consultants (CCKK, 1982).

Note the sharp end point of the 700 mm contour line. The map makers were very careful in how they drew this line, since it has been found that there were, at the start of the project, virtually no raingauges located in the north west part of the project area. Other regions which initially appear to lack rain gauges are i) around the Western and Eastern Wetlands; ii) the Ruaha National Park lying between the Eastern Wetland and the Mtera Reservoir; iii) the high catchment, except for the headwaters of the Ndembera and Chimala rivers.

3.2.2 Historical rainfall information

As part of their subcontract, the Water Resources Engineering Programme (WREP) of the University of Dar es Salaam were requested to examine all reliable historical rainfall records. They obtained copies of raw data for 100 stations from the Directorate of Meteorology headquarters. Seventy of these lay outside the project area, and the remaining 30 within the project area; of the latter, only 13 were located within the plains.

Although many of the records had lengths of over 40 years, there was a considerable amount of missing data. Fuller details are given in Supporting Report No 11. The following criteria were used to decide whether data with some missing periods were acceptable:

- Rainfall months were accepted if at least 28 days out of 30 are available.
- Rainfall years were accepted if at least 11 months out of 12 are available.

A technique called double mass analysis was used to compare each individual rainfall station with those surrrounding it. This appraisal resulted in all 100 stations being judged reliable.

The distribution of the reliable stations in relation to the project area is shown in Figure 3.2. The pattern is rather uneven. The rainfall stations tend to lie either along the main road between Iringa and Mbeya as it passes through the project area, or lie in clusters on the tea and wattle estates of Mafinga and Njombe Districts on the eastern side and Rungwe District on the south western side. The lack of stations in the Usangu Plains themselves and in the north west part of the project area is notable.

Mean annual rainfall was calculated by two different methods: i) arithmetic mean; and ii) spatial interpolation using a kriging technique. Although the methods gave comparable estimates over the 11 subcatchments, the values differed over larger areas such as the high catchment or catchment upstream of river station 1KA27 at Hausmann's Bridge on the Great Ruaha river. The reason given for this was that the arithmetic mean was distorted because there were far more rainfall stations at higher altitudes than in the plains. Therefore the kriging technique was generally more accurate, though when using daily rainfall values, some of which were zero, it became unstable, so it was necessary then to revert to the arithmetic mean technique.

The WREP team undertook a number of further analyses of this large collection of rainfall data (Supporting Report No 11), looking at such variables as the dates of onset and cessation of the rains, the duration and magnitude between onset and cessation, and the duration from onset to latest planting out date (20^{th} February) for rice. An example of the spatial variation of the latter over the project area is shown in Figure 3.3. It was found that rains in the high catchment started earlier and ceased later than in the plains, so that the duration there was 17 decads, compared with only 15 decads in the plains. The rainfall magnitude in the high catchment (1 100 mm) was also larger than that in the plains (675 mm).

3.2.3 Long term trends in rainfall

A number of analyses of the historical rainfall were undertaken to detect long term trends. In Section 4.3.1, the results of examining for trends in the areal rainfall for 13 subcatchments are presented. Four larger regions were also examined, namely the high catchment, the plains, and the whole of the catchment upstream of two river gauging stations, 1KA27 and 1KA59, on the Great Ruaha river. Some of the areas exhibited a decreasing trend, but they were not significant.

Trends in the date of the onset of the rains are examined in Section 4.3.4. Commentators in the project area have suggested that the onset date of the rains has been becoming later and later during recent decades. However, a detailed analysis has failed to show any evidence for this perception. Rather a cyclical variation in the onset dates about their mean values was noted.

3.2.4 Rainfall data observed since the start of the SMUWC project

To fill some of the missing gaps in the network mentioned previously, raingauges were established at several locations by the SMUWC Project (Table 3.1, Figure 3.4). Three months after the project commenced four raingauges were placed around the Eastern Wetland at N'Giriama, Upagama, Igava and Ikoga. Another was established at Msangaji, an isolated village far into the north west of the project area.

At the start of the second wet season, two further raingauges on the north west side were added at Sangambi and Idunda. The network in the Western Wetland was also strengthened by the addition of two new stations at Ukwaheri and Kapunga Drain, and the rehabilitation of the historical station at Igurusi. In the north east two other stations at Madibira and Sadani were rehabilitated.

At the start of the third wet season two historical stations were rehabilitated, one at Usangu Ranch at the side of the Western Wetland, and the second at Malangali Secondary School on the eastern boundary of the project area.

Daily or monthly records were collected from a number of other organizations, giving a total of 44 stations currently being operated in or close to the project area. Rainfall totals for the five month period 1 December to 30 April were abstracted, and they are shown plotted for the wet seasons 1998/99 and 1999/00 in Figure 3.4; these are the months during which the majority of rainfall occurs, with normally only scattered showers before and after this period.

Data for several stations in the high catchment to the south of the project were incomplete for 1999/00, because the Directorate of Meteorology (DoM) was still awaiting submission of field sheets. Records from five stations in Ruaha National Park were obtained by making several field visits to this area; it is notable that only one of these stations presently submits their records to the DoM.

A more detailed examination of the areal rainfall distribution for various parts of the project area is presented in Appendix B, together with monthly rainfall data collected by the SMUWC project.

Table 3.1 Daily rain gauges installed by the SMUWC project

Station name	Easting	Northing	Date of start of record
N'Giriama	667427	9091296	1 Dec 98
Upagama Primary Sch	638232	9071732	1 Dec 98
Igava Primary Sch	660532	9051828	1 Dec 98
Ikoga Primary Sch	677933	9070103	1 Dec 98
Msangaji	601201	9107800	16 Jan 99
Idunda	633175	9098848	5 Nov 99
Sangambi Primary Sch	566586	9056952	3 Nov 99
Ukwaheri Primary Sch	606948	9062221	4 Nov 99
Igurusi FAO (UVIP)	592400	9025600	Restarted 9 Nov 99
Sadani Primary Sch	722200	9089200	Restarted 3 Nov 99
Madibira	701500	9091900	Restarted 1 Sep 99
Kapunga Drain	618000	9049000	1 Jan 00
Malangali Secondary Sch	704000	9052900	Restarted 25 Nov 00
Usangu Ranch	579000	9049800	Restarted 19 Oct 00

3.2.5 Summary of rainfall distribution

The rainfall during each of the first two years of the SMUWC project was particularly low. For example, at the raingauge at Madibira, the 5 month rainfall total for December-April in 1998/99 was 71% of its long term mean, and in 1999/00 it was 66%. These values each possess a return period longer than 10 years

The differences between the rainfall that fell over six important regions of the project area are summarised in Table 3.2.

Table 3.2 Variation of rainfall over project area in 1998/99 and 1999/00

Region in project area	Mean rainfall total 1 Dec 98 – 30 Apr 99 (mm)	Mean rainfall total 1 Dec 99 – 30 Apr 00 (mm)
Eastern Wetland	513	440
Western Wetland	531	372
Ruaha National Park riverine reach	417	392
High catchment in the north east	622	679
High catchment in the north west	572	668
High catchment in the south west	939	717

Rainfall is uniformly low over the Usangu Plains, but with slightly higher values over the north west side. During the dry years of 1998/99 and 1999/00, the total in the 5 months December to April nowhere exceeded 500 mm, except at N'Giriama, Kimani, Upagama and Idunda.

In the 1999/00 year there was failure of the rains in the southern part of the Western Wetland, with totals for the four months January-April not exceeding 280 mm.

The rainfall amounts along the riverine reach in the Ruaha National Park are even lower than in the Eastern Wetland, and decrease further going downstream in a north easterly direction.

Higher rainfall occurs in the high catchment to the north east, south east, south and south west of the plains. A newly established station at Msangaji, located in the north west high catchment, also indicated higher rainfall amounts in this region, particularly during the month of March.

One possible overall explanation for these general rainfall patterns is that the prevailing rain-producing winds come from the south-east. These could produce a rain shadow in the lee of the escarpment running along the south east edge of the Usangu Plains, but produce higher totals as the winds hit the rising ground on the north-west edge of the Usangu Plains.

3.3 Evaporation

3.3.1 Introduction

Evaporation rates are calculated from climate data such as temperature, windspeed, radiation and humidity. Inspection of several of the climate stations within the project area showed that many of them were in a poor state, and up-to-date records representative of the two areas of most interest, the plains and high catchment, were unlikely to be available. However some synoptic stations operated by the Department of Meteorology at airports located outside the project area, such as at Mbeya and Iringa (Nduli), were operating satisfactorily.

The SMUWC project decided not to establish a network of new manual climate stations. This would have involved heavy investment with only at most two years of records available by the project completion date. Instead, it was decided to rely on two alternative approaches: collecting historical data and making use of the network of automatic stations currently being installed by the RBMSIIP project.

3.3.2 Historical climate information

Four irrigation schemes have been constructed during the last 30 years within the project area at Mbarali, Kimani, Kapunga and Madibira. Considerable efforts were expended on tracking down copies of the engineering design manuals for these schemes, but even manuals for recently completed schemes were difficult to trace. Among the appendices of these manuals was much useful information from historical climate stations. These are collated together in Appendix F of Supporting Report No 9. For example, monthly values of potential evapotranspiration ET_o from the Madibira station are listed in Table 3.3 (Halcrows, 1995). This record is representative of the evaporation from the Eastern Wetland and the plains surrounding it.

Table 3.3 Long term mean monthly estimates of potential evapotranspiration

Month	Madibira Potential evapotranspiration (Penman) ET_o (mm)	Mbeya Catchment Open water evaporation (Penman) EO (mm)	Mbeya Catchment 80% of EO values (mm)	Dodoma Potential evapotranspiration (Penman-Monteith) ET_o (mm)
January	142	114	91	170
February	124	105	84	174
March	140	111	89	165
April	136	103	82	159
May	145	112	90	150
June	140	119	95	145
July	152	131	105	143
August	170	144	115	148
September	188	155	124	154
October	213	167	133	168
November	194	134	107	188
December	157	115	92	176
Annual total	1901	1510	1207	1939

An historical climate station, now closed, representative of the conditions in the high catchment, was located in the hills just north of Mbeya at an altitude of 2 428 m. This was established for the Mbeya catchment experiments established by the East African Agricultural and Forestry Research Organisation (EAAFRO). Monthly climate records were obtained for this station, and the Penman open water evaporation EO over the 12 years of record, January 1958-December 1969, are summarised in Table 3.3. An estimate of potential evapotranspiration ET_o over the high catchment can be taken as 80% of these EO values; these can be directly compared with the higher values shown for Madibira, representing conditions on the plains, for which the annual total is 57% larger.

The Water Resources Engineering Programme (WREP) collected daily records of climate variables from seven stations located both within and adjacent to the project area. Some of these stations are operated by the Directorate of Meteorology, some by the Ministry of Water and others by private organisations. The location of four of these stations, at Iringa, Igawa, Madibira and Mbeya, are shown in Figure 3.2. Their analysis is described in chapter 3 of Supporting Report No. 11. There were considerable periods of missing data. WREP estimated the mean annual values of potential evapotranspiration as: Dodoma 1 900 mm, Iringa 1 700 mm, and Mbeya 1 600 mm. They found close agreement between values at Dodoma and Madibira, but since the latter record only had 8 years of data, they considered the long record at Dodoma would be a good representation of evaporation over the Usangu plains (Table 3.3).

3.3.3 Long term trends in evaporation

A 39 year record of potential evapotranspiration at Dodoma was tested for any long term trends in evaporation. A slight increasing trend was detected, but it was found to be not statistically significant. Further details are given in Section 4.3.1.

3.3.4 Climate data observed since the start of the SMUWC Project

In September 1998, just when the SMUWC project commenced, a programme of work initiated earlier by the RBMSIIP project to improve the collection of climate data in the whole of the Rufiji basin was just coming to fruition. They had purchased a number of automatic weather stations which record, on solid state storage devices, all the climatic variables necessary for the calculation of evapotranspiration. During the period October 1998 – January 1999, five of these stations were installed in the project area (Table 3.4).

Table 3.4 Automatic weather stations installed by RBMSIIP project

Station number	Station name	Easting	Northing
97.3514	Iringa	797805	9140200
98.3400	Madibira	700300	9093200
98.3406	Igawa	651000	9031000
98.3413	Matamba	606800	9011600
99.3401	Njombe	694066	8967846

The data from the two stations at Madibira and Igawa should provide estimates of potential evapotranspiration that are representative of the plains, while Matamba and Njombe are representative of conditions in the high catchment. A complete period of 12 months daily climatic data has been downloaded from three of these stations, and during the coming months it is hoped to obtain data from the remaining two stations, which have been delayed due to problems with the Ministry of Water computer at Mbeya. These data will be processed by the Penman-Monteith method to provide daily estimates of potential evapotranspiration.

Estimation of the water balance of the Usangu catchment requires estimates of evaporation losses for different parts of the basin. Potential evapotranspiration rates which are representative of different parts of the project area (the high catchment, the Eastern Wetland and the plains) have been obtained from reports on irrigation schemes and from climate stations in and around the project area.

3.3.5 Measurement of windspeed at Makambako

The area around Makambako along the eastern boundary of the project area is notorious for persistent strong winds. The limits of this phenomenon extend from the centre of Makambako to 20 km north along the road to Iringa, and about 10 km west along the road from Makambako to Mbeya. The easterly and southern limits are unknown. It is possible that this natural resource might be exploited in future for the generation of power by modern windmills. Towards this end, on 3 November 1999 the SMUWC project installed a cup anemometer for measuring the cumulative wind run during each day and each night. It is located at Iramba village (UTM Grid Ref: 710184E 9036353N) along the road from Makambako to Iringa.

Twelve continuous months of daily wind speeds have now been collected. The monthly wind speed varies up to a maximum of 1.6 m/s (recorded in October 2000). Each day can be further subdivided to determine the day-time and night-time speeds. Analysis shows that night-time speeds are less than half those of the corresponding daytime speeds during the period July-November 2000 (Figure 3.5).

The speeds recorded are rather lower than expected. This may be due to the exposure of the anemometer. It is mounted on a pole 2 m above an anthill, but down wind of a bamboo plantation. Both of these features may be affecting the reading adversely. It may be preferable to re-mount the instrument on the top of a 10 m tower, free of any upwind obstructions.

3.4 River flows

3.4.1 Introduction

River flow records have been observed by the government in the project area since the 1950s. The stations were operated successfully until the mid-1980s, but since then financial constraints have prevented routine field visits, and several stations fell into disrepair during the 1990s. The RBMSIIP project is currently assisting the Ministry of Water to rehabilitate most of the priority stations. These gauging stations are located in the vicinity of the roads that circle around the perimeter of the Usangu Plains. There were never any stations located in the centre of the plains or near the wetlands themselves.

The approach adopted by SMUWC has been to install a few new permanent stations close to the wetlands themselves, and also make a temporary rehabilitation of some of the historical stations until the full RBMSIIP rehabilitation took place. These observations have been supplemented by a network of spot discharge measurements at numerous sites where no permanent station was envisaged. Meanwhile all the essential historical data has been collected from the Ministry of Water archives.

3.4.2 Historical river flow information

The locations of the historical river flow stations are shown on Figure 3.2. The 13 most important perennial rivers flowing into the Usangu plains from the high catchment each possess a gauging station, and there are two stations located on the stretch of the Great Ruaha river where it flows through the Ruaha National Park downstream of the outlet of the Eastern Wetland.

Water level and discharge measurement records were obtained by WREP from the Ministry of Water (Supporting Report No. 11). The two earliest records, at the stations on the Kimani river at Great North Road and the Great Ruaha river at Salimwani, commenced in 1954. All stations possessed substantial amounts of missing data, varying from 9% to 25% over the period of record; this was particularly apparent in the 1990s, when the water level readings tailed off.

Rating curves were drawn up by WREP. Most of the larger rivers in the east and south of the project area had reliable curves, the several smaller catchments in the south west had poor quality curves. The main problem was that the taking of current meter discharge measurements ceased in the early 1980s, so the rating curves may not be strictly valid for the full period of water level observations. However, they have been applied to obtain daily flow values.

Double mass analysis was applied to test the reliability of each record. As a consequence it was necessary to review the water level and rating curve information for certain years at some stations, and prepare new flow records where necessary. Two methods were used to infill missing data so that full length records for the period 1954-98 were available for all 13 gauged catchments. One of these was cross correlation with records from neighbouring stations. However, when no neighbouring stations possessed records, a rainfall-runoff modelling technique was employed (Supporting Report No. 11).

3.5 Water availability

Many of the rivers flowing down from the high catchment are used to supply irrigation schemes. The historical river flows were analysed to determine the availability of flows at different times of the year.

At several of the stations, the early years of record prior to 1964 were not considered reliable. Analysis was therefore confined to the 35 year period 1965-99. The daily flows were summed to obtain totals over ten day periods; these periods are known as decads. The frequency of occurrence of the 36 values obtained for each of the 35 years was then examined, to obtain a long term mean value for each decad, as well as a value which was exceeded four years out of five. As an example, the variation of these two values for each decad is shown in Figure 3.6 for the Mbarali river. For the mean value it should be noted that at the end of the dry season it first rises appreciably in the 3rd decad of November, the peak value occurs in the 3rd decad of March, and the end of the steep receding part occurs during the 1st decad in June. For the value exceeded 4 years out of 5, the dates are slightly different: the first rise is later during the second decad of December, the peak value occurs in the same decad as the mean value, and the end of the steep receding part occurs earlier in the second decad of May.

What is very noticeable from this analysis is that the four main perennial rivers entering the Western Wetland, namely the Chimala, Great Ruaha, Kimani and Mbarali, all have very similar behaviour, with dates quite close to those shown for the Mbarali river in Figure 3.6, although the flow values themselves will differ between rivers. However the Ndembera river, entering the Eastern Wetland from the north east, has a slightly different behaviour, due to the seasonal wetland at high elevation in its upper catchment.

3.5.1 Long term trends in historical river flow

The historical series of river flows were examined for any long term increasing or decreasing trends. In Section 4.3.4, this analysis is described in more detail for the flow record at station 1KA27 Hausmann's Bridge on the Great Ruaha river. The aim was to determine the exact nature of the reported decrease in the flows in the Great Ruaha downstream of the Eastern Wetland. Three separate analyses were conducted; the annual and wet season flows did not show any apparent trends, but the dry season flows showed a marked decrease.

The rivers running down from the high catchment were also analysed for trends; this is reported in Section 4.3.2. The aim was to determine whether dry season irrigation in the high catchment results in any decrease in flows. However the results were inconclusive, with some catchments giving decreases and other catchments giving increases. It is thought that this was due to the unreliable nature of the river records. Consequently it was decided to undertake a further analysis of the two flow records which possessed the highest quality. This is described in the following paragraphs.

The two records chosen were from the stations 1KA9 Kimani river at Great North Road and 1KA15A Ndembera river at Ilongo. The Kimani river flows down from the high catchment in the south of the project area; its catchment area is 459 km^2 and its mean annual flow is 5.79 m^3/s. The Ndembera river flows down from the high catchment in the north east of the project area; its mean annual flow of 6.17 m^3/s is very similar to that of the Kimani, but its catchment area of 1 107 km^2 is over twice as large.

Table T7.2 of Supporting Report No 11 shows that these two rivers have, of all the 13 subcatchments, the lowest percentage of missing data. The Kimani has 11% missing from a 46 year record, while the Ndembera has 9% missing from a 44 year record. Table T7.3 of the same report shows that the Kimani rating curve, valid for the period 20/08/55-15/04/83, and the Ndembera rating curve, valid for the period 06/08/64-18/12/82, are both considered reliable. But these periods only last for about half the length of the water level records, so little is known about the reliability for recent years. One encouraging fact is that the rating curve for the Kimani river drawn up by the SMUWC project for 1999/00 closely matches the historical rating curve (Section 3.4.5), while that for the Ndembera river has a similar shape to its historical rating curve.

The water year 1 August-31 July was used to obtain annual flow volumes for each station. The 34 year period 1966-99 was used for analysis of trends, because of some doubts about the quality of earlier parts of the records. A decreasing trend in annual flows was found on both rivers, a value of –0.072 m^3/s/year on the Kimani and a value of –0.022 m^3/s/year on the Ndembera; neither result was statistically significant. What is more interesting is that the Kimani river apparently exhibits a steeper decline than the Ndembera, yet it is known from field visits that the Kimani catchment headwaters are virtually free from human interference, with certainly no dry season irrigation. On the other hand there is definitely some dry season irrigation in the Ndembera river headwaters.

3.5.2 River flow information observed since the start of the SMUWC project

Key river gauging stations in the project area are listed in Table 3.5.

Table 3.5 River flow stations used for SMUWC Project

River	Station	Easting	Northing	Altitude (m asl)	Catchment area (km^2)	Start/restart of record
Umrobo	Gt North Rd	574909	9025081	1 260	63.5	1 Apr 1999
Chimala	Chitekelo	607306	9014062	1 890	170	21 Jan 1999
Gt Ruaha	Salimwani	622243	9016503	1 145	785	1 May 1999
Kimani	Gt North Rd	629183	9021765	1 075	459	1 Sep 1996
Mbarali	Igawa	651581	9028846	1 115	1 542	1 Oct 1997
Gt Ruaha	Nyaluhanga	635479	9067437	1 007.184[1]	10 121	25 Oct 1998
Ndembera	Ilongo	738361	9086002	1 665	1 107	19 May 1999
Ndembera	Madibira U/S	704750	9090250	1 115	1 812	1 July 1999
Ndembera	Madibira D/S	704443	9090015	1 105	1 812	19 Jan 1999
Gt Ruaha	N'Giriama	666815	9091232	1 005.225[1]	20 810	22 Oct 1998
Gt Ruaha	Msembe Ferry	709328	9146923	815	23 520	17 Jan 1999

[1] Elevation of zero on staff gauge.

With the assistance of hydrometric technicians from the Ministry of Water office in Mbeya, two new stations were installed in October 1998, one month after the project commenced. One was located on the Great Ruaha river where it enters the Eastern Wetland at Nyaluhanga. The other was located at N'Giriama where the Great Ruaha river leaves the Eastern Wetland. Both stations consisted of 4 m of staff gauge, which is read once daily by a villager living close by. RBMSIIP installed a second manual station at Nyaluhanga in September 1999 at a site about 200 m downstream of the SMUWC site. SMUWC staff rehabilitated three historical stations, two on the Ndembera river at Madibira and Ilongo, and one on the Chimala river at Chitekelo. Another existing station was located on the Great Ruaha river at Msembe Ferry, where it passes through the Ruaha National Park. This station was rehabilitated by the RBMSIIP project, and there are gauge readers living there who are employed permanently by the Ministry of Water.

Every two months the technicians undertook spot discharge measurements at the stations listed in Table 3.5 and at a network of locations on rivers, irrigation canals and drains (Figure 3.7). These allowed a picture to be built up slowly of the complicated flow patterns in the alluvial fans and irrigation schemes. While such measurements could be taken by wading during the low flow periods, it proved more difficult to take measurements at high water levels on the larger rivers. The cableway at Msembe Ferry was not operational and measurements from the bridge at the park entrance proved unsatisfactory due to the turbulent water. The arrival of the airboat in May 1999 allowed a limited set of discharge measurements during the recession phase to be taken at both Nyaluhanga and N'Giriama, and further such measurements were taken during the 2000 wet season. High flow measurements at the remaining stations, except Umrobo, were taken off the road or railway bridges located there. All these measurements were used to draw up rating curves (Table 3.6), to allow conversion of water levels to flows.

For the following four stations the new rating curve developed by SMUWC for the years 1999 and 2000 closely matched the historical curve: Chimala river at Chitekelo, Great Ruaha river at Salimwani, Kimani river at Great North Road and Great Ruaha river at Msembe Ferry; (for the Msembe Ferry station there were two historical rating curves, and it was the earlier one, valid 13/12/63-08/05/79, that matched the SMUWC curve for 1999/2000). This gives greater confidence in using the medium and high flow parts of their rating curves, since the historical curves were fitted to far more discharge measurements in this range than the new curves.

At two of the most important stations on the Great Ruaha river, at Nyaluhanga and N'Giriama, difficulties were encountered in drawing up a satisfactory rating curve. At Nyaluhanga the bottom of the channel is silty, and the bed level changes from year to year. This means a new section of curve at the lower flows is needed each season. At N'Giriama the water in the single low flow channel flows over its banks at medium flows as gauge height 5.99 m is reached, and a second channel starts conveying flows. This means that there is a distinct bend in the rating curve as this level is reached.

The airboat was used at both these stations to take high flow discharge measurements by the well known boat method, when access by vehicle was otherwise impossible. However, most of these boat measurements were questionable due to erroneous field techniques being used. This means that the medium to high flow part of the rating curve at Nyaluhanga still needs improvement. A correlation between the water levels at N'Giriama and at Msembe Ferry downstream allowed the stable rating curve at the latter station to assist in drawing up the rating curve at N'Giriama for the medium and high flow range.

Table 3.6 Rating curves used between October 1998 and December 2000

Number	River	Location	Starting dates	Rating curves	Comments
1KA7A	Chimala	Chitekelo	21/01/99	$Q = 19.901 (h + 0.15)^{2.466}$	Fitted to D/Ms Nos 1 – 9. This is in very close agreement with historical rating $Q = 21.344 (h + 0.08)^{2.115}$ applied from 14/03/64 to 10/12/91, except in the lowest part below GH 0.15m. More low flow D/Ms needed to confirm which curve to choose, although it will not make much difference.
1KA8A	Gt Ruaha	Salimwani	16/11/98	$Q = 3.625 (h + 0.47)^{3.157}$	Fitted to D/Ms Nos 1 – 13, excluding Nos 14 and 15. This rating agrees at low flows with historical rating [$Q = 11.563 (h + 0.10)^{2.284}$] applied from 05/12/64 to 15/09/86, and is in reasonable agreement with it at medium and high flows.
1KA9	Kimani	Gt North Rd	16/11/98	$Q = 7.337 (h + 0.08)^{2.647}$	Fitted to D/Ms Nos 1 – 10, but power value constrained to 2.647, the same as the historical rating curve [$Q = 10.054 (h – 0.0)^{2.647}$] applied from 20/08/55 to 15/09/86.
1KA11A	Mbarali	Igawa	01/12/98	$Q = 6.97 (h + 0.50)^{3.208}$	Constant set equal to 0.50m to agree with lowest part of historical rating [$Q = 6.281 (h + 0.50)^{2.79}$] applied from 27/10/64 to 19/03/76. Although not fitted to them freely, this rating agrees well with D/Ms Nos 1 -2, 6 – 13. Does not agree with D/Ms 3 – 5, 14.

Table 3.6 Rating curves used between October 1998 and December 2000 (continued 1)

Number	River	Location	Starting dates	Rating curves	Comments
1KA15A	Ndembera	Ilongo	19/05/99	$Q = 9.001 (h – 0.68)^{2.679}$	Rating curve revised 4/10/00. Fitted to D/Ms Nos 1 - 8, 10 – 11.
1KA33A	Ndembera	Madibira	19/01/99	$Q = 7.551 (h – 1.16)^{1.749}$	Rating curve revised 4/10/00. Fitted to D/Ms Nos 1 – 10, 12, excluding Nos 11, 13 - 15. Weir control appears damaged, so rating probably not applicable after 30/04/00: station 1KA33B should be used instead after this date.
1KA33B	Ndembera	Madibira	13/06/99	$Q = 1.331 (h – 0.14)^{3.085}$	Rating curve revised 4/10/00. This station to be used in preference to 1KA33A from 1/5/00 onwards. Fitted to D/Ms Nos 1 – 4, 6, 8, 10 - 11.
1KA51A	Umrobo	Gt North Rd	01/04/99	$Q = 7.499 (h + 0.05)^{2.251}$	Fitted to D/Ms Nos 1, 8 – 12, but rating curve is not well defined.
1KA59	Gt Ruaha	Msembe	01/01/99	$Q = 20.502 (h – 0.39)^{3.299}$	Same as historical rating curve used from 13/12/63 to 08/05/79. Since D/Ms Nos 1 and 2 are not considered precise because they were taken from the bridge, it is felt that the historical rating is the best since it has been fitted to many D/Ms with stages greater than 1.61 m.

Table 3.6 Rating curves used between October 1998 and December 2000 (continued 2)

Number	River	Location	Starting dates	Rating curves	Comments
1KA70	Gt Ruaha	N'Giriama	01/01/99	$Q = 0.0$	Fitted by comparison with flows on Gt Ruaha at Msembe, and not by using the D/Ms observed at N'Giriama. The stage at N'Giriama and the stage three days later at Msembe were assumed to possess the same discharge.
			16/03/99	$Q = 7.96 (h - 4.42)^{2.354}$ upto 5.99 m $Q = 0.74 (h - 4.47)^{8.202}$ from 6.00m upto 6.08 m $Q = 8.16 (h - 4.47)^{3.162}$ from 6.09m upto 10.0 m	
			20/09/99	$Q = 0.0$	
			12/02/00	$Q = 7.159 (h - 4.48)^{2.204}$ upto 5.92m	
1KA71	Gt Ruaha	Nyaluhanga	25/10/98	$Q = 6.972 (h - 5.90)^{2.056}$	High flow D/Ms were modified because of various problems in field techniques.
			17/04/00	$Q = 11.554 (h - 5.93)^{1.540}$	

At Madibira the manually-read temporary station on the Ndembera river, opened by the SMUWC project in January 1999, was supplemented by the rehabilitation by RBMSIIP of a nearby upstream station during July 1999, where an electronic logger was installed. The different rating curves at each station provided similar estimates of daily flows during their common period of record until April 2000. At that time the weir control of the downstream station sprung a leak, and this station was eventually closed down in October 2000. Records from the downstream station for the period from 19 January 1999 until 30 April 2000 were used for further analyses, and from 1 May 2000 onwards only the record of daily flows from the upstream station were used.

Neither the rating curve nor the water level record at the station on the Umrobo river proved satisfactory. Consideration should be given in future to selecting one of the other minor rivers, that are monitored in this south west part of the project area, as a representative station.

There were three historical stations in the project area that the Ministry of Water office in Mbeya continued to operate prior to the commencement of the SMUWC project. During the rehabilitation carried out by RBMSIIP in 1999, care was taken to retain the same staff gauge zero level as was used previously. This means that the new rating curves developed by SMUWC for these stations can be applied retrospectively. The Kimani and Mbarali river stations have reliable records available from 1 September 1996 and 1 October 1997 respectively, but for the Great Ruaha river at Salimwani the wet season record in 1998/99 possessed some odd water levels, so the record should only be accepted commencing from 1 May 1999.

3.5.3 Comparison of flows between stations

Some examples of the flow records collected are shown in Figures 3.8 and 3.9. In Figure 3.8, the observations from the Chimala river at Chitekelo are compared with those from the Ndembera river at Madibira. Both these rivers flow down from the high catchment and are measured at points before they enter the plains. The Chimala flows from the southern escarpment and shows the typical variations of a mountainous catchment, with steep rising and falling flows during the main part of the wet season. It is noteworthy for the sustained recession during the dry season, which indicates good contributions from groundwater sources. The Ndembera river, by contrast, enters from the high land situated on the east of the project area. Its source area is the high level Ndembera wetland, which produces a smoothing effect on the flows leaving it. Although its catchment area is over 10 times as large as that of the Chimala, it only produces flow volumes of the same order of magnitude; this is due to the lower rainfall over this catchment.

Figure 3.9 compares the flows in the Great Ruaha river at two locations, the outlet of the Eastern Wetland at N'Giriama and at Msembe Ferry approximately 80 km downstream. There is close agreement between the shapes of the two curves. But no significance should be attached to the similarity of the magnitudes of the flows from each station, because, as mentioned in section 3.5.2, the rating curve at Msembe was used to draw up the medium and upper ranges of the rating curve at N'Giriama. However, even if a different rating curve was employed at N'Giriama, the timings of the start of main rises, the peak flows, and the returns to zero flow would remain unchanged, so still remain similar to those reocrded at Msembe. The difference in flows at the start of the wet seasons indicates that the Msembe Ferry station is receiving tributary flows from the sand rivers in the Ruaha National Park, before the main flood has started flowing from the Eastern Wetland.

3.6 Wetlands

3.6.1 Introduction

The overall area of the Usangu Wetlands can be conveniently divided into two main portions, the Eastern Wetland and Western Wetland (Figure 1.1). Although in each individual wetland there is a very complex network of channels and wetlands, at the connecting point between them, called Nyaluhanga, there is a constriction where all the rivers are reduced to a single channel over a short distance of about 200 m. The Mbeya Water Master Plan (CCKK, 1982) notes that the existence of a ridge in the underlying rock formation is the reason for this constriction.

During the 1998 dry season the Eastern Wetland contained just one main body of perennial swamp, the *ihefu* swamp, which was supplied by only two major rivers, the outflow from the Western Wetland along the Great Ruaha river at Nyaluhanga and the River Ndembera flowing in from the northeast at Madibira. For about three months at the end of the 1998 dry season no water was observed leaving the *ihefu* swamp through the single outflow at N'Giriama at the north edge of the wetland. The perennial *ihefu* expanded during the 1998/99 wet season to a seasonally flooded wetland area about ten times greater in total area. All the major rivers entering the Eastern Wetland, including the outflow from the Western Wetland at Nyaluhanga, have to pass through this seasonal wetland to reach the single outflow over a rock sill at N'Giriama.

In contrast to this scenario, during the 1998 dry season the Western Wetland contained several isolated small bodies of perennial swamp associated with buried river channels (Section 3.7.2). During the 1998/99 wet season these did not join up to form a single area of seasonally flooded wetland in the western system. Connecting these separate swamps and wetlands was a complex maze of channels, some flowing all the year round whilst others dried up. The national topographic 1:50 000 maps of this area are based on May 1977 aerial surveys, but since the published literature mentions several major shifts in the location of some of these channels, it is true to say that there was no up-to-date map showing their present locations at the start of the SMUWC Project in September 1998.

Hydrological field investigations of the Usangu Wetlands during the SMUWC Project have been concentrated mainly in the Eastern Wetland, whilst irrigation field investigations have been concentrated mainly in the Western Wetland.

The behaviour of the Eastern Wetland is difficult to interpret. However, since it consists of a single main body of water means that it is easier to construct a conceptual water balance model there than for the far more complex picture in the Western Wetland. But comparison of the 1998/99 wet season river flows leaving the Western Wetland at Nyaluhanga with those entering it from the high catchment shows that the effects of the Western Wetland cannot be neglected.

3.6.2 Eastern Wetland

At the start of the SMUWC Project in September 1998 there was little hard information available about the Eastern Wetland. Much of the published information concerned the hilly regions surrounding the wetland and the alluvial fans leading down towards it, but virtually nothing about the wetland itself. A perennial swamp and seasonal wetland were known to exist, but even published estimates of its surface area varied widely. The best ways to gain access to the wetland were also unknown to the SMUWC team.

A study of the processes and functioning of the Eastern Wetland has been carried out and is contained in Supporting Report No. 14. In this section more detailed survey information relevant to determining the water balance of the wetland will be described.

A series of surveys using several different procedures were used to gain information about the wetland (Table 3.7). The aerial surveys, combined with satellite observations of vegetation contrasts, were used to estimate the extreme variations of surface area of the wetland at the end of the dry and wet seasons respectively, as follows:

21 January 1999	Perennial swamp	64 km^2
2 May 1999	Seasonal wetland	615 km^2
11 May 2000	Seasonal wetland	260 km^2
7 November 2000	Perennial swamp	27 km^2

Most of the surface area of the perennial swamp is covered by aquatic vegetation, but in the centre lie pools of water which remain permanently open during the whole of the year. These pools were surveyed during a hydrographic survey conducted on 13-16 June 1999, by plumbing the depth using a ranging rod, and noting the location with a hand held global positioning system instrument (Figure 3.10). The area of the open pools during 1999 was found to be 9.6 km^2. The amount of open water tends to vary over the years, and the 1:50 000 topographic sheets, based on May-July 1977 aerial surveys, show these open water areas having a different pattern to that of June 1999, with a total area of just 1.5 km^2 (Figure 3.11).

During November 1998, eight permanent concrete survey control points (SMUWC 1-7, 11) were erected around the southern, eastern and northern perimeters of the seasonal wetland, as shown in Figure 3.12. Three more control points, SMUWC 8-10 were added on the north-western perimeter during the 1999 dry season, and finally the last point SMUWC 11E on the north east arm was positioned in September 2000. Using the Directorate of Surveys (DOS) national survey pillar No 231x6 near Ikoga as a datum at altitude 1019.700 m asl, a double levelling survey was conducted by foot around the complete circuit of all these control points. The misclosure error of -0.188 m was considered acceptable, and the estimated absolute altitudes of the control points are given in Table 3.8. These altitudes differ from the preliminary values shown in Table 3.11 of the Interim Water Resource Report for the following two reasons. They were initially surveyed using a differential GPS method, which give values which were considered slightly less accurate than those from the topographic levelling. Secondly, during the GPS survey, no allowance had been made for the height of the instrument, when commencing the survey from the DOS survey pillar.

Table 3.7 Aerial and topographic surveys of the Eastern Wetland

Date	Survey type	Transport	Personnel	Data stored
Oct 98	Initial aerial reconnaissance	Plane	T Franks L Mbuya N Mandeville	Map and photos in office files
Nov 98	Topographic, low water levels	Vehicle & foot	Univ of DSM	Office file
21 Jan 99	Aerial, perennial swamp outline	Plane	N Mandeville	Technical Data Volume: Water Resources, Mar 2001
2 May 99	Aerial, seasonal wetland outline	Plane	A Graham G King N Mandeville	Technical Data Volume: Water Resources, Mar 2001
10-13 May 99	Topographic, high water levels	Vehicle & foot	Univ of DSM	Office file
May-July 99	Reconnaissance and discharge measurements	Airboat	N Mandeville L Mbuya	Office files
July 99	Hydrographic, perennial swamp open water areas	Airboat	L Mbuya	Technical Data Volume: Water Resources, Mar 2001
Sep 99	Differential GPS, control point altitudes	Vehicle & foot	Univ of DSM	Office files
Sep – Oct 99	Topographic, low water levels	Vehicle & foot	Univ of DSM	Office files
20 May 2000	Aerial, seasonal wetland perimeter	Plane	N Mandeville R Olivier	Technical Data Volume: Water Resources, Mar 2001
June 2000	Hydrographic, seasonal wetland, northern end	Airboat	L Mbuya	Office files
25 July – 4 Aug 2000	Topographic, control beacons, north west side	Vehicle and foot	MATI Igurusi	Office files
15 – 29 Aug 2000	Topographic, profiles of seasonal floodplain on north west side	Vehicle and foot	MATI Igurusi	Office files
7 – 12 Sep 2000	Topographic, control beacons, eastern side	Vehicle and foot	MATI Igurusi	Office files
27 Sep – 14 Oct 2000	Topographic, north west channel	Vehicle and foot	MATI Igurusi	Office files
4 – 14 Nov 2000	Topographic, control beacons, southern side	Vehicle and foot	MATI Igurusi	Office files
7 Nov 2000	Aerial, perennial swamp perimeter	Plane	N Mandeville L Mbuya K Bashar R Olivier J Berkoff	Technical Data Volume: Water Resources, Mar 2001

Table 3.8 SMUWC control points

Control point	Easting	Northing	Altitude (masl)
SMUWC1	635369	9069262	1017.406
SMUWC2	654948	9064836	1015.205
SMUWC3	664641	9065831	1016.364
SMUWC4	674375	9072617	1014.940
SMUWC5	679402	9090371	1020.359
SMUWC6	676043	9091641	1019.767
SMUWC7	667358	9091576	1015.927
SMUWC8	656483	9089496	1018.963
SMUWC9	651957	9085518	1016.111
SMUWC10	642425	9081960	1021.821
SMUWC11	684811	9095914	1026.397
SMUWC11e	680278	9097118	1029.918
DOS Pillars			
230 x 2 Chalusetta	656444	9102644	1336.335
230 x 3 Mawale	653207	9084426	1015.929
230 x 4 Utuya	625932	9068701	N/A
230 x 6 Ikoga	676323	9091641	1019.700

System: Clarke 1880 Projection: UTM

The altitudes of SMUWC5 and SMUWC6 control points are approximately 5 m higher than the other ones erected in 1998. Initially there was some concern about the accuracy of these points, but subsequent installation of further points at SMUWC11 and SMUWC11E confirmed that these were higher still. This indicates a significant gradient to the north east up the Ndembera valley and suggests that the swamp in the Ndembera floodplain may be perched above the *ihefu* swamp. Contours on the 1:50 000 topographic map indicate that the altitude of the Ndembera 'arm' close to the tail of the main drain of the new Madibira rice scheme lies 18 m above the altitude of the main perennial swamp. Similarly, to the west of the outer perimeter of the Eastern Wetland shown in Figure 3.12, the topographic maps indicate a perched wetland 6 m above the main perennial swamp.

A profile along the wetland, running from SMUWC1 to SMUWC7 control point locations, is shown in Figure 3.13. In general the slopes are extremely gentle; for example the river surface in August 2000 shown drops a total of 3.5 m over a distance of 50 km, which is a mean slope of about 1:14 000.

Spot level measurements of the bank, bottom and water surface were observed at regular intervals along the North West Channel and the transverse channels connecting the perennial swamp to the North West Channel. On some of the transverse channels coarse cross-sections were taken. These are discussed more fully in Sections 6.3.6 and 6.3.7 where water management options for possible clearance of these channels are discussed. Figure 6.5 shows the locations of both sets of channels, and Figure 6.6 provides a profile of the North West Channel plotted from this topographic survey.

A water level station was erected on 22 October 1998 at the outflow of the wetland at N'Giriama, consisting of a 4 m vertical staff gauge. It was found to measure successfully the water level in the wetland during the high water levels of the wet season. However, towards the end of the 1998 dry season, when the levels dropped extremely low due to the late arrival of the 1998/99 wet season, the pool immediately upstream of the outflow rock sill became separated from the main pool of the perennial swamp shown in Figure 3.12. Remedial action was therefore needed, so two additional water level stations were erected on 14 June 1999 at Ruaha and Nyangokolo Swamps in the open water pools at the centre of the perennial swamp (Table 3.9, Figure 3.12). This work could not be started until the arrival of the airboat on the wetland on 14 May 1999.

Table 3.9 SMUWC swamp gauges

Gauge	Easting	Northing	Gauge zero m asl	Start of record
Ruaha swamp	666486	9075066	1010.159	14 June 1999
Nyangokolo swamp	667431	9076924	1010.113	14 June 1999

Water levels in the Ruaha and Nyangokolo swamps were monitored everyday from 14 June 1999 up to the present. Figure 3.14 shows the fall in water level in each swamp during both the 1999 and 2000 dry seasons and the recovery at the beginning of the 1999/2000 wet season. It is noticeable that even though the two stations are about 2.5 km apart, they do not behave identically. The graph suggests that they become hydraulically isolated towards the end of the dry season and then start to fill at different times, possibly from different source rivers, at the start of the wet season.

Using discharges in the Great Ruaha river recorded at two measuring stations, N'Giriama itself and Msembe Ferry further downstream, a relation was established (Figure 3.15) between the discharges passing over the outflow sill at N'Giriama and the water levels recorded there. The equation for this rating curve is given in Table 3.6. According to this fitted equation, when the vertical staff gauge measures a height of 4.42 m the discharge in the channel becomes zero; in practice it was observed that the discharge became zero at a gauge height of 4.30 m which is equivalent to an absolute altitude of 1009.525 m asl. In fact, although there is rock underlying the current lowest point in the river channel, the channel itself becomes blocked at low flows by debris brought down from the wetland, and this means slight variations can occur in this height at which the discharge becomes zero.

Much of the survey information collected was used to construct a three dimensional representation of the seasonal wetland, from which the perimeter outlines at various water levels were abstracted (Figure 3.12). These outlines were used to determine the relationship between swamp water level at N'Giriama and the surface area and corresponding volume of water contained in the swamp (Figure 3.16).

To examine the effect of the Eastern Wetland on the rivers entering the wetland, a comparison is made in Figure 3.17 of the difference between the discharges observed during the period 1 January 1999-30 November 2000 for the main inflow, the Great Ruaha river at Nyaluhanga, and the outflow at N'Giriama. During the wet season other rivers such as the Ndembera, Kyoga and Kimbi also enter the Eastern Wetland, so the total incoming flow is larger than that shown for Nyaluhanga. But the flow at Nyaluhanga is by far the largest individual river inflow, and represents a major proportion of the total inflow to the Eastern Wetland.

Unlike for Nyaluhanga, the discharges at N'Giriama are minimal until March. Then, after an initial sharp jump, they possess a smoother rise than those for Nyaluhanga, and then after the peak decrease less steeply. This smoothing effect is a direct consequence of the river flows passing through the seasonal wetland. During the first year, the peak flow, 128 m^3/s at Nyaluhanga occurs on 14 April 1999, while the peak flow at N'Giriama, 99 m^3/s is smaller and occurs 12 days later on 26 April. During the second year, the peak flow of 57 m^3/s at Nyaluhanga occurs on 14 April 2000, while the much smaller peak flow at N'Giriama of 16 m^3/s occurs 13 days later on 27 April. The area below each flow curve shown represents the total volume of flow, and the reduction in this volume between the stations at the entrance and exit of the Eastern Wetland is due to temporary storage in the wetland and subsequent evaporation. It was noted above that during the 1999 wet season the surface area of the seasonal wetland reached 615 km^2, so a large loss of water can occur since the daily rate of evaporation from a body of water covered by floating vegetation is about 5 mm per day at that time of year.

3.6.3 Western Wetland

Information about the locations of the channels, swamps and wetlands of the Western Wetland has been gradually accumulated over the project duration. The main sources are given in Table 3.10.

Table 3.10 Aerial surveys of the Western Wetland

Date	Survey type	Transport	Personnel	Data stored
14 Oct 1998	General reconnaissance	Plane	T Franks L Mbuya N Mandeville	Map and photos in office files
2 May 1999	Wetland	Plane	A Graham G King N Mandeville	Technical Data Volume: Water Resources, Mar 2001
5–11 May 1999	Livestock	Plane	A Graham Mr Mwaluko	Comments on main features of each 3 x 3 km grid square
9–13 Oct 1999	Livestock	Plane	A Graham	Comments on main features of each 3 x 3 km grid square
20 May 2000	Flooded areas	Plane	N Mandeville R Olivier	Technical Data Volume: Water Resources, Mar 2001
7 Nov 2000	Dry season flows	Plane	L Mbuya K Bashar J Berkoff R Olivier N Mandeville	Office files

Figure 3.18 shows a schematic map of rivers entering the Western Wetland, and the location of intake canals for the main irrigation schemes. To illustrate the smoothing effect of the overall Western Wetland on the flows in the rivers, as they pass from the high catchment down to the lower end of the wetland, a comparison between two rivers is made in Figure 3.19. The Chimala River at Chitekelo is measured high up on the Chimala escarpment where the Chimala-Matamba road crosses this river. This is one of the four major rivers, rising in the high catchment to the south of the Usangu plains, that flow all the year round. The figure shows the variation of the daily flows in cubic metres per second in the river during the period 1 February 1999-31 August 2000. The sharp rises and falls in the flows are typical of such a mountain river, for which the steep gradients give a quick response to rainfall.

The second river illustrated is the Great Ruaha river where it passes Nyaluhanga, at the location of the constriction at the downstream end of the Western Wetland. The variation of flows is shown for the period 1 January 1999-30 November 2000. The main rise of the river flow at Nyaluhanga is much more gradual, though the decrease after the peak is equally steep for both rivers. Between Chitekelo and Nyaluhanga the Chimala River has rushed down a gorge, crossed an alluvial fan, been partly diverted through smallholder irrigation schemes, passed through a wetland, and discharged along a meandering river channel. All these different physical features play a part in smoothing down and delaying the sharp peaks noted in the upper river station at the head of the Western Wetland.

3.6.4 Environmental functions study

A more detailed study, described separately in Supporting Report No 14, was undertaken to enhance the scientific understanding of the environmental functions of the Usangu wetland. This study focuses on gaining systematic scientific knowledge on how the Usangu wetland functions so that when decisions on the future of the wetland are made, they can be based on a scientific understanding, thereby enabling the impacts of those future decisions on the wetland to be estimated at a time when they are made.

The Environmental functions study examined processes and functions of the wetland. The main functions were:

- Hydrological functions
- Hydrochemical functions
- Biological functions of higher plants
- Functions and processes of the microbial and invertebrate communities
- Ecological balance of the wetland.

During the course of this study it became apparent that the environment of the Usangu wetland had changed over the period since the late 1960s, which is the earliest date for which information on the wetland is available. Change has taken place principally in terms of:

- Replacement of wild animals by livestock and pastoralism on the plains
- A decrease in water flows
- An increase in area of swamp
- A reduction in the species richness of the fish community
- A reduction in flooding of the Western Wetland.

These environmental changes are discussed more fully in Section 5.4 of Supporting Report No 14.

3.7 Groundwater

3.7.1 Introduction

Groundwater forms an important component of the hydrological system of the Usangu catchment. A limited study of the groundwater resources of Usangu is being carried out by the Ministry of Water's Regional Hydrogeologist as part of RBMSIIP, including drilling four new groundwater monitoring boreholes. SMUWC has made a brief review of the groundwater system in the basin and has liaised closely on this with the Ministry of Water at national and regional level. The SMUWC Hydrogeologist visited the project area in September 1999 and May 2000, and reviewed available information on geology, geomorphology, groundwater occurrence and a survey of shallow wells and boreholes that had been conducted by RBMSIIP in January 1999. So as not to duplicate efforts, SMUWC's approach has been to develop a conceptual model of the nature and occurrence of recharge and discharge of groundwater in Usangu, and to form an opinion on the contribution provided by groundwater to the water balance and the water resources of the Usangu wetland.

The geology of the area is shown in Figure 3.20. This indicates that the central part of Usangu is contained in a fault-controlled basin which is filled with lake deposits (clays, silts and sands). Surrounding the basin are complexes of both granitic and basic metamorphic rocks. In the south west of the catchment there is a series of basaltic volcanic rocks, the Rungwe volcanics.

3.7.2 Hydrogeological zones

The current understanding of the hydrogeology of the project area is best described by dividing the area into a number of hydrogeological zones, illustrated in Figure 3.21, which can be summarised as follows:

Gondwana & Post-Gondwana (6% of project area)

There is pronounced topographical relief on the Gondwana & post-Gondwana land surfaces, as it is a heavily dissected plateau. Saprolite is thin or non-existent on the valley slopes, but can attain considerable thickness on the plateaux. The baseflow regime of the rivers is a function of the contribution from springs, seeps, bank storage, and artesian discharge. Springs are very common, and constitute the major discharge contribution during the dry season, rendering most water courses perennial. Boreholes are unlikely to be successful in this area, unless they happen to hit some fractures, or are drilled in the patches of alluvium in the river valleys, and groundwater supply will usually come from springs.

African (32% of project area)

The African land surface is quite extensive in the project area, forming the plateau above the Chunya escarpment, and the area around Sao Hill. The infiltration capacity of the soils is good, and due to the relatively flat topography, overland flow is much reduced. Interflow is an important part of the river discharge, and river recession curves should be relatively long. The main rivers are perennial, with dry season run-off consisting of baseflow derived from springs and seeps. Generally, groundwater is struck in the lower part of the saprolite, and the water level rises closer to the surface revealing confined conditions. There is usually a secondary water table in the upper clayey part of the saprolite. This water body is rather stagnant due to the low permeability of the clay, but it provides leakage to the main lower aquifer in the in situ weathered rock. Springs and seeps are again common, and once direct run-off has ceased, shortly after rainfall events, the entire flow of the rivers draining the zone is derived from groundwater.

Field reconnaissance of the Gondwana/Post-Gondwana and African Zones reveals little soil erosion, with gullying only occurring on a very limited scale (and often related to features such as road construction). There are large treeless areas covered in permanent grass, but reports vary as to whether or not these areas were at one time forested, or have always been open grassland. A very characteristic feature of the African Zone, especially above the Chunya escarpment, is the occurrence of dambos. A dambo is a grass-covered almost treeless flat area following the course of a river. In many cases, no well-defined river course can be seen during the dry season. The formation of dambos is not completely understood.

Rungwe Volcanics (3% of project area)

This zone is treated separately because it has significantly different geology from the two zones mentioned so far (although the elevation and relationship to the Usangu Flats are similar). As the name suggests, these rocks were extruded by volcanoes in the Rungwe group. They consist of a mixture of basalts, ash and pumice, and are usually divided into Older and Younger Extrusives. The topography is very irregular, with the volcanic ash easily eroded, forming deeply incised valleys. Studies have shown there to be a considerable amount of groundwater in storage, and nearly all the rivers originate as springs. A large proportion of the water supply for Mbeya comes from such springs. Again, for the rivers in this zone draining to the Usangu basin, the flow is entirely supported by baseflow throughout the dry season. Pumice and ash from the Younger Extrusives is widespread, and in places obscures the Basement Complex and Lake Deposits. This can be seen in the area around Mahango, with fertile volcanic soils and plentiful groundwater supporting good vegetation cover and large trees.

Scarp (6% of project area)

The Scarp Zone refers to the actual scarp faces themselves, mainly along the southern and western sides of the Usangu Flats (the Chimala and Chunya escarpments), and typically some 800 m high. Here, most rainfall runs off directly, because of the steep slopes, and any groundwater will drain rapidly. On steep hillsides, only the lower horizon of the saprolite is preserved, and the hydraulic gradient will be large, with rapid drainage of groundwater. Perennial groundwater will only be found in valley bottoms and along foothills. Characteristic features of the scarp areas are the frequent occurrence of springs, mainly the result of lithological discontinuities (such as the transition from weathered to fresh rock). However, for practical purposes, it is safe to assume that there is no general groundwater flow down the scarp faces. The Scarp Zone therefore forms a useful control for the rivers which drain the catchments above the scarp. The points at which the rivers cross the Scarp Zone can be regarded as representing the entire flow generated by their catchments to that point. Where faults have caused the escarpment, mineralised groundwater of deep-seated origin is likely to occur, which is not normally found along erosion scarps. This groundwater is typically high in minerals such as iron, manganese, and fluoride.

Post-African (24% of project area)

The Post-African Zone is below the main escarpments surrounding the Usangu Flats, and in some classifications would include the alluvial fans (which are treated here separately). The alluvial plains and fans, of Neogene age, are common because of the faulting and resulting change of base level of erosion. The land surface in the Post-African Zone is rather unstable, and erosion is still taking place. Bedrock is frequently outcropping, showing the youthfulness of the land surface. The clay minerals are often washed out of the topsoil leaving a sandy surface behind. This should allow good infiltration, but there is a high incidence of surface run-off when the critical slope angle is exceeded. This is demonstrated by the fact that most tributaries of the main rivers across the Post-African land surface do not carry water during the dry season. Wells drilled in low-lying areas usually strike water in the upper part of the saprolite, with confined conditions. Rest water levels are comparatively shallow, with 50% of wells having a rest water level of less than 5 m below ground level. The yields of such wells are unpredictable, but generally will only support handpump abstraction at rates of less than 1 l/s, with a danger of running dry at the end of the dry season. Springs and seeps are far less common, and are usually associated with major fault lines.

Alluvial Fans (19% of project area)

This zone includes areas sometimes referred to as the debris slope or the scarp pediment, and consists of colluvial and alluvial deposits, starting at the foot of the steep escarpments on the southern and western sides of the Usangu Flats, and spreading out towards the Usangu Flats in large fans. The width of the zone varies from a few hundred metres to several kilometres (the widest parts being the Kimbi and Kioga fans). This is a very important zone hydrogeologically, as the deposits are generally very permeable, and have good porosity. Groundwater flow is intergranular and generally unconfined. The upper parts of the fans offer plenty of opportunity for surface water to infiltrate, both from rainfall and from the river channels.

Deposits are mostly fine and coarse sands and gravel, although there are also silts and clays. Infiltration capacity on the sands is very high, and groundwater levels respond rapidly to rainfall. During the dry season, only main rivers still carry water, and the base flow regime is supported by effluent groundwater discharge. Groundwater levels coincide with the water level of the river at the river bank. Alluvial sands have a large storage capacity, and the groundwater body is often recharged by influent tributaries during a period after the rainy season. Groundwater levels are usually very shallow, particularly in the toe areas of the fans, with the groundwater feeding springs which discharge along these toe areas. The alluvial fans offer good prospects for irrigation, although there are places where the alluvial fan formations are run through with sandy ridges that are too permeable for flood irrigation. The main irrigation schemes are situated on the fans (as indeed are many abstraction wells).

The Kimbi and Kioga fans are large alluvial fans formed over a long period of time by the Kimbi and Kioga rivers and their distributaries. There is usually a gradation in sediment size, with coarser particles being deposited first, closer to the scarp, becoming finer out towards the plains. Several stages of fan can be distinguished on satellite imagery, and it is likely that these fans (in common with the smaller fans) formed at roughly the same time as the upper layers of the lake deposits. This results in a complex configuration of overlapping layers of alluvial fan and lake bed deposits (often discontinuous both vertically and horizontally), cut through by meandering and frequently changing channels.

Lake Deposits (10% of project area)

This zone covers the whole of the Usangu Flats apart from the alluvial fan areas mentioned above. The sediments are very variable, and can completely change character within relatively short distances. They consist of soft sandstones, siltstones, and tuffaceous sediments. Outcrops of soft white calcareous diatomite have been recorded towards the centre of the flats. Groundwater is usually confined or semi-confined by clay layers, and the soils are generally characterised by imperfect or poor drainage. Across the western part of the flats, the deposits include volcanic ash layers of various thicknesses interbedded with the alluvial material mentioned above. Lithological logs from five boreholes drilled in this zone in 1981 around Luhanga and Ukwaheri reveal a highly layered structure with fine-grained alluvial sand interbedded with silt and clay. There are various opinions on how deep these lake bed sediments are, but airborne geophysics suggests they could be more than 200 m thick in the western part. There is evidence of a north-west to south-east trending flexure axis across the Usangu Flats, coinciding with the constriction between the Western and Eastern Wetlands at Nyaluhanga.

Buried channel deposits (the remains of old river channels) are known to occur, and these can form locally significant aquifers. Surface pools are supported by local groundwater in some of these old river channels, and can survive for much longer into the dry season than pools purely supplied by surface run-off. The pools form important temporary water supplies for livestock. The nature of the lake deposits is such that it is highly likely that groundwater moves out under the Usangu Flats from the alluvial fans, passing through the many sandy layers and buried channels. It is also likely that this groundwater eventually reaches the permanent swamp. Although this groundwater contribution is insufficient to maintain dry season flow in the Great Ruaha downstream of the swamp exit, it may very well be maintaining the swamp level higher than it otherwise would be if surface water were the only input.

3.7.3 Summary of hydrogeological conceptual model

Bearing in mind the description of the hydrogeology above, the overall conceptual model can be summarised as follows:

- There is extensive groundwater recharge over all the upland areas above the scarp. The groundwater is released through springs and seeps into the perennial rivers which drain these areas. The vast majority of the dry season flows in these rivers is provided by baseflow from groundwater.
- As the rivers reach the bottom of the scarp, they flow across the permeable sediments of the alluvial fans and parts of the lake deposits, where there is plenty of opportunity for surface water to infiltrate in the wet season. Some of this infiltration reappears as springs at the toes of the fans, and also as baseflow in the rivers.
- The alluvial fans merge into the lake deposits in a complex system of overlapping layers of permeable sands and gravels, and much less permeable silts and clays. Some shallow wells exploit perched water tables close to the surface, while deep boreholes can penetrate sand lenses with groundwater under artesian pressure.
- Groundwater moves out under the Usangu Flats through the many sandy layers and buried channels. The destination of this groundwater is most likely to be the permanent swamp. Groundwater could enter the swamp through a number of mechanisms, such as at fairly shallow levels through sandy deposits, or slow seepage vertically upwards from deeper semi-confined layers. There is definitely a groundwater component in the water balance of the permanent swamp, but it is not yet possible to quantify it.

- The process of seasonal flooding of the plains could very well be assisted by groundwater, rather than relying entirely on surface flow down the river channels. That is, in certain areas there may be a shallow water table which rises to ground level during the rains.
- There is no evidence of a deep exit for groundwater out of the basin, and this is supported by the presence of hot springs and saline groundwater, such as that found in certain boreholes near the escarpment at Madibira.

The important elements of this conceptual model are illustrated in Figure 3.22, which shows a schematic cross-section through a sequence of upland zone, scarp, alluvial fans, lake deposits, and permanent swamp.

3.7.4 Wells and boreholes

Information on wells and boreholes in the project area has been collected from a variety of sources, such as a field survey conducted in January 1999 by a Government Hydrogeologist, RBMSIIP reports, the Water Master Plan which covers the area, and test pumping reports. The locations of identified wells and boreholes are shown in Figure 3.23, and the collected information is presented in Supporting Report No. 7. Shallow boreholes are normally drilled using an auger and are usually not more than 20 m in depth. Occasionally, shallow wells may be dug by hand, but there is no tradition of constructing hand dug wells in Usangu. Some deep boreholes have also been drilled, usually by rotary drilling rig. All types of well and borehole are normally equipped with a hand-pump. The deep boreholes that have been drilled on rice farms are occasionally equipped with motorised pumps. There is very little information on aquifer properties, as most test pumping was carried out purely to establish that the well or borehole is capable of producing a sufficient yield to support a hand-pump. Groundwater quality data have also been collected and Section 3.7.2 presents a summarising assessment of groundwater quality in the area.

3.8 Water quality and contamination/pollution impact

3.8.1 Data collection

One of the objectives of the SMUWC hydrology programme is to develop an understanding of the water quality functions of the Usangu wetland, and to develop an assessment of the current status and risk of pollution. This section presents a summary of the work that has been carried out on water quality; a full report is presented in Supporting Report No. 13.

There was very little original water quality data and information on contamination/pollution available prior to the commencement of the project. The project purchased a substantial amount of field testing equipment early in 1999 to enable simple indicator parameters like EC, pH, DO, PO_4, NO_3-N, CO_2, alkalinity and temperature to be measured in the field. Samples have also been analysed in the Ministry of Water Zonal Laboratory in Mbeya for settleable matter, turbidity, colour, hardness, calcium, magnesium, ammonia, chloride, fluoride, manganese and total iron. Over the project, some nine sampling rounds, each of around 20 sites, have been undertaken at approximately bi-monthly intervals by Ministry of Water technicians. A water quality database has been initiated which currently contains over 4000 individual results. In nearly all cases, sampling has coincided with measurements of flow or water level to enable seasonal effects to be assessed. Sample locations enable an overall picture of variation in water quality over the project area to be obtained (Figure 3.24).

The sampling points are located on:

- Headwater rivers

- Irrigated rice farms
- Usangu swamp
- Groundwater sources.

3.8.2 Interpretation of water quality results

Headwaters river water quality

All the waters in the project area have a low electrical conductivity (EC <150 µS/cm). This is indicative of a low concentration of all dissolved salts in the water which makes the water suitable for any use. The generally low EC of the headwater rivers is a consequence of both the purity of the rainfall (EC <15 µS/cm) and the slow weathering rate of the mainly igneous and metamorphic rocks.

The only parameter which varies significantly is the bicarbonate ion, with small supporting variations in calcium, magnesium and sodium ions. This is a direct indication of the degree of weathering and/or length of contact time. The close relationship of EC to alkalinity, indicating the dominance of bicarbonate ion, is clearly shown in Figure 3.25 for the local groundwater, indicating the close similarity between many of the groundwaters and surface waters in this area, as most originate from similar rock types.

The essential nutrient parameters, nitrogen (as nitrate) and phosphorous (as phosphate), remain consistently low throughout the year at around the 0.05 – 0.10 mg/l detection limits. Other nutrients like sulphur as sulphate, boron and copper are also very low in all river waters.

Water quality changes in the irrigated rice farms

There are four major irrigation schemes diverting water from the Chimala, Great Ruaha, Mbarali and Ndembera rivers. Although crops (mainly rice) are grown largely during the wet season, some growth occurs throughout the year. The main intake gates are generally left open throughout the year, causing most of the dry season river flows to pass through the irrigation canals, where much of the water is lost through evaporation. Only in some instances, such as in the Madibira scheme on the Ndembera River, have significant return flows to rivers downstream been observed.

The analytical data (available in Supporting Report No. 13) suggest the following trends, which are common to all four schemes:

- An increase in EC and bicarbonate of 50-150% (relative to a low starting figure).
- An increase in pH of 0.1-0.3 units.
- An increase in Temperature (T) of 3-5^{o}C.
- An increase in Iron (Fe) of 0.1-0.4 mg/l (some will be as suspended micro particulates).
- A decrease in Dissolved Oxygen (DO) of 1-3 mg/l.
- A slight seasonal increase in Nitrate (NO_3-N) of 0.1-0.2 mg/l.
- An increase in turbidity by a factor of 5-10 times.
- An increase in dissolved organic carbon of 100-150%.

These variations are consistent with the flow environments found within the farms. They reflect the influence of evaporation from shallow, sluggish canals and drains which make up the irrigation systems, and the influence of the reduced oxygen (low redox) environments found within rice paddies. The latter is caused by soil/water organic activity and mineralisation of both C and N- species.

Water quality changes in the Usangu wetland

Analytical data from several stations in the Eastern Wetland suggest that it has a similar effect but of slightly lower magnitude to that of the irrigated rice farms, ie

- An increase in EC of 50-100%.
- An increase in temperature of 1-2^{o}C.
- A decrease in DO of 1-2 mg/l.
- An increase in Fe of 0.2 mg/l.

One very important difference is the big decrease in turbidity values caused by the wetland, with values of several hundred JTU upstream of the wetland contrasting with values below the detection limit (5 JTU) in the *ihefu.* This is exactly the opposite effect to that seen in the rice farms where the turbidity is increased by a factor of 5-10 times. The *ihefu* therefore is acting as a settling basin where the suspended sediments decrease by a factor of around 100.

A further important factor is that the water column in the *ihefu* becomes highly stratified, with the surface water layers (a few cm thick) being warmer (+3-5^{o}C), supersaturated with oxygen (>120%) and alkaline (pH some 1-2 pH units above the rest of the water column). Conversely, the water at depth is cooler, acidic (pH <7) and completely devoid of dissolved oxygen.

The overall effect of the *ihefu* on the water quality is to reduce its turbidity, reduce its nutrient and dissolved oxygen content and pH, and increase its EC, DOC (dissolved organic carbon) and bicarbonate content. This represents a change from an inorganically dominant oxygen rich input, to an organically modified oxygen depleted output.

A more detailed discussion of the hydrochemical functioning of the *ihefu* is given in Supporting Reports No. 13 and 14.

Groundwater quality

There is only a limited amount of groundwater quality data available for the project area, and that collected information is presented in Supporting Report No. 12. The main body of groundwater quality data for Usangu is provided by samples taken and analysed during the survey of wells and boreholes carried out in January 1999. The following comments can be made about these data:

- Turbidity and colour results are very high in many of the boreholes. Turbidity results greater than 5-10 NTU are unusual for groundwater, and there are some 10 boreholes with turbidity >100 NTU. This suggests problems with sampling, pumping, borehole construction, or contamination (or a combination of any or all of these).
- There are very low levels of the nutrient species NH_3, NO_2, and NO_3 throughout, which signifies an absence of contamination with fertilisers, sewage, decaying matter, etc. There are no analyses for phosphate, but in the light of the near-total absence of N-species, there would probably be little or no phosphate (<0.1 mg/l PO_4).
- The near absence of sulphate throughout (<5 mg/l SO_4 detection limit) has implications for soil fertility, as sulphur is an essential element for plant growth. When deficient in soils, it is usually because of leaching, adsorption onto clay minerals, or crop removal, although in this area the source availability is particularly low.
- There are low levels of Fe and Mn throughout, and most probably all other trace metals. This reflects the alkaline, oxidising environment of weathering and infiltration which prevents mobilisation of these metals into groundwater, even though they are definitely present in the soil and rocks.

- The analyses show that virtually all the waters are of a low to medium mineralised sodium bicarbonate type.
- The Ca and Mg hardness values are generally rather low, only reaching more 'normal UK' levels of 20-40 mg/l in a few boreholes (around Kilambo, Ijumbi, Madibira and Ikoga). Even with the higher Ca waters, the Na^+ ion still dominates in these $NaHCO_3$ type waters. This lack of metal ions is due to the fundamental geological nature of these very old, hard, metamorphic, granitoid rocks where, apart from SiO_2, only Na^+ and K^+ ions from the feldspar minerals are available to go slowly into solution. The formation of stable clay minerals from the micas, etc, mops up excess SiO_2, all the Al, and much of the K^+ and other ions (Ca^{2+} and Mg^{2+}), leaving very little left over to dissolve in the groundwater to neutralise the carbonic acid from the soils.
- A graph of conductivity against alkalinity is given in Figure 3.25. The fact that the data points fall on a well-defined straight line reveals that virtually all the dissolved minerals in the groundwater are those which cause alkalinity, such as bicarbonates.

Overall conclusions of the water quality assessment

Water quality results throughout the Usangu catchment area appear to be characterised by a lack of most ordinary constituents apart from sodium bicarbonate alkalinity and calcium hardness. This is due both to the very low EC of the rain water (EC <15 µS/cm) and the relative insolubility of the acid igneous and metamorphic rocks which constitute most of the catchment area geology.

There are generally no major constituents, other than bicarbonate, which exceed 10 mg/l, and minor constituents are present at levels around the normal detection limits of around 0.1-0.2 mg/l. Trace metals are generally undetectable at <0.01 mg/l

The Usangu wetland, like all wetlands, exists in a very delicate ecological and hydrobiological balance between energy and nutrient input and biological growth output. The water-plant-sediment interface is important in determining the uptake and release of nutrients.

The very low levels of nutrients (N and P) are barely detectable in most inflowing river waters at around the 0.05-0.1 mg/l detection levels. There are indications of slight seasonal increases in these levels as water passes through both the rice farms and the swamp, but again the concentrations remain always very close to the analytical detection limits.

3.8.3 Assessment of contamination potential

In a predominantly natural, rural area like the Usangu wetland and its catchment, overall contamination potential is limited to diffuse sources of human and animal excreta, or special incidents like localised oil/fuel spillages at the few garages and on main roads in the area, or the use of agrochemicals. There is no evidence from the analytical results that surface waters have been affected in any way. The large volumes of river waters would require major and sustained inputs of contaminant to register any significantly raised levels in any spot sampling check.

The swamp is likely to be an area where contaminants could settle out, precipitate and/or collect and concentrate. Some detailed analyses of the sediments for levels of nutrients and potential contaminants have been conducted as a baseline check of the present status of the swamp (available in Supporting Report No. 14). The results show very low levels of all the main nutrients C, N, P and S, with nitrogen deficiency being very common throughout. All trace element results also show low to very low levels throughout all samples tested, indicating that whilst contamination, or an excess of natural levels, is not a problem, the lack of nutrients and trace elements is limiting biological production in this area.

The results of a questionnaire to farmers on their use of agrochemicals indicated only a minor and sub-optimal use of fertilisers, such as urea and ammonium sulphate, and the occasional use of herbicides such as 2 4-D-amine, Roundup and Ronstar. On this evidence, it was decided not to submit any samples for Gas Chromatography-Mass Spectromtery (GCMS) testing for herbicides or pesticides.

The following section deals with investigations of irrigation water use.

3.9 Irrigation water use

3.9.1 Introduction

The irrigation component of the SMUWC water programme has been concerned with:

1. Gaining an understanding of irrigation processes and community management of irrigation. This is dealt with in Supporting Report No. 9.
2. Gaining an understanding of the impact of irrigation on water availability downstream.

Three main analyses have been undertaken to date, and are described below. The first was an assessment of the irrigated area within the Usangu plains and its historical development (Section 2.2). The second was an assessment of the impact of irrigation abstractions on the hydrology of Usangu. The third was the examination of irrigation efficiency. Further details may be found in Supporting Report No. 8.

3.9.2 Historical development of irrigation in Usangu

The growth in the irrigated area of rice has been outlined in Section 2.2. By careful examination of the history of irrigation development in Usangu, it was possible to propose five time periods, separated by notable events such as the huge flood in 1968 or the changes in marketing conditions for rice introduced in 1986 (Table 3.11).

Table 3.11 Time periods identified in the analysis of Usangu hydrology

Time period no.	Event	Date	Description of events
1		1935-1967	Initial condition, pre El Niño flood event in 1968
	A	1967/68	Omitted as an El Niño year, which caused channel changes in the Ruaha
2		1969 to 1973	Before Mbarali rice farm constructed, post channel changes.
	B	1972	Mbarali constructed, but break is set at 1973
3		1974 to 1985	Post Mbarali, pre expansion in rice
	C	1986 onwards	General expansion in rice and change in market conditions
4		1986 to 1991	Post expansion in rice, pre-construction of Kapunga scheme
	D	1992	Kapunga is constructed, weirs across Chimala, and Chimala channel is diverted.
5		1992 to 1999	Post Kapunga and Chimala river changes, continued expansion of rice, construction of nine other upgraded intakes, introduction of widespread dry season irrigation, Madibira constructed in 1998, change from bucket irrigation to furrow irrigation in some Mkoji rivers

The approximate area under irrigated rice at the end of each time period is given in Table 3.12. The individual abstractions of irrigation water from all the sub-catchments were summed to give a total abstraction of 45 m^3/s (Section 2.2). This total was adjusted pro rata using the cumulative area under irrigation to provide an estimate of the cumulative abstraction at the end of each previous period.

Table 3.12 Rate of growth of irrigated rice area and abstraction within selected periods

Time period	Total rice area at end of period (ha)	Estimated total abstraction at end of period (m^3/s)
1935-1967	8 500	11
1968-1973	15 000	17
1974-1985	36 000	29
1986-1991	31 000	34
1992-1999	40 400	45

3.9.3 Impact of irrigation abstractions on the hydrology of Usangu

Several techniques were used to assess the impact of irrigation abstractions on stream flows downstream. Some findings are given below; all relate to the actual (gross) water use. Further details are given in Supporting Report No. 8.

The impact of irrigation abstractions is defined by expressing the gross volume of water consumed by irrigation as a percentage of the inflows to the Usangu Plains. The gross volume consists of the amount of water abstracted by the irrigation schemes less any water draining from the schemes and returning to the rivers downstream. On an annual basis, the gross irrigation impact is judged to lie in the range 30% to 50% depending on the amount of water available to the system.

The wet season is defined as from the 3rd decad in November to the end of April (162 days). The gross irrigation impact during the wet season is 25% in a wet year to 40% in a dry year. There is more than sufficient water in the rivers in the middle of this season to supply the total of 45 m^3/s currently abstracted for irrigation.

The dry season is from 1st May to the end of the 2nd decad in November (203 days). The observed dry season impact averages over 85% for most individual sub-catchments. For some rivers in the Mkoji sub-catchment the dry season impact in 1999 was observed to be 100%. The theoretical gross irrigation model estimates the impact as lying in the range 56% in a wet year to 64% in a dry year.

An important finding of the work on irrigation concerns the increase in concrete/upgraded diversion weirs and intake structures. It is believed that improved weirs allow water levels to be raised so that command of land becomes possible during low flow periods. This has enabled dry season cropping, and has brought forward preparation of fields for rice nurseries and transplanting as farmers seek to take advantage of higher prices of early-planted rice. But the practice is likely to increase the total abstraction of stream flow at the end of the dry season, so possibly affecting downstream flows. The recent increase is spectacular. Before 1990 only 13% of the total irrigated area was supplied by concrete intakes; by 2000 this percentage has risen to 45%.

3.9.4 Efficiency of irrigation

The efficiency of irrigation has been studied in Usangu. There are three main conclusions from this work:

The first is that annualised efficiency of irrigation in Usangu appears to be between 60% and 65%, which includes excessive water used during the dry season. Without the excessive water use in the dry season, irrigation has the potential to be 70 to 75% efficient.

The second finding is that efficiency changes during the year. Figure 3.26 shows this difference as a barchart of total volume of water required to meet net and gross needs. Wet season efficiency is about 75%, but dry season efficiency is approximately 15-20%. In the dry season, more water is abstracted than is needed to meet net crop needs. This water is used for domestic and other purposes (Appendix A).

The third conclusion is that the water supply duty of around 0.9 to 1.2 l/s/ha is half of the 2.0 l/s/ha stated to be the water duty for rice irrigation in the Usangu area. It is not clear what level of efficiency is included in the figure of 2.0 l/sec/ha, but it is thought by irrigation officers that the efficiency of rice irrigation in the Usangu area is approximately less than 30% (and that "the improvement programmes will raise this to 40%"). When 1.0 l/s/ha (derived from the ratio of supply to area) is compared to 2.0 l/s/ha, the evidence points to higher efficiencies than currently perceived.

In summary, gains in efficiency can most cost-effectively take place through control of water abstraction during the dry season when net rice demand is small. In other words, partially shutting intake gates during the dry season will raise efficiency, allow water to pass downstream and yet not overly reduce the productivity of rice.

3.10 Summary

This section has described in some detail the approach taken by SMUWC to the collection of data for the investigation of the causes of the cessation of the outflow from the Usangu wetland. This data has included rainfall, evaporation, river flows, the seasonal behaviour of the wetland, the use of water for irrigation and water quality data. At the start of the project very little was known about the hydrological system in Usangu. The information collation and field work programme have enabled a clearer picture of the system to develop. This information was used to develop a hydrological model of the Usangu basin. The modelling of the Usangu basin is described in the next section.

Figure 3.1 Distribution of mean annual rainfall (source: CCKK, 1982)

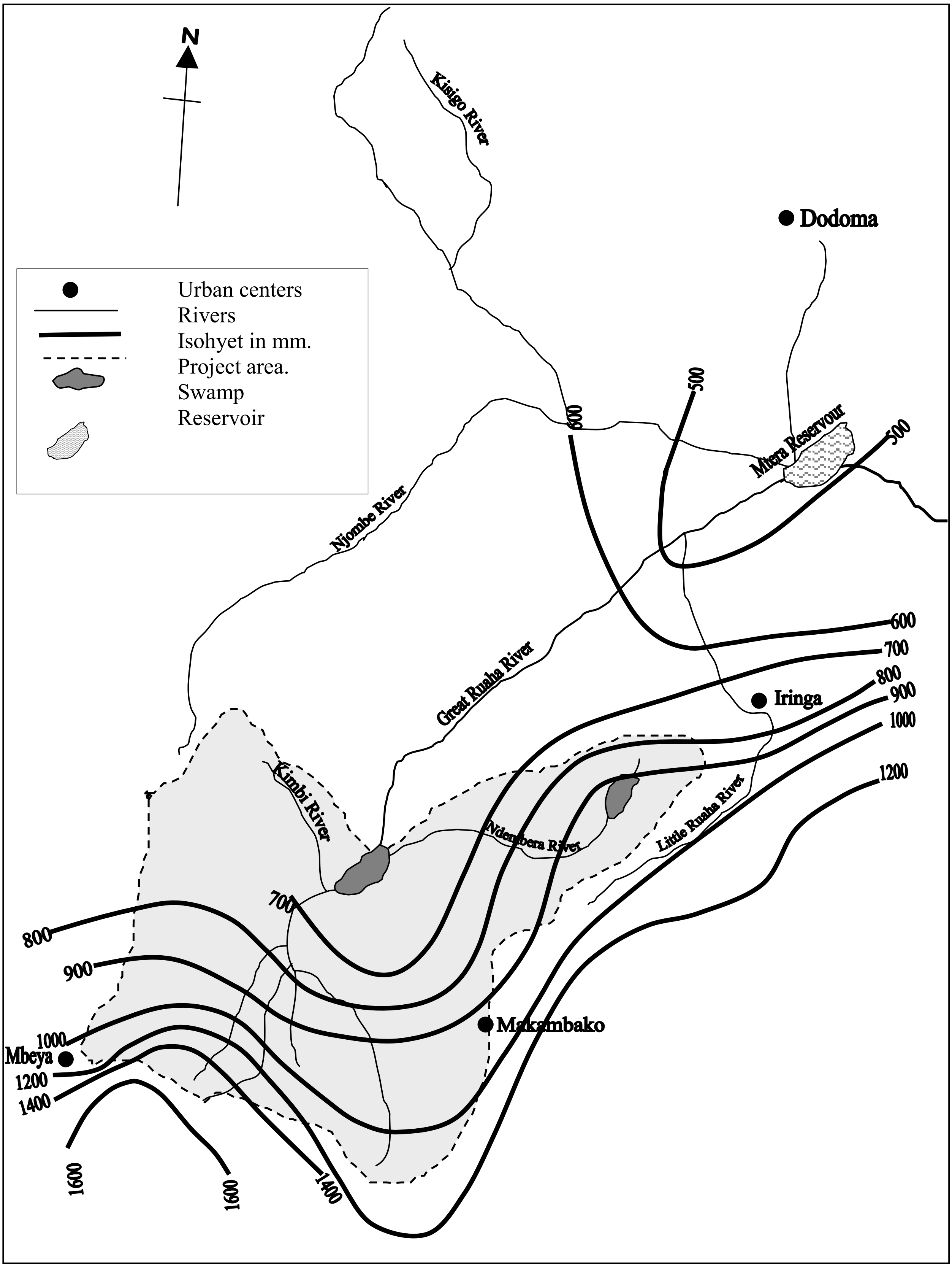


Figure 3.2 Official hydrometric network used in the analysis of historical data

GIS Map

Figure 3.3 Spatial variation of depth of rainfall (mm) between the onset of rains and the latest date of planting rice (20 February)

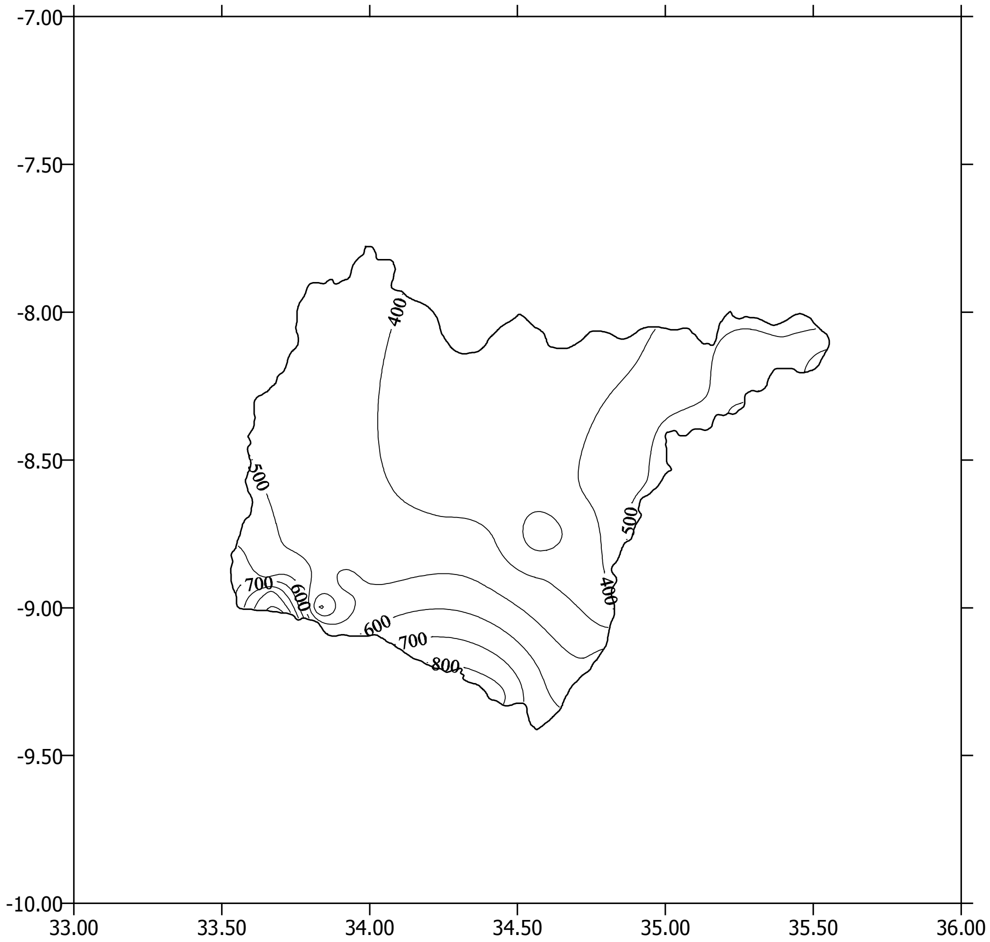


Figure 3.4 Total rainfall (mm) for the periods: 1 December 1998 to 30 April 1999; and 1 December 1999 to 30 April 2000

GIS MAP

Figure 3.5 Wind speed at Iramba village, Makambako

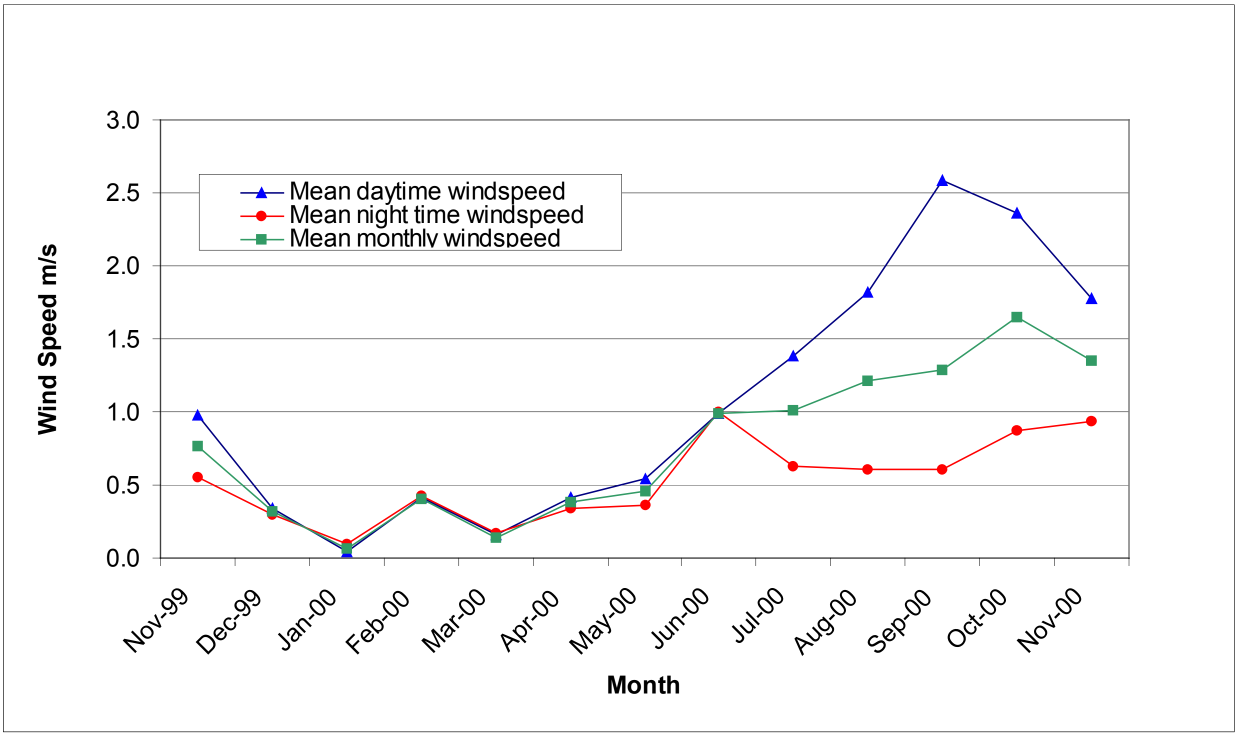


Figure 3.6 Variation of decad mean flow and flow exceeded four years out of five at the Mbarali river at Igawa

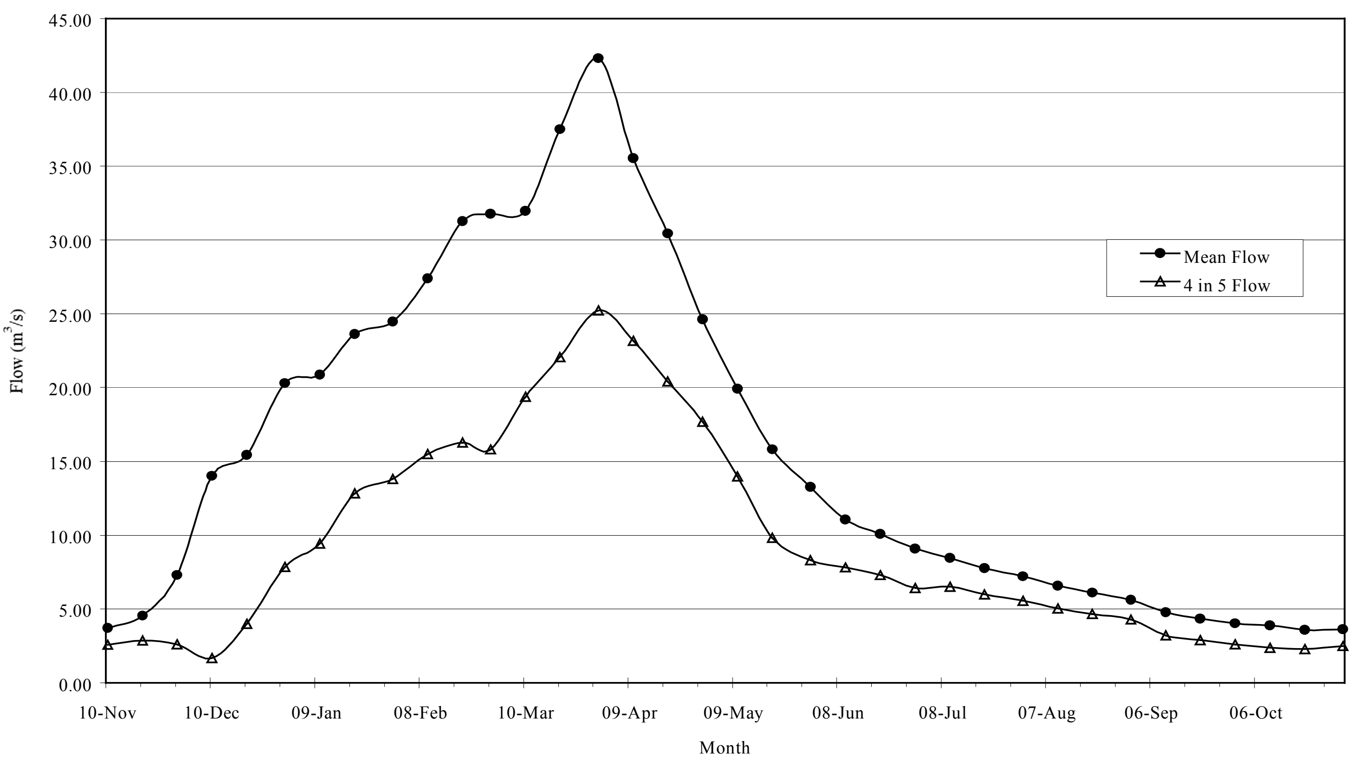


Figure 3.7 SMUWC hydrometric network

GIS Map

Figure 3.8 Comparison of flows between Chimala River at Chitekelo and Ndembera River at Madibira

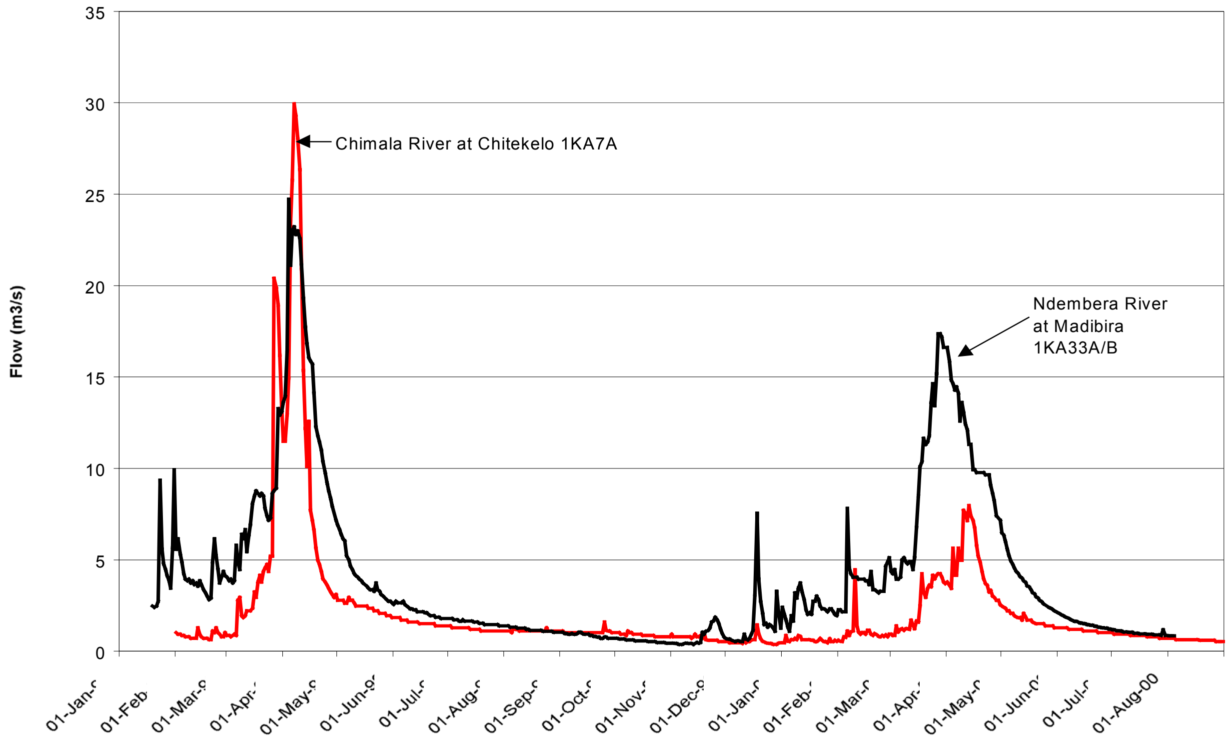


Figure 3.9 Comparison of flows between Great Ruaha river at N'Giriama and Great Ruaha river at Msembe Ferry

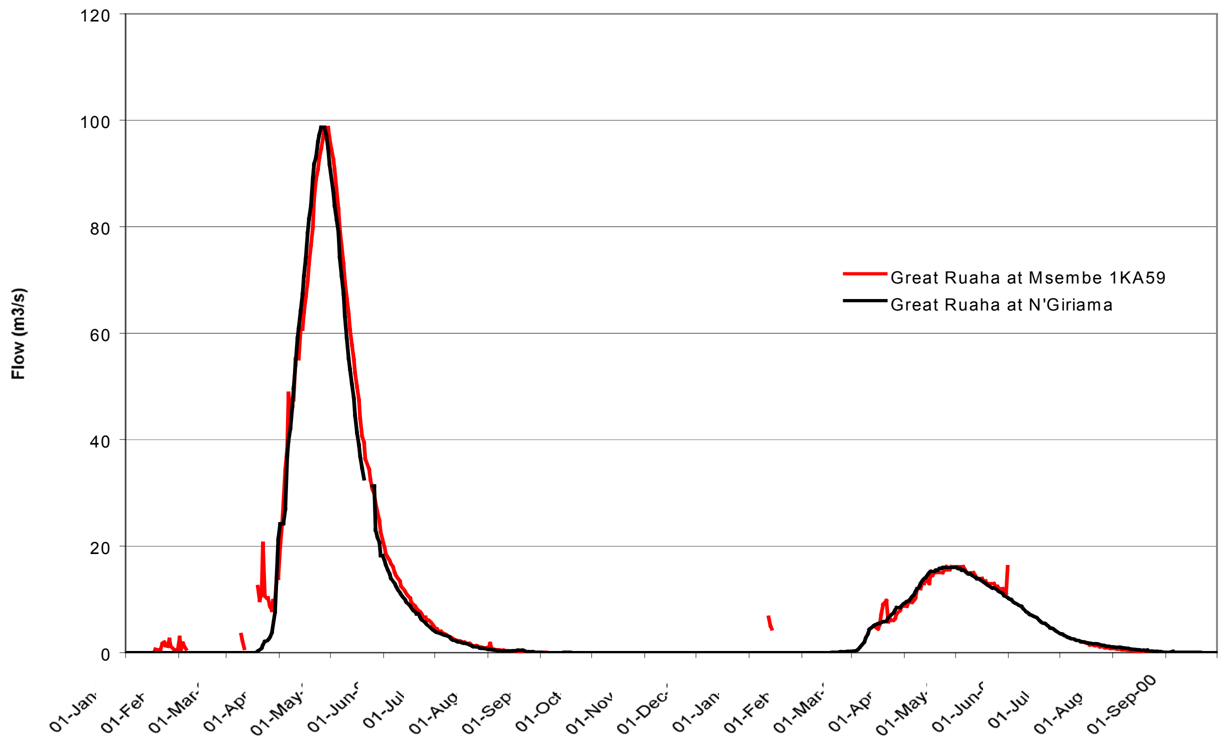


Figure 3.10 Open water lagoons in the Eastern Wetland, as surveyed by airboat 13-16 June 1999

No digital file

Figure 3.11 Open water lagoons in the Eastern Wetland, from 1:50 000 topographic maps based on aerial surveys May-July 1977

No digital file

Figure 3.12 Eastern Wetland: seasonal changes in extent of flooded area 1998-2000

GIS Map

Figure 3.13 Profile of the Eastern Wetland from Nyaluhanga downstream to N'Giriama

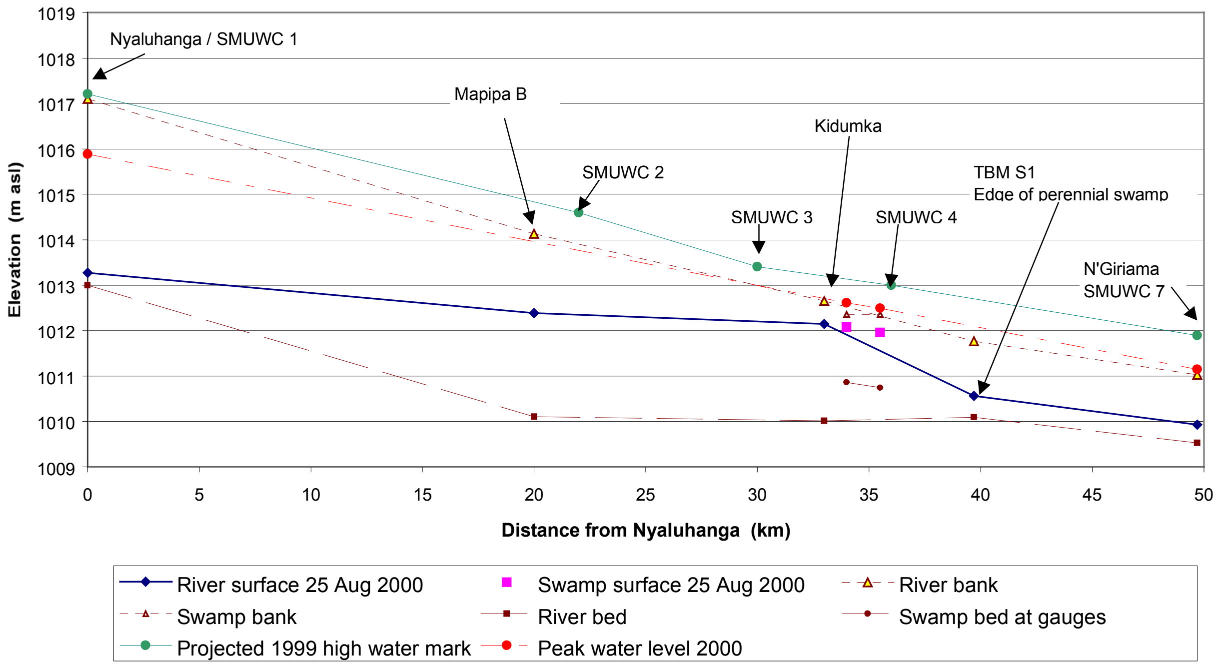


Figure 3.14 Comparison of water levels in Ruaha and Nyangokolo swamps

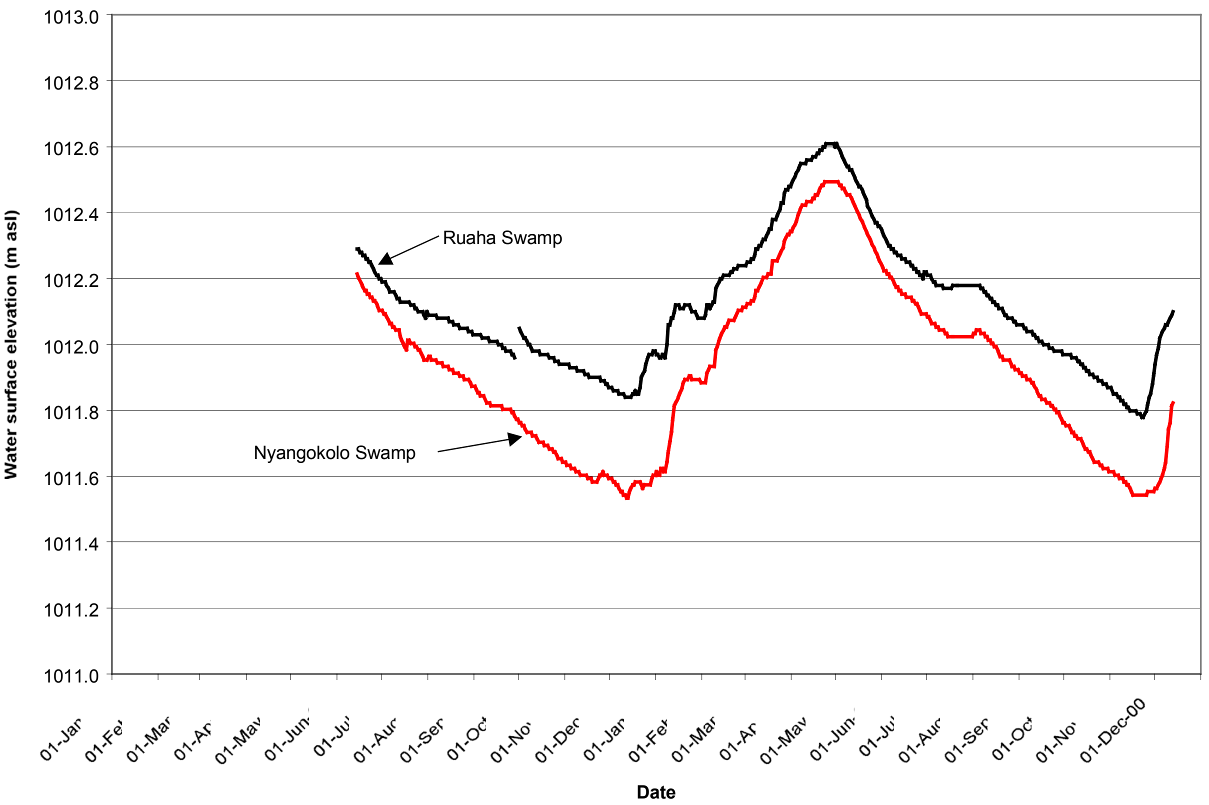


Figure 3.15 Rating curve for Great Ruaha river at N'Giriama, valid for period 16 March – 19 September 1999

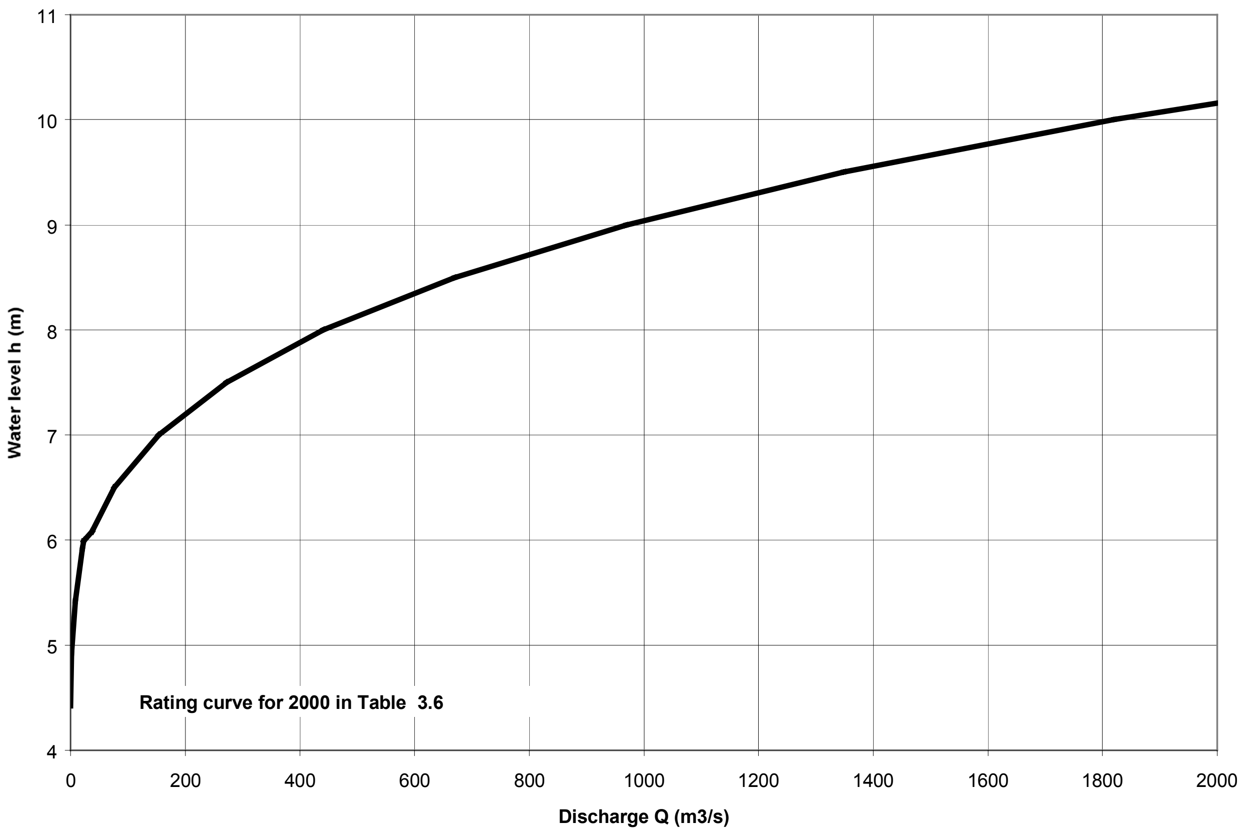
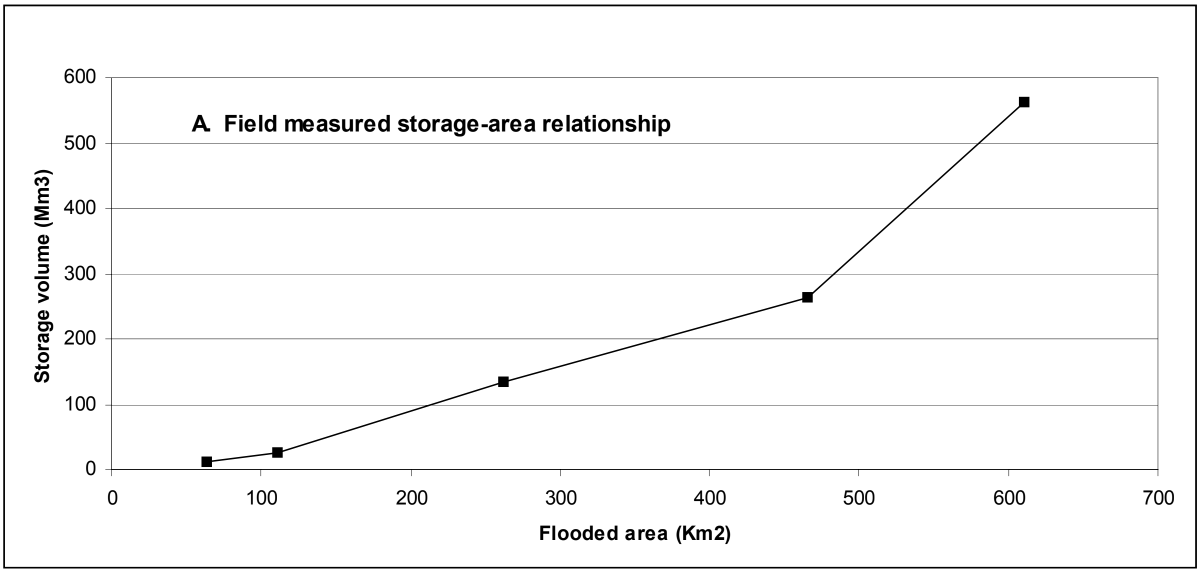


Figure 3.16 Swamp water level-flooded area-storage volume curves



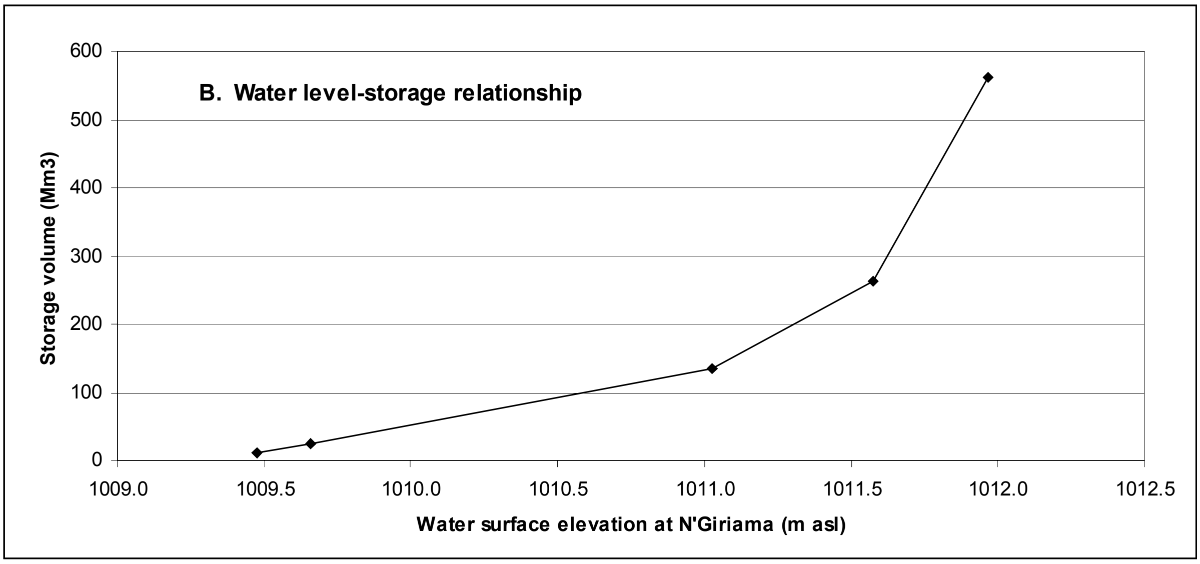


Figure 3.17 Comparison of flows between Great Ruaha river at Nyaluhanga and Great Ruaha river at N'Giriama

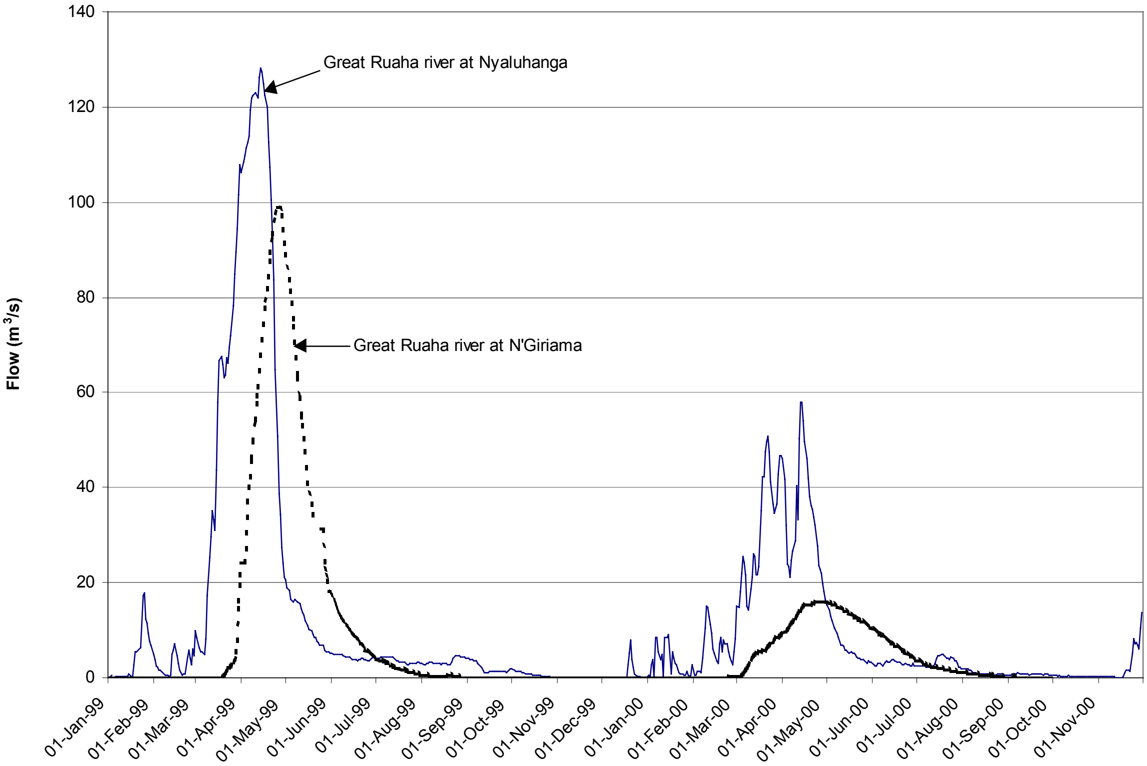


Figure 3.18 Schematic map of river flows into the Western Wetland, 24 November-6 December 1999

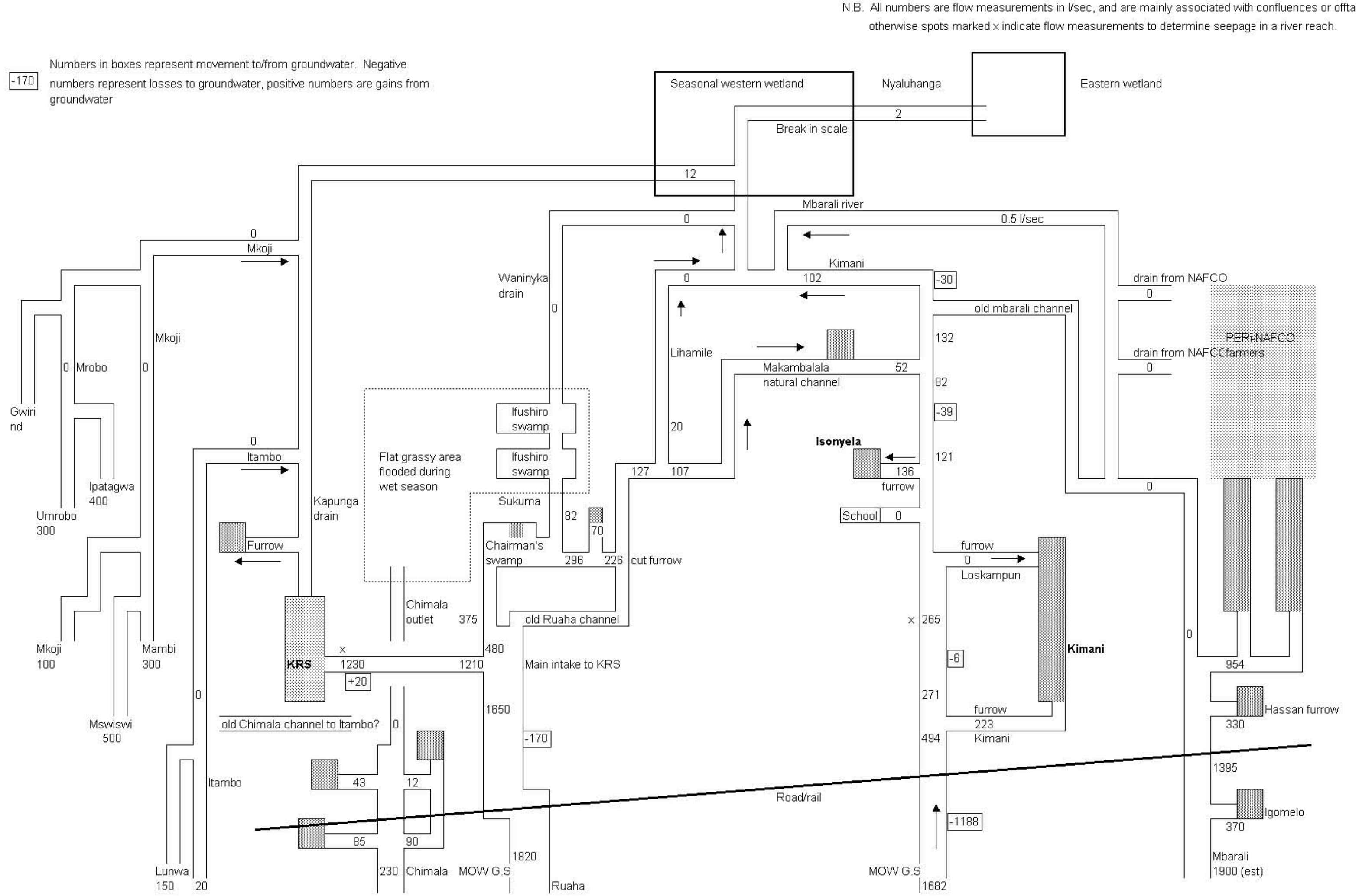


Figure 3.19 Comparison of flows between Chimala River at Chitekelo and Great Ruaha river at Nyaluhanga

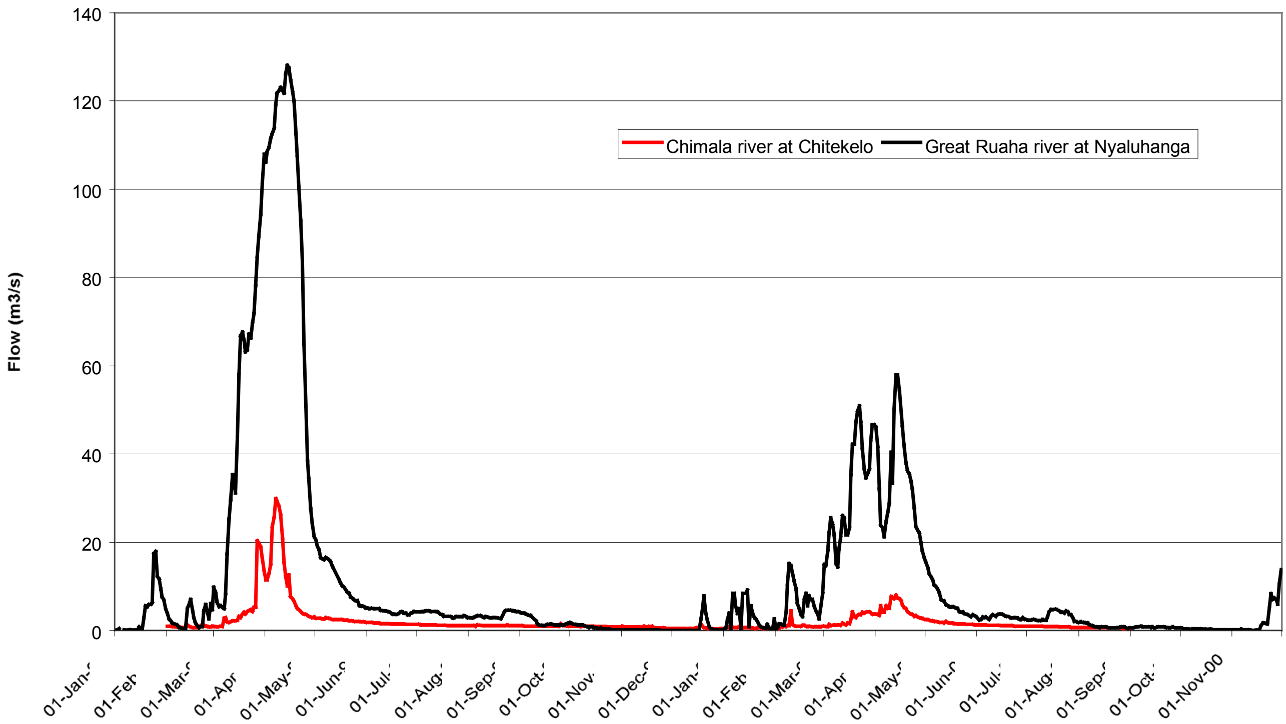


Figure 3.20 Geology

GIS file

Figure 3.21 Revised hydrogeological zones

GIS file

Figure 3.22 Schematic diagram of hydrogeological conceptual model

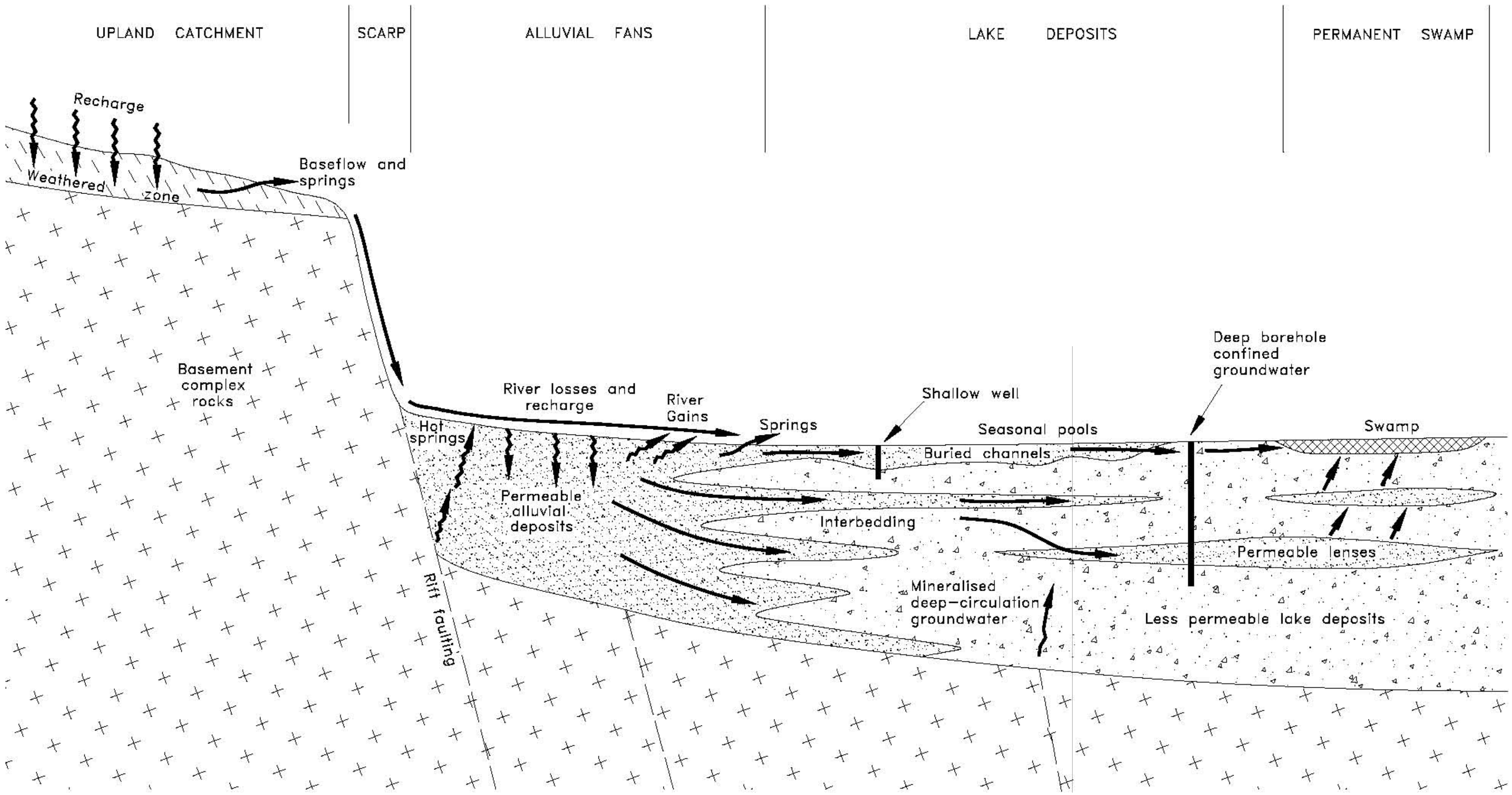


Figure 3.23 Locations of wells and boreholes

GIS MAP

Figure 3.24 SMUWC surface water quality network

GIS MAP

Figure 3.25 Relationship between alkalinity and electrical conductivity for groundwaters in the Usangu Basin

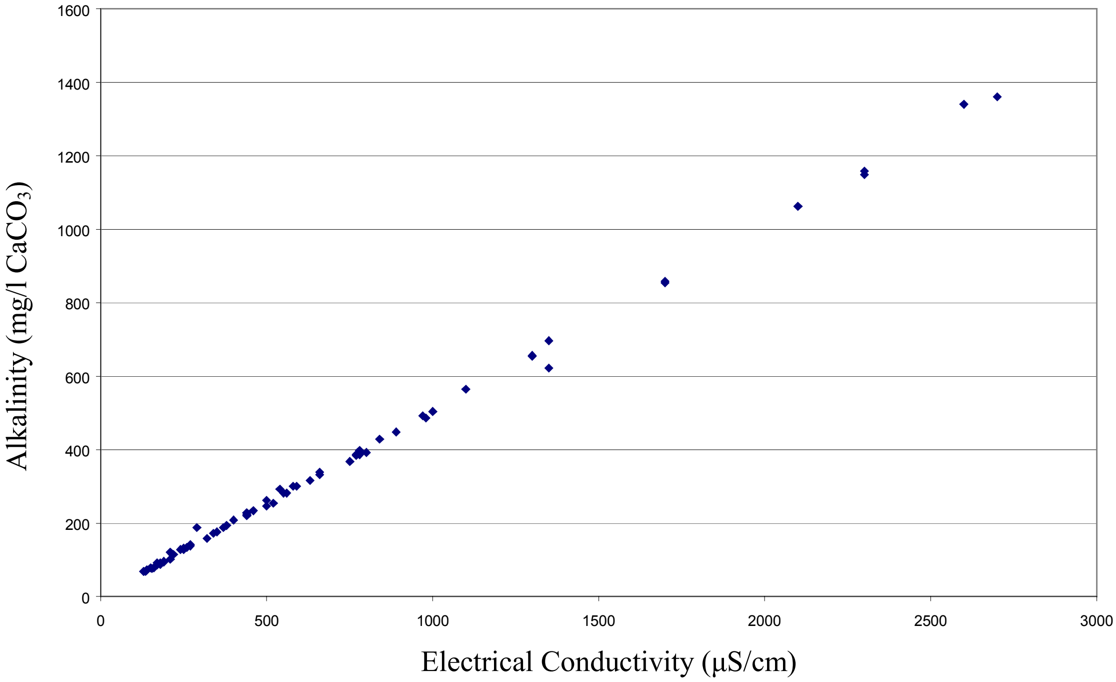
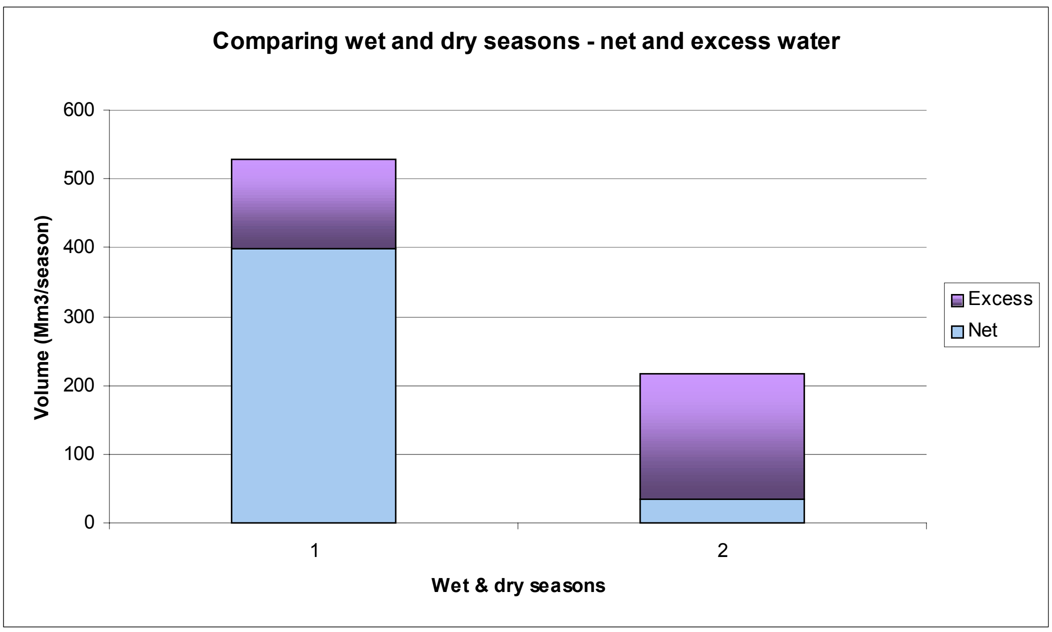


Figure 3.26 Rice irrigation efficiency in wet and dry seasons



4 MODELLING OF THE USANGU BASIN

4.1 Introduction

Six major water resource systems have been identified in the Usangu catchment (Figure 1.1). The SMUWC project envisaged that the best way to understand the functioning of the water resources system of the Usangu catchment, and to test the effect of different water management options on the availability of water in the Eastern Wetland and in the Great Ruaha river downstream, was to develop a computer model of the complete basin. Supporting Report No. 11 presents a detailed report on the modelling. This section presents a brief overview.

The model encompasses the first five of the six subsystems shown in Figure 1.1. The lowest point considered is at the river gauging station at Msembe, at the downstream end of the Ruaha National Park riverine reach. Modelling of the Mtera and Kidatu hydropower schemes was not included, because Mtera had been examined under a previous study commissioned by the RBMSIIP project.

The original aims of the modelling were:

i) to provide greater understanding of the relationships between natural inflows to the Usangu Plains, wetland size and outflow;

ii) to provide understanding of what changes would occur to inflows and outflows due to a reduction in rainfall, or an increase in evaporation;

iii) to provide understanding of what changes would occur to inflows and outflows due to a change in land use in the high catchment;

iv) to provide greater understanding of the effects on outflows of the diversion of inflows to irrigation schemes or fan swamps,

v) to examine a combination of scenarios.

The following five submodels were developed:

i) High Catchment Rainfall Runoff Model (HCRRM)

ii) Irrigation Impact Model (IIM)

iii) Fan Catchment Model (FCM)

iv) Swamp Hydrological Model (SHM)

v) Hydrological Routing Model (HRM).

The individual submodels are collectively known as the Usangu Basin Model. The relationships and the linkages between the component models are shown in Figure 4.1. The model is essentially a surface water type model, concentrating on the relationships between the input of rainfall, the production of runoff and the routing of the river flows through several different types of water resource systems. It compares the river flows estimated by the model at the downstream locations of N'Giriama, Hausmann's Bridge or Msembe with the observed flows at those river gauging stations. Groundwater processes are not included in the model because, although a conceptual submodel of groundwater flow has been formulated (Section 3.7), there are insufficient groundwater observations within the plains against which to calibrate it. Neither does the model incorporate water quality variables.

The Water Resources Engineering Programme (WREP) of the University of Dar es Salaam was subcontracted in August 1999 to develop the model following the outline given above. Supporting Report No. 11 describes the model development in detail.

Initially all relevant historical rainfall, evaporation and streamflow data were collected together, and stringent quality control procedures were applied to ensure that the database used in the subsequent modelling was of a sufficiently high standard. This phase was completed in January 2000, and is reported in detail in Sections 2, 3, and 4 of Supporting Report No. 11.

The modelling phase itself started in November 1999. Efforts focussed on the five subsystems listed below, and these are summarised in subsequent sections.

i) High catchment
ii) Irrigation schemes
iii) Alluvial fans
iv) Eastern wetland
v) Riverine reach.

Details of the progress made up to the end of the SMUWC project are given in Section 7 of Supporting Report No 11. These initial investigations show that further field data needs to be collected for i) the alluvial fans; ii) the Western Wetland. In addition, the following submodels need to be further refined: i) irrigation abstraction submodel; ii) Western Wetland.

The Usangu Basin Model will be used to test various strategic options for managing the water resources in the project area. Examples of such options, which are discussed in Section 5 include regulation of dry season irrigation abstractions or building a low weir at the outlet of the Eastern Wetland. Some of the benefits or difficulties associated with each scenario can be tested with the model, without committing any expense on construction work or alterations to existing irrigation procedures in the field.

It was envisaged that, at the start of the modelling work, a staff member from the Ministry of Water/Rufiji Basin Water Office would be seconded to the WREP modelling group. This would have contributed directly to strengthening of MOW/RBWO in hydrological modelling, hydrological analysis and problem conceptualisation. Unfortunately, no one was available during the data quality control and computer modelling phases, but two short training courses were given by the WREP team to staff from RBWO and MOW towards the end of the SMUWC project. The aim of these courses was to allow the trainees to obtain hands-on experience of running the Usangu Basin Model, and gain experience in editing data files and analysing and interpreting the model output. The Usangu Basin Model was installed on the computer at RBWO, backed up by a comprehensive User Manual written by WREP.

4.2 High catchment rainfall-runoff submodel

The high catchment in the project area has been divided into 11 separate subcatchments. Within eight of these subcatchments, there exists one or more river gauging stations from which the records can be used to estimate the runoff from the whole subcatchment. A disadvantage, pointed out in Section 3.4.2, was that these records possessed a considerable amount of missing data.

Three subcatchments, the North West, the Kimbi, and the North East, are at present totally ungauged, and their combined area forms two thirds of the total ungauged area. Initially it was anticipated that the HCRRM submodel might be used to estimate their runoff from the rainfall occurring over these three subcatchments. However, due to the absence of any historical raingauges in these areas, this approach was not possible, and an alternative procedure of runoff estimation was used. This involved equating their behaviour to that of the South East subcatchment, gauged at station 1KA10A Mlomboji.

Section 3.4.2 introduced two methods that were used for reconstructing the missing portions of the records from all 13 gauged catchments in the basin to ensure that a complete record existed from 1954-98 for subsequent analysis. The first of these, the cross-correlation technique, was used in those cases where a concurrent record existed at a neighbouring station. A period was chosen within the validity of the rating curves at both stations, and a linear pertubation model that took account of the seasonal mean flow was fitted. This model was then used to estimate the missing flow records.

If no records existed at any neighbouring river station, the second method, the HCRRM submodel, was used instead (Supporting Report No 11). A concurrent period of daily rainfall and runoff was used to calibrate the submodel. Two different submodels were tested, the Linear Pertubation Model, which is essentially a regression technique, and the Xinanjiang Model, which is a conceptual model. In practice, the Linear Pertubation Model was chosen, because its average model efficiency was 84% compared with that of 76% for the Xinanjiang Model, and it was simpler to use. Although this HCRRM rainfall-runoff model was satisfactory, it is thought that the areal rainfall over the subcatchments may be biased towards the higher altitudes, leading to an overestimate of rainfall over the subcatchment, and thus an overestimate of reconstructed river records.

4.3 Irrigation abstraction submodel

The Irrigation Abstraction submodel (IAM) is described in Section 7.3 of Supporting Report No 11. The IAM has some similarities with the Irrigation Impact Model (from which it was developed), described in Appendix F of Supporting Report No 9. However, these two submodels are now not the same, and it is the IAM submodel which is summarised here.

The IAM submodel uses records over the period 1954-98 of subcatchment flows, and rainfall and potential evapotranspiration over the plains. Each run of the submodel is for the full period of records, and uses 10 day totals. Most of the results are presented in summary form as averages for three windows: 1954-74, 1974-85, and 1985-98. These periods are based on irrigation development at the time. The IAM submodel adopts two distinct methods in accounting for irrigation water use:

i) An approach based on diversion of river flows up to the capacity of the offtake structures. This is known as the Constant Abstraction option. This requires no irrigated area assumptions since diversions are dependent only on offtake capacity and river flows. If the river flow is less than the offtake capacity, then a proportion of the flow is abstracted. This proportion varies from river to river, lying between 50% and 100%. It is assumed that no diversions return to the river.

ii) An approach based on the assumption that the area irrigated is a dynamic response to river flows and crop water requirements, with the irrigated area building up in ten-day steps as river flows rise. This is known as the Crop Water Requirement option. Field requirements are based on published FAO methodology. No allowance is made for any differences due to type of irrigation (i.e NAFCO farms, modernised smallholder, traditional smallholder, peri-NAFCO areas). A delivery efficiency of 70% is adopted. No allowance is made for return flows.

Some initial trials of the submodel have been carried to determine how well its output compares with irrigation trends in the past. The results, which are presented in Supporting Report No. 11, are given for the three windows, ie, initial trials were primarily designed to simulate the past. The model is also intended to be used to simulate the effects of various future irrigation water management options.

4.4 Fan catchment submodel

A number of alluvial fans are located between the foot of the high catchment escarpment and the Usangu wetland. The irrigation schemes are located on the upper part of these fans. After part of the river flows have been diverted into these irrigation schemes, the remaining flows travel across the lower parts of the fans to reach the wetlands. In this section two types of fan catchment submodel, representing the behaviour of this lower part of the fans, are described. Further details may be found in Section 7.4 of Supporting Report No 11.

Two out of the 11 subcatchments do not possess any alluvial fans at all, and flow directly into the Eastern Wetland. These are the Ndembera river and the North East subcatchment. The remaining 9 subcatchments possess one of two types of fan. The first of these is where the river enters the head of the fan and then spreads out over the whole fan in an even fashion without any defined channels. Examples of these subcatchments are the Kimbi river, the North West subcatchment (Mjenje), and the Eastern subcatchment (Kioga). In this case the fan catchment submodel consisted of a daily water balance component together with a kinematic wave representation of overland flow. The submodel indicated high losses of water from the fans through evaporation.

The second type of fan is one where the river passes through the fan, but it is contained in a definite channel. In this submodel a US Soil Conservation Service curve was used to estimate lateral inflow, and a Muskingum Cunge technique used to route flow along the channel. This type of submodel was applied to six subcatchments, namely South West subcatchment (Mkoji), Chimala, Great Ruaha, Kimani, South East subcatchment (Mlomboji), and Mbarali. All these fans are relatively small, and the submodel showed that there was little gain or loss of water over the fans, so the inflows are very similar to the outflows.

The first type of fan submodel indicated initial estimates of losses over the fans comparable to the volumes of water abstracted for irrigation. While it is thought that these may be overestimates, and will need further refinement, it did show that fans were an important subsystem of the overall hydrological cycle in the project area, so must be included in any future modelling work. In addition, more accurate field data on the geometry and soil characteristics of the fan will need to be collected.

4.5 Swamp hydrological submodel

4.5.1 Western Wetland

Preliminary ideas on a suitable submodel for the Western Wetland are contained in Section 7.5 of Supporting Report No 11.

The Western Wetland is a seasonal wetland that collects all the flows from 7 subcatchments in the surrounding highlands. Any excess water that does not evaporate passes out through a single outlet at Nyaluhanga. During the dry season this flow is entirely confined within the river channel there, but during the wet season the level in the river rises and the water spills out over the banks. Field work indicates that this transition occurs when the flow in the river reaches 110 m^3/s. At higher water levels flow occurs both in the channel and in a parallel direction along the flood plains on either side of the river. Since the width of the northern floodplain is 2 km, and that of the southern flood plain is 5 km, discharges much higher than 110 m^3/s will be observed during these peak water levels.

The wetland acts as a floodplain in the sense that water flows in the river channels up to the bankful level. Any flow in excess of the bankful level causes the rivers to overflow their banks and flood the surrounding area. When water spreads over the flood plain, substantial amounts of water are lost to evaporation. For extremely dry years, when the flow may be contained within the banks, the effect of the flood plain may be negligible.

Topographic surveys undertaken in 1999 and 2000 gave priority to mapping the Eastern Wetland. Information such as river cross sections, extent of the flood plain, a rating curve for the floodplain at Nyaluhanga (the outlet of the wetland) which includes flood plain flows, and longitudinal profile of the main river channel, has yet to be collected for the Western Wetland.

The model component to represent the behaviour of the Western Wetland is still at an early stage of development. Further work is needed to develop a realistic submodel of the Western Wetland. Access to any port of the wetland by land in the wet season is a particular problem. Access by airboat to those areas which are flooded in the wet season may be possible. Collection of hydrological data will be dependent mainly on field work in the dry season and use of automatic data logging devices in the wet season.

4.5.2 Eastern Wetland

A submodel to simulate the behaviour of the Eastern Wetland has been developed, based on water balance concepts suggested by Sutcliffe and Parks (1989). They have successfully applied these concepts to four other wetlands located in different countries of Africa. Further details of the submodel development are contained in Section 7.9 of Supporting Report No. 11.

The upstream inputs to the model are the flows in the Great Ruaha river at Nyaluhanga and the Ndembera river at Madibira. The rainfall over the wetland is estimated from the records for the three raingauges installed by the SMUWC project at N'Giriama, Upagama and Ikoga. The standard potential evapotranspiration for each decad found for the Usangu Plains is used to estimate evaporation from the flooded surface area of the wetland. The relationships between storage, outflow and surface area (for example, Figure 3.16) were prepared from topographic surveys conducted around and across the wetland, and the rating curve found for the swamp outlet at N'Giriama.

4.6 Hydrological routing submodel

After the Great Ruaha river leaves the Eastern Wetland at N'Giriama, it flows about 30 km down to the site of the historical river gauging station 1KA27 Hausmann's Bridge. Just downstream of this station two major tributaries enter from the west, and then the river flows about another 50 km to reach the river gauging station 1KA59 at Msembe Ferry.

The Hydrological Routing Submodel (HRM) was developed specifically to relate the daily river flow records observed at these two stations. Once calibrated on common periods of record, it was used to reconstruct missing data and extend each record to arrive at reliable records which spanned the complete period 1957-98. The application of the submodel is described in more detail in Sections 3.5.3 and 5.3.5 of this report, and Section 4.3 of Supporting Report No 11.

The submodel was fitted separately to wet and dry season records. During the early part of the wet season, the flows at the downstream station 1KA59 were often much higher than those observed at the upstream station 1KA27; however, because these differences were assumed to occur because of tributary inflow in the intervening reach, they were not included in the fitting of the submodel. A simple linear relationship showed that during the wet season, the downstream daily flows were essentially the same magnitude as those of the upstream flows, with a lag time of zero days. During the dry season the downstream flows were 92% of the upstream flows, with a lag time of zero days (Table 5.3, Section 5.3.4). This difference in magnitude was attributed to evaporation loss from the numerous pools forming the intervening river reach.

More sophisticated routing models, such as the Muskingum technique, are deemed suitable for river reaches like the Great Ruaha, where the area of intervening tributary catchments is small in comparison with the total upstream catchment. But applying this method showed no improvement in fit over the simple linear relation type submodel.

Because the submodel showed that the daily flows at Hausmann's Bridge and Msembe Ferry were so similar, it was also assumed that flows at N'Giriama and Hausmann's Bridge were the same (Section 5.3.4), because the total area of intervening tributaries was even smaller than that between the first two stations.

4.7 Water balance of the Eastern Wetland

The Swamp Hydrological submodel was used to simulate the behaviour of the Eastern Wetland for the two years 1999 and 2000 (Figure 4.2, Section 4.5.2). One outcome of this modelling work was initial estimates of the overall water balance for this subsystem, which are shown in Figures 4.3 and 4.4 respectively for each of these years. The water balance of the Eastern Wetland is also presented and discussed in Section 2.4 of Supporting Report No. 14.

The period considered during 1999 lasted 345 days from 21 January to 31 December, and since the storage at the beginning and end of this period was estimated by the submodel to be the same (8.5 Mm^3), the change in storage was taken as zero. The period in 2000 was slightly less, at 304 days, and the storage over this period increased from 8.5 Mm^3 to 14.5 Mm^3, a difference of +6.0 Mm^3. Only data observed from 1 January up to 31 October 2000 was used during the second period. Subsequent observations, collected after completion of this Water Resources Supporting Report, would allow the period used to be increased to a value comparable to the first period.

The inflow to the wetland from the north east corner is reduced as follows, to allow for water diverted for irrigation. Although the location of the station at Nyaluhanga where the flow in the Great Ruaha river is monitored lies downstream of the main irrigated areas of the Western Wetland, the same is not true for the Ndembera at Madibira. Here the Madibira Smallholder Agriculture Development Project laid out an irrigation scheme in 1998 with a maximum area under command of 3 000 ha. During the 1998/99 wet season a total of 450 ha of paddy was cultivated by the first group of smallholders, while this increased to 1 800 ha in the 1999/00 wet season. The project anticipates that the full 3 000 ha will be taken up during 2000/01.

Using the cropping calendar and water application rates contained in the design report for this project (Halcrow, 1995), estimates were made of the total wet season volumetric gross demand consumed by the scheme during the complete cropping period. This is equal to the difference between the diversion flow through the primary canal at the headworks and the outflow down the main drain at the tailend of the scheme. For an area of 450 ha this was estimated as 7 Mm^3, and for an area of 1 800 ha as 29 Mm^3. When the full 3 000 ha are taken up this consumption will equal 49 Mm^3. These values of gross demand were subtracted from the observed natural flow of the Ndembera river at Madibira to give the net volume of water inflowing to the north east corner of the wetland (Figures 4.3 and 4.4).

The loss of water, denoted as L, over the flooded surface of the seasonal wetland was calculated as:

$$L = A\,(E - P)$$

Where: A = Area
E = Evaporation
P = Rainfall.

The cumulative total of L during the two seasons is shown as the lower line in Figure 4.5. During the wet season, the rate of rainfall is approximately the same as that of evaporation, so the cumulative value hovers around zero. Immediately after the wet season, the wetland is close to its maximum surface area for that year, so the greatest rate of increase of the cumulative total of L occurs. As the area of the wetland declines during the dry season, so the rate of increase of cumulative L also declines, becoming close to zero again at the start of the next wet season.

Over the first period of 345 days, L increased from zero to 256 Mm^3. At the end of the second period of 304 days, L reached a value of 478 Mm^3, an increase of 222 Mm^3. These differences were used in Figures 4.3 and 4.4 to represent the total net loss of water from the surface of the wetland.

The main inflows to the wetland occur from the two rivers, the Great Ruaha at Nyaluhanga and the Ndembera at Madibira (less abstraction of irrigation water). While this may represent the situation realistically during the dry season, there is likely to be an additional contribution during the wet season from the two other rivers, the Kimbi and Kioga, which flow into the wetland downstream of Nyaluhanga. These two rivers were not measured during 1999 and 2000, and an estimate of their contribution is difficult to make. In Section 3.5 of Supporting Report No. 12 it was also considered likely that there was a groundwater contribution entering the wetland from semi-confined aquifers and buried river channels, but the quantity was unknown.

These several unknown contributions have been combined together, and their total volume estimated by taking the difference between the other inflows and outflows to the Eastern Wetland, so allowing the overall water balance to balance. During 1999 this total additional contribution was 29 Mm^3, which is 5.1 % of the inflow from the two main rivers (Figure 4.3); during 2000 it was 36 Mm^3, which is 12.0 % (Figure 4.4). Because 1999 was a wetter year than 2000, it would be expected that this additional contribution during this year would slightly exceed that of 2000, not as found from the method above; so there is still scope for further improvement to this water balance.

4.8 Application of the swamp hydrological submodel

The swamp hydrological submodel was applied to the Eastern Wetland in order to look at the impact of irrigation abstractions. Initial analysis was carried out by varying the input from Nyaluhanga, whilst monitoring swamp dynamics and the outflow into the Great Ruaha River.

The success of the submodel may be judged by comparing modelled and observed outflows at N'Giriama. This is illustrated in Figure 4.2 for the two years of records available 21 January 1999 – 31 October 2000. These two years are particularly dry; in terms of the total annual outflow volume at Ngiriama (which is assumed to be very similar to that recorded at Hausmann's Bridge and Msembe river gauging stations), the value in 2000 is the lowest in the period 1958-2000, and that in 1999 it is the third lowest.

The variation of wetland surface area and storage simulated by the submodel under current abstraction rates is shown in Figure 4.6. There is close similarity between the fluctuations in storage simulated by the model and in the water levels observed in Ruaha and Nyangokolo swamps (Figure 4.7). These results are also presented and discussed in Supporting Report No. 14.

The wet season was taken as the period 1 January-30 April each year, and the dry season 1 May-31 December. The dry season and wet season abstraction rates were adjusted in turn, and the submodel used to test the effects of increasing or decreasing these rates on the values of surface area and storage of the wetland. The main conclusions were as follows:

i) The minimum values of both the surface area and storage volume in the perennial swamp, reached at the end of the dry season in December, are controlled exclusively by the amount of water abstracted from the rivers flowing into the Eastern Wetland during the dry season 1 May - 31 December.

ii) An increase in current rates of dry season abstraction will lead to lower values of both surface area and storage. If this rate is increased sufficiently, the values of the minimum surface area and volume at the end of the dry season will be reduced to zero in drier years. Over time, this would lead inevitably to the loss of the perennial swamp, although a seasonal wetland would remain.

For example, an increase in the current dry season abstraction rate by 5 m^3/s would be sufficient to allow this scenario to occur in both 1999 and 2000 (Figure 4.8). Even an increase by 3 m^3/s would have been sufficient to reduce the minimum surface area of the perennial swamp in 1999 to around 10 km^2.

Current overall rates of abstraction from the total inflow to the Usangu Plains during the dry season under two different rainfall scenarios are estimated (Section 2.8 of Supporting Report No. 8) to be

Normal to wet year	15.9 m^3/s
1 in 5 year return period dry year	9.6 m^3/s

So even an increase in these current rates by as little as 30% would be sufficient to cause great problems for the future existence of the perennial swamp.

iii) Conversely, if a decrease in present dry season abstraction rates could be introduced, it would prevent the surface area and storage in the perennial swamp sinking to the low levels that have been observed in recent years (Figure 4.8).

For example, a lowering of present abstraction rates by 7 m^3/s would allow the perennial swamp to maintain sufficient minimum storage to allow a continuous outflow of at least 0.3 m^3/s throughout the critical periods in both 1999 and 2000. Even a decrease of 6 m^3/s would be sufficient to restrict the period of zero flow to just one month, before the outflow recommenced.

iv) Abstraction of irrigation water during the wet season prior to this dry season has no affect at all on the minimum values of either the surface area or storage attained at the end of the dry season (Figure 4.9).

v) Starting from the end of the dry season at 31 December 1999 (shown in Figure 4.9), abstraction of additional irrigation water during the subsequent wet seaon 1 January – 30 April 2000 will lead to further reductions in the surface area and storage in the perennial swamp prior to the start of the main flood rise in mid-March 2000.

vi) The outflow from the Eastern Wetland is directly related to the amount of storage remaining in the perennial swamp. A decrease in the value of minimum storage reached at the end of the dry season will lead to an earlier cessation of flow in the Great Ruaha river. At this time of the year all the tributaries joining the Great Ruaha river between N'Giriama and Msembe are completely dried up. The main cause of the gradual earlier onset of the date when the Great Ruaha river dries up, therefore, the gradual increase in the total dry season abstraction from the rivers flowing into the Eastern Wetland.

vii) During the last seven years, the dates when the flow in the Great Ruaha river restarted lay within the period 22 November – 19 January (Table 2.5, Figure 4.10). During 1999 and

2000 the first substantial outflow from the Eastern Wetland occurred much later in March. Therefore, certainly during these two years, and probably by analogy for the preceding four years, the onset of the flows was due entirely to inflow from the tributaries joining the Great Ruaha river between N'Giriama and Msembe.

viii) After the storage in the perennial swamp reaches its minimum in December, its value needs to increase during the subsequent wet season to at least 33 Mm^3 for the outflow to start, and to at least 50 Mm^3 for a more substantial outflow of 0.5 m^3/s to occur. The simulated storage dropped below this critical value of 50 Mm^3 from 6 September 1999 to 8 March 2000, a period exceeding 180 days. This is far longer than the 111 days for which the Great Ruaha river dried up in the Ruaha National Park that year (Table 2.5, Figure 4.10).

The dates when these outflows first occur are governed by the rates of abstraction of water in the immediately preceding dry season and the current wet season, either separately or in combination. Increases in either rate of abstraction will lead to a slower rate of increase in the storage of the perennial swamp, and a consequent delay in the date when these outflows restart.

ix) Additional wet season abstraction of irrigation water slightly reduces the maximum surface area and storage reached during the peak of the flood in April; but the timing of the peak remains unaffected (Figure 4.9).

For example, an additional abstraction of 15 m^3/s, where available, will reduce the peak surface area in 1999 by 7% from 566 km^2 to 529 km^2 and in 2000 by 31% from 357 km^2 to 247 km^2. So even in the latter year, with the lowest observed flows since 1958, the maximum area flooded by the seasonal wetland will still be substantial, equal to that observed in June during the recession in a normal year.

This particular value of additional abstraction is sufficient to raise the current irrigated area of 42 000 ha used in a normal-to-wet year up to the maximum irrigable area of 55 000 ha. This is the estimated upper limit to land available for rice cultivation under the existing water available in Usangu plains. It follows that if wet season irrigation is allowed to expand gradually to its full potential, without any restrictions imposed from outside, the Eastern seasonal wetland will continue to be covered by flood waters each year without fail, though the maximum surface area attained will be slightly reduced.

x) Further wet season irrigation will reduce the total annual volume of outflow into the Great Ruaha river at the outlet of the Eastern Wetland (Table 4.1). This will lead to a reduction of inflow to Mtera Reservoir, and a consequent slight loss in hydropower production.

Table 4.1 The effect of additional loss of water in the wet season (1st January to 30th April) on the areal extent of the swamp and swamp outflow for the years 1999 and 2000

Additional loss in wet season (Cumecs)	Max. aerial extend in year 1999 (km^2)	Max. aerial extend in year 2000 (km^2)	Outflow volume for 1999 (Mm^3)	Outflow volume for 2000 (Mm^3)	%reduction in outflow 1999	%reduction in outflow 2000
0	566	357	318.6	105.7		
2	560	338	309.2	94.6	3.0	10.5
4	554	320	302.2	87.2	5.2	17.5
6	548	304	285.3	73.5	10.5	30.5
8	542	288	276.7	64.2	13.1	39.3
10	537	274	269.5	56.0	15.4	47.1
15	529	247	257.3	37.8	19.2	64.3
20	521	221	248.4	22.6	22.0	78.7
30	509	169	232.6	4.4	27.0	95.9
40	497	123	218.7	0.01	31.4	99.9

For example, assuming the same additional abstraction of 15 m^3/s for wet season irrigation as used previously, the volume of outflow during 1999 will reduce by 19% from 319 Mm^3 to 257 Mm^3, and in 2000 by 64% from 106 Mm^3 to 38 Mm^3. It should be noted that the absolute loss of volume is similar in both years, 62 Mm^3 in the first and 68 Mm^3 in the second. Although this loss is a significant proportion of the outflow observed during these two dry years, it can be shown that in the longer term it will reduce the hydropower production only slightly.

Based on historical records (CCKK, 1982), the long term mean annual inflow into Mtera Reservoir is 114 m^3/s, which is equivalent to an annual volume of 3 600 Mm^3. A loss in outflow of 62 Mm^3 per year will reduce this inflow by 1.7%. Even if the full abstraction of 15 m^3/s for the 4 months 1 January-30 April, which is equivalent to a loss of 158 Mm^3, were carried through to an equal loss of outflow from the Eastern Wetland, the reduction in long term inflow to Mtera would be only 4.4%.

It follows that if wet season irrigation is allowed gradually to expand to its full potential, the consequent additional loss of downstream inflows to Mtera Reservoir will be of the order of 2–5 % of the historical natural inflows.

xi) From the submodel simulation, it is also possible to conclude that the rapid rise in irrigated area over recent years (Figure 2.1), leading to increased wet season irrigation, will probably have caused some reduction in outflow from the Eastern Wetland, consequently reducing inflows to Mtera Reservoir.

Present overall rates of abstraction for irrigation during the wet season are estimated (Section 2.8 of Supporting Report No. 8) to be:

Normal to wet year	38.4 m^3/s
1 in 5 year return period dry year	27.8 m^3/s

Table 4.2 shows the result of reversing the current wet season abstraction, and increasing the inflow to the Eastern Wetland. For example, an increase of 40 m^3/s over 4 months will increase the volume of outflow by 73% from 319 Mm^3 to 551 Mm^3 in 1999, and by 258% from 106 Mm^3 to 380 Mm^3 in 2000. This is an increase of 232 Mm^3 and 274 Mm^3 respectively, compared to the additional inflow of 420 Mm^3. This increase, represented as a proportion of the total inflow to Mtera Reservoir, lies in the range 6.4 to 7.6% during these two dry years. In wetter years the increase is likely to be smaller. .

Table 4.2 The effect of increased flow during the wet season (1st January to 30th April) on the areal extent of the swamp and swamp outflow for the years 1999 and 2000

Flow increase in wet season (Cumecs)	Max. aerial extend in year 1999 (km^2)	Max. aerial extend in year 2000 (km^2)	Outflow volume for 1999 (Mm^3)	Outflow volume for 2000 (Mm^3)	%increase in outflow 1999	%increase in outflow 2000
0	566	357	318.7	105.7		
2	572	379	328.8	117.9	3.2	11.5
4	576	397	340.3	130.3	6.8	23.3
6	581	414	351.8	143.0	10.4	35.3
8	586	432	363.3	156.1	14.0	47.6
10	590	448	374.8	169.3	17.6	60.2
15	599	487	403.9	203.5	26.8	92.5
20	608	525	433.1	238.2	35.9	125.3
30	622	600	491.8	308.4	54.3	191.8
40	640	672	550.9	379.7	72.9	259.3

Without having detailed records of inflow and outflow to the Eastern Wetland during a normal to wet year, it is difficult to judge the exact effect of current wet season irrigation abstractions, but it is unlikely that they would have reduced the natural inflows to Mtera Reservoir by more than 5% up to 1980; this is the year when the reservoir was constructed and the total irrigated area in Usangu was about 20 000 ha (Figure 2.1). By year 2000 the total irrigated area stood at 42 000 ha, when the reduction then would not exceed 10%. So the reduction in inflows to Mtera Reservoir due to upstream wet season irrigation is unlikely to have exceeded 5% since it was first constructed.

xii) During the course of the year the flooded area within the Eastern Wetland will vary from month to month, with minimum values normally occurring in December and maximum values in April/May. The variable L, where L = A(E – P) will represent the surplus of evaporation E over rainfall P occurring over the surface area A of the flooded wetland.

Simulation by the submodel indicated that the total annual volume of L was 256 Mm^3 for 1999 and 222 Mm^3 for 2000. Since these are particularly dry years, the mean value of L over a period of typical years is likely to be slightly higher, say 280 Mm^3.

One longer term water management option that could be considered is to drain the wetland and construct major artificial channels that would convey the flows in the two main inflowing rivers, the Ndembera and Great Ruaha, directly to the outlet at N'Giriama without loss of water from the flooded surface area of the existing wetland. The consequent increase in outflows from the drained wetland must be equal to the 280 Mm^3 currently lost to evaporation. Compared with the mean annual inflow to Mtera Reservoir of 3 600 Mm^3, this increase would form 7.8% of the total. Draining of the Eastern Wetland would therefore slightly increase the volume of inflows to Mtera Reservoir available for power production.

xiii) Another water management option that has been tentatively suggested for Usangu is to construct a high dam at N'Giriama that would entirely flood the complete Eastern Wetland, forming a reservoir several metres deep. The aim of this scheme would be to form an additional storage facility to that at Mtera, and so ultimately increase hydropower production downstream.

One advantage of this scheme is that for those years when surplus water currently flows over the flood spillway at Mtera Reservoir, the upstream reservoir at N'Giriama would be able to store this wasted water and let it out gradually as soon as the water level in Mtera dropped sufficiently to offer spare capacity to receive it. However, the number of years when flood spill has occurred at Mtera since its construction in 1980 is very limited, namely between January and June in 1998.

A serious disadvantage of any reservoir formed behind a dam at N'Giriama is the large amounts of evaporation that would occur from it. The seasonal wetland, because it is covered by grass and other vegetation, reflects more short wave radiation than open water, and so evaporates at close to the potential evapotranspiration rate of 1940 mm per year. In contrast the water surface of the deeper reservoir would evaporate at the open water rate of 2 420 mm per year, which is 25% higher.

For a reservoir surface area of around 615 km^2, the value of variable L is estimated as 1 070 Mm^3 for a median year of 690 mm rainfall depth. This is an increase of 790 Mm^3 over the existing losses (280 Mm^3) from the wetland, which would cause a 22% decrease in the mean annual inflow (3 600 Mm^3) to Mtera Reservoir. As a proportion of the mean annual flow (2 240 Mm^3) in the Great Ruaha at Msembe, this value would rise to 35%, and to just satisfy this evaporation rate would require a mean annual inflow to the Eastern Wetland of 34 m^3/s.

4.9 Summary

A model of the Usangu basin has been developed by WREP. The modelling work is described in detail in Supporting Report No. 11. The model has been installed in the Rufiji Basin Water Office and training in its use has been given to government officers.

The model will allow various strategic options for managing the water resources in the project area to be tested. Examples of such options, which are discussed in Section 6, include regulation of dry season irrigation abstractions or building a low weir at the outlet of the eastern wetland.

One important point to highlight is the dampening effect of the swamp hydrological submodel of the Eastern Wetland. From Figures 4.3 and 4.4 it will be seen that for a given inflow into the Eastern Wetland, there are two separate outflows, namely the evapotranspiration from the surface of the wetland and the outflow down the channel of the Great Ruaha river. Increased inflows will cause both increased evapotranspiration as well as increased channel outflow. Similarly decreased inflows will lead to decreased evapotranspiration as well as decreased channel outflow. This means that the fluctuations in channel outflow must be less than the fluctuations in inflow. This is one reason why sizeable increases in irrigation abstractions upstream cause only a moderate reduction in channel flows downstream.

In the next section, Section 5, a series of analyses are presented to demonstrate present thinking on the causes of the cessation of river flow based on the information which is currently available.

Figure 4.1 The Usangu Basin Model

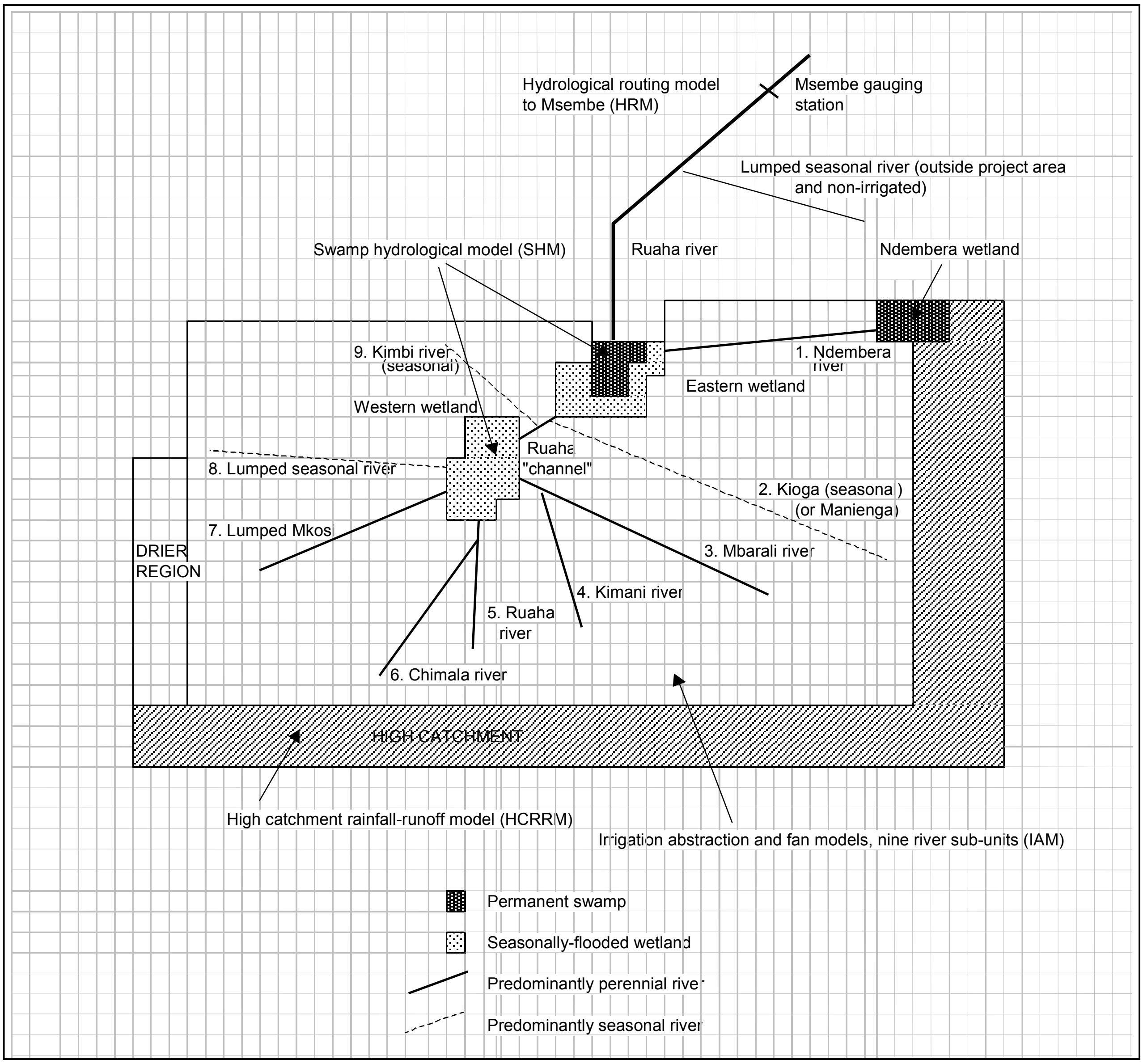


Figure 4.2 Comparison of observed and simulated outflows from the Eastern Wetland

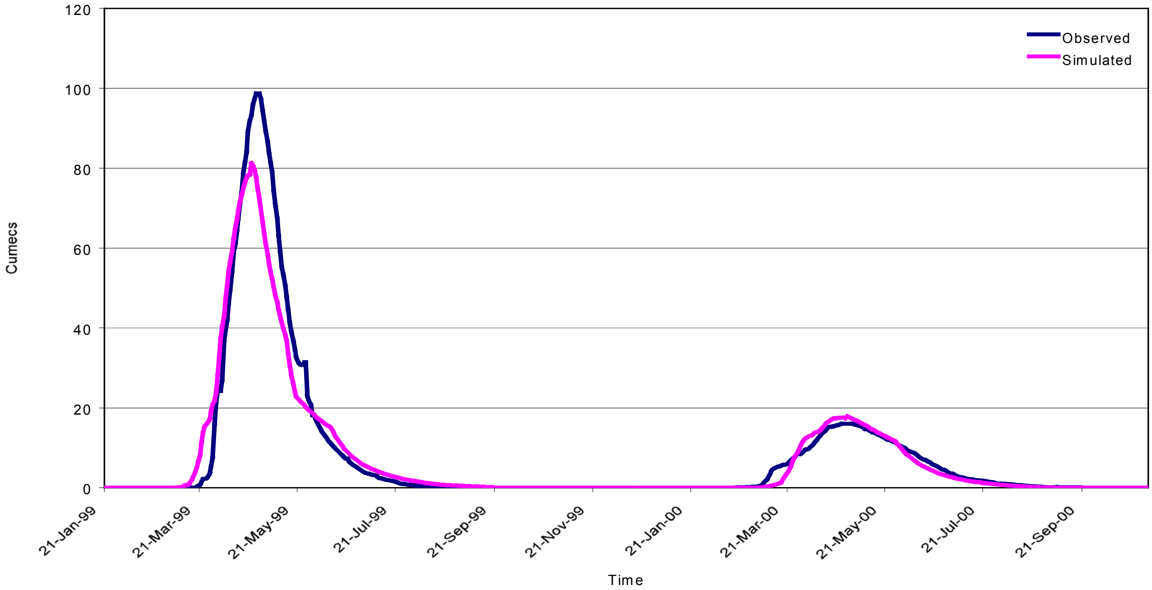


Figure 4.3 Estimated water balance (Mm^3) of the Eastern Wetland in 1999

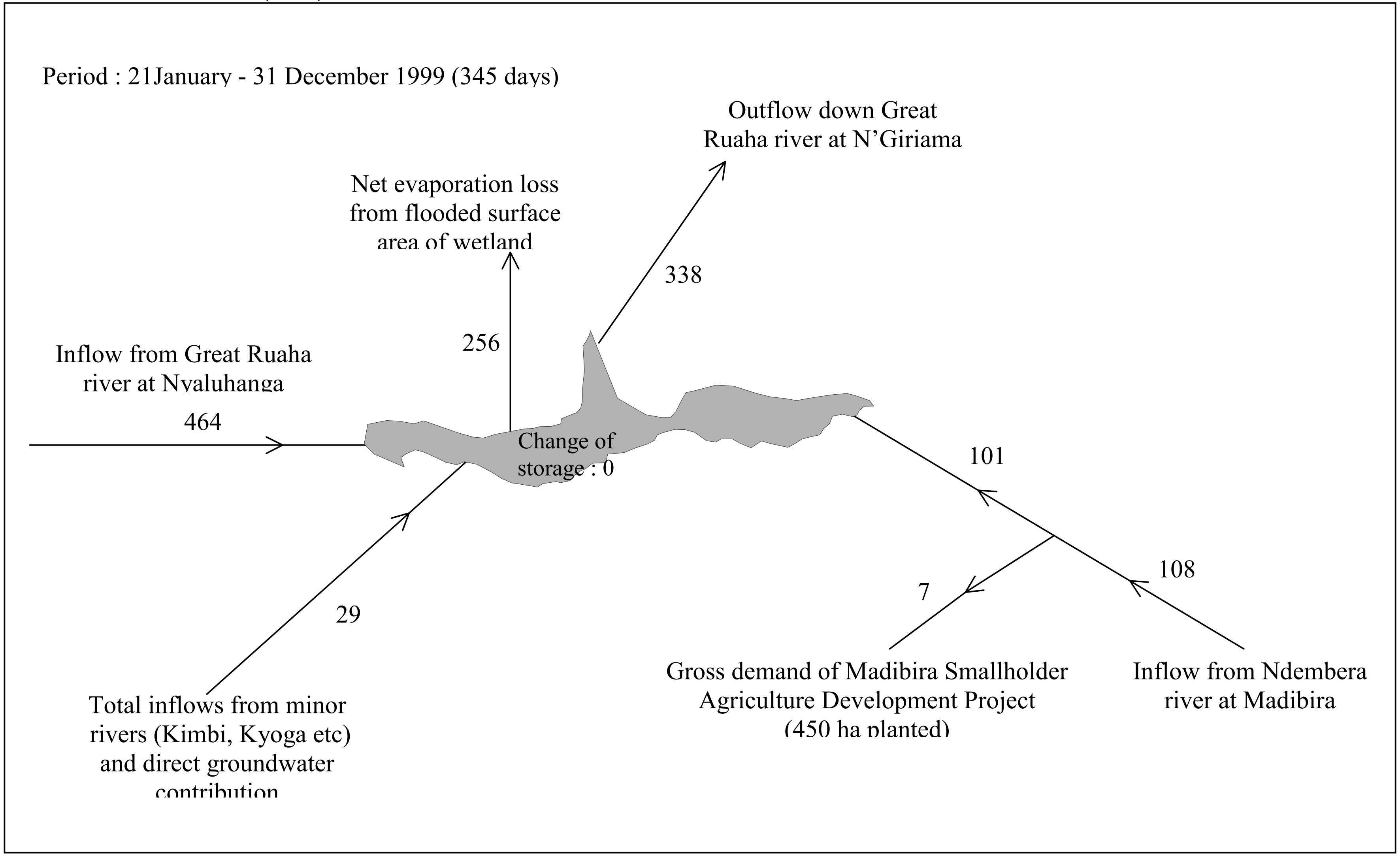


Figure 4.4 Estimated water balance (Mm^3) of the Eastern Wetland in 2000

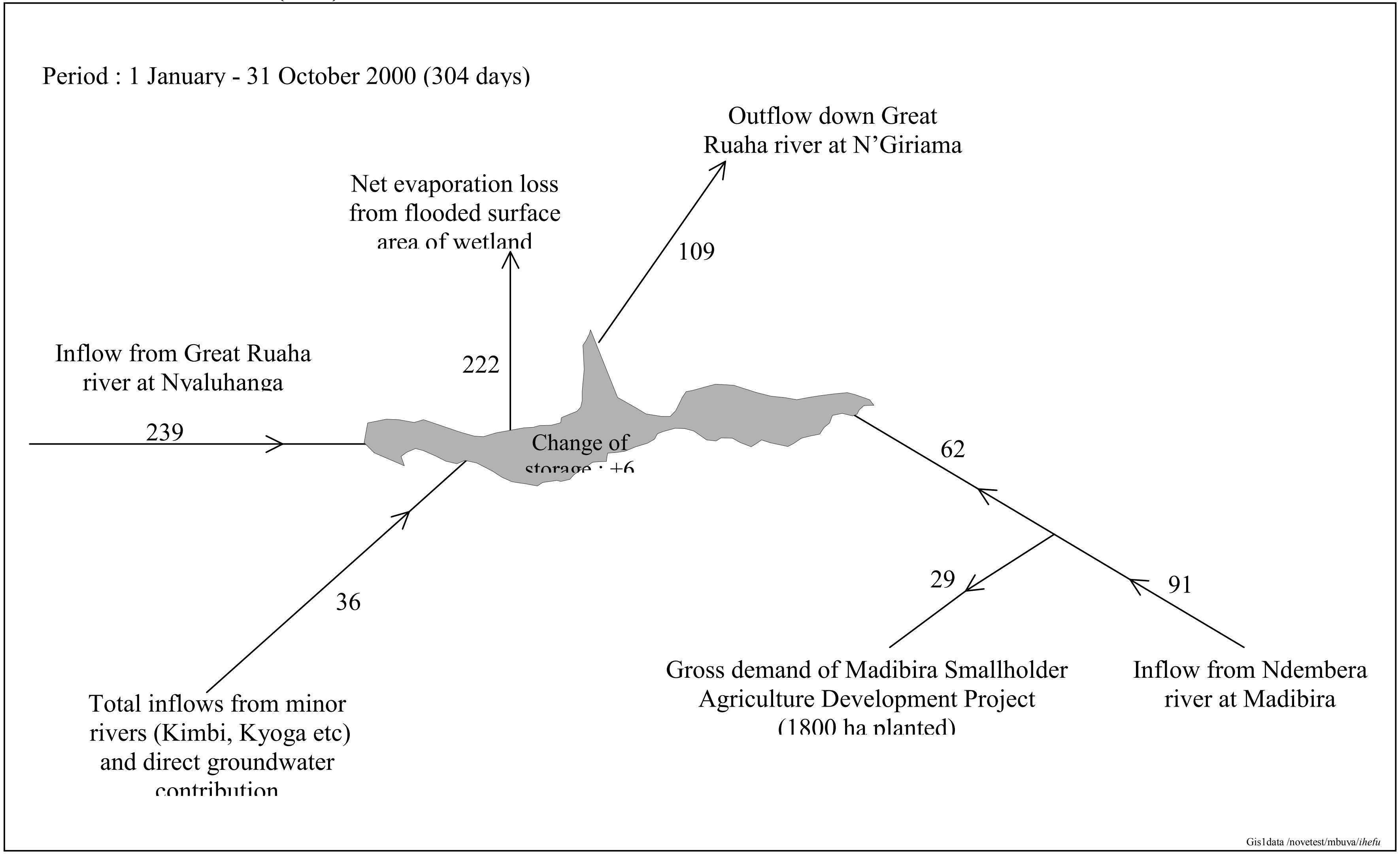


Figure 4.5 Cumulative net evaporation over the Eastern Wetland for January 1999-October 2000

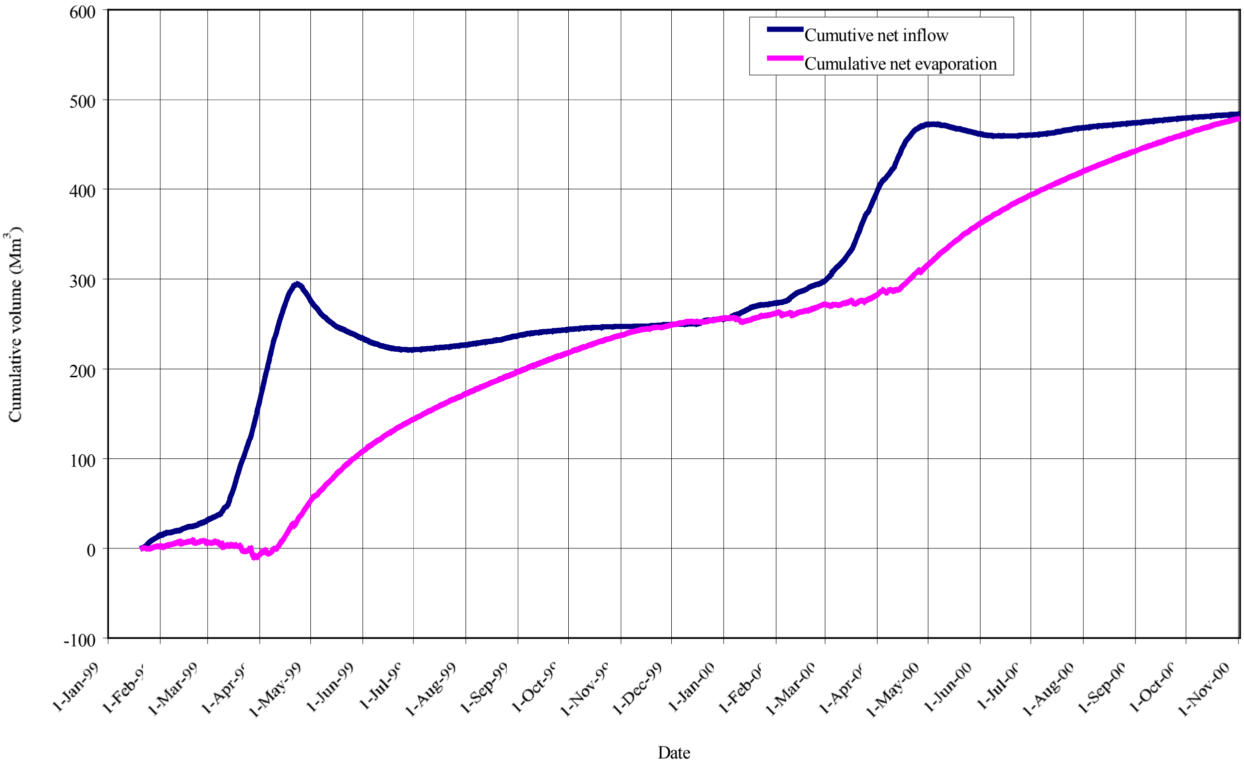


Figure 4.6 Predicted flooded area and volume in storage, Eastern Wetland, 1999-2000
Figure 4.7 Predicted storage and observed swamp water levels, Eastern Wetland, 1999-2000

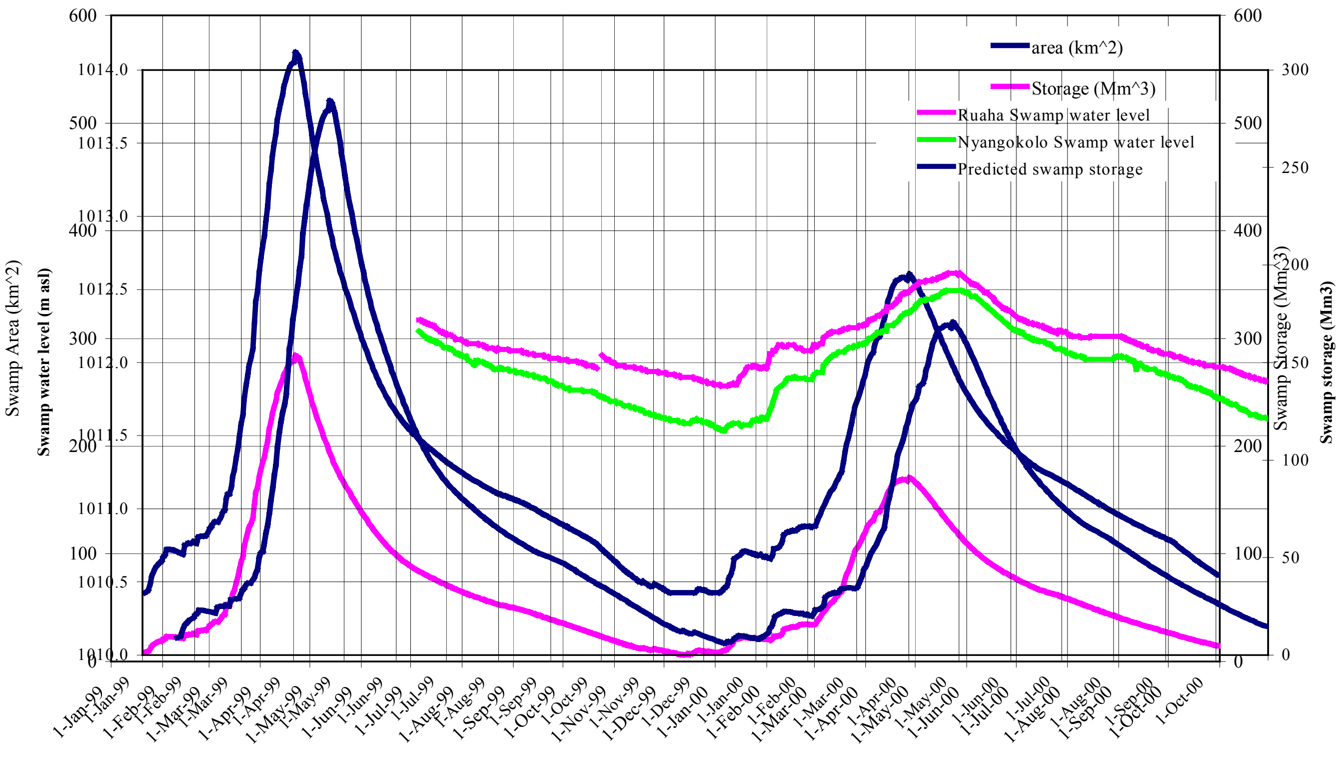


Figure 4.8 Effects of additional dry season irrigation on storage and surface area
Figure 4.9 Effects of additional wet season irrigation on storage and surface area

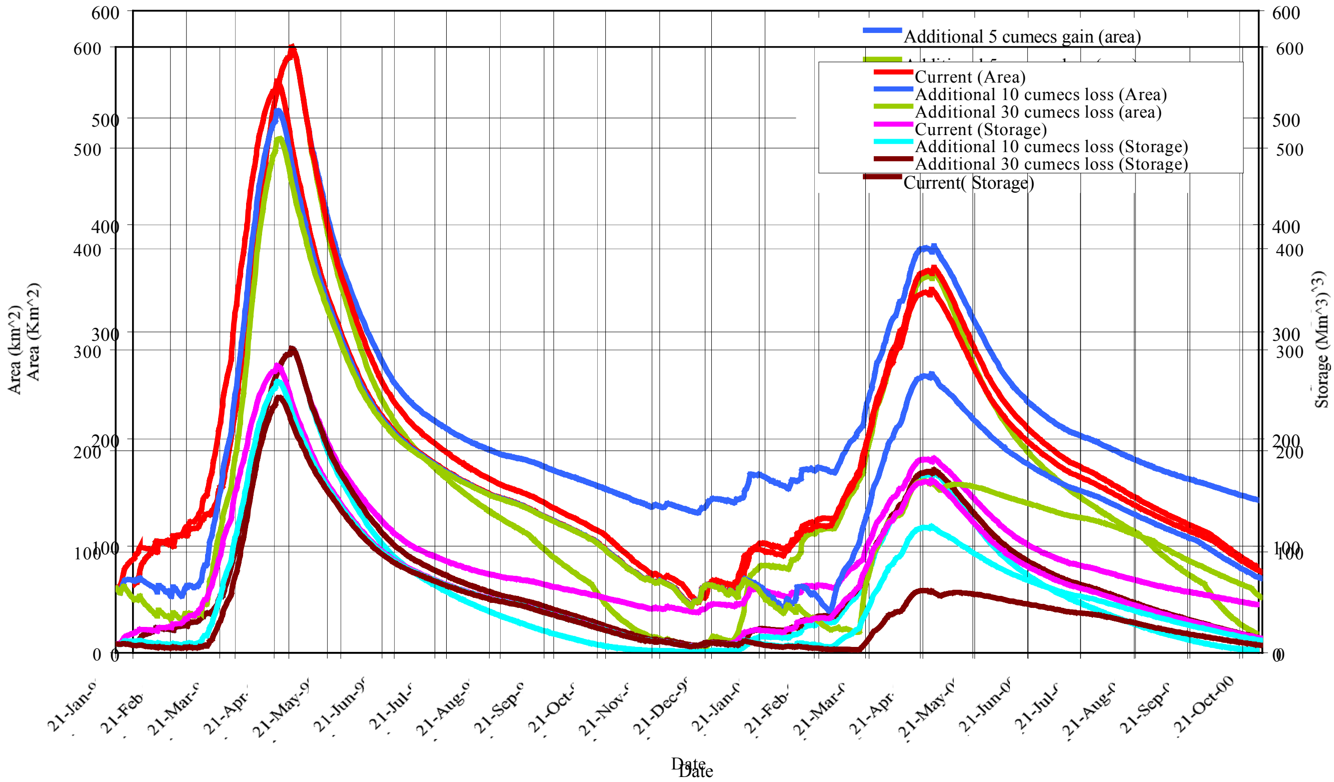
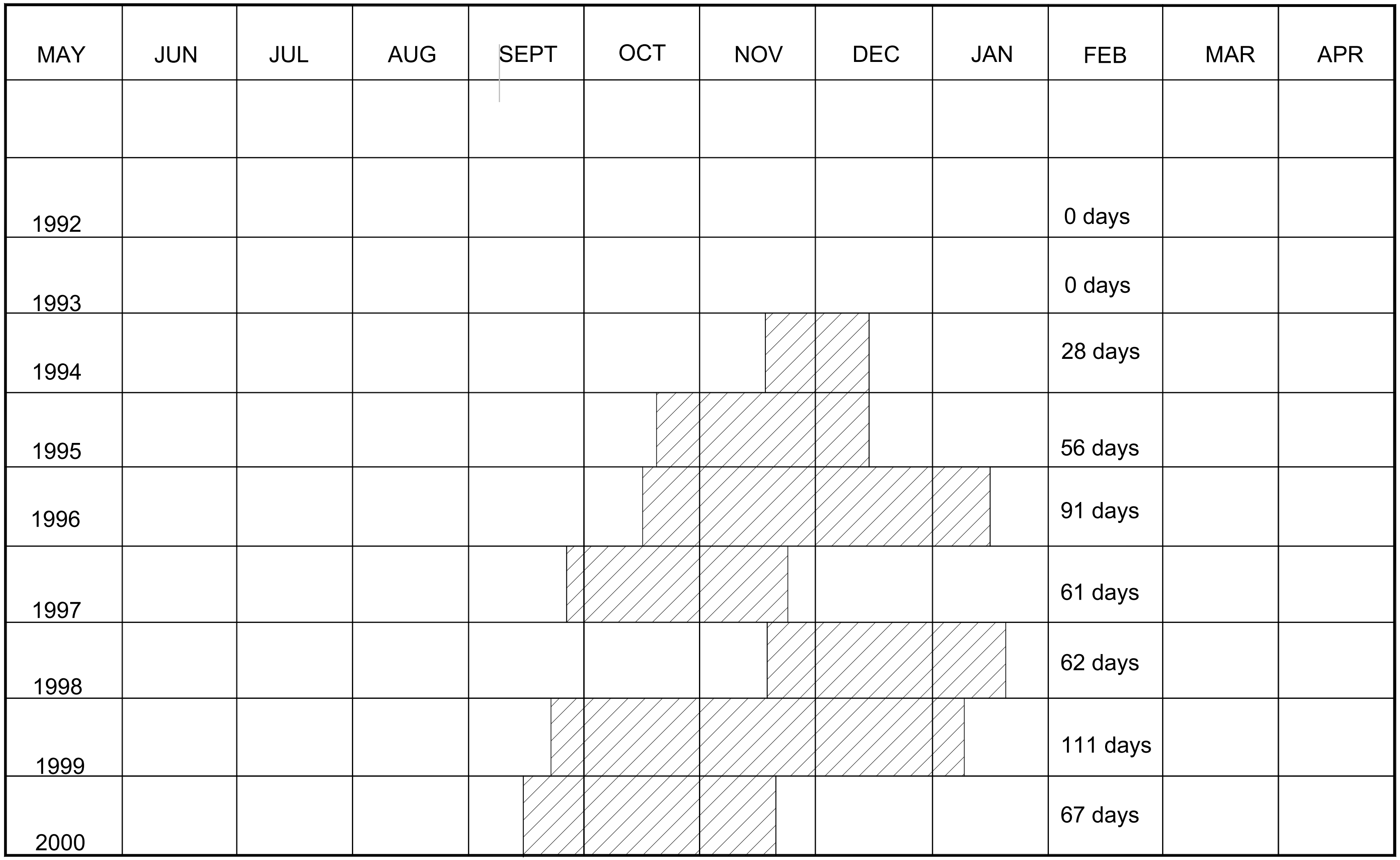


Figure 4.10 Periods of no flow in Great Ruaha river observed at Stolberger camp in Ruaha National Park



5 POSSIBLE CAUSES OF HYDROLOGICAL CHANGES IN USANGU

5.1 Introduction

The previous section has described SMUWC's approach to data collection and the study of the causes of the cessation of flow out of the Usangu wetland. There have been many causes put forward in the past, by a variety of institutes and individuals, to account for the drying up of the Great Ruaha river during the 1990s. Ideas have also been formulated by the SMUWC project team during the course of the project. In Section 5.2 these ideas have been collected together into nine separate possible causes. These possible causes are analysed in Section 5.3. The analysis leads, in Section 5.4, to several conclusions and the identification of work that still needs to be done in order to reduce the uncertainty over the possible causes of hydrological changes in Usangu.

The possible causes are now outlined. Brief background explanations are given to help the reader understand the suggested reasoning.

5.2 Possible causes

5.2.1 Long term trends in rainfall and evaporation rates

Possible cause 1: There have been long term changes in rainfall and evaporation rates in the project area, which have altered the hydrological balance

The main variables driving the hydrological cycle are rainfall and evaporation. Both the amount of runoff produced in the high catchment, and the water balance of the seasonal wetlands are critically dependent on the differences between the observed rates of rainfall and potential evapotranspiration. If persistent decreases in rainfall or increases in potential evapotranspiration have occurred over the longer term in the project area, these could be sufficient to cause reduction of flows in the Great Ruaha river downstream.

It is also possible that changes have taken place in the timing of the onset and/or the end of the rains, causing a change in the length of the dry season.

The analysis of rainfall and evaporation is presented in Section 5.3.1.

5.2.2 Dry season irrigation in the high catchment

Possible cause 2: Smallscale irrigated agriculture in the high catchment has increased in the last 10 years, and has begun to reduce river flows arriving in the Usangu plain in the dry season

The high catchment forms a vital part of the project area, because most of the runoff contributing to the wetlands in the Usangu plain originates from there. Since about 1989, several small areas in this region have been converted to the planting of vegetables, particularly potatoes. Irrigated areas in the high catchment are almost entirely along narrow valley floors, are localised and small. However, these small but possibly extensive abstractions may cause significant reductions in the river flows, which are routinely measured at gauging stations located at the foot of the escarpment, where the rivers arrive at the plain.

The analysis of dry season irrigation in the high catchment is given in Section 5.3.2.

5.2.3 Changes in river channels

Possible cause 3: Channel changes on rivers have occurred due to a number of factors, and these have contributed to changes in the hydrology of the Usangu plain

After the rivers leave the steep rocky channels through the escarpment they cross alluvial fans before entering the wetlands. The soft soils and gentle slopes of these fans provide unstable river courses, and there have been many instances in the recent past of abrupt changes of course of both major and minor rivers. Some of these changes are from natural causes, such as erosion and siltation, and it can be expected that further unpredictable changes will occur in future. Others are caused by man-made activities, particularly the construction of irrigation works, such as furrows or drainage embankments, on both small scale and larger irrigation schemes, and dug channels that transfer streamflows from one subcatchment to another. As a result the alluvial fans contain a complex network of small and large channels, several of which change from year to year. If any of these changes result in diversion of river flows either into fan swamps or to spreading out over the soils of the alluvial fans, then large losses of water will occur from evaporation which can reduce the runoff downstream substantially.

The analysis of changes in river channels is presented in Section 5.3.3.

5.2.4 Rice irrigation

Possible cause 4: Rice irrigation is responsible for significant abstractions at the beginning of the wet season, resulting in a delay in the time of onset of the natural rise of river flows downstream of the project area and also lower wet season flows in the Great Ruaha river

For the perennial rivers flowing from the high catchment, upstream of any irrigation abstractions, the flow at the end of the dry season is low and decreasing slowly with time. At the start of the wet season the first light rainfall showers in the high catchment are absorbed by the dry soils, but once the rain starts in earnest the flows in the rivers rise quickly, soon reaching rates comparable to those mid-way through the dry season.

If, however, these rising flows are diverted into irrigation furrows, and only small flows pass downstream of the offtake weir to provide compensation to downstream users, the natural rise in the lower river will be delayed. The length of the delay will depend on how rapidly the upstream river rises, because the flow in the river must exceed the total capacity of all the abstraction furrows before surplus water can find its way downstream to increase discharge.

In recent years there has been a tendency for rice irrigators to start their cultivation earlier and earlier, in order to gain from the higher prices for their product in the market. This means that all, rather than most, of the early wet season rising flows are diverted. This is likely to cause longer delays before the river downstream starts to rise.

The demand for irrigation water for rice is about 25% to 42% of the wet season flows in the rivers at the point of diversion, depending on climatic and hydrological conditions (Tables 2.5 and 2.6). This demand (giving rise to the irrigation 'impact') relative to inflow increases in drier years when less water is present to satisfy the abstraction capacity in Usangu of approximately 45 cumecs. The volume of water abstracted in the wet season is therefore likely to affect wet season flow downstream.

The analysis of the effect of rice irrigation on downstream hydrological changes is presented in Section 5.3.4.

5.2.5 Dry season abstraction in the Usangu Plains

Possible cause 5: Dry season abstraction for irrigation and other purposes on the alluvial fans is responsible for early reduction of dry season flows downstream of the project area

After the main rice crop has been harvested, a minority of farmers practice dry season irrigation of vegetables such as beans and tomatoes. These crops are normally planted on fields close to the top end of the wet season irrigation schemes where the supply of water from the river is more reliable when flows are low. The majority of these farmers are located on the alluvial fans to the south west side of the Usangu plain, closer to the main market outlet at Mbeya; here their activities consume much of the low flows available in subcatchments such as the Mkoji. Further to the east where some of the large state owned irrigation schemes are located, less dry season irrigation is practised. The overall crop water demand for dry season cropping is quite small, perhaps no more than 3 cumecs.

However, abstraction remains high during the dry season; between 10 cumecs (in a 4 in 5 year exceedance dry year) and 16 cumecs (in an average year). This water is used for purposes other than irrigating crops. These are: the supply of water through cropped fields to tail-end late-planted rice fields; the conveyance and supply of water for domestic use and livestock; the use of water for early preparation of land for the next wet season rice irrigation; and the rather haphazard and uncontrolled watering of fields where no crop is present. The latter can happen when fishermen and duck-hunters allow water into fields to create suitable conditions to sustain their livelihoods. These uses of water result in gross water utilisation far larger than that required to meet the net crop need, and they encourage the continuous opening of intake gates throughout the dry season. It is believed that this pattern of water use and the open intake gate settings are responsible for early reduction of dry season flows downstream of the project area.

Analysis of dry season irrigation effects is presented in Section 5.3.5.

5.2.6 Changes in the perennial swamp of the Eastern Wetland

Possible cause 6: Changes in the hydraulic regime of the Eastern Wetland have occurred which, for a given inflow into the wetland, cause a reduction in corresponding outflow

The Eastern Wetland consists of an enclosed area full of alluvial deposits. Two main perennial rivers, together with several ephemeral ones, flow into the wetland, with a single outflow at N'Giriama to the north. The Eastern wetland slopes extremely gently between the south western upstream end at Nyaluhanga and the outlet sill at N'Giriama, with a total drop of 3.6 m over a distance of 50 km along the main channel. These conditions allow for an unstable hydraulic regime affected by deposition and erosion, with much evidence of previous river channels, now long since abandoned, and changes in size, volume and location of open water lagoons in the perennial swamp.

These changes to river channels are not all natural, as fishermen and livestock herders working in the wetland have played a part in both opening and closing off smaller channels at different times for their own benefit. The hydraulic flow of water across such gently sloping ground is likely to be affected by any resistance from aquatic vegetation, which is reported to have grown markedly since the 1970s.

The analysis of changes in the perennial swamp is presented in Section 5.3.6.

5.2.7 Surface runoff contribution from the plains

Possible cause 7: The contribution of surface runoff from the plains to the Usangu wetland is significant in relation to river flow originating from the high catchment and, connected to this, changes to surface runoff in the plains caused by livestock are equally significant

The area of the plains, including all the alluvial fans across which the main rivers flow, is approximately 4 850 km^2, compared to the total area 15 960 km^2 of the high catchment surrounding the plains on the east, south and western sides. Although much runoff is generated in the high catchment due to large depths of rain falling there, the contribution of surface runoff from the plains needs to be considered further, since even a small depth over the plains might contribute a reasonable volume because of the size of the area.

The large concentrations of cattle roaming the *mbuga* at the downstream end of the alluvial fans will affect the soil by compacting the surface. This compaction may affect the infiltration capacities of the soil, and so change the surface runoff entering the wetland.

The analysis of the surface runoff contribution from the plains is presented in Section 5.3.7.

5.2.8 Groundwater contribution to the wetland

Possible cause 8: The contribution of groundwater to the Usangu wetlands is sufficient to maintain outflow to the Great Ruaha river during the dry season

The main groundwater recharge areas are the upland portion of the catchment above the escarpments, and the alluvial fans immediately below the escarpments. Groundwater is likely to reach the wetlands through lenses of permeable deposits, or through buried river channels. Groundwater also supports the flow in the rivers by baseflow contributions, especially in the lower parts of the alluvial fans, where deposits are finer. Groundwater may contribute, with the surface water inflow, to maintaining the outflow from the wetlands during the dry season.

The analysis of the groundwater contribution is given in Section 5.3.8.

5.2.9 Deforestation in the high catchment

Possible cause 9: Deforestation in the high catchment has led to decreased flows reaching the Usangu plains

The high catchment is the part of the project area that produces the most surface water runoff contribution to the rivers. It is thought that extensive deforestation may have taken place over this area during the last century.

Previous experimental catchment studies have shown that changes in total forest cover cause significant changes to the amount of runoff occurring for the same amount of rainfall. The possibility that this phenomenon has caused decreases to the flows in the rivers reaching the Usangu plains, and ultimately the Great Ruaha river, must be investigated.

The analysis of deforestation is presented in Section 5.3.9.

5.3 Analysis of possible causes

5.3.1 Possible cause 1: Long term trends in rainfall and evaporation rates

To examine for long term trends in rainfall, the daily records from 100 stations were selected for the 44 year period 1955-98. An arithmetic averaging technique was used to determine the daily areal rainfall over each of the sub-catchments shown in Table 5.1.

In addition, areal rainfall was calculated over larger catchments such as the whole of the project area down as far as the two streamflow stations on the Great Ruaha river, at Hausmann's Bridge and Msembe. Separate estimates of mean annual areal rainfall were made for the high catchment and the plains. The sequence of annual areal rainfall values for the catchment upstream of gauging station 1KA59 at Msembe is shown in Figure 5.1. A decreasing linear trend is noted, but it is not found statistically significant (Table 5.1). Similarly, Figure 5.2 shows the annual sequence of areal rainfall over the high catchment; this part of the catchment is particularly important as it is where most of the runoff is generated. Again a slightly decreasing trend is evident, but it is not statistically significant. Figure 5.3 shows the annual sequence of areal rainfall over the Usangu Plains. Again, a slightly decreasing trend is evident, but it is not statistically significant.

The results of examining for trends in all the 11 sub-catchments are shown in Table 5.1. Four of the subcatchments exhibited an increasing trend, four revealed a decreasing trend, while there were insufficient raingauges located close to the other three subcatchments to make a worthwhile analysis. None of the sub-catchments exhibited a decreasing trend which was statistically significant.

Although these trends in the rainfall are judged to be not statistically significant, it is known that the amount of runoff generated from rainfall is very sensitive to slight changes in the rainfall value. Since it is ultimately changes in runoff in the sub-catchments, rather than rainfall, that might affect the river flows downstream and therefore the wetland behaviour itself, a general procedure for converting annual values of rainfall to runoff is needed. Further analysis is still required in the future that would convert the annual rainfall sequences to annual runoff sequences, and the latter should then be analysed for trends.

To examine for long term trends in evaporation, a search was made for long records of climate data collected from within the project area. No reliable records exceeding about 12 years were found that did not have several periods of missing data. It was necessary, therefore, to collect records for the 39 year period 1959-97 (the period of record available) from Dodoma, one of the main synoptic stations operated by the Directorate of Meteorology. Although it is located a considerable distance to the north of the SMUWC project area, the dry climate there was judged to be similar to that occurring over the low-lying plains and wetland areas of the project area.

Daily records of temperature, humidity, wind run and bright sunshine were collected and processed by the Penman-Monteith technique to produce daily estimates of potential evapotranspiration; annual values of these estimates are summarised in Figure 5.4. Inspection reveals that the values appear very consistent for the period 1959-90, with possibly slightly higher values for the last 7 years of the record. A fitted trend line indicated a slight increase in the long term, but it was not found to be statistically significant.

A study of the timing of the onset of the rains in Usangu has been made and is reported in Section 5.3.4.

Table 5.1 Results of linear trend analysis of annual rainfall

Station code	River Name	No. of rainfall stations	Start year	End year	No. of years	Mean annual rainfall (mm)	Slope of the trend line (mm/year)	T statistics	T critical	Remarks
1ka7a	Chimala at Chitekelo	10	1955	1998	44	1480.6	-8.676	-1.72	2.6996	No significant trend
1ka8a	Gt Ruaha at Salimwani	13	1955	1998	44	1411.8	-2.948	-0.61	2.6996	No significant trend
1ka9	Kimani at Great North Road	8	1955	1998	44	1003.8	6.392	1.90	2.6996	No significant trend
1ka10a	Mlomboji at Mlomboji	5	1955	1998	44	928.8	0.952	0.25	2.6996	No significant trend
1ka11a	Mbarali at Igawa	22	1955	1998	44	1169.6	0.556	0.24	2.6996	No significant trend
1ka12	Halali at Iyayi	11	1955	1998	44	817.4	0.493	0.28	2.6996	No significant trend
1ka15a	Ndembera at Ilongo	15	1955	1998	44	971.1	-0.022	-0.01	2.6996	No significant trend
*1ka16	Lunwa at Igurusi	19	1955	1998	44	1400.6	-4.334	-1.16	2.6996	No significant trend
1ka23a	Hukuni at Iyayi	10	1955	1998	44	795.7	-0.070	-0.04	2.6996	No significant trend
1ka27	**Gt Ruaha at Hausmann's Bridge**	**83**	**1955**	**1998**	**44**	**836.8**	**-4.570**	**-2.58**	**2.6996**	**No significant trend**
1ka33b	Ndembera at Madibira	18	1955	1998	44	944.8	-0.687	-0.33	2.6996	No significant trend
*1ka51a	Umrobo at d/s GNR		1955	1998	44	1312.2	-6.445	-1.84	2.6996	No significant trend
*1ka50a	Mswisi at Mswisi		1955	1998	44	1424.5	-5.293	-1.40	2.6996	No significant trend
1ka56	Ruaha at Malangali		1955	1998	44	1362.1	10.885	-1.76	2.6996	No significant trend
1ka59	**Gt Ruaha at Msembe**	**98**	**1955**	**1998**	**44**	**810.4**	**-4.204**	**-2.46**	**2.6996**	**No significant trend**
	Mkoji	13	1955	1998	44	1448.4	-4.407	-1.30	2.6996	No significant trend
	High Catchment	**70**	**1955**	**1998**	**44**	**1529.2**	**-5.759**	**-2.16**	**2.6996**	**No significant trend**
	Usangu plains	**13**	**1955**	**1998**	**44**	**735.6**	**-2.991**	**-1.59**	**2.6996**	**No significant trend**

* These are small subcatchments of Mkoji their rainfall data is taken from the neighbouring stations

5.3.2 Possible cause 2: Dry season irrigation in the high catchment

Details of the full areal extent of dry season irrigation in the high catchment are not at present known. During field trips a number of small schemes fed from springs in the headwaters of the Great Ruaha river above Salimwani have been visited. Other vegetable growing areas are known to exist in the headwaters of sub-catchments such as the Mkoji, but it is not known whether they are irrigated using those streams as sources. Field visits have confirmed that no such activities have occurred in the headwaters of the Kimani subcatchment to date, so this subcatchment may be selected as a control.

Overflights and ground visits have indicated that traditional valley-bottom cultivation, known as *vijaruba*, is prevalent in the headwaters of the Ndembera, Kioga and eastern Mbarali subcatchments. This practice is described in more detail in Section 6.7.6.

It is also known that these types of vegetable irrigation are a relatively recent phenomenon, so three time periods were chosen for analysis: up to 1988, 1989-93, 1994-98, with the first window representing the natural state of the streams before the onset of this type of irrigation. These periods bear no relation to the time periods previously chosen (Section 3.9.2) for the wet season rice irrigation, which commenced on the alluvial fans at a much earlier time.

To determine any effects of dry season irrigation in the high catchment, the records from the river gauging stations at the foot of the escarpment were examined. Two analyses were undertaken for the three time windows mentioned above. First, the low flow end of flow duration curves were compared, and some differences were detected, but not consistently. Second, the volumes of runoff during the dry season, 1 July–30 November, for each year of record, were compared and a linear trend line fitted. Results were inconclusive, with some of the sub-catchments showing a decreasing trend and others an increasing trend. A major difficulty is that the Kimani sub-catchment, being used as a control, exhibited a decreasing trend in annual volumes of dry season flow, even though no dry season irrigation has ever been practised on this subcatchment.

It is not possible to provide definite proof, from examining the streamflow records, that dry season irrigation is reducing flows downstream. But the extensive nature of this practice, even if individual areas are limited, will, in all likelihood, cause a slight, but increasing, reduction to flows towards the end of the dry season.

5.3.3 Possible cause 3: Changes in river channels

The rivers on the Usangu plains frequently silt up their beds and periodically break their banks leading to new courses and flooding. This is because on reaching the plains their gradient decreases abruptly and considerable deposition of alluvial sediment then occurs. For example, in its upper reaches, south of the Tanzam Highway, the Kimani River flows at relatively high velocity, at or near bedrock, in an incised river valley. The river undergoes a rapid change of slope, from about 1% down to 0.2%, within a 4 km reach immediately downstream of the Tanzam Highway. This change of slope reflects a change of geomorphological setting from a deeply incised mountain valley to an alluvial floodplain.

Table 5.2 lists some of the changes known to have occurred on the five main perennial rivers crossing the alluvial plains. The changes can occur for either natural or man-made reasons, or even a combination. For example an extreme flood can cause the river to overtop and erode its banks, or during the construction of a large irrigation scheme the rivers in the area can be diverted by flood embankments. But several of the changes are due to traditional irrigation diversions being developed in unsuitable locations; when a large flood arrives the river may choose to follow the irrigation channel, rather than its previous downstream course.

Table 5.2 Known historical channel changes to main perennial rivers

Year	River	Channel change	Natural or Man-made	Source
End of 1800s	Mbarali	During 1800s used to flow across the north-east corner of Mbarali Farm 1, but now moved to southern boundary of this farm	Natural	Hazelwood & Livingstone, 1978
1930s	Mbarali	Moved further west, and took over lower course of Kimani River	Natural	Hazelwood & Livingstone, 1978
Prior to 1949	Kimani	Major relocation, starting from the very upstream end of the floodplain	Uncertain	WER Engineering Ltd, 1993
1949	Kimani	Moved 1-2 km west to new channel, starting from point 1 km north of existing Mbuyuni weir	Partly natural as old course was close to maturity, partly triggered by traditional irrigation canal	WER Engineering Ltd, 1993
1955	Great Ruaha	One channel existed before this date, two after it with one going to swamp and the other on original course	Probably through irrigation cut	Lankford, 1999 Hazelwood & Livingstone, 1978
1968	Great Ruaha	Changed direction to spread into series of swamps, old channel abandoned	Natural	Lankford, 1999
1970s	Chimala	Diverted through old irrigation channel, to form Chosi River	Man-made	Hazelwood & Livingstone, 1978
1974	Ndembera	Moved south west to flow diagonally across alluvial plain, creating seasonal swamp	Disastrous flood	Madibira Rice Project, Review of Feasibility, June 1992

Table 5.2 Known historical channel changes to main perennial rivers (continued)

Year	River name	Channel change	Natural or Man-made	Source
1990	Chimala	Previously flowed to join Itambo River, now flows into Ifushiro swamp, due to irrigation bund	Man-made	Lankford, 1999
1990	Great Ruaha	Drainage altered by irrigation flood protection bunds	Man-made	Lankford, 1999
1995	Mbarali	Channel moved further north, back to flowing along southern boundary of Mbarali Farm 1	Natural	Lankford, 1999
1998	Ndembera	River rerouted back to its old course further north east, during construction of Madibira rice project	Man-made	Field visit to Madibira Rice Project, 1999

It is noticeable that each river has at least two separate dates when changes have occurred, some even more than this. Since these rivers between them convey over 80% of the inflow from the high catchment to the wetlands, there is no doubt that these channel changes have caused alterations to the downstream flows. But it is difficult to attach quantities both to the diverted flows and the flows remaining in the river channels.

It is concluded that changes in channels are likely to have contributed in the past to changes in the hydrology of the Usangu Plains. However, it is not possible to link specific channel changes with the hydrological records of stations downstream and to quantify the contribution to the hydrological change.

5.3.4 Possible cause 4: Rice irrigation

In this section summaries of two separate analyses are presented. The first analysis is described in detail in Supporting Report No 11 as part of the computer modelling of the Usangu Basin undertaken by WREP. The second analysis draws on the application of the Sutcliffe-Parks submodel to the Eastern Wetland, which is described in Section 4.8.

Before examining the delay between the onset of the rains and the onset of the rise in the hydrograph downstream, a study was done of the timing of the onset of the rains. The question of interest was whether there has been any long term shift in the date of the onset of the rains.

The 100 daily rainfall records were divided into 6 groups (A to F), according to whether their mean date of onset of the rains fell in the 30th, 31st, 32nd, 33rd, 34th, or 35th decad (10 day period) respectively, commencing from 1 January (Appendix C). The majority of the records fell within the three groups C, D and E. For each ten year period the mean date of onset of the rains for a single group was calculated. The result was expressed in decads since the start of the calendar year. For example, if the date of onset was found to be 32, this would be the period 11-20 November. The results for all 6 groups are shown in Figure 5.5. In general cyclical variation in the onset dates can be seen, but apparently no long term increasing or decreasing trend with time. There is therefore no trend in the timing of the start of the rains that could cause a similar trend in the start of the rise of river flow.

Analysis of the effect of rice irrigation has focused on investigation of whether it has affected the delay between the onset of the rains and the onset of the main rise in the hydrograph downstream, and whether it has affected wet season flow volumes in the Great Ruaha river.

To determine whether wet season rice irrigation has affected the onset of the main rise in hydrograph on the Great Ruaha river, the flow record and areal rainfall series for the river station at Hausmann's Bridge were examined. For the rainfall series, the date of onset of the rains for each year was abstracted. For the flow record, the date of onset of the main rise in the hydrograph was abstracted. The difference in days between these dates is shown in Figure 5.6 for each year of the period 1958-98. The windows belonging to each phase of the irrigation development in Usangu are also shown. The average delay is 75 days between the onset of the rains and the corresponding main rise in the hydrograph downstream, and there does not appear to be any discernible long term trend in this variable. So it appears from this analysis of the Hausmann's Bridge records that wet season rice irrigation has had no effect on the timing of the main rise of the hydrograph downstream of the Usangu wetland.

In order to investigate the effect of wet season abstractions for rice irrigation on downstream flows, it was necessary to fill in and extend flow records that were missing at Hausmann's Bridge. The daily flow records at Msembe Ferry and at Hausmann's Bridge were compared over their common period of record. The upstream station, 1KA27 Hausmann's Bridge, possesses records from 1957 to 1988; the downstream station, 1KA59 Msembe Ferry, has records from 1963 to 2000.

Some sophisticated hydrological routing models were used initially, but when these proved unsatisfactory a simpler regression relation was fitted for separate dry and wet season periods. Different lag times of between 0 and 4 days were tried, but, somewhat surprisingly, the lag time of zero days proved the best. The regression equations obtained are shown in Table 5.3. These indicate that during the dry season the flows at the downstream station Msembe Ferry are slightly less than those at the upstream station; this is probably due to evaporation from the extensive shallow pools on this river reach.

Table 5.3 Seasonal relationships between flows at 1KA59 Msembe Ferry and 1KA27 Hausmann's Bridge

Season	Regression equation	Lag time (days)
Dry season 1 June-31 January	Flow at 1KA59 = 0.9217 Flow at 1KA27	0
Wet season 1 February-31 May	Flow at 1KA59 = 1.0046 Flow at 1KA27	0

Employing these regression equations in both directions it was possible to infill the missing flow records at both stations for all the 42 years 1957-98, except for the three years 1988-90. During this period insufficient reliable records existed at either station, and it was necessary to employ a rainfall-runoff model to reconstruct the daily records.

The reconstructed record for Hausmann's Bridge station is shown in Figure 5.7. An analysis was undertaken to detect any trends in the mean flows for the three different periods:

i) Annual, 1 January-31 December (Figure 5.8)

ii) Wet season, 1 January-31 May (Figure 5.9)

iii) Dry season, 1 July-30 November (Figure 5.10)

The short horizontal lines in these figures, showing mean flows for limited periods, include some of the windows used to indicate different phases in the development of irrigation in Usangu plains (Section 3.9.2). Table 5.4 shows that only the trend for dry season discharges is statistically significant.

So, although there is a marked decline in dry season flows, there does not appear to be any corresponding decline in wet season or annual flows. Figure 5.11 shows that the wet season flows form the greater part of the annual flows, and the dry season flows are represented by the small differences between wet season and annual flows for each year of record. So this marked dry season flow reduction will not produce a corresponding decline in the annual flows, if the wet season flows hold steady during the longer term. This suggests that inflows to Mtera Reservoir from the Great Ruaha catchment are not decreasing, and therefore that a decrease in inflows does not explain the lowering of reservoir levels and shortages of power described in Section 2.7.

The lack of significant change in downstream flows in the wet season, despite the large abstraction (estimated at 19% of the river flow at the point of diversion in an average year (Table 2.3), suggests that abstractions in the wet season are taking water out of the system that would have been lost anyway before reaching Hausmann's Bridge gauging station.. This loss would have occurred by evaporation in either the Western or the Eastern Wetland. The areal extent of flooding of the Eastern Wetland is not thought to vary much from year to year. This is because of the relatively abrupt increase in slope at the outer edge of the surrounding floodplain. This, in turn, would imply that the variation in evaporative loss occurs in the Western Wetland. This is supported by the diverse nature of vegetation (*mbuga* mixed with woodland) in the Western Wetland, which indicates variation in the natural extent of flooding from year to year in this area.

Table 5.4 Result of linear trend analysis, 1KA27 Great Ruaha river at Hausmann's Bridge

Period	River Name	Start year	End year	No. of Years	Mean flow (m^3/s)	Slope of trend line (m^3/s per year)	T Statistics	T Critical	Remarks
Annual	Gt Ruaha at Hausmann's Bridge	1958	1998	41	68.95	-0.950	-1.05	2.7086	No significant trend
	Gt Ruaha at Msembe	1958	1998	41	71.06	-0.943	-1.03	2.7086	No significant trend
Wet season	Gt Ruaha at Hausmann's Bridge	1957	1998	42	153.22	-1.941	-0.87	2.704	No significant trend
	Gt Ruaha at Msembe	1957	1998	42	152.39	-1.790	-0.90	2.70	No significant trend
Dry season	Gt Ruaha at Hausmann's Bridge	1957	1998	42	7.58	-0.273	-4.90	2.704	Significant declining trend
	Gt Ruaha at Msembe	1957	1998	42	7.18	-0.251	-4.83	2.704	Significant declining trend

It appears that, because wet season outflow from the Eastern Wetland has not changed significantly, the abstraction for irrigation has removed water that previously would have flooded and been lost from the Western Wetland. Water that causes the flooding and outflow (in the wet season) from the Eastern Wetland is still flowing past Nyaluhanga.

If this is so, this would suggest that the losses that used to occur in the Western Wetland have been, to some extent, transferred to and now occur in the irrigated areas. This would account for the observed lack of a significant downward trend in wet season flows in the Great Ruaha river downstream of the Eastern Wetland.

The application of the Sutcliffe-Parks submodel to the Eastern Wetland (Section 4.8) gave results which were at variance with those described above. It was found, for instance, that an increase in the rate of wet season upstream abstraction created delays to the time when the downstream hydrograph at N'Giriama initially started to rise; however the timing of the peak flow was unaffected. Another consequence of these increased abstractions was that the wet season volumes of outflow from the Eastern Wetland were slightly reduced. However, the minimum storage and surface area of the perennial swamp reached at the end of the dry season were independent of the abstractions, and depended only on the rate of dry season inflows.

It is concluded that although rice irrigation is responsible for significant abstractions at the beginning of the wet season, it does not affect the time of rise of the river flow downstream of the project area; nor does it cause noticeably lower wet season flows.

5.3.5 Possible cause 5: Dry season abstraction in the Usangu plains

A significant downward trend in dry season flows in the Great Ruaha river has been identified (Figure 5.10, Table 5.4). In the reach of river between Hausmann's Bridge and the outlet of the Eastern Wetland at N'Giriama, there are only a few minor tributaries. Bearing in mind the close similarities between the flows at Hausmann's Bridge and Msembe Ferry downstream, as given by the regression equations in Table 5.3, the assumption was made that there would also be little difference between the flows at Hausmann's Bridge and those at N'Giriama. Therefore the 42 year record of daily flows at Hausmann's Bridge was taken as occurring at N'Giriama, without any changes in magnitude. It was also assumed that there had been no major changes over this 42 year period to the rock sill at the outlet. The rating curve for N'Giriama (Table 3.6, Figure 3.15) was used to convert the flows at Hausmann's Bridge to the equivalent daily water levels at the wetland outlet (Figure 5.12). The water levels actually observed by SMUWC field staff at N'Giriama during 1999 and 2000 are also added for comparison.

Figure 5.12 provides a good visual image of several important findings. Regarding the maximum water levels attained each year, several reached above the 1013.0 m level at the start of the record, including the three consecutive high rainfall years of the early 1960s, when several large African lakes, including Lake Victoria, reached extremely high levels. This is followed by a group in the mid-1970s which all lay below 1012.5 m, due to the series of low rainfall years. In the period 1980-96 there was a slight recovery; only the years 1997, 1999 and 2000 appear low, separated by the very high value occurring during 1998.

Examination of the minimum water levels tells a different story. In the first 15 years the fluctuations appear sensible and natural, with lower water levels reached at the end of dry years (when the preceding rise is small), and high water levels at the end of wet years (when the preceding rise is larger than normal). From the mid 1970s these minimum levels appear to have declined, until they dipped below the level of the rock sill in the early 1990s.

It is immediately tempting to attribute this observed decline to the gradual increase in dry season abstraction of irrigation water upstream that has occurred over the last 30-40 years. While this reason certainly cannot be excluded, there may be other factors at work which need further investigation. For example, wet season abstractions for irrigation may cause less water to enter the Eastern Wetland, resulting in lower swamp water levels at the end of the wet season. This could contribute to the downward trend in outflows at the start of the dry season.

As another example, in 1974 the Ndembera river flooded and created a new path, so that a group of wetlands was created on the plains where the present Madibira irrigation scheme was constructed recently. It is possible that during the dry season the flow of the Ndembera was swallowed up by these wetlands, and no dry season flow from this river reached the Eastern Wetland. The effect on the downstream flows at N'Giriama is exactly the same as abstraction for dry season irrigation, diversion of streams into a fan swamp, or spreading of flows over an alluvial fan, so it is difficult to assign blame to one of these causes until all others, including blockage of channels between wetland and the outlet, have been fully investigated. In Supporting Report No. 11, an analysis is described which estimates the relative differences between fan losses and those due to dry season abstractions.

The most important conclusion to be drawn is that Figure 5.12 provides definite evidence that the reduction in dry season flows in the Great Ruaha river is not a recent phenomenon. It has certainly been going on since the mid-1970s, and possibly even earlier. But public awareness was raised only when it progressed far enough for the water levels at the end of the dry season to dip below the rock sill itself, and cut off the flows completely to the downstream river.

Another notable feature of Figure 5.12 is the difference, between the early part of the record and the most recent period of the 1990s, in the decrease in flows (called the recession) after the annual maximum value. During the 1960s this is a smooth curve with a decreasing gradient as the end of the dry season approaches. In the 1990s, for the same magnitude of annual maximum, the curve starts dropping smoothly but then plummets steeply to zero flow.

A more detailed study of the recession curves for the record at Hausmann's Bridge was conducted. Figure 5.13 shows mean recession curves for the 3 month period mid-August to mid-November. Each recession curve represents the mean of a group of several years' recessions. The years are grouped according to the periods of irrigation development mentioned previously in Table 3.12. The top line represents the period prior to 1974, with a long sustained recession, giving a flow of about 3 m^3/s from the wetland at the end of the dry season. Between 1974 and 1985 there is a lower but still sustained recession; it is steeper than the first curve for the same magnitude of flow, and at the end of the dry season the flow from the wetland is reduced to about 0.5 m^3/s. The remaining two curves represent the conditions since 1986, with very low and steep recessions which are not sustained, and flow drops to zero before the end of the dry season.

For an unchanged rock sill at the outlet, with a fixed rating curve, steepening of the recessions can be caused by one or more of three things:

i) Reduction of inflow to the wetland, due either to dry season abstractions (for irrigation or other purposes) or diversion of river flows into fan swamps or onto alluvial fans where evaporation and percolation losses take place.

ii) Increase in evaporation from the wetland.

iii) Reduction in the volume of stored water in the wetland that is physically connected to the outlet.

Although it appears that dry season crop water requirements are not excessive (Table 2.3), in recent years the canals to the main state irrigation schemes have been abstracting large flows of water for other purposes. This is undoubtedly contributing to the drying up of flows through Nyaluhanga into the Eastern Wetland. The flow at Nyaluhanga has been observed to come close to ceasing at the end of the dry seasons of 1998 and 2000, and in 1999 it actually dried up for several weeks. This is considered likely to be one of the major causes of the decline in outflow from the Eastern Wetland in the dry season.

Evaporation from the Eastern Wetland could change as a result of an increase in surface area of open water. This is discussed further in Section 5.3.6.

A change in the volume of stored water in the wetland that is physically connected to the outlet could arise in the dry season as a result of a blockage in the wetland. This could cause a separation of the wetland into sections which are isolated from the outlet. The drainage of the sections which remain connected to the outlet would give rise to steeper recessions by virtue of their lower storage volumes. Such blockages are discussed further in Section 5.3.6.

It is concluded that dry season abstraction on the alluvial fans is one of the factors responsible for the early reduction of dry season flows downstream. An increase in evaporation and blockages in the wetland can have a similar effect and these are considered in the following section.

5.3.6 Possible cause 6: Changes in the perennial swamp of the Eastern Wetland

People living close to the Eastern Wetland express opinions that several changes have occurred to it during the last 25 years. Interviews with the local inhabitants of Rujewa and users of the swamp point to the following significant changes having occurred in the Eastern Wetland since the 1970s:

- Location and surface area of the perennial swamp, eg it is no longer possible to drive in a direct line from Ikoga to N'Giriama in the dry season.
- Location, surface area and volume of open water lagoons in the perennial swamp.
- Channel configuration from year to year due to various causes, eg, lack of hippopotami maintaining open channels, local fishing practices, and the blocking of channels by causeways to allow livestock access to additional grazing lands without loss of animals in the channel bottom mud.
- Land cover and land use, eg, increased growth of aquatic vegetation in the perennial swamp (indicated by the increase in time needed by fishermen to reach the centre of the swamp from the edge of the *mbuga*), displacement of grazing wildlife from the *mbuga* by livestock.

Three such changes, which can in some way be measured, are discussed here.

Area covered by aquatic vegetation

Changes have occurred over time to the open water lagoons in the centre of the perennial swamp. For example, Figure 3.11 is traced from the standard set of 1:50 000 topographic maps of Tanzania; this shows the location of the open water lagoons based on aerial surveys in May-July 1977. Twenty-two years later the lagoons took the form shown in Figure 3.10, based on the hydrographic survey carried out by SMUWC during June 1999. Not only have the lagoons markedly altered their location, but their total size has increased from 1.5 km^2 to 9.6 km^2.

The fishermen relate a different story concerning vegetation cover. They complain that since the early 1970s, there has been a considerable growth of vegetation which has made it much more difficult for them to reach the centre of the perennial swamp from the edge of the seasonal wetland. Where before it might take 2 hours to canoe this distance, now it takes 6 hours. Some of this vegetation is quite thick, and needs a panga to cut a channel through it. Topographic surveys conducted in October 2000 of the channels lying between Kidumka and the North West channel confirmed this impression. The majority of the channels are still located in exactly the same position as they are shown on the 1958 aerial photographs (this comparison is also described in Section 5.4.4 of Supporting Report No. 14). At that time they were said to be about 20 metres wide, 2-3 metres deep, with a steady flow of water throughout the year. Now they are still the same width, but covered by a thick mat of aquatic vegetation, with no visible open water surface, and topographic surveys show that the depth below the mat has been reduced to 1.0-1.5 m.

So it seems that over the years there may have been an increase of vegetation along the outer periphery of the wetland, but a decrease in the centre. Such changes are important, because they can alter the rate of evaporation from the swamp and lead to either a corresponding gain or loss of water from the wetland compared with the alternative scenario. Evaporation from open water takes place at a rate approximately 25% greater than that from a surface covered by aquatic vegetation, because the change in the reflective capacity of the surface allows less incoming radiation to be reflected back into the atmosphere. For example, if the surface of the wetland was completely covered by aquatic vegetation, the total evapotranspiration loss during the year is estimated as 1 940 mm, while if the surface was all open water the evaporation loss is estimated as 2 420 mm; This represents an increase of nearly half a metre.

If there had been a very marked change over the years from a complete cover of aquatic vegetation to a completely open water surface, then this difference would cause a large loss of volume of water stored in the wetland at the end of each dry season, and so ultimately reduce the flows downstream in the Great Ruaha river. In practice, it appears there have been some changes to the cover of the wetland, but nothing as extreme as this.

It is concluded that the main effect of the change in vegetation (growth of reeds since the early 1970s) has been to impede the flow of water through the wetland. Channel blockages are discussed below; it is likely that the growth of vegetation has contributed to such blockages.

Siltation

Another possible change occurring to the wetland is in siltation. This is discussed in further detail in Sections 3.3-3.5 of Supporting Report No. 13 Water Quality Assessment.

The results show a distinct progression of generally clear and low turbidity inflowing river waters across the alluvial fans picking up fine, suspended sedimant from the areas of the rice farms and other cultivation/irrigation drainage systems, which then remains in suspension until flow velocities reduce within the initial *ihefu* areas. Sediment is then deposited, causing a gradual infilling of the western swamps, including the western end of the Ruaha swamp, thereby building up a soft, oozy mud layer on the floor of the swamps. Progressing eastwards through the Ruaha and Nyangokolo swamps, the muddy, bottom ooze decreases and the water progressively clarifies until a clear water with much reduced weed and lily cover is reached in the Lyangulaje swamp to the east.

A crude estimate of sedimentation rates within the *ihefu* from the small amount of data available suggests that some 30 000 tonnes of suspended sediment flow into the Eastern Wetland in an average year. The one third of the flow, which is estimated to proceed into the Ruaha swamp, would there settle out an average depth of around 20 mm of soft, gelatanous sediment if evenly deposited across an area the size of the Ruaha swamp. This is a highly significant amount since, with an average probed soft sediment depth of around 700 mm, it suggests that progressive siltation has been a dominant mechanism within the *ihefu* for only the past few decades – since the construction of the large commercial rice farms.

Channel blockages

There is some evidence that water from the perennial swamp is presently prevented in some way from reaching the outlet of the wetland at N'Giriama at the end of the dry season. Initially it was thought that the reason the Great Ruaha river dried up for the last few years was that the water level in the perennial swamp eventually sunk so low that it was below the level of the rock sill. A field inspection in January 1999, after the normal rains failed to come in December 1998, showed that there was still a pool of water at the outlet, but its level had sunk below the rock sill. But on moving upstream from there it became apparent that the river reach was just a series of disconnected pools, with no water flowing between them. An aerial survey in the same month revealed that the perennial swamp still covered an area of 64 km^2, so there was a great volume of water still stored upstream of the outlet.

After the altitudes of the control beacons were confirmed by topographic survey in November 2000, it was possible to calculate the relative heights of the perennial swamp and the outlet. Results indicate that the water level of the perennial swamp at Nyangokolo swamp on 14 October 2000 lay 2.17 m above the rock sill, and even the bottom of this part of the swamp lay 1.23 m above the rock sill. At the northernmost tail of the perennial swamp, close to temporary bench mark (TBM) MA1, the water level still lay 0.95 m above the rock sill, while the swamp bottom there lay 0.38 m above the sill. Therefore these surveys indicate that the perennial swamp is perched above the level of the outlet, and there is some sort of blockage preventing the water contained in it reaching the outlet at the end of the dry season. This concept is shown in Figure 5.14. These blockages may be either formed naturally, due to siltation or dense aquatic vegetation growth, or alternatively man-made, either from causeways erected by the pastoralists across the channels or from blocking off of certain channels by the fishermen. The effect of the blockage is to reduce the volume of water in storage that can drain through the outlet. The reduced storage volume produces lower outflows and steeper recessions during the dry season, as shown in Figure 5.13. The blockage of the perennial swamp is also discussed in Section 2.5 of Supporting Report No. 14.

On the basis of the information currently available, it is concluded that changes in the hydraulic regime of the Eastern Wetland have occurred, and that these are a possible cause of the reduction in outflow. However, it is difficult to separate the effect of changes in the wetland from the effect of dry season abstraction upstream.

5.3.7 Possible cause 7: Surface runoff contribution from the plains

The plains are delineated by the sharp change in gradient of the river channels at the base of the escarpment, so that all the major alluvial fans are included within the area of the plains. The plains are divided into two roughly equal portions, one of 2 360 km^2 surrounding the Western Wetland, and the other of 2 480 km^2 surrounding the Eastern Wetland. Their combined area is 4 850 km^2, which is just 30% of 15 960 km^2, the total area of high catchment surrounding the plains on the eastern, southern and western sides. So although the plains appear extensive when crossing them, partly caused by their extreme flatness, they actually form less than a quarter of the complete project area.

To estimate the surface runoff likely to occur from the plains, use has been made of the regional rainfall-runoff relation shown in Figure 5.15. To obtain this, Drayton *et al* (1980) analysed observed river flows and areal rainfall from 38 catchments spread throughout Malawi. Since this country is located immediately to the south, with similarities of both topography and seasonal rainfall distribution, the relation is considered applicable to the SMUWC project area.

The broad relation marked 'Runoff' shown in Figure 5.15 indicates that, although runoff increases as rainfall becomes larger, runoff is not just a fixed proportion of rainfall. If P represents the mean annual rainfall (mm), and Y represents mean annual runoff (mm), then this relationship is represented by the equation Y = 0.71 (P – 690). This means that if the rainfall during one year is very low, say less than 690 mm, then no runoff occurs, and only when rainfall exceeds 690 mm does runoff start to occur. Of the rainfall excess above 690 mm, 71% is converted to runoff, and the remaining 29% serves to give a gradual increase in the actual evaporation amount.

The mean annual rainfall occurring over the project area was shown earlier in Figure 3.1. The immediate surrounds of the Eastern Wetland receive, on average, between 600 and 700 mm per year. Between 700 and 800 mm fall on the plains around the Western Wetland, gradually increasing to 900 mm at the foot of the southern escarpment.

Applying the broad rainfall-runoff relation to this estimated mean annual rainfall indicates that, in principle, no runoff depth occurs from the dryland of the plains surrounding the Eastern Wetland. This includes both the gently sloping land covered by thorn bushes which lies above the wetland, and the flatter *mbuga* where the cattle graze during the dry season, but which is covered by seasonal wetland during the rainy season. However some runoff will be generated over the alluvial fans in the plains surrounding the Western wetland, in fact at any place where the rainfall exceeds 690 mm. But the small runoff depth, combined with the minor proportion of the project area covered by the plains, means that the contribution of runoff from the plains will be, in general, low.

It must be emphasised that this is a broad relationship which is applicable only to dryland conditions. During very intense storms some small amounts runoff will occur, but most of it will be evaporated during subsequent days of sunshine. Of course as soon as the *mbuga* is covered with water, then any rainfall will make a 100% contribution to the increase in water stored in the wetland itself. But the most important principle remains, that the major portion of the surface runoff feeding the wetlands is produced by the upland areas surrounding the plains which receive the higher rainfall, and very little, if any, is produced from the plains which surround the Eastern Wetland.

In addition to the low rainfall, the soils and topography of the floodplain themselves inhibit runoff. At the end of the dry season the clay soils are highly cracked, enabling any surface runoff to run down the cracks. Absorption of water by the clays from below and above causes the soils to swell at the base and at the top of the profile, closing the cracks. Horizontal movement of water through the clay soils is minimal. The very flat slopes (1:14 000) and slightly undulating topography promote surface ponding on the floodplain, preventing surface water from reaching the swamp in significant quantities.

Since minimal runoff occurs from the plains under natural conditions, the incremental impact of livestock on the generation of runoff is negligible. Under natural conditions the *mbuga* would have been populated by herds of grazing wildlife. These would have had a similar effect on the soils as the cattle today. Areas which are under grazing pressure are located in areas of bomas on the alluvial fans surrounding the *mbuga*. Such overgrazed areas would normally produce increased runoff, but owing to the low rainfall actually produce little runoff. This is supported by a general lack of gullying and serious erosion on the Usangu Plains.

It is concluded that the contribution of surface runoff from the plains surrounding the Eastern Wetland is insignificant in relation to the river flow originating from the high catchment. Changes to surface runoff in the plains caused by livestock are equally insignificant.

5.3.8 Possible cause 8: Groundwater contribution to the Usangu wetland

The nature of the lake deposits in the Usangu basin (Section 3.7.2) is such that it is likely that groundwater moves out under the Usangu Flats from the alluvial fans, passing through the many sandy layers and buried channels. It is also likely that groundwater reaches the permanent swamp. Groundwater enters the swamp through a number of mechanisms, such as horizontal flow at shallow levels through any sandy deposits, or more general seepage upwards from deeper semi-confined layers, driven by vertical hydraulic gradients.

A quantitative analysis of groundwater flows is not possible with the information available. In the water balance described in Section 4.7, the inflow from groundwater, combined with the surface inflow from the Kimbi, Kioga and other minor rivers, was estimated to lie in the range 29-36 Mm^3. However, it is clear by virtue of the fact that outflow from the *ihefu t*o the Great Ruaha river ceases in the dry season that the groundwater contribution is insufficient to maintain dry season flow in the river downstream of the swamp exit.

Despite this, groundwater may very well be maintaining the swamp level higher than it otherwise would be if surface water were the only input. In addition, the process of seasonal flooding of the plains could be assisted by groundwater, rather than relying entirely on surface flow down the river channels. That is, there may be places where there is a shallow water table which rises to ground level during the rains.

5.3.9 Possible cause 9: Deforestation in the high catchment

The problem to be addressed is: what is the effect on the runoff from an upland catchment, brought about by marked changes in the amount of forest cover? This is a problem that has interested people from many different countries, and a series of paired experimental catchments have been established over the past years to find an answer to this question.

In this approach two neighbouring upland catchments are selected, with, if possible, as many similar characteristics as possible, for example soils, geology, topography, areal rainfall, aspect and altitude. The only major difference between them should be their land use cover. One out of a pair might be covered by native forest, the other by tea estates; or for another pair the cover might be pine forest plantation on the first, with smallholder cultivation in the other. Each of the catchments are then extensively monitored over a long period of time by networks of rain gauges, climate stations, streamflow stations, soil moisture and ground water probes. The observations are processed and the differences between the runoff from each of the pair assessed, making allowance for slight differences in the rainfall falling on each catchment.

Two such experimental studies are located close to the project area. One was established during the period 1958-1968 (since closed) on the hills immediately above Mbeya to the north of the town, on the south west perimeter of the project area. The other was established during 1993 in the Kilolo area of Iringa District in the Little Ruaha basin near the north east corner of the project area, and is still operational in 2000.

The first study was established by the East African Agricultural and Forestry Research Organisation (EAAFRO), with the assistance of the Forest Department and the Department of Water Development and Irrigation. The two catchments chosen are situated on volcanic ash which overlies weathered gneiss of the Pre-Cambrian Basement Complex. The combination of these two parent materials gives rise to a very porous but structurally stable soil. One of the catchments is forested, with an area of 16.3 ha, and possesses very steep valley sides at an average slope of 30 degrees near the weir. The other catchment is cultivated, and 20.2 ha in area, of which about 50% is cultivated in any one season. The climate station that served both catchments was located at latitude 8 degrees 50 minutes south, and longitude 33 degrees 28 minutes east, at an altitude of 2 428 m. This elevation means that the catchments are located at an equivalent altitude to the high catchment to the south of the SMUWC project area, which rises to just under 3 000m at its highest point.

Table 5.5 shows the water balance calculated for the two catchments (Edwards and Blackie, 1981). The numbers shown do not exactly match due to other small variables, such as soil moisture and groundwater storage, not being included in the table.

Table 5.5 Water balance (mm) for Mbeya catchments for period 1958-68

Catchment	Rainfall R	Streamflow Q	Actual evaporation AE	Open water evaporation EO	Ratio AE/EO
Forested	1 924	541	1 381	1 510	0.92
Cultivated	1 657	667	970	1 484	0.65

The catchments at Mbeya are located on volcanic soils with high infiltration rates. Surface runoff constitutes only a small proportion of total streamflow under the indigenous forest cover, and this did not change for the cultivated catchment. The conclusion of the study was that the replacement of evergreen forest by smallholder cultivation on very steep slopes resulted in a large increase in water yield. There was a marked decrease in both interception and dry season transpiration in the cultivated catchment, giving an overall increase in baseflow. Because of the remarkably stable, porous nature of the ash-derived soils, only marginal increases in surface runoff were recorded but the dry season baseflow rate was doubled. While a similar increase in water yield can be expected following this land use change in other unimodal rainfall areas, maintenance of seasonal flow patterns and of water quality is critically dependent on soil type.

The second set of experiments was established by the HIMA project on three small upland catchments (Gossage, 1999). The catchments are similar in most respects (Table 5.6) except land use cover: the Mgera catchment is mainly montane evergreen forest while the Gendavaki and Muhu catchments are mainly cultivated or grassland mixed with ‘bush’.

Table 5.6 Main physical characteristics of the HIMA catchments

Characteristic	Mgera catchment	Gendavaki Catchment	Muhu catchment
Catchment size (km^2)	5.16	4.48	4.87
Altitude range (m)	1 890 to 2 030	1 895 to 2 045	1 850 to 2 030
Average slope (%)	20 to 30	20 to 30	20 to 30
Mean annual rainfall (mm)	1 300	1 300	1 300
Approximate vegetation cover	85% forest 15% cultivated	70% cultivated 30% grassland/bush/woodlots	67% cultivated 23% bush/grassland 10% forest/ woodlots

Table 5.7 shows the rainfall and runoff for the dry (June–Nov) and wet (Dec–May) seasons, together with their annual totals, for the period 1993-96.

Table 5.7 Rainfall and runoff depths for each season, HIMA catchments

Period of record	Mgera catchment		Gendavaki catchment		Muhu catchment	
		Forest cover		Cultivated		Cultivated
	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)	Rainfall (mm)	Runoff (mm)
Wet season	1 057	163	1 170	261	1 030	221
Dry season	50	86	120	190	90	170
Total annual	1 107	249	1 290	451	1 120	391

The results show that annual runoff from the forested catchment was around 40% lower than that from the cultivated/grassland/bush catchments. The dry season runoff was 50% lower than that from cultivated/grassland/bush catchments. In addition it was found that the lowest average daily flow recorded at the end of the dry season from the forested catchment was around 70% lower than that from the cultivated catchments. This is important for people who rely on these streams for their water requirements at the end of the dry season.

The two catchment studies described above, located close to the project area, along with 91 other such studies located in other tropical parts of the world (Bonell *et al.,* 1993), lead to the following important conclusions.

i) Reduction of forest cover increases water yield.

ii) Establishment of forest cover on sparsely vegetated land decreases water yield.

iii) If changes in forest cover occupy less than 20% of total catchment area, then no change in annual water yield results.

Some previous commentators point to the loss of forests over the high catchment in the south of the project area as a likely cause of the reduced flows in the Great Ruaha river feeding the wetlands. At the time of writing (December 2000) SMUWC did not have any firm information about the extent of such possible deforestation. It is still planned to compare the area of forest cover denoted on the 1963 topographic maps (based on aerial photography from 1957/58 and 1948/49) with the levels shown on subsequent versions of topographic maps and satellite photographs, to determine whether there have been any changes. This analysis will be fully described in Supporting Report No 1.

But even if such deforestation was extensive, the conclusions above indicate that such a loss is more likely to increase the flows of the Great Ruaha river downstream, rather than decrease them. It is therefore concluded that deforestation in the high catchment has not led to decreased flows reaching the Usangu Plains.

5.4 Review of possible causes

5.4.1 Introduction

The analysis in the previous sections has confirmed that the reduction in dry season flows in the Great Ruaha river is not a new phenomenon, but has been going on since at least the mid 1970's. Only when it caused the Great Ruaha river to dry up in 1994 and in each subsequent year has public awareness been raised.

The following nine possible causes have been proposed and analysed in order to explain the hydrological changes:

- Long term trends in rainfall and evaporation rates.
- Dry season irrigation in the high catchment.
- Changes in river channels on the Usangu plains
- Wet season rice irrigation.
- Dry season abstraction in the Usangu plains
- Changes in the perennial swamp of the Eastern Wetland.
- Surface runoff contribution from the plains.
- Groundwater contribution to the wetland.
- Deforestation in the high catchment.

This list mirrors causes put forward previously by institutions and individuals to explain observed changes. However, previous studies did not benefit from a scientific database and analysis with which to support arguments. The present analysis is still slightly incomplete and further work needs to be done in order to be able to firmly accept or reject some of the possible causes. This section reviews and integrates results obtained so far and outlines the further work that is needed.

5.4.2 Review

Possible factors affecting the yield of water to the plains from the high catchment are rainfall, evaporation, dry season irrigation in the high catchment and deforestation. Although slight downward trends in rainfall occur for half of the 13 gauged subcatchments forming the high catchment, where most runoff is generated, they are statistically insignificant. However, a slight (insignificant) reduction in rainfall may cause a larger, significant reduction in runoff in the rivers. This needs further investigation.

Trends in runoff have not been adequately analysed yet, owing to the poor quality of most of the flow records. However, for two subcatchments with the best quality historical flow records over the period 1965-98, no significant decreasing trends in runoff were found. For the same reason it has not been possible to confirm whether or not dry season irrigation in the high catchment has caused a reduction in water flows reaching the plains; but the weight of evidence suggests that it causes a small, but increasing, reduction in these flows. Some work is needed to improve the quality of the flow record, such as by further checking of rating curves and by rainfall-runoff modelling, before any trends in flow that may be due to either rainfall or irrigation may be determined with confidence.

Cyclical variations in the date of onset of the main rainy season in the project area have been found, but there is no long term systematic trend with time.

It also appears that there are no trends in evaporation that could contribute to reduced water availability downstream.

It is not yet clear whether deforestation has occurred in the high catchment during the period of hydrological records (since the mid 1950's). Ongoing analysis of historical aerial photography over the high catchment is indicating that the extensive areas which are currently rolling grasslands have always been so for at least the last 50 years, and never did possess any forest cover. In any case it is likely that, if deforestation has occurred, it would lead to an increase in flows, particularly baseflow, reaching the plains, not lower flows.

Surface runoff generation in the plains and the impact of livestock water consumption and trampling have been shown to have an insignificant impact on water resources in Usangu. Similarly, groundwater plays no direct role in the maintenance of outflow from the Eastern Wetland, although it might maintain the swamp water level at a higher level than would be the case if groundwater inflows to the wetland did not exist. Groundwater may also play a role in the flooding of the *mbuga* during the wet season. Further work is needed to estimate the contribution made by groundwater to the overall water balance of the catchment, and to consider the contribution of rice irrigation flooding to groundwater recharge.

The analyses of the possible causes has identified a number of factors that could contribute to the drying up of the Great Ruaha river in the dry season. It is probably a combination of these that is the true cause. Essentially, the reduction in dry season outflows must be due to one or both of:

- A reduction in inflow to the Eastern Wetland in the dry season and possibly also in the early part of the subsequent wet season.
- Changes occurring in the Eastern Wetland itself.

Firstly taking wet season flows; the analysis has shown that there has been no substantial change in swamp outflow in the wet season. This implies that rice irrigation in the wet season has had little effect on the Eastern Wetland. An idea that has been put forward to explain the lack of apparent impact is that wet season abstractions merely take that water which would have been lost anyway by evaporation during the seasonal flooding in the Western Wetland under natural conditions. That loss is now taking place on the irrigation areas. It is hypothesised that the water that used to flow from the Western Wetland through Nyaluhanga to the Eastern Wetland under natural conditions has continued to get through. It has also been shown that further wet season abstraction would start to reduce inflows to the Eastern Wetland, and ultimately would lead to a slight reduction in hydropower generation downstream at Mtera and Kidatu power stations.

Regarding dry season flows; that dry season inflows to the Eastern Wetland have reduced, contributing to the reduced outflow, is beyond question. Inflow from the Western Wetland through Nyaluhanga has been observed to virtually cease in the dry seasons of 1998, 1999 and 2000. A number of factors can contribute to these reduced inflows and the contribution or importance of each needs to be determined. Most important is the abstraction of large proportions (averaging 87% and up to 100% on individual subcatchments) of dry season river flows by both state farm and smallholder irrigation schemes. Only approximately 25-28% of the flow is required for meeting crop water requirements on the 2 500 ha of land that is actually irrigated. The rest of the diverted water is used for other purposes such as land preparation for the next wet season, domestic water supplies, brick making and livestock watering. Such large abstractions appear to be unnecessary. They lead to large evaporation and percolation losses during a period when very limited irrigation is taking place, cause rivers to dry up downstream of diversion points, and cause inflows to the Eastern Wetland to cease (although percolating water probably recharges the groundwater system, it is effectively lost to the river system for a long time).

The diversion of dry season flows into irrigation schemes is not the only process that can cause flows to reduce downstream. Changes in river courses, natural or man-made, that cause the diversion of rivers into fan swamps or onto alluvial fans, where large losses can take place by evaporation or percolation, also contribute to reduce inflows to the Eastern Wetland. A number of changes in river courses have been documented in Table 5.2. What effects these changes have had and what effect they presently have is not known. It is difficult to quantify such effects in the absence of measurements. It will be necessary to use the Usangu Basin Model to isolate the effect of the different processes.

The reduced inflows to the Eastern Wetland in the dry season, and possibly in the early part of the subsequent wet season, undoubtedly contribute to the reduced outflows and the eventual cessation of outflow. However, again, there are other factors, which operate within the Eastern Wetland, which may also contribute to reducing the outflow. These could include:

- An increase in evaporation from the wetland.
- A reduction in the volume of stored water in the wetland that is physically connected to the outlet.

An increase in water loss from the swamp by evaporation could result if, over time, the area of open water increased at the expense of the area covered by swamp vegetation. The difference in annual evaporation between an open water surface and a vegetated swamp surface is about 0.45 m of water in this region of Africa. An increase in the area of open water of about 8 km^2 has been found by a comparison of topographic maps based on 1977 aerial photography with ground surveys carried out in 1999 by the project. However, this change is insufficient to cause the observed reduction in outflow. There is also evidence that the vegetation cover is increasing in other parts of the swamp, which would tend to reduce the loss.

With regard to a possible reduction in the volume of stored water in the wetland that is physically connected to the outlet; it has been observed that the level of the bottom of the perennial swamp is perched above that of the exit. It is known that just upstream of the exit from the Eastern Wetland there is a minor seasonal wetland or pool (from which the outflow through the exit occurs) which in the dry seasons of 1998, 1999 and 2000 became disconnected from the main perennial swamp. Flow from the perennial swamp to the pool and through the exit ceased. From this it appears that there is some kind of blockage, either a levee and/or vegetation which is preventing water from draining from the main perennial swamp through the exit in the dry season. Water is being held back in the swamp and this is contributing to the cessation of outflow.

In the wet season the blockage is underwater and the water surface extends from the perennial swamp (and from the seasonally flooded wetland area) to the exit, so causing outflow to occur. The blockage starts to act as the water level drops during the dry season, isolating the perennial swamp from the exit. The subsequent drainage of the reduced volume of stored water in the minor seasonal wetland that is physically connected to the outlet would result in, and account for, the observed steep recessions in the outflow during the dry season. Figures 5.12 and 5.13 show that dry season recessions have not always been steep, but that this phenomenon has developed since the 1980s and possibly before then. Finally, it is worth noting that evidence from surveys suggests that other sections of the Eastern Wetland, for example swampy areas in the north east and far west, also appear to be raised above the level of the perennial swamp and the exit.

5.4.3 Summary

Nine possible causes have been put forward and analysed to explain the reduction in outflow from the Usangu basin. A number of conclusions have been reached (Table 5.8) and areas of remaining uncertainty identified. It is important for ecological and economic reasons to, among other objectives, increase water availability in the Eastern Wetland in order to maintain its functions and value to society (see Supporting Report No. 14) and to restore dry season flow regime in the Great Ruaha. The next section lists the objectives of water resources management in Usangu and identifies, based on the results of the above analyses, the possible options for achieving those objectives.

Table 5.8 Summary of analyses

Possible cause	Observations
1. Long term trends in rainfall and evaporation rates	A decreasing, but statistically insignificant, trend in rainfall over the high catchment was detected. Further work is needed to determine whether this would cause significant reductions in runoff from the high catchment. Cyclical variations were detected in the timings of both the onset and end of rains, but no long term trends. No trends were found in the evaporation record examined. Unlikely to be a significant contributing factor to hydrological changes in the Usangu Plains.
2. Dry season irrigation in the high catchment	Probably a contributing factor, but unable to provide firm evidence to demonstrate it.
3. Changes in river channels	Changes in channels occur which cause changes in the hydrology of the plains, but it is difficult to link historical channel changes to the hydrological changes recorded downstream.
4. Rice irrigation	Evidence from two different analyses gave conflicting results. So it is not certain whether or not rice irrigation decreases wet season outflows from the Eastern Wetland, or causes delays to the time of main rise of the downstream hydrograph.
5. Dry season abstraction in the Usangu Plains	A key factor in explaining reduced outflow from the basin.
6. Changes in the perennial swamp of the Eastern Wetland	A contributing factor to hydrological change.
7. Surface runoff contribution from the plains	Not a contributing factor to hydrological change.
8. Groundwater contribution to the wetland	Not a contributing factor to hydrological change.
9. Deforestation in the high catchment	Not a contributing factor to hydrological change.

Figure 5.1 Variation of annual areal rainfall (mm) over the catchment upstream of river gauging station 1KA59 Great Ruaha river at Msembe Ferry

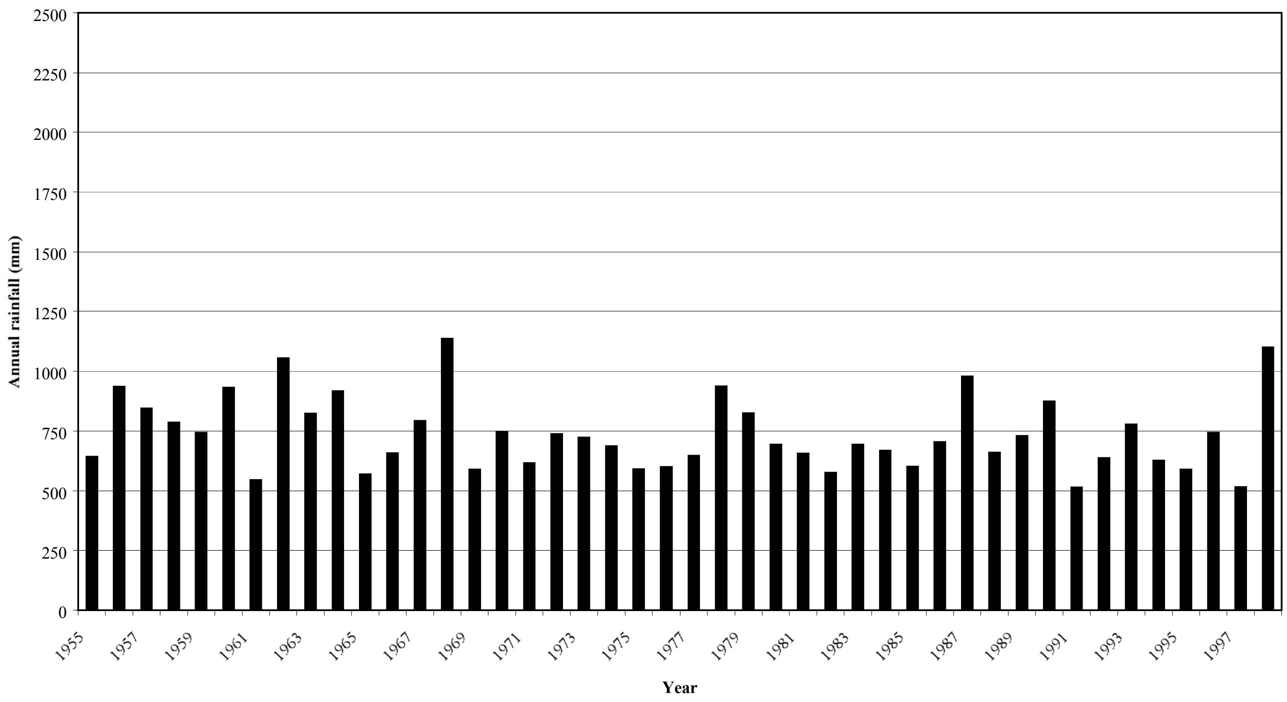


Figure 5.2 Variation of annual areal rainfall (mm) over the high catchment

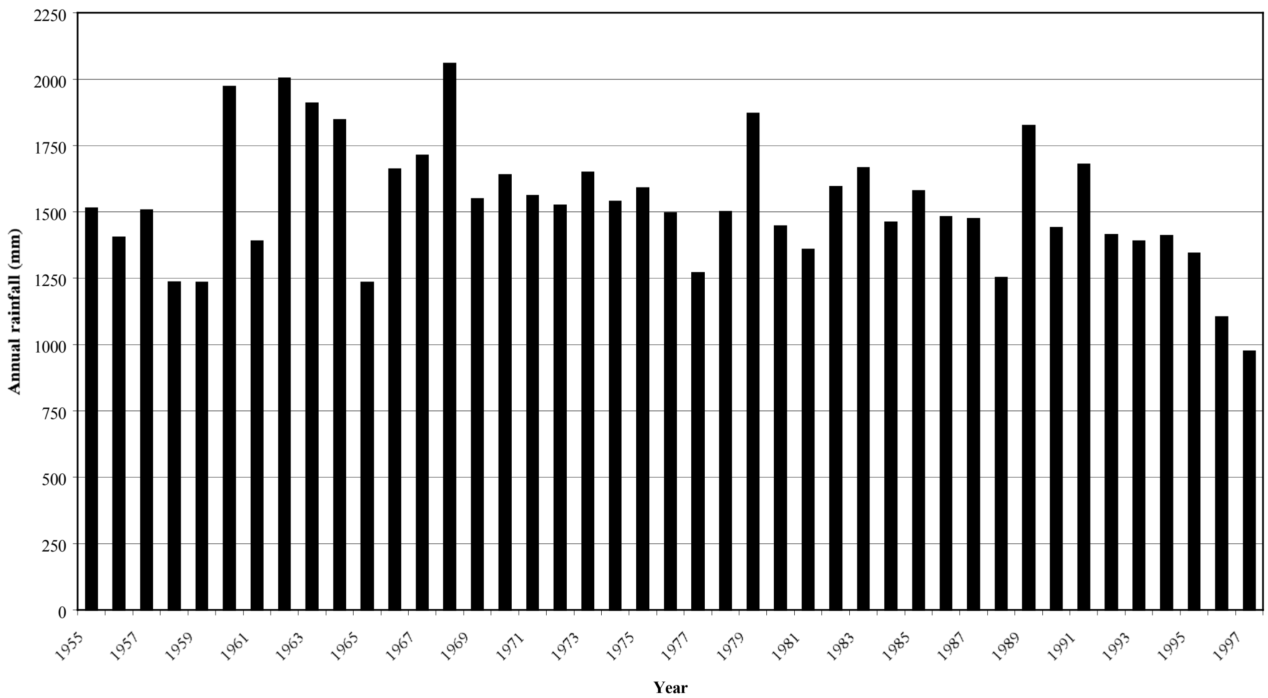


Figure 5.3 Variation of annual areal rainfall (mm) over the Usangu Plains

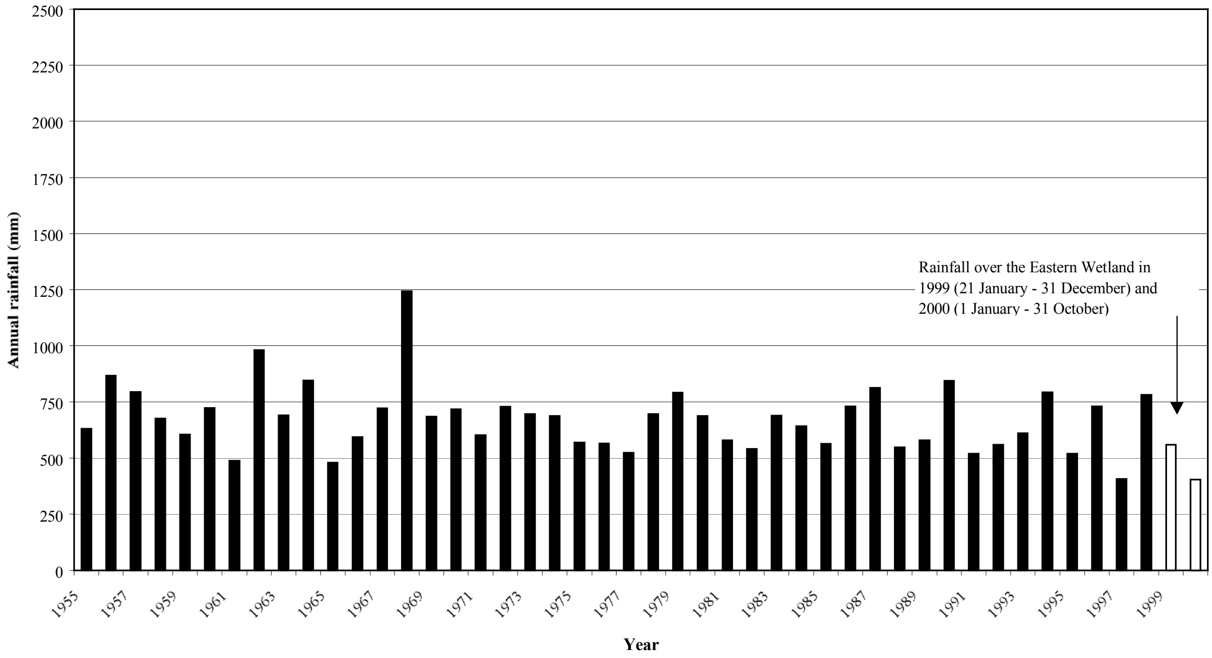


Figure 5.4 Variation in annual values of potential evapotranspiration (mm) at Dodoma meteorological station

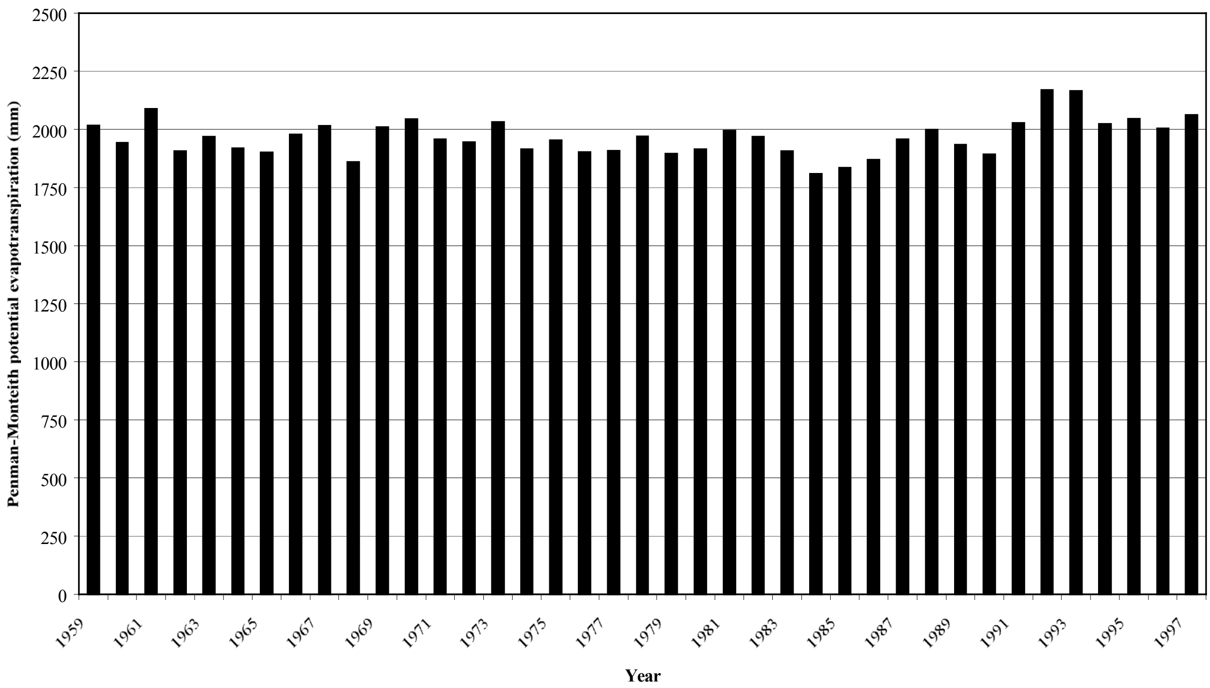


Figure 5.5 Variation in the onset time (decads from 1 January) of the rains

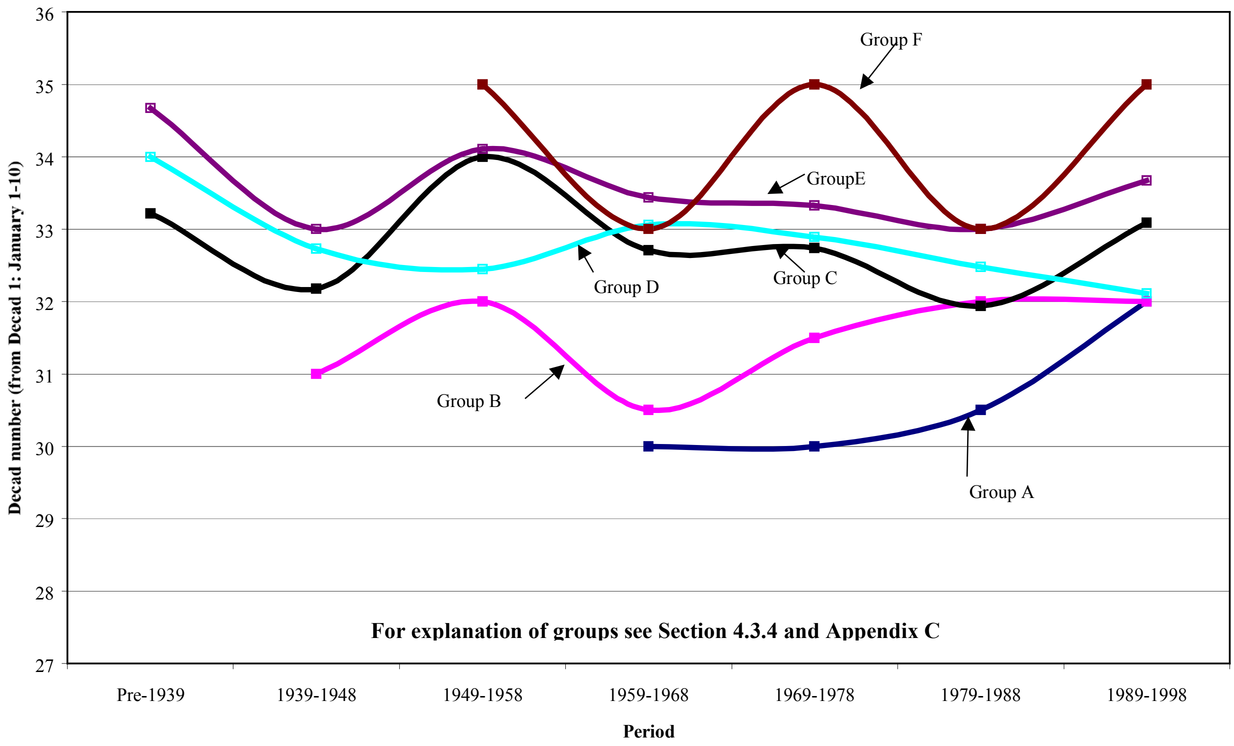


Figure 5.6 Annual variation in the lag between the onset of the upstream rainfall and the onset of discharge in the Great Ruaha river at Hausmann's Bridge

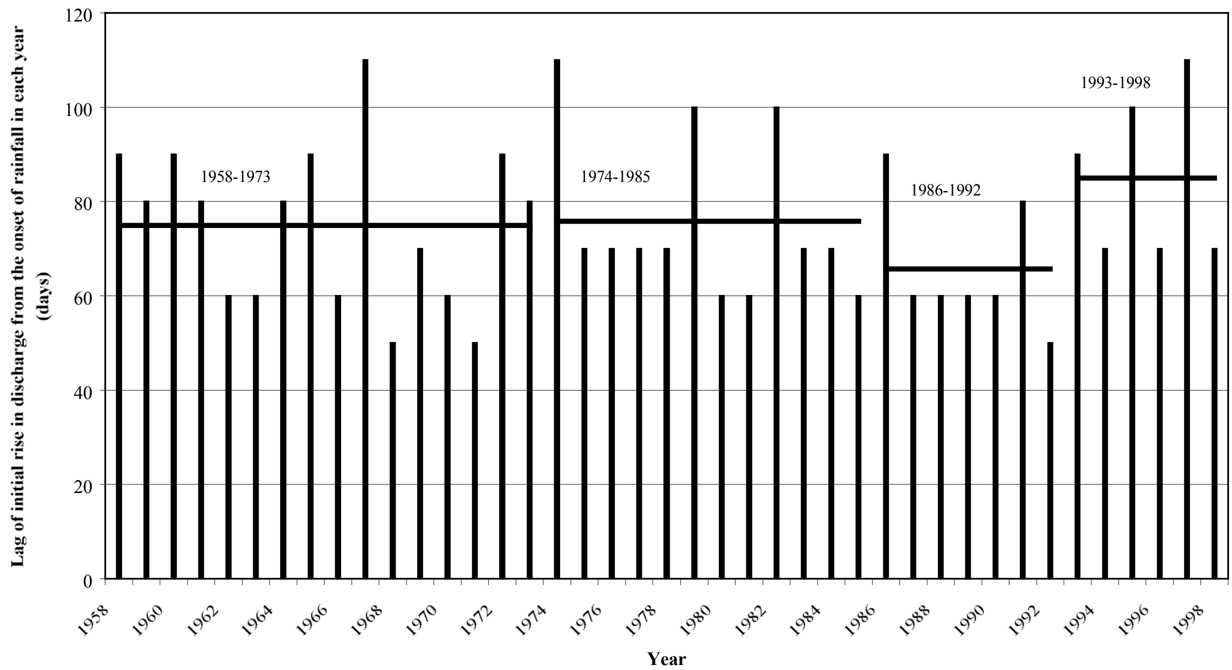


Figure 5.7 Reconstructed discharges at Hausmann's Bridge (1KA27)

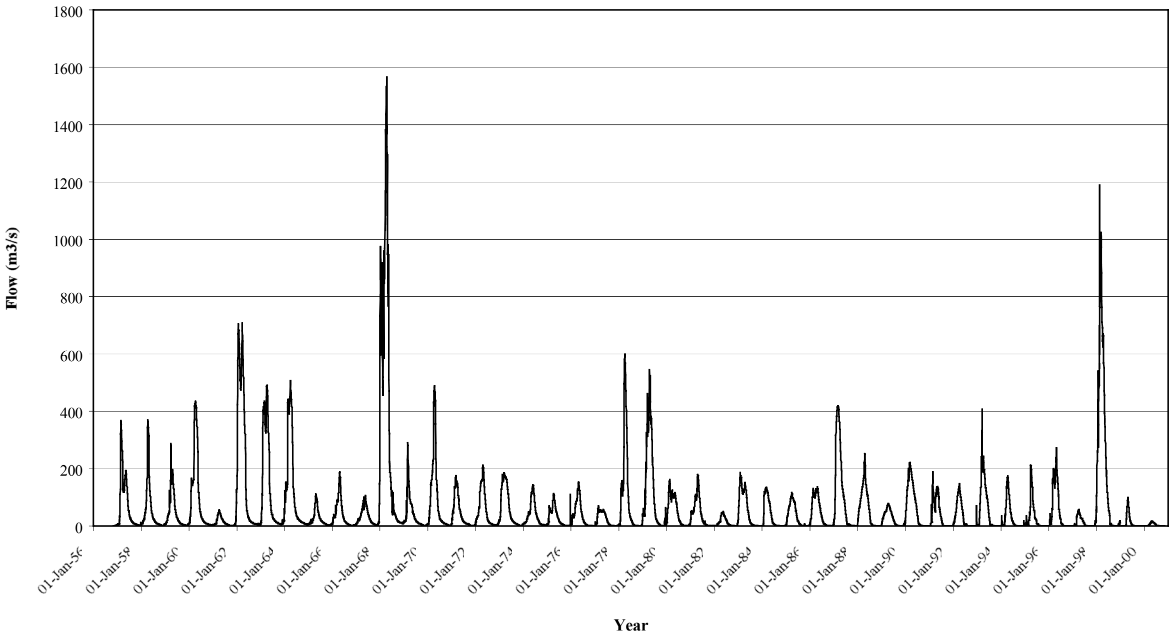


Figure 5.8 Variation of annual mean discharge at river gauging station 1KA27 Great Ruaha river at Hausmann's Bridge

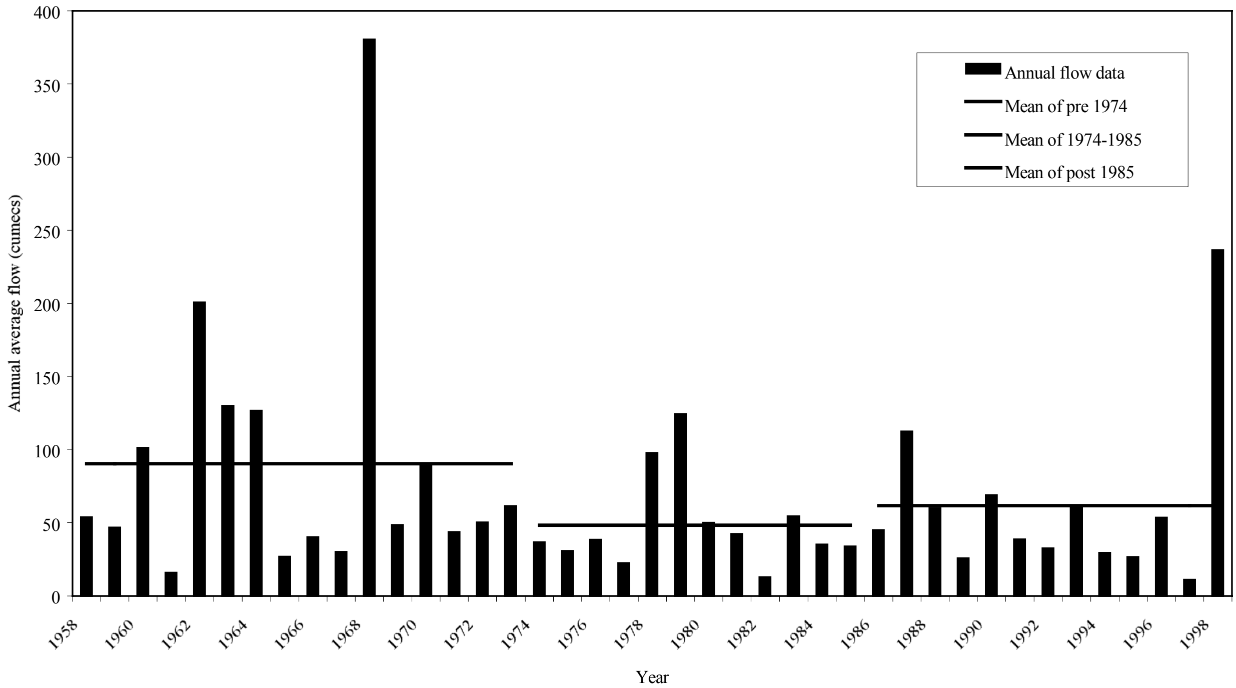


Figure 5.9 Variation of mean discharge during each wet season (1 January-31 May) at river gauging station 1KA27 Great Ruaha river at Hausmann's Bridge

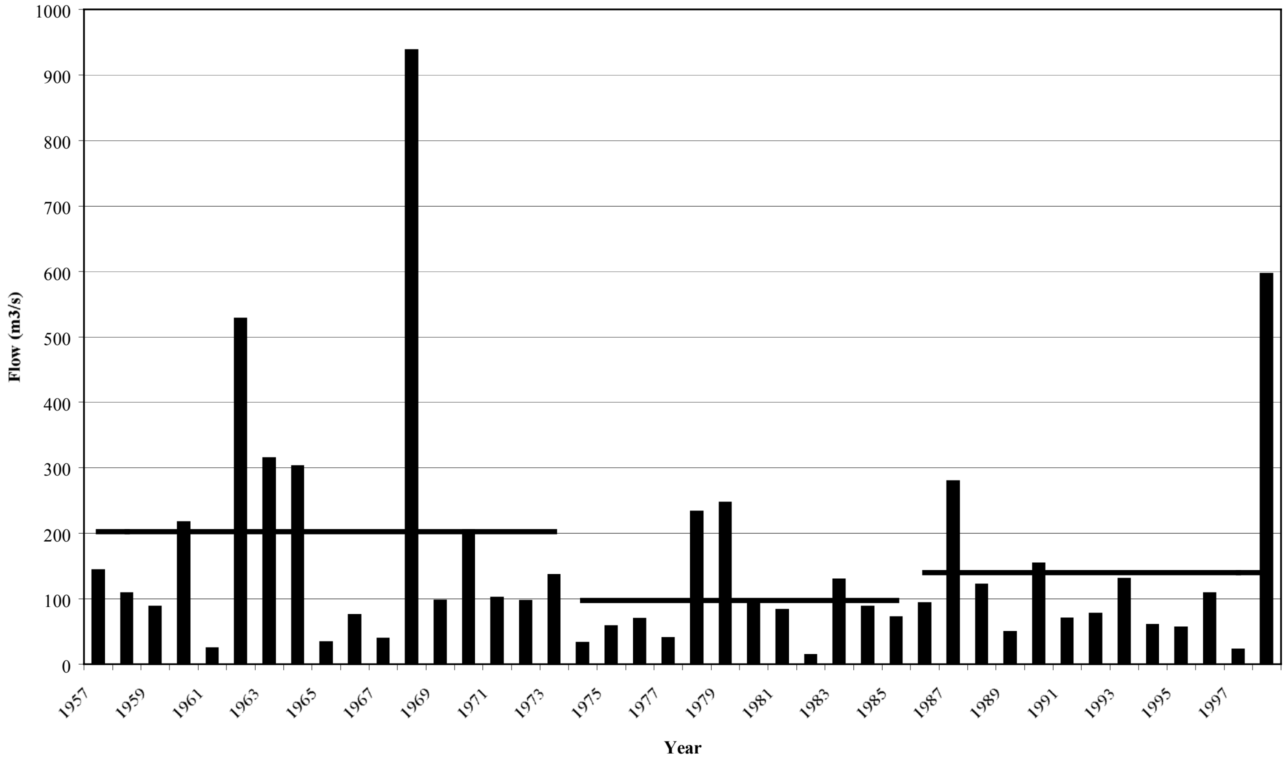


Figure 5.10 Variation of mean discharge during each dry season (1 July-30 November) for Station 1KA27 the Great Ruaha river at Hausmann's Bridge

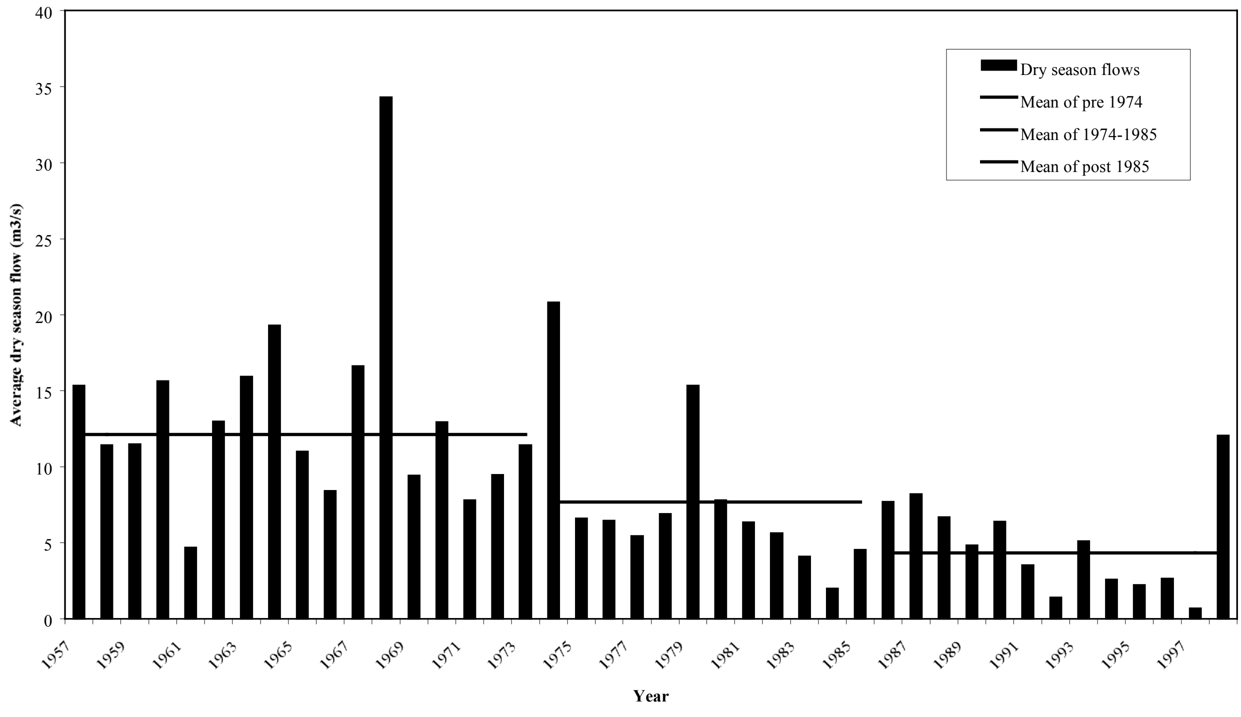


Figure 5.11 Wet season flow volumes (1 January-31 May) Great Ruaha river at Hausmann's Bridge expressed as a proportion of total annual flows

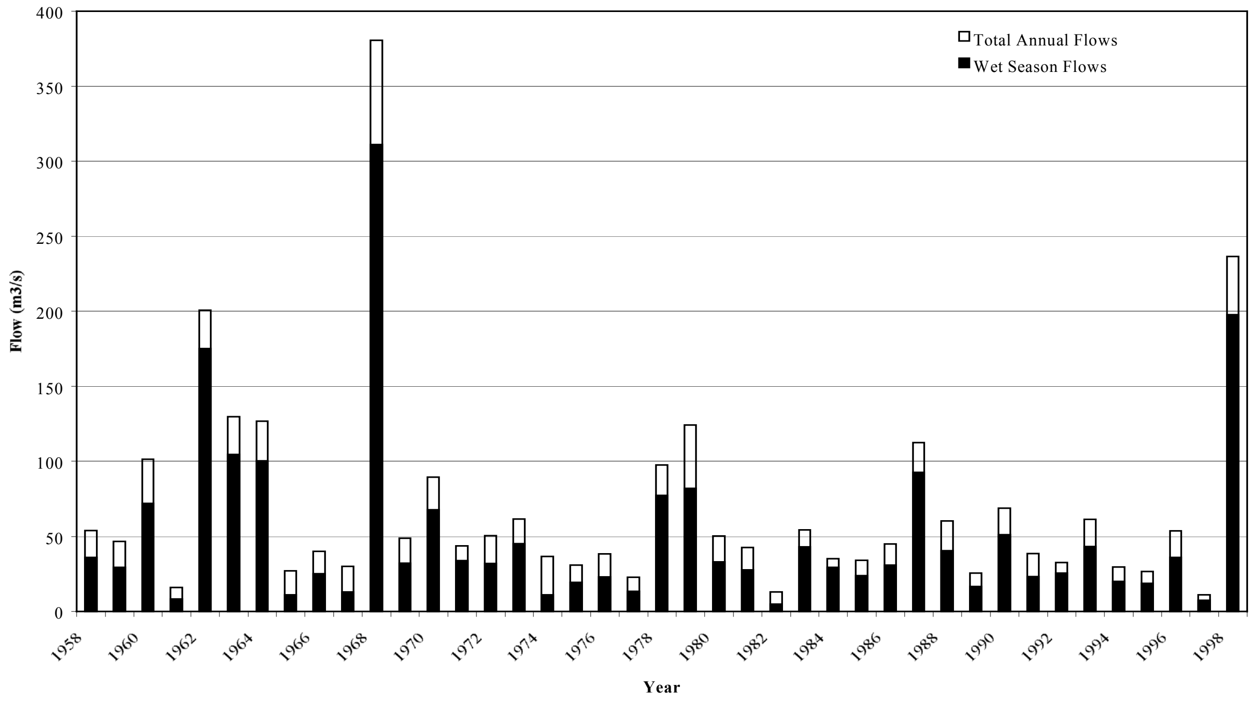


Figure 5.12 Equivalent water levels at N'Giriama from the reconstructed Hausmann's Bridge flow records

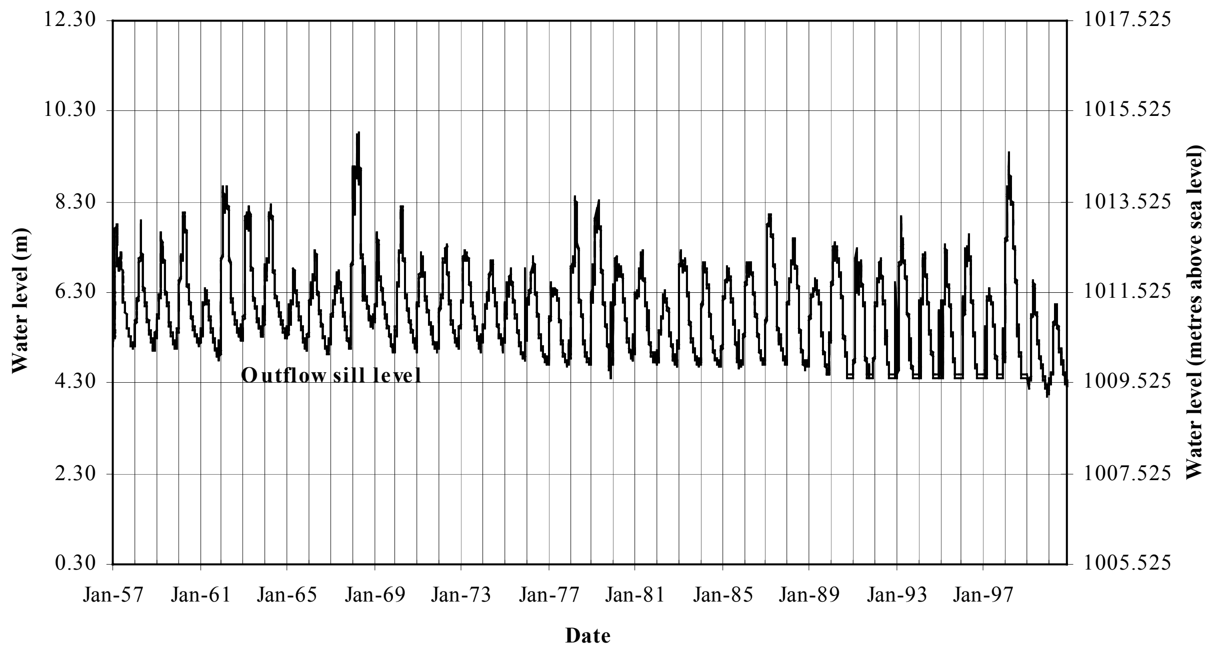


Figure 5.13 Gradual reduction in mean values of dry season recession flows over four time periods at 1KA27 Great Ruaha river at Hausmann's Bridge

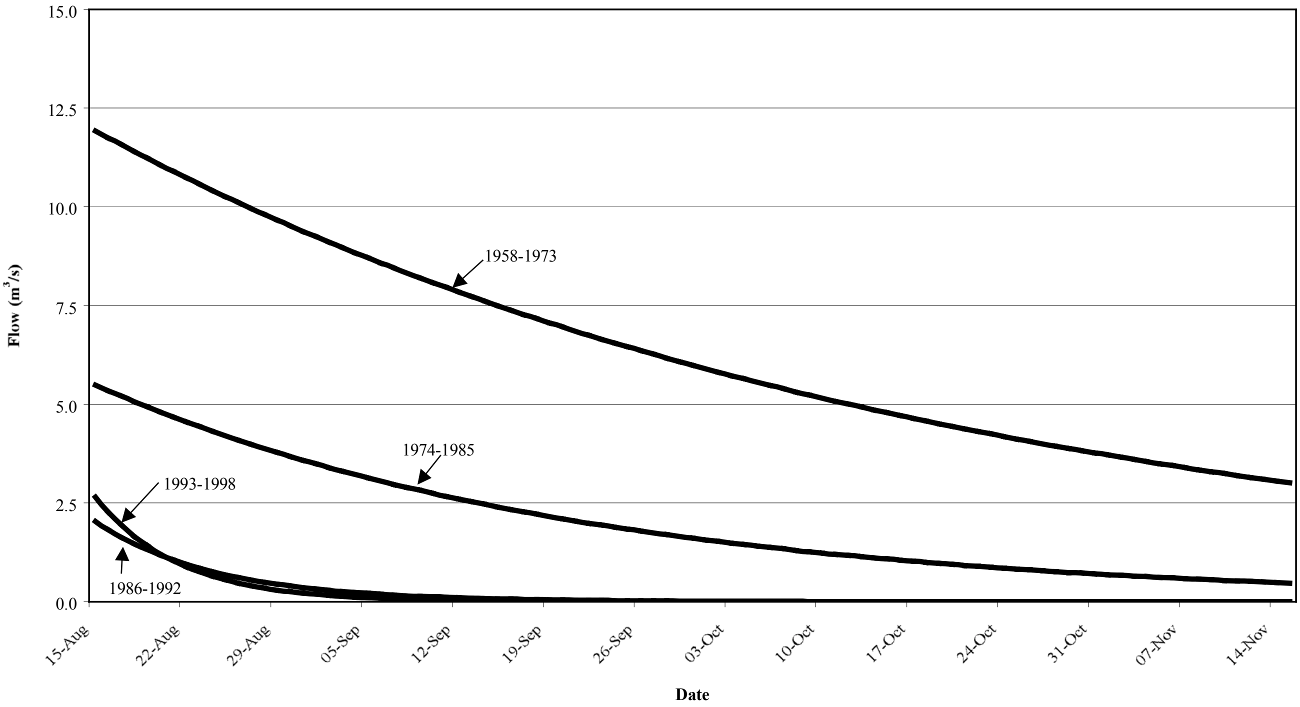


Figure 5.14 Present understanding of main water flows through Eastern Wetland in dry season

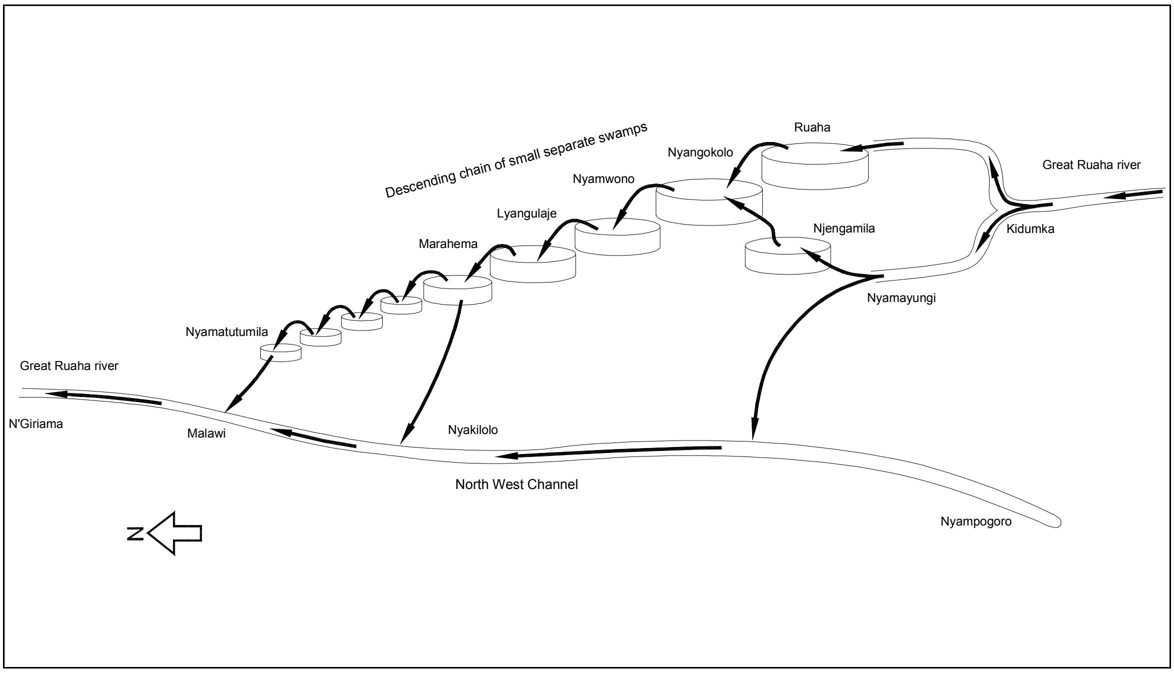
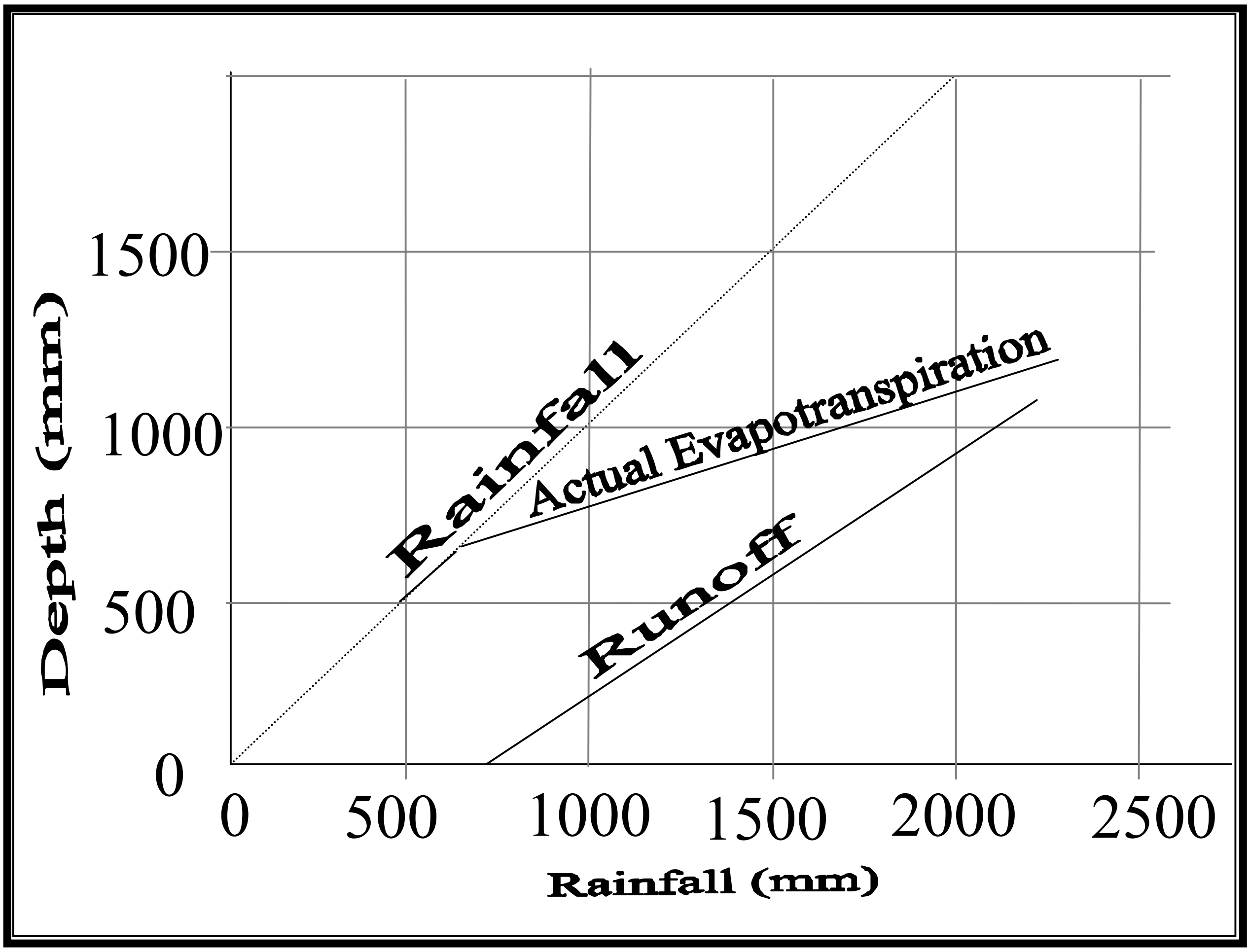


Figure 5.15 Relation between annual values (mm) of rainfall, runoff and actual evapotranspiration



6 OPTIONS FOR WATER MANAGEMENT IN USANGU

6.1 Major objectives

Consideration of the possible objectives for water resources management in Usangu led to the preliminary list of five shown below. This list is not meant to be exhaustive, and other objectives may be added after further discussion. Neither is the list given in any order of priority. Some of the objectives may be mutually incompatible, and it will be the responsibility of all the stakeholders at national, regional and local level, to determine what weight, if any, should be given to individual objectives.

1. Restore the low flow regime through Ruaha National Park so that it is environmentally acceptable.
2. Maintain or increase annual inflows to Mtera Reservoir, to secure future hydropower generation at Mtera and Kidatu power stations.
3. Maximise the production of irrigated rice in Usangu and minimise social conflict over water sharing.
4. Maintain or improve the water environment of the Eastern Wetland.
5. Maintain or improve the runoff-producing ability of the high catchment.

Section 6.2 presents a list of the management options for attaining the above objectives. Section 6.3 discusses those options relating to Objective No. 1 above. Section 6.4 discusses the options for attaining Objective No. 2. Section 6.5 discusses the options for attaining Objective No. 3. Section 6.6 discusses the options for Objective No. 4 and Section 6.7 those for Objective No. 5.

6.2 List of options

A full list of all the water management options considered during the course of the SMUWC project is presented in Table 6.1. Again, the list is not meant to be exhaustive, and other options may be added in the future. The discussion about these options in this chapter has been confined to their water aspects. However it must be emphasised that there are numerous linkages to other sectors of the project, for example livestock, fisheries and wildlife. Understanding of these linkages is essential both to selection among options, but also to the options themselves, and sometimes these other sectors may effect the viability of the option, or vice versa.

Table 6.1 List of water management options for the Usangu basin

Objective	Options
1. Restore the low flow regime of the Great Ruaha river through Ruaha National Park so that it is environmentally acceptable.	**Downstream of the Eastern Wetland** 1.1 Construct boreholes along riverine reach to augment flows in Great Ruaha river. 1.2 Construct dams on the minor tributaries of Great Ruaha river to release flows during the dry season. 1.3 Construct groundwater boreholes to supply watering holes along the Great Ruaha river valley. **Within the Eastern Wetland** 1.4 Construct a minor channel from Ndembera river near drain of Madibira Rice project to Great Ruaha river at N'Giriama which conveys low flows past the Eastern Wetland 1.5 Construct a low weir at wetland outlet at N'Giriama, to store part of the flood flows during the wet season and then release them steadily during the dry season through a regulated outlet. 1.6 Clear blockages along section of North West Channel in Eastern Wetland that connects downstream end of perennial swamp to the outlet at N'Giriama: a) remove cattle causeways and other obstructions presently existing along the North West Channel b) remove debris blocking the outlet channel at N'Giriama to improve passage of low flows 1.7 Clear blockages along Great Ruaha river, from Kidumka to the North West Channel, during its passage through the Eastern Wetland: a) remove reed growth presently forming barrier to flow from Nyaluhanga to N'Giriama during its passage through the Eastern Wetland b) re-open channels, connecting Great Ruaha river at Kidumka to North West Channel, that used to flow during historical times

Table 6.1 List of water management options for the Usangu basin (continued 1)

Objective	Options
	On the alluvial fans upstream of the Western Wetland 1.8 Reduce the amount of river water abstracted by the major irrigation schemes during the dry season: a) define a start date for first field wetting and nurseries when the main intake is opened; b) define a finish date when main intakes can be closed down at the end of season; c) develop/strengthen/implement byelaws which ban the use of dry season cropping in rice farms; d) provision of borehole water supplies to villages presently dependent on farm canal/drain water in dry season for domestic and livestock use, in order to reduce the need to maintain canals flowing; e) before boreholes are provided, it is necessary to define intake gate settings for the dry season in such way to divert a proportion of the flow (e.g. not more than x% of river flows); f) examine whether significant savings can be made by growing short season varieties of rice; g) maintenance of secondary and tertiary irrigation canals 1.9 Improve conveyance and reduce losses to groundwater along the natural river channels crossing the alluvial fans by diverting the low flows during the dry season straight through the primary canals of major irrigation schemes and out of the main drains, without any diversion into secondary canals; 1.10 Block entrance of Ifushiro fan swamp to prevent inflow of dry season flows from Great Ruaha river, which are currently totally lost to evaporation. 1.11 Increase capacity of existing small channel connecting Great Ruaha river to Kimani river 1.12 Improve the conveyance of flows along the four main rivers (Great Ruaha, Ndembera, Kimani, and Mbarali – the so-called 'red routes'), by examining existing channels and eliminating any illegal abstractions, blockages or evaporation/percolation losses;

Table 6.1 List of water management options for the Usangu basin (continued 2)

Objective	Options
	On the high catchment
	1.13 Increase volume of runoff produced by the high catchment by reducing the total area currently covered by forests. Likewise there should be no additional land area earmarked for planting of trees(afforestation), which, if implemented, would cause a decrease of runoff.
	1.14 Construct reservoirs on main rivers flowing down from high catchment, to store water from the flood flows during the wet season and then release this water steadily during the dry season;
2. Maintain or increase annual inflows to Mtera Reservoir, to secure future hydropower generation at Mtera and Kidatu power stations.	**Within the Eastern Wetland**
	2.1 Construct major channel to convey wet season flows in Great Ruaha river from Nyaluhanga to N'Giriama which bypasses perennial swamp.
	2.2 Construct major channel to convey wet season flows in Ndembera river from downstream of main drain of Madibira Smallholder Agriculture Development Project to N'Giriama, which bypasses perennial swamp.
	On the alluvial fans upstream of Western Wetland
	2.3 Construct major channel, bypassing Ifushiro fan swamp, to divert wet season flows in Great Ruaha and Chimala rivers which currently enter this fan swamp;
	2.4 Convert existing small channel, which connects Great Ruaha river to Kimani river, into a major channel for conveying wet season flows;
	Options that would have adverse effects on Objective No. 2
	2.5 Construct reservoirs on main rivers flowing down from high catchment, to store water from flood flows during the wet season, and then release it steadily during the dry season;
	2.6 Construct a high dam at the outlet at N'Giriama, to store water throughout the year over the complete Eastern Wetland, and then release any surplus down the Great Ruaha river to Mtera Reservoir;

Table 6.1 List of water management options for the Usangu basin (continued 3)

Objective	Options
	2.7 Increase the area of irrigated rice during the wet season from its current level of 42 000 ha;
3. Maximise the production of irrigated rice in Usangu and minimise social conflict over water sharing.	**In irrigation areas**
	3.1 Ensure more disciplined and equitable sharing of existing water abstracted for irrigation;
	3.2 Establish river management systems for each major subcatchment in the Usangu Basin, based on Water User Associations;
	3.3 Introduce shorter season rice crop;
	3.4 Establish a more robust rice extension service designed to meet farmers' needs.
	3.5 Increase the amount of water abstracted during the wet season to increase the present irrigable area from 42 000 ha to the maximum irrigable area of 55 000 ha
	On the high catchment
	3.6 Construct upstream reservoirs to provide additional flow during start and end of dry season, on shoulders of irrigation demand curve;
	Management intervention
	3.7 Apply the concept of Irrigation Management Transfer to the large state rice irrigation schemes at Kapunga and Mbarali, in order to ultimately save water upstream, increase rice production and enhance rural livelihoods;
4. Maintain or improve the water environment of the Eastern Wetland.	**Upstream of the Usangu wetland**
	4.1 Increase river inflows into the Eastern Wetland during the dry season;
	4.2 Monitor inflow of fertilisers from both rainfed and irrigated cropped areas upstream;

Table 6.1 List of water management options for the Usangu basin (continued 4)

Objective	Options
5. Maintain or improve the run-off producing ability of the high catchment.	**On the high catchment** 5.1 Prevent any further substantial areas of land being earmarked for afforestation, except in exceptional cases on small patches to prevent soil erosion. Encourage carefully controlled deforestation, in areas where this would not lead directly to degradation of the land; 5.2 Implement suitable land-husbandry techniques to prevent gullying and soil erosion, particularly on steep slopes; 5.3 Encourage more active management of woodlands and forests, to preserve groundcover during the rainy season; 5.4 Explore institutional links and other ways that will allow principal downstream beneficiaries of river flows (people and organisations involved with irrigation, livestock, fisheries, environment, wildlife, and hydropower) to support practical measures preventing degradation of the high catchment; 5.5 Encourage active management of the grasslands in the high catchment, including controlled burning, to maintain their status as historical grasslands; 5.6 Continue to monitor extent of valley floor cultivation in the headwaters of rivers on the eastern edge of the project area;

6.3 Discussion of options for Objective 1

6.3.1 Option 1.1: Construct boreholes along riverine reach to augment flows in the Great Ruaha river

A brief review was conducted in September 1999 of the potential for groundwater to maintain the flow in the Great Ruaha river as it flows through the Ruaha National Park. A desirable flow in the river throughout the dry season is of the order of 0.5 – 1.0 m^3/s. The review revealed that it is definitely not practicable to maintain that flow from groundwater. While there are plenty of examples of successful boreholes and shallow wells in similar geological formations, they are all regarded as 'successful' only in terms of small scale drinking water supply. Typical yields are of the order of 1 or 2 l/s, so over 500 boreholes would be required, which is a completely unrealistic prospect.

There is certainly potential to build sand dams along the course of the Great Ruaha and/or its tributaries in the park, but they would only provide sufficient water for water holes, and would not yield enough water to keep sufficient water flowing in the main river. Incidentally, from anecdotal information, the occurrence of groundwater in the park (from springs and shallow wells) has not been affected over the period which has seen dry season flows cease in the main river itself.

6.3.2 Option 1.2: Construct dams on the tributaries of the Great Ruaha river to release flows during the dry season

There are several long tributaries, such as the Jongomero River, which enter the Great Ruaha river between the outlet of the Eastern Wetland at N'Giriama and the headquarters of the Ruaha National Park at Msembe. During the wet season these rivers respond quickly in the form of small flash floods, but after that they appear dry for many months. However their beds are filled with sand, so often there is a very small flow of water under the surface even at the end of the dry season, which is exploited by elephants and certain game lodges as a water supply. One option would be to construct large dams on these tributaries, to store water from the flash floods, which would then be released as compensation water during the critical months at the end of the dry season to replace the missing flow in the main river.

Unfortunately, analysis shows that this is not practical, because there is insufficient total water available spread among too many tributaries. The difference in mean annual flows between the gauging stations at Hausmann's Bridge and Msembe Ferry is only 2.1 m^3/s. The resulting total runoff volume, 66 Mm^3, is equivalent to just 24 mm of annual runoff depth over the 2 710 km^2 of this semi-arid region. This is less than half the 53 mm runoff depth over the complete basin upstream of Mtera Reservoir, which receives a flow of 114 m^3/s over a catchment area of 67 950 km^2. With this limited total flow available in the tributaries it is not feasible to construct storage dams to provide the compensation releases of 15.8 Mm^3 required to supply up to 1 m^3/s over a 6 month period. If the total flow was confined to only one tributary then this option could be investigated further to identify a single suitable dam site, but since it is known that there are at least four tributaries entering this reach of river, this would necessitate an individual dam installed on each tributary.

6.3.3 Option 1.3: Construct boreholes to supply watering holes along the Great Ruaha river valley

Artificial watering holes could be established within Ruaha National Park, at regular intervals along the banks of the Great Ruaha river, in order to supply wildlife during those critical months when the main river ceases flowing. Water could be abstracted either from groundwater by boreholes sunk into the river banks, or from dams located beneath the surface of the sand rivers forming tributaries of the Great Ruaha river. Pumps could be powered by an appropriate source, such as diesel, solar or wind.

There is considerable experience in Southern Africa (Namibia, Botswana and South Africa) using these techniques, even in those regions with a much more arid climate than the Ruaha National Park. The rate of water supply from these two alternative sources would both be very limited, but sufficient for providing drinking water to a variety of animals, both large and small. However it is questionable whether it would be sufficient to keep watering holes large enough to provide a suitable habitat for herds of crocodiles and hippopotami throughout the critical dry period, and this would need further investigation.

6.3.4 Option 1.4: Construct a minor channel from Ndembera River to Great Ruaha river which bypasses the Eastern Wetland

In this option a minor channel would be cut to convey low flows, from the Ndembera River downstream of the outlet of the Madibira Smallholder Agriculture Development Project, towards the Great Ruaha river at N'Giriama (Figure 6.1). Unlike many of the rivers disgorging into the Eastern Wetland the Ndembera is a perennial river, and according to the records at the Ilongo and Madibira river gauging stations, has never dried up completely during the period 1956–89

(Halcrow, 1995) . Even during the extremely dry year of 2000, although the river virtually dried up at Ilongo, with minimum daily flow of 0.05 m^3/s, it still maintained a minimum flow of 0.29 m^3/s at Madibira. It is therefore worthwhile to explore whether this might provide a suitable source from which to transfer the 0.5–1.0 m^3/s compensation flows required at N'Giriama.
Two potential diversion points on the Ndembera river were chosen, located at 11.8 km and 16.4 km respectively from N'Giriama. The first point, denoted NR1, was at grid reference 0678372E 9092020N, while the second, NR2, was at grid reference 0682027E 9093550N. Field surveys established that the water levels at these points lay 9 m and 11 m above the river sill level in the Great Ruaha river at N'Giriama, indicating that there was sufficient head to pass the water through a channel. The ground profile from NR2 to NR1 dropped steadily, with a total difference of 3 m, but from NR1 to SMUWC6 survey beacon (Figure 6.1) the ground was essentially level. Although the direct survey line from SMUWC6 to SMUWC7 at N'Giriama indicated higher intervening ground, there is a historical river channel lying south of this, which it is thought could provide a potential channel route from SMUWC6 as far as N'Giriama.

Examination of the flow record of the Ndembera River at Madibira established that the lowest flows during the year occurred during the first decad in November. Table 6.2 presents flows for the first decad in November and their exceedance values.

Table 6.2 Frequency of low flows in Ndembera River at Madibira

Exceedance values	Mean discharge for decad 1-10 November (m^3/s)
9 years out of 10	0.38
4 years out of 5	0.48
3 years out of 4	0.64
1 year out of 2	1.69

From Table 6.2 it appears that, while in an average year the median flow is sufficient to supply the transfer channel with sufficient compensation water, every four years the available water would drop to the lower limit of what is required. In addition there would be losses occurring along the channel which would mean the flow arriving at N'Giriama would be even less.

Although the Madibira Smallholder Agriculture Development Project has currently adopted a policy of not abstracting water during the dry season, there appear to be some losses due to other causes occurring between the river gauging station and the potential channel diversion points NR1 and NR2 (Figure 6.1). Field measurements taken during the 2000 dry season indicated losses of about 0.5 m^3/s along this natural river channel, though it was not clear whether it was due to infiltration to groundwater or offtake to traditional smallholder irrigation use. There was also evidence observed in September 2000 of a new smallholder irrigation scheme being constructed upstream of the proposed diversion point for this transfer channel.

Bearing in mind all these existing and potential losses, it is considered that there is insufficient water available to allow a continuous transfer of water from Ndembera River, to replace the inadequate flows at N'Giriama, even though there is enough difference in head over the length of the channel to permit such a transfer. Another major disadvantage of this option is that neither of the two proposed sites offers suitable ground conditions for a permanent diversion structure. Reliance would need to be placed in a traditional smallholder type weir, which would need rehabilitating annually to function satisfactorily.

6.3.5 Option 1.5: Construct a low weir at wetland outlet

Every year since river records commenced at Hausmann's Bridge in 1957, the Eastern Wetland has filled up gradually during the wet season until it flows over the rock sill at N'Giriama and down the Great Ruaha river. Even in 2000, during which the inflows into the Usangu plains from the high catchment were exceptionally small, this phenomenon still occurred, but only just. The aim of this present option, of constructing a low weir at the outlet, is to store part of the flood water occurring in the wet season and then release it steadily during the dry season through a regulated outlet.

The complicated network of channels of the Great Ruaha river at the outlet of the Eastern Wetland is shown in Figure 6.2. A cross section of the Great Ruaha river at the location of the rock sill is shown in Figure 6.3, viewed from upstream. There are two broad channels, with the eastern one about three times the width of the western one. Bare rock underlies much of the eastern channel, and it is thought that it also extends under most of the western channel. The altitudes of the lowest levels of both channels given by a survey were in close agreement ; however debris collects in the deeper pockets during the passage of high flows in the wet season, so the exact altitude of the lowest point may vary slightly from year to year. Examination of the water levels in the upstream pool at the time when flow ceased during each of the years 1998, 1999 and 2000 suggest that the sill level should be taken as gauge height 4.30 m which is equivalent to 1009.525 masl.

Suppose a low 2 m high weir with crest level 1011.5 m is constructed extending across both channels (Figure 6.3). The weir could be designed to be overtopped at high water levels, with flow then occurring across the full 600 m width of the river, as currently happens without the weir in place. An adjustable outlet gate could be incorporated into each side of the weir, so that a compensation flow of 0.5 – 1.0 m^3/s could be released whenever the water level fell below crest level.

The channels and seasonal wetland lying upstream of the weir have an extremely small slope, so it is difficult to be sure of quite how far upstream the effects of the weir will be felt, without further detailed investigations. However preliminary survey results show that the weir crest level lies about 1 m above the water surface of the northernmost tail of the perennial swamp, which is located at a distance of 7 km from the outlet; this latter water surface level occurred in early October 2000 just as the outflow from the whole wetland ceased. At the normal rate of evaporation occurring over the wetland (1 940 mm/year), this additional 1m depth of water would evaporate over a period of 6 months, if there was no substantial inflow of water to the perennial swamp during the dry season, which is currently the case. So a weir of this height would be unable to supply any compensation water for more than about 5 months maximum, before it ran out of available storage.

Increasing the crest level of the weir leads to two problems. First, at the height of 1 011.5 masl proposed above, the water surface upstream just coincides with the bank full level of the North West channel. Increasing the height any more than this would result in the upstream weir pool extending over a large area of the seasonal wetland, forming a shallow pool which would occupy valuable grazing resources (Figure 6.4). Secondly a higher weir might well result in too much of a constriction at the outlet, reducing the flows which pass in the wet season, ultimately leading to reduced hydropower production downstream.

It is not known exactly what area of perennial swamp would be covered by this additional 1 m depth of water, as access makes this area difficult to survey. A detailed hydrographic survey during a future wet season may be necessary. Table 6.3 gives estimates of what compensation releases are possible from an upstream weir pool with surface areas of 3, 8 or 17 km^2 respectively.

Table 6.3 Compensation releases possible from different inundated areas of perennial swap

Surface area (km^2)	Additional storage (Mm^3)	Compensation flow (m^3/s)	Period of compensation flow (months)
3	3	0.5	1.5
3	3	1.0	1
8	8	0.5	3
8	8	1.0	2
17	17	0.5	4
17	17	1.0	3

Due to the peculiar channel layout at the outlet (Figure 6.2) during low flows water flows out only through the channel on the western side (Figure 6.3). When the water rises in the wet season, the water flows over the shoulder dividing the two channels and then flows out through both channels (Figure 6.2). It may be possible to use this attribute to reduce the overall length of the weir substantially, by constructing a weir across only the 91 m wide western channel, and using the eastern channel as a high flow flood discharge channel.

It is recommended that this option of designing a weir is investigated in more detail by a specialised hydraulic engineer.

6.3.6 Option 1.6: Clear blockages along section of North West Channel in Eastern Wetland that connects downstream end of perennial swamp to the outlet at N'Giriama

The existing perennial swamp stores substantial quantities of water. For example, at the end of the 1998/99 dry season on 21 January 1999, aerial survey established the total area of the perennial swamp as 64 km^2. Subsequent hydrographic and topographic survey established that the corresponding volume of water stored in the perennial swamp on that date was 8.5 Mm^3.

In contrast, a compensation release of 0.5–1.0 m^3/s through the outlet for a period of 6 months requires a volume lying between 7.9 and 15.8 Mm^3.

Field surveying showed that in mid-October 2000 the water surface of Ruaha swamp, at the higher southern end of the perennial swamp, lay 2.17 m above the rock sill at the outlet, and even the northernmost tip of the perennial swamp, lying about 7 km from the outlet, lay 0.95m above the rock sill. With this substantial volume of water apparently perched above the level of the outlet, it is worth exploring whether it is possible to tap it gradually for a steady compensation release during the dry season. Certainly it should be considered as a serious alternative to forming an artificially enlarged perennial swamp, which is the ultimate result arising from the option of the construction of a low weir, mentioned previously.

The northern arm of the perennial swamp is connected to the North West Channel by two short channels. One of these flows westwards from TBM MA2 to TBM L2, while the other flows northeast from TBM MA1 to TBM L1 (Figure 6.5). There is little drop in water surface altitude over the length of either of these channels.
The North West Channel was surveyed in early October 2000 all the way from TBM K1 to N'Giriama; a longitudinal profile is given in Figure 6.6. Instead of there being a gradual reduction in water level moving from TBM L2 to N'Giriama, it will be noticed that there are a series of uneven steps. This suggests that there are some constrictions, either natural or artificial, which impede the smooth flow of water down this channel. In particular, there is a sharp 0.5 m drop over the 1 km section immediately downstream of TBM L1, and a 0.2 m drop over the 0.5 km section immediately downstream of TBM N2 (Figure 6.6). Further investigation may reveal what form these constrictions take.

Another small constriction was seen near Malawi fishing camp, about 0.5 km upstream of TBM L1 (Figures 6.5 and 6.6) This was a cattle causeway, used by the livestock herders to move their cattle across any channel containing standing water in a way that reduces the chance of the animals getting stuck in the thick glutinous mud at the bottom of the channel. If there is no water in the channel, the mud will eventually dry out towards the end of the dry season with sufficient hardness to support animals crossing without a causeway. This particular causeway had a small opening that allowed passage of a slight flow, but other causeways further south entirely block the channel at low water levels, later being overtopped as the water gradually rises at the beginning of the wet season.

In this water management option it is recommended that the full 9 km length of this channel from TBM L2 to N'Giriama is investigated, preferably by an experienced hydraulic engineer, to recommend and implement practical measures to improve the ability of the channel to pass low flows of water. The complicated multi-channel system in the vicinity of the outlet (Figure 6.2) should also be investigated to see if there is some modest programme of work for lowering the elevation of the rock sill, since the bottom of the widest section of the North West Channel, located 1 km upstream of the sill, lies at more than 0.5m below the sill.

6.3.7 Option 1.7: Clear blockages along Great Ruaha river, from Kidumka to the North West Channel, during its passage through the Eastern Wetland

One of the main changes to have occurred within the Eastern Wetland over the last 40 years is modification to the major channels connecting the Great Ruaha river at Kidumka to the North West Channel. It is not so much a change in location, but concerns more about their inability to convey low flows, by becoming blocked by aquatic vegetation or cattle causeways.

The 1958 aerial photos show two main channels connecting the *ihefu* downstream of Kidumka with the North West Channel, one from Nyamayungi to Nyampogoro, the other from Lyangulaje swamp to Nyakilolo (Figures 5.14 and 6.5). A third channel was said to exist going from Lyangulaje swamp to Nyamatutumila. Baluchi hunters in the 1960s and fishermen in the 1970s who visited the wetland both describe them as 20 metre wide flowing channels, clear of vegetation, with a depth of 2-3 m, through which small boats propelled by outboard motors could be taken all the way from Kidumka to N'Giriama.

Recent surveys of these channels indicate that most of the channels still remain in exactly the same location as in 1958, but are now blocked by a thick mat of aquatic vegetation or reed beds. Even with the shallow-draft airboat, used by the SMUWC project, it is difficult at low water to travel through this mat of vegetation, and at slightly higher water levels it is easier to travel across the adjoining flooded *mbuga* rather than along the channel itself.

Cross sections surveyed indicate that there is still about 1 metre of depth in the centre of these channels. Although it is not known exactly how much silting has occurred over the last 42 years, it can at least be stated that the channels are, in general, not completely blocked by silt.

A few of the channels are completely or partially blocked by causeways erected by the pastoralists in order to convey their cattle across standing water to reach additional grazing areas. One particularly solid causeway is located 1 km downstream of TBM L3, which completely blocks flow along the main North West channel at medium to low water levels (Figure 6.6).

More changes have occurred right in the centre of the perennial swamp. Thirty years ago there was only one large body of water, namely at Lyangulaje swamp, with its banks covered by Ambatch plants (*Aeschynomene elaphroxylon),* the so-called *ihefu* trees. The surface of this pool was clear of vegetation, and it contained herds of hippopotami. The rest of the centre of the swamp was composed of open river channels, which spilled out over the seasonal wetland when the water level rose in the wet season.

At the present time much of the Lyangulaje swamp is covered by aquatic vegetation, the perennially flooded area extends much further, and nearly all the hippopotami and the *ihefu* trees have disappeared. Upstream of this there are now a series of swamps, such as Nyangokolo and Ruaha, each containing different areas of water, some covered by aquatic vegetation and some open. These individual swamps are separated by beds of tall reeds, through which it is possible to make a passage by airboat. But regular collection of staff gauge observations have shown that the adjacent Ruaha and Nyangokolo swamps maintain different water levels throughout most of the year, which indicates that these reed beds impede the flow in one of the historical channels of the Great Ruaha river, which passes through both of these and other adjacent perennial swamps.

The objective of this water management option is to clear away all the many different types of blockages in the various channels of the Great Ruaha river connecting Kidumka to the North West channel, and then further on downstream along this channel to N'Giriama. These measures would assist in increasing the passage of low flows through these channels, though possibly not as far as restoring them to the level encountered 40 years ago, due to the silting that has probably taken place in the intervening period.

The two major routes identified are shown in Figure 6.5 and 6.6 . The fall in water level between Kidumka and TBM L3 at Nyampogoro, observed in the first half of October 2000, was 0.81 m, and from there to TBM L2 near Malawi fishing camp was 0.73 m, and from there to N'Giriama a final drop of 0.94 m. So there is a total head of 2.48 m present to drive the water towards the outlet.

6.3.8 Option 1.8: Reduce the amount of river water abstracted by the major irrigation schemes during the dry season

One of the most vital management options is to increase the amount of inflow reaching the Eastern Wetland during the dry season June to November. If this is not done, the future existence of the perennial swamp is open to serious doubt, and the present combination of perennial swamp and seasonal wetland could easily change to leave just a seasonal wetland, with no permanent water in the centre (Section 4.8). Even some of the other remedial water management options, discussed above, to restore the low flow regime of the Great Ruaha river through the Ruaha National Park, would have a much greater chance of success if there was substantially more dry season inflow into the wetland in future.

During the remaining period, December to May, the inflow is sufficient to increase the storage of water in the wetland markedly and the surplus then overflows the rock sill at N'Giriama and flows off down the Great Ruaha river. This wet season overflow has happened without fail every year to date since records commenced in 1957.

Even during the extremely dry year of 1999/2000, when river inflows to the Usangu plains were markedly reduced, this overflow occurred, but the rate reached only a maximum of 16 m^3/s. This is in contrast to the maximum daily overflow rate of at least 990 m^3/s which occurred during the *el niño* year of 1997/98. Despite this large inflow during the wet season the Great Ruaha river downstream dried up on 18 November 1998 for a period of 2 months. From this observation it is argued that, rather than any change in wet season inflows being of most concern, the critical issue is to reverse the reduction in dry season inflows to the Eastern Wetland that have occurred during recent years.

To illustrate this point, Table 6.4 summarises the flows entering the Western Wetland, at the end of September 2000, from the three largest perennial rivers. Losses between the point where the rivers leave the escarpment and enter the Western Wetland account for 86% of their upstream flows, leaving only 14% to flow further downstream to Nyaluhanga.

Seven sub-options for reducing the amount of water abstracted by the major irrigation schemes during the dry season are listed in Option 1.8 of Table 6.1. These arose from detailed discussion by the Usangu Water Management Committee, a group established by SMUWC, that brought together the managers of the three large state irrigation schemes located on the Usangu plains (Figure 6.7), together with technical representatives of the district and regional administrations concerned with irrigation and water supply. This is a short list of the most promising 45 ideas submitted and discussed during the second meeting of this committee. These ideas are expanded on further in Appendix I of Supporting Report No 9.

The majority of the sub-options are concerned with the timing and amount of flows passing through the primary canals, and how the current and future cropping calendars will influence these values. During recent years there have been a number of factors which have influenced managers and smallholders alike to start irrigation earlier in the season, and similarly other factors which have tended to extend the end date of the irrigation cycle. As a consequence the total length of the irrigation season has expanded greatly, and the number of months during which the main canals have been kept flowing has also increased. So much so that on some schemes at present the main abstraction gates are kept permanently open virtually the whole year, except for a brief period of 2 or 3 weeks when maintenance and cleaning of the main canal are conducted.

Table 6.4 Losses to groundwater and abstraction from the three major perennial rivers as they cross the alluvial fans into the Western Wetland

River name	Flow on 30/09/00 (m^3/s)	Percentage of sum of three river flows (%)
Great Ruaha river at Salimwani	1.65	38
Kimani river at Great North Road	0.74	17
Mbarali river at Igawa	2.00	46
Sum of above three river flows	4.39	100
Losses across the alluvial fans	3.77	86
Great Ruaha river at Nyaluhanga	0.62	14
Downstream compensation flow, if it is allocated 83% of sum of three river flows	3.64	83
Resulting increase in flow in Great Ruaha river at Nyaluhanga	3.02	69

As a consequence of these arrangements, the amount being diverted during the dry season is much more than is actually being consumed by the crops. The main aim of all these sub-options is to save this water, and allow it to be passed down the natural river channels. One way of doing this is to allow full abstraction of irrigation water without limit during the wet season December – May. During the remaining months of the year, June – November, only a certain percentage of the river flow is allowed to be diverted down the main canal. This can be done either by adjusting the gate settings to allow only a reduced, but constant flow, to be diverted from the river, or by allowing diversion of full flow for only a limited number of hours during every 24 hours.

For example, the main canal could be diverting all flows available in the river for 2 hours in the morning, and then another 2 hours in the afternoon. The local communities, in consultation with the irrigation managers, could decide the exact hours when the canal gate would be opened or closed to suit their domestic arrangements. For the remaining 20 hours of the day all the flow would pass down the river channel, and on into the Eastern Wetland. On this basis 83% of available river flows would be allocated as compensation flow to the Eastern Wetland during the dry season, and 17% allocated to satisfy dry season irrigation of vegetables, and domestic and livestock water needs.

If this diversion policy were adopted on the 3 major rivers shown in Table 6.4, then the compensation flows in September 2000 downstream could rise from 0.62 to 3.64 m^3/s. During the wet season 100% of the river flows up to the maximum canal capacity would be allocated to paddy irrigation, and only the surplus of river flows above the maximum canal capacity would be offered as compensation flow downstream to the Eastern Wetland.

6.3.9 Option 1.9: Improve conveyance and reduce losses to groundwater from the natural river channels crossing the alluvial fans

Where the main perennial rivers cross the shallow gradients of the alluvial fans their channels are meandering; consequently the water velocity is very low during the dry season, and there is considerable resistance to the passage of the water along the channel. The increased length of channel due to the meanders means that there is a larger area of channel bottom from which infiltration to groundwater can occur.

In contrast to this, the artificial channels belonging to the primary canals and drains in the major irrigation schemes (Figure 6.7) are designed to offer less resistance to the flow of water, due to their regular cross section, straight alignment and steadily sloping longitudinal profile. This ensures that the canals are much shorter than the alternative natural river channels, and the velocity of the water is greater. Because the area of the canal bottom is much less than the river channel, the amount of water lost to groundwater should be reduced. In addition the upstream portion of the primary canals close to the abstraction point are lined with concrete; this means the large losses into the coarser alluvial gravels found here are much reduced.

Therefore this means that, given a dry season low flow in the river at the irrigation headworks and the need to convey it with the minimum of losses to the point where the main drain flows back into the natural river, it is preferable to divert it direct through the main canal and drain of the irrigation scheme with the secondary canal offtakes closed, rather than let it flow down the natural river channel.

This proposed option is particularly suitable for the Great Ruaha river where it crosses the alluvial fans (Figure 3.18). There are no traditional smallholder irrigation offtakes on this river between the foot of the escarpment and the Kapunga irrigation headworks. The canal which diverges here supplies the Kapunga Smallholder Irrigation Project and the Kapunga Rice Project. At the foot of the alluvial fans, drains from these two schemes join the Itambo river, which then has a continuous channel connection down to the point where it rejoins the Great Ruaha river upstream of Nyaluhanga.

In contrast, the natural course of the Great Ruaha river immediately downstream of the headworks does not allow for the smooth conveyance of low flows (Figure 3.18). The broad single channel passes through the Chairman’s swamp, then divides into three smaller meandering channels; one of these, the Makambabala, flows into the Kimani subcatchment, the second, the Lihamile, eventually flows into the Mbarali river, and the third flows into the Ifushiro fan swamp, where the water is entirely lost to evaporation during the dry season.

In this management option it is suggested that during the dry season most of the low flows occurring in the Great Ruaha river should be diverted straight through the Kapunga irrigation primary canal and drains into the Itambo river.

The same general procedure could definitely be considered for the Madibira Smallholder Agriculture Development Project, where the combination of the main canal and drain within the scheme provide a much more direct route between the headworks and the point where the drain flows back into the Ndembera river (Figure 6.1). In contrast the river channel below the headworks skirts around the eastern and northern side of the scheme along a much longer meandering course.

This option could also possibly be considered for Mbarali Rice Farm No 1, provided the main drain here has a direct connection, free from any blockages, back to the Mbarali river (Figure 3.18). During the dry season the drain from Mbarali Farm No 2 does not convey low flows back to the Mbarali/Great Ruaha river, so this option is not applicable here.

Before introduction of this option is considered for any of the three schemes, detailed discussion will need to be held with both the scheme managers and the local communities who are presently dependent in some way on the river or canal water in their subcatchment. The managers will still require a period of closure of the main canal for annual maintenance and cleaning, while the local communities must have access to alternative domestic and livestock water supplies.

6.3.10 Option 1.10: Block entrance of Ifushiro fan swamp to prevent inflow of dry season flows from Great Ruaha river

As discussed under Option 1.9 above, the main channel of the Great Ruaha river, downstream of the Kapunga Rice Project irrigation abstraction offtake, divides into three smaller channels (Figure 3.18). The most westerly of these channels eventually flows into the Ifushiro fan swamp. During the dry season this area consists of a few square kilometres of perennial swamp, with no definite outlet stream; all the perennial flow entering the swamp is lost by evaporation. However, during the wet season a much more extensive seasonal wetland is formed from flood waters supplied from the Great Ruaha river, and water then drains through the wide Waninyka drain into the Itambo/Mkoji river system. So the Great Ruaha river in this area takes a completely different course in the dry season compared with the wet.

In this water management option the channel supplying the fan swamp would be blocked at the start of the dry season, and the flow in it diverted to the two other channels of the Great Ruaha river. Water in both of these channels eventually reaches the Great Ruaha river at Nyaluhanga, the central one joining the Mbarali river and the easterly one via the Kimani and then the Mbarali rivers. During late-November/early-December 1999 all three of these channels were flowing steadily, and their flows were measured as 82, 20 and 107 l/s respectively, starting from the west. If the channel leading to the Ifushiro swamp were blocked in the dry season, the downstream contribution from the Great Ruaha river could be increased from 127 to 209 l/s, an increase of 65%.

There is one small village located on the south west side of the Ifushiro fan swamp, close to where the inflowing channel reaches the perennial part of the swamp. Studies would need to be done to see how much this village is dependent on the perennial flow in this channel, before any option for blocking it off is implemented.

6.3.11 Option 1.11: Increase capacity of existing small channel connecting Great Ruaha river to Kimani river

The most easterly of the three channels into which the Great Ruaha river currently splits in the dry season, mentioned in the previous section, is called the Makambalala (Figure 3.18). The origins of this channel are unclear, but it may have been constructed as an artificial channel to convey water from the Great Ruaha river to provide additional supply to irrigation schemes in the Kimani subcatchment; it has certainly been in existence for some years.

In this option the capacity of this channel could be increased by widening and deepening it, and removing any blockages to a smooth flow of water. The length of this channel, from where it leaves the Great Ruaha subcatchment to its confluence with the larger Kimani river channel, is, at 4 km, much shorter in comparison with that of the central Lihamile branch of the Great Ruaha river, which takes a meandering course northwards for 15 km before joining the Mbarali river (Figure 3.18).

The aim of this option would be to transfer more of the flows, which currently pass down the central Great Ruaha channel, into the Makambalala, and so boost the total combined volume of flow contributed by the Great Ruaha river downstream of its confluence with the Mbarali river.

6.3.12 Option 1.12: Improve the conveyance of flows along the four main perennial rivers

The objective of this option is to maintain a minimum flow into the Eastern Wetland during the dry season from key upstream rivers. A flexible approach is adopted for each subcatchment depending on the supply/demand characteristics of each river. Because it has some similarities to policies for improving traffic management schemes in the United Kingdom, the 'red routes' name used there has been adopted to describe this water management option. Fuller details are given in Appendix B of Supporting Report No 9.

Red routes would be those perennial rivers with few offtakes where natural losses could be minimised, and where dry season irrigation is poorly developed and can be further controlled by informal or formal legislation. Seasonal rivers would not be red routes as water supply in these is very dynamic and unpredictable. Also, perennial rivers with many offtakes and extensive dry season irrigation would not be selected, for example the Chimala river and the seven perennial streams of the Mkoji subcatchment (Figure 3.18). The four possible red routes are listed in Table 6.5:

Table 6.5 Possible red route rivers

River	Number of offtakes	Offtake description
Kimani	5	1 medium 4 minor
Great Ruaha	2	1 large 1 minor
Mbarali	3	1 large 2 medium
Ndembera	6	1 large 5 minor

The calendar year would be divided into three different periods

1 June – 31 October	Net dry season irrigation demand is less than river flow supply; but excessive wastage of water exists to make gross demand higher than river flow supply; Recommend staged series of compensation flows; Red river concept should be applied during this period;
1 November – 15 January	Irrigation demand greatly exceeds river flow supply; Set targets for staged compensation flows; No controlling action possible; The length of this period must be kept within strict time limits;
16 January – 31 May	River flow supply exceeds irrigation demands; No controlling action needed; Allow for natural allocation of water;

During June to October users would be encouraged to take less water and would be given greater attention by water officers. Each river would need to be tackled separately taking into account the nature of water use. Options would be selected from the following: intake gate control, cropping patterns, water fees and rights, proportional water rights, cross-seasonal water licences, and irrigation management extension advice.

6.3.13 Option 1.13: Increase volume of runoff produced by the high catchment by reducing the total area currently covered by forests. Likewise there should be no additional land area earmarked for afforestation, which, if implemented, would cause a decrease of runoff

The current forestry policy at district, regional and national level actively encourages the planting of trees. If these are directed in practice towards the formation of small woodlots or the prevention of soil erosion then they will have overall beneficial effects, with no deterioration to the water resources within the project area.

However it can be shown from numerous experiments around the world that planting of extensive areas of forests will eventually cause a reduction in the runoff occurring further downstream. If a policy were adopted of covering the rolling grasslands presently existing in the headwaters of many of the subcatchments in the project area with substantial forest plantations, this would cause problems for the downstream users of water.

The area of irrigable land in the Usangu Plains is limited by the amount of water available, and even a slight decrease in supply, particularly in the critical September-November and April-June periods, would ultimately mean a loss of potential paddy cultivation. So it is very important that these headwaters are carefully protected from any major changes in land use that directly reduce the availability of water resources.

A preferable policy from the water resources viewpoint would be to encourage carefully controlled deforestation, in areas where this would not lead directly to degradation of the land. However there are currently almost no large areas of forest in the high catchment, so this would be of little practical benefit.

6.3.14 Option 1.14 Construct reservoirs on main rivers flowing down from the high catchment, to store water from flood flows during the wet season and then release this water steadily during the dry season

A regulating reservoir is designed to store surplus water in the river during the wet season, and then release it during the dry season to benefit downstream users. Construction of such regulating reservoirs on any of the main rivers flowing into the Usangu Plains will have the following three advantages:

- able to enhance the natural river flows in April-June and again in October-December, to permit an increase in the area of land under irrigation; these periods are known as the shoulders of the irrigation demand curve, and the shortage of natural flows at these two times are the main limitations as to how much land may be irrigated from any particular river;
- if there is a prolonged dry spell in the middle of the cropping season, which is likely to have a severe adverse impact on yields, the reservoir can be used to enhance the flows during this critical period;
- able to enhance the natural river flows in the period August-October, which will improve the minimum river inflows to the perennial swamp, and consequently enhance the flows down the Great Ruaha river through Ruaha National Park.

The construction of such regulating reservoirs also leads to a major disadvantage:

- Reservoirs will reduce the inflows to Mtera Reservoir, and cause a consequent decrease to the amount of hydropower generated.

A Preliminary Reconnaissance Survey of the Rufiji Basin was undertaken by the Food and Agriculture Organisation of the United Nations (FAO) in 1961. One part of their terms of reference was: 'The extent to which storage is required, and the sites of dams to achieve that storage, along with an estimate of probable construction costs for each dam, is to be investigated'.

They identified sites for dams on four of the main perennial rivers flowing down to the Usangu Plains, which represented technically feasible solutions for water control (Table 5.6). The mean regulated outflow represents the constant flow that could be maintained in the downstream river throughout an average year due to the erection of the dam. According to two basic economic criteria, shown in the last two columns of Table 6.6, it is apparent that the proposed reservoir at Ngalenge on the Ndembera river is the most economical of the four.

Table 6.6 Regulating reservoirs proposed for the perennial rivers

Reservoir	River	Mean annual inflow (m^3/s)	Mean regulated outflow (m^3/s)	Operational reservoir capacity (Mm^3)	Cost (UK£ - 1961)	Cost per unit of outflow (UK£/m^3/s)	Cost per unit of capacity (UK£/Mm^3)
Upper Great Ruaha	Upper Great Ruaha	9.32	8.39	129	3 604 600	430 000	27 900
Kimani	Kimani	5.26	4.73	83	1 849 450	391 000	22 300
Mbarali	Mbarali	12.8	11.5	138	2 832 500	246 000	20 500
Ngalenge	Ndembera	3.73	2.55	61	408 000	160 000	6 740
					Cost (US$ - 1985)	**Cost per unit of outflow (US$/$m^3/s$)**	**Cost per unit of capacity (US$/$Mm^3$)**
Lugoda	Ndembera	6.0	4.0	210	6 800 000	1 700 000	32 000

This latter scheme was studied in more detail by the consultants Sir William Halcrow & Partners in 1985, as part of the Detailed Engineering Study of the Kapunga/Madibira Rice Project. The proposed site of the dam is at Lugoda, which is essentially the same location as Ngalenge, but the operational reservoir capacity has been raised from 61 to 210 Mm^3, which gives a revised regulated outflow of 4.0 m^3/s (Table 6.6). When the Madibira Rice Project was finally constructed in 1998 it was decided not to incorporate the Lugoda regulating reservoir into the scheme.

Construction of a regulating reservoir is an expensive method for enhancing the downstream flows in the Great Ruaha river and increasing the production of irrigated rice. Before embarking on such a course of action it is preferable to examine options for ensuring the operation of the existing run-of-river irrigation schemes are as good as their design permits, and that every drop of water flowing down from the high catchment is used to best effect.

Some suggestions for improved operation are listed under Options 3.1-3.4. Certainly introduction of a shorter season variety of rice, strict adherence to a compact cropping calendar, and a more disciplined sharing of existing water abstracted for irrigation would have positive effects without great financial burdens. The amount of land available for wet season paddy irrigation could be increased but at the same time more water would be made available during the dry season to enhance the downstream flows in the Great Ruaha river.

6.4 Discussion of options for Objective 2

6.4.1 Option 2.1: Construct major channel to convey wet season flows in Great Ruaha river from Nyaluhanga to N'Giriama which bypasses perennial swamp

One longer term water management option that could be considered is to drain the Eastern Wetland completely, and construct major artificial channels that would convey the flows in the two main inflowing rivers, the Great Ruaha at Nyaluhanga and Ndembera at Madibira, directly to the outlet at N'Giriama. This would avoid the loss of water which currently occurs from the flooded surface area of the existing wetland.

In Section 4.8 the size of this loss has been estimated by using the Sutcliffe-Parks submodel to simulate the behaviour of the Eastern Wetland. The loss during the very dry years of 1999 and 2000 was estimated as 256 Mm3 and 222 Mm3 respectively; during an average year it is believed the loss would be slightly higher than this, say 280 Mm3. This latter Figure is 7.8% of the long term mean inflows to Mtera reservoir. This means that if major construction works were undertaken to create two bypass channels around the Eastern Wetland, then inflows to Mtera reservoir could be increased by about 8%, with consequent, but slightly lower, increases in hydropower production at Mtera and Kidatu power stations, since some of the increase in inflows will be lost by increased evaporation from Mtera reservoir.

Construction of just a single bypass channel from Nyaluhanga to N'Giriama, to convey the Great Ruaha river around the Eastern Wetland, would at first sight appear to be a useful option. This is because the Great Ruaha entering the Eastern Wetland currently conveys about four to five times as much water as the river Ndembera at Madibira, and this will rise to six to eight times as much, once the Madibira Smallholder Agriculture Development Project is developed to its full capacity of 3000 ha. However the Eastern Wetland behaves in an unexpected manner, and analysis shows that this one channel will only provide between 56% and 68% of the total effect of constructing both channels, under the inflows observed during 1999 and 2000. So constructing just one channel seems of much less benefit than constructing both channels.

6.4.2 Option 2.2: Construct major channel to convey wet season flows in Ndembera river, from downstream of Madibira Smallholder Agriculture Development Project, to N'Giriama, which bypasses perennial swamp

In this option a single channel, bypassing the Eastern Wetland, would be constructed to convey the flood flows from the Ndembera river towards the outlet at N'Giriama.

It is estimated that this channel on its own would enhance the inflows to Mtera reservoir by only 1.4% under current natural flows in the Ndembera river. Once the Madibira Smallholder Agriculture Development Project was developed to its full capacity of 3000 ha, with consequent increase in water abstracted from the river, this increase in inflows to Mtera reservoir would fall to just 0.7%.

It does not seem worthwhile to construct this channel on its own. However the option of building the combination of two channels, to convey the majority of the inflows to the Easter Wetland direct to the outlet, would be worthy of further study.

6.4.3 Option 2.3: Construction of major channel, bypassing Ifushiro fan swamp, to divert wet season flows in Great Ruaha and Chimala rivers which currently enter this fan swamp

One of the branches of the Great Ruaha river, downstream of the diversion canal for the Kapunga Rice Project, leads into the Ifushiro fan swamp (Figure 3.18). During the dry season this is just a small perennial swamp, but in the wet season the flood flows from the Great Ruaha river supply it with sufficient water to greatly expand its surface area. Consequently these flood flows are temporarily stored in the fan swamp, and are unable at that time to flow down the channels leading to the Eastern Wetland. In May and June each year, after the main flood peak in the Eastern Wetland has passed, this fan swamp drains its stored water into the river channels downstream and so supplies the Eastern Wetland.

Since the construction of the Kapunga Rice Project in 1990, the course of the Chimala river has been diverted from its original course, and now flows into the Ifushiro fan swamp. During the height of the wet season the flood flows from this river flow along an artificial channel cut along the eastern boundary of the Kapunga Rice Project, and into the northern end of the Ifushiro swamp.

In this option a large channel would be constructed to divert the flood flows in these two rivers around the Ifushiro fan swamp, and convey them into the Great Ruaha river at Nyaluhanga. This would have the advantage of avoiding both the reduction in size and delay in the flood peak due to the dampening effect of the fan swamp, and also the loss of water due to evapotranspiration from the surface of the swamp. A higher and shorter flood peak from these two rivers would be conveyed all the way down to the Eastern Wetland. Due to way that this wetland behaves as a system, having a single overflow at N'Giriama, this altered flood peak would ensure more water would leave by the outlet, and flow down the Great Ruaha river to Mtera reservoir.

6.4.4 Option 2.4: Conversion of existing small channel, which connects Great Ruaha river to Kimani river, into a major channel for conveying wet season flows

The layout of the three channels of the Great Ruaha river downstream of the diversion canal to the Kapunga Rice Project has been described previously in Section 6.3.10. The most easterly of these channels normally conveys a certain proportion of the low flows in the Great Ruaha river across into the Kimani river (Figure 3.18).

The aim of this option would be to increase the size of this channel and construct associated works which would allow most of the flood flows remaining in the Great Ruaha river downstream of the irrigation headworks to be diverted into the Kimani river, and from there conveyed down the existing channel network eventually to the Eastern Wetland. The effect of enlarging this channel would be essentially similar to that of the previous option, namely to avoid the dampening effect of the Ifushiro swamp and the associated loss of water due to evaporation, and so ultimately increase the inflows to Mtera reservoir.

It may not be practicably possible to include the diversion of the flood flows from the Chimala river in this option, so the benefits may be less than Option 2.3.

6.4.5 Option 2.5: Construction of reservoirs on main rivers flowing down from high catchment, that store water from flood flows during the wet season, and then release it steadily during the dry season

The advantages to irrigated agriculture of constructing upstream regulating reservoirs has been discussed previously in Section 6.3.14. They are not only able to enhance the natural river flows during the critical shoulders of the irrigation demand curve, but also able to provide security of flow during any prolonged dry period during the middle of the cropping season. An additional benefit they could bring is their ability to enhance the river inflows to the perennial swamp during the middle of the dry season, which would in turn alleviate the current loss of dry season flows observed in Ruaha National Park downstream.

However, set against these three benefits, is one major disadvantage, namely that such regulating reservoirs are likely ultimately to reduce the inflows to Mtera reservoir, and so decrease the amount of hydropower produced. This arises from their proposed location upstream of the Eastern Wetland, and the consequent interaction between the reservoir and wetland subsystems. This latter subsystem, with its single outflow over a rock sill at N'Giriama, is very sensitive to the size of the flood inflow during March-April each year; the size and duration of the peak inflow determine exactly what volume of water overflows the rock sill and flows out down the Great Ruaha river to Mtera.

The principle behind the operation of a regulating reservoir is that it reduces the size of the flood peaks in the river, by storing the water in the wet season, and then enhances the natural river flows during the dry season, by releasing water from this storage. So construction of regulating reservoirs on the rivers flowing down from the high catchment will reduce the peak inflows to the Eastern Wetland, which will in turn reduce the outflow downstream to Mtera reservoir. Another detrimental side effect may be that the annual flooding of the seasonal wetland will be less pronounced, which may interfere with the normal breeding of fish which occurs in this part of the wetland.

This operation could be analysed in detail by modifying the computer-based Usangu Basin Model to include various proposals for upstream regulating reservoirs, and test the effect on downstream inflows to Mtera reservoir. In the meantime, to preserve the current levels of inflows to Mtera reservoir and associated hydropower production, it is suggested that no regulating reservoirs should be proposed for construction in the project area.

6.4.6 Option 2.6: Construction of a high dam at the outlet at N'Giriama, to store water throughout the year over the complete Eastern Wetland, and then release any surplus down the Great Ruaha river to Mtera Reservoir.

Another water management option that has been tentatively suggested for Usangu is to construct a high dam at N'Giriama that would entirely flood the complete Eastern Wetland, forming a reservoir several metres deep. The aim of this scheme would be to form an additional storage facility to that at Mtera, and so ultimately increase hydropower production downstream.

An initial analysis of this idea is described in Section 4.8, which discusses the application of the Sutcliffe-Parks computer submodel to explain the behaviour of the Eastern Wetland. The benefit of this option is that it would allow storage of surplus flood water in the extremely wet years, such as 1998, when it was necessary to allow flood spillage at Mtera for several consecutive months. The disadvantage of this option is that the reservoir site has a poor configuration, with a large surface area and a shallow depth of water, leading to very high losses from evaporation. In a normal year these could reduce the annual inflows to Mtera reservoir by over one fifth.

This option of a reservoir in the Eastern Wetland was originally suggested as an alternative location to that of Mtera, when that scheme was originally being considered. However, now that Mtera reservoir has already been constructed, the option of a second reservoir at N'Giriama, to provide additional storage to that existing at Mtera, does not appear attractive on initial analysis. In fact the losses from evaporation occurring every year may well outweigh any gains from storage of exceptional floods, like those that occurred in 1998. For this reason the construction of a dam at N'Giriama is not recommended.

6.4.7 Option 2.7: Increasing in the area of irrigated rice during the wet season from its current level of 42 000 ha

Recent surveys have shown that the maximum irrigable area in the Usangu plains, without construction of upstream regulating reservoirs, is 55 000 ha. This is 31% greater than the present irrigable area of 42 000 ha. Efforts will be made by the farmers in the coming years to gradually increase the cultivated area to attain this limit, using a number of techniques, as discussed in Section 6.5.5. One consequence of this will be that larger quantities of water will be abstracted from the rivers during the wet season, and the question must be posed as to what effect this will have for hydropower production.

Application of the Sutcliffe-Parks model to simulate the behaviour of the Eastern Wetland was described in Section 4.8. The submodel was used to show that additional abstraction over the current level during the wet season would cause a reduction in the inflows to Mtera reservoir. For example, to increase the irrigable area from 42 000 to 55 000 ha would need an additional combined abstraction from all the upstream rivers entering the Usangu plains of approximately 15 m^3/s. This would cause a reduction in mean annual inflows to Mtera reservoir of between 2-5%.

To retain the long term security of future hydropower production at Mtera and Kidatu power stations it is recommended that the maximum irrigable area should not be allowed to exceed its current level of 42 000 ha.

6.5 Discussion of options for Objective 3

6.5.1 Option 3.1. Ensure more disciplined and equitable sharing of existing water abstracted for irrigation

This objective has two parts to it, the maximisation of irrigated rice and the minimisation of social conflict. In this objective, they are linked together because greater spreading of available water is a precursor to, and a result of, the minimisation of social conflict, and because greater spreading of water raises the productivity of the water used. Total production increases because farmers who currently use large amounts of water will not detect lower yields when they save some water, but water-short farmers will benefit from the extra water supplied from those water savings.

Observations show that upstream intakes tend to abstract more water than downstream intakes, and that on the whole, within irrigation systems, top-enders have first call on water. This situation has increased with the construction of modified and upgraded intakes, whereby concrete weirs can block the river so that the whole flow is diverted through the sluice gate.

To improve the equitable sharing of water it is possible to consider changes to intakes on rivers to improve sharing of water. Such designs as proportional divisors and castellated weirs fall into this category. Modifications to existing gates could also be reviewed. (See Appendix G on "Discussion on improvements to intakes", Supporting Report No. 8).

Infrastructural changes within irrigation systems to assist in fairer sharing of water could also be considered. These can be proportional dividers, extra canals and extra intakes (see Appendix I on "Improvement of Usangu Irrigation", Supporting Report No. 8). Extra division points and canals group farmers into smaller negotiating units where they can more carefully divide or cycle the available water. Extra canals provide water to tail-end farmers without using field-to-field transmission of water which leads to higher evaporation of water than is necessary.

Higher standards of infrastructure maintenance will also help distribute water according to design. In contrast, allowing weeds to grow, and sediments to build up, promotes higher water levels in upper reaches of canals and therefore higher discharges into upstream fields creating temporary swamps or unnecessarily deep water. Re-building, cleaning, reshaping and raising of canal walls channels water correctly and reduces seepage and spillage.

In addition, improved planting schedules ensure a more uniform growing pattern over larger areas. This helps farmers control water, and help spread benefits further. Improvements to infield planting schedules have been observed in Usangu. For example, in the Kapunga smallholder system, during recent drought years, farmers decided to co-ordinate their planting dates to improve water control.

6.5.2 Option 3.2. Establish river management systems for each major subcatchment in the Usangu Basin, based on Water User Associations.

The need to promote community-based mechanisms for managing water resources is recognised by all stakeholders. Farmer groups, co-operatives and water user associations have existed in Usangu in one form or another for many years. Supporting Report No. 9 contains findings on community water management, which shows that farmers readily organise to discuss water management. However, the future carries greater challenges of managing scarce water supplies, resolving conflict and of ensuring a more equitable division of water between irrigators and between sectors.

To meet these challenges, it is recommended that the SRMP (subcatchment resource management programme) is continued with, and if possible copied to other rivers in Usangu. As Supporting Report No. 19 explains, the SRMP addresses natural resources in general, as well as the key resource of water. Furthermore, the SRMP attempts to strengthen Water User Associations at the canal and system level within irrigation systems on the rivers. This inter- and intra-system focus on community water management is believed to be one of the most important parts of the future management of allocation of water within the Ruaha river basin.

6.5.3 Option 3.3. Introduce a shorter season rice crop

Currently, the popular rice varieties used in Usangu (e.g. Kilombero) take 140-160 days to ripen. This means that the total duration of irrigation increases which reduces the availability of water for downstream needs. In addition, accidental mixing of seeds means that some farmers wait longer for patches of their fields to ripen when much of their paddy is due for harvest. If the season could be shortened then water could be provided downstream earlier. The aim, therefore, is to find a desirable, popular, shorter season rice crop.

During recent years, short-season basmati varieties (an aromatic type with a price premium and 120 day season length) have been tested in Usangu on a small scale, and with some success. Providing this variety to other farmers, along with advice on cultivation, might increase its eventual wider uptake.

Extension messages (see Section 6.5.4 below) might encourage farmers to use cleaner seeds that do not mix varieties thereby allowing even ripening and shorter seasons.

6.5.4 Option 3.4. Establish a more robust rice extension service designed to meet farmer's needs.

Although an extension service nominally exists in the Usangu area, few farmers reported receiving visits by extension agents. However, many of the farmers interviewed during the course of the study expressed great interest in obtaining advice relevant to their needs. A modern needs-orientated extension service could help, alongside other interventions, to bring about changes in water control and rice cultivation. For example, such a service could cover the following topics:

The cultivation of shorter-season varieties (see above) could be promoted in order to reduce gross water needs.

With a shorter season variety, it might be possible to encourage more top-end farmers to obtain a second rice crop by ratooning from the existing transplanted rice. This would increase total production but would have implications for extending water use during March to June, thereby decreasing flows downstream of irrigation systems.

Farmers might be encouraged to withhold irrigation from rice some 3 to 4 weeks before harvesting to save water. The extension service could demonstrate how this works and why it has a low impact on yield.

The water-saving benefits of reducing the depth of standing water in fields to below 10 cm, again with minimal impact on yields, could be examined through farmer-managed on-farm trials.

The subject area of 'farming business skills' (eg, monitoring inputs, costs and incomes) could be explored. Usangu farmers rarely carry out monitoring of costs. Yet when a gross margin analysis of a farm was conducted by an irrigation efficiency researcher allied to the SMUWC project, it was demonstrated, much to the surprise of the farmer involved, that the farm made an operating loss over the year. The farmer expressed his interest in knowing more about such tools.

Farmers, groups of farmers and the extension agents could review nursery management, again with the objective of saving water, reducing conflict and maintaining rice production. This could cover placement of nurseries, the duration of irrigation of the nursery before transplanting, and the selling of seedlings from group-organised nurseries.

The time spent between first field wetting (in order to prepare and plough fields) and the transplanting of seedlings has important impacts, when scaled up, on the total volume of water abstracted from rivers. Extension agents could work closely with farmers to encourage by-laws that minimise time wasting once water arrives at a farmer's field. This would save water and promote a more transparent sharing of available resources.

A wet and dry season intake-operating schedule could be discussed, with a view to partially closing intakes during the dry season. Thus on a set date (between May and early July) the gates would be closed down and then later, between mid October and mid December, they could be opened up again. The consequences of canal operating schedules could be discussed openly, so that such changes could be introduced with the agreement of farmers. Therefore, an extension service might be integral to the success of the future management of the four red route rivers; Ruaha, Mbarali, Kimani and Ndembera.

Extension agents could help strengthen and facilitate decision-making during dry years when less water is available. For example, they could resolve issues on how reduce the total command area such as how to decide what the core irrigated area will be.

6.5.5 Option 3.5. Increase the amount of water abstracted during the wet season to increase the present irrigable area from 42 000 ha to the maximum irrigable area of 55 000 ha

Although Option 2.7 (above) recommends that the present maximum irrigated area of 42 000 ha should not be exceeded, stakeholders may resolve to expand rice up to the maximum irrigable area of 55 000 ha. Although this might only be achievable in normal-to-wet years, such a move would place further demands on the total maximum intake abstraction in Usangu, currently estimated at 45 m^3/s.

Several interventions could ensure more water is abstracted for rice so that area under rice increases. These are: continue with the upgrading of remaining traditional intakes; increase the capacity of upgraded intakes to enable more water to be abstracted; add further canal distribution infrastructure; and keep intakes open during rainy periods to ensure more water is delivered to the tail end of command areas.

Such expansion of rice would decrease volumes of water entering the wetlands and reservoirs on the Great Ruaha river. It is also likely that further expansion of rice would probably exacerbate conflict over water resources by increasing the numbers of farmers cultivating in tail-end, risk-prone areas. For these reasons it is recommended that the amount of water abstracted should not be increased.

6.5.6 Option 3.6. Construct upstream reservoirs to provide additional flow during start and end of dry season, on shoulders of irrigation demand curve

The previous discussion on Option 1.14 in Section 6.3.14 presents the notion that upstream reservoirs could be built to augment dry season flows in certain rivers. This stored water could be used to increase rice production rather than to meet environmental demands. In particular, rice production could be increased by using this water to ensure predictable flows at the beginning of and at the end of the dry season, and to meet any shortfall during a prolonged dry spell during the wet season. However, as is pointed out in Section 6.3.14, construction of a regulating reservoir is an expensive method of increasing the production of irrigated rice. Cheaper methods would include Options 3.1 to 3.4.

6.5.7 Option 3.7. Apply the concept of Irrigation Management Transfer to the large state rice irrigation schemes at Kapunga and Mbarali

The Kapunga and Mbarali rice farms (Figure 6.7) are currently managed partly as Government farms, with management and employees cultivating rice, and partly as smallholder schemes, with rice farmers paying land rents to the management. Observations show that both types of growers use excessive amounts of water and do not achieve yields found elsewhere in Usangu. By applying the concept of Irrigation Management Transfer to the large state rice schemes it may be possible to save water use in these farms, increase rice production and enhance rural livelihoods by settling greater numbers of families on a more permanent basis. The argument is that converting these farms to the kinds of smallholder systems found elsewhere in Usangu raises farmer density, introduces inter-farmer competition for water, and therefore raises an individual farmer's care for water. See Appendix A of Supporting Report No. 8 for further details.

6.6 Discussion of options for Objective 4

6.6.1 Option 4.1: Ensure reliable inflow of river water to Eastern Wetland during the dry season

The productivity of the perennial swamp in the Eastern Wetland is limited by water availability. If water is restricted less biomass will be produced (Section 3, Supporting Report No. 14). It is therefore important for the health of the water environment that sufficient water is supplied to the Eastern Wetland.

It is known that the seasonal wetland flooded every year since records started in 1957. This was true even in the exceptionally dry year of 2000. Therefore the supply of water is not a problem in the wet season. It is during the dry season that it is important to ensure a sufficient inflow into the perennial swamp to prevent it from drying out and to maintain outflow into the Great Ruaha river. This will preserve the biological and hydrological functions of the wetland. This option will be achieved if Options 1.8 to 1.12 inclusive are implemented (Sections 6.2 and 6.3).

6.6.2 Option 4.2: Monitor inflow of fertilisers from both rainfed and irrigated cropped areas upstream

The Eastern Wetland is in a relatively undergraded condition. This is important because many of the World's wetlands are presently contaminated by excess nutrients and this leads to eutrophication (eutrophication is the excessive production of organic material, particularly algal blooms, whose decay imposes a heavy oxygen demand, resulting in anaerobic conditions). The present condition of the Eastern Wetland is largely due to the relatively light use of fertilisers on farms upstream. If fertiliser use were to increase markedly from its present low level this may put at risk the nutrient status of the Eastern Wetland. It is suggested that for the time being a watching brief should be maintained by the Rufiji Basin Water Office on fertiliser (and pesticide) use in the catchment. Nitrates should be monitored on a two monthly basis at Nyaluhanga, and at river gauging stations on the Great North Road. If any large scale change in farming practices is proposed upstream of the wetland an Environmental Impact Assessment should be carried out to determine its potential effects on the wetland.

Section 3.8 discusses water quality and the risk of pollution by fertilisers. Supporting Report No. 13 presents a detailed assessment of water quality in the Usangu basin.

6.7 Discussion of options for Objective 5

6.7.1 Option 5.1: Prevent any further substantial areas of land being earmarked for afforestation, except in exceptional cases on small patches to prevent soil erosion. Encourage carefully controlled deforestation in areas where this would not lead directly to degradation of the land

The current forestry policy at district, regional and national level actively encourages the planting of trees. If these are directed in practice towards the formation of small woodlots or the prevention of soil erosion then they will have overall beneficial effects, with no deterioration to the water resources within the project area.

However it can be shown from numerous experiments around the world that planting of extensive areas of forests will eventually cause a reduction in the runoff occurring further downstream. If a policy were adopted of covering the rolling grasslands presently existing in the headwaters of many of the subcatchments in the project area with substantial forest plantations, this would cause problems for the downstream users of water.

The area of irrigable land in the Usangu Plains is limited by the amount of water available, and even a slight decrease in supply, particularly in the critical September-November and April-June periods, would ultimately mean a loss of potential paddy cultivation. So it is very important that these headwaters are carefully protected from any major changes in land use that directly reduce the availability of water resources.

A preferable policy from the water resources viewpoint would be to encourage carefully controlled deforestation, in areas where this would not lead directly to degradation of the land. However there are currently almost no large areas of forest in the high catchment, so this would be of little practical benefit.

6.7.2 Option 5.2: Implement suitable land-husbandry techniques to prevent gullying and soil erosion, particularly on steep slopes

There is little evidence of wide-spread soil erosion existing in the subcatchments located in the mountains to the south of the project area. Mostly it occurs in isolated patches where the underlying rock is softer. The problem is more prevalent in the headwaters of the Kyoga and Ndembera rivers on the eastern side of the project area (Figure 6.7).

The option considered here is to implement suitable land-husbandry techniques to prevent any further soil erosion or the formation of gullies. The Danida-funded HIMA project has been established in these upland areas since the early 1990s. It is currently active in the Makete District (Bulongwa and Matamba subdistricts) in the south of the SMUWC project area and in Iringa Rural District (Kilolo subdistrict) in the east of the SMUWC project area. Among its many sectors of work, one of them is the introduction of good land husbandry techniques such as these.

6.7.3 Option 5.3: Encourage more active management of woodlands and forests to preserve ground cover during the rainy season

Each year there is a build up of combustible undergrowth in the miombo forest that grows on the slopes overlooking the Usangu Plains. If left unburnt, it will, after several years, provide sufficient material to supply a very severe fire that will damage the miombo trees themselves. This will ultimately lead to a loss of ground cover that could affect the stability of these slopes during the rainy season.

It is suggested that a more active management of the woodlands and forests should be initiated. Under this system there would be controlled burning of the miombo forest each year. The miombo trees are hardy enough to survive a light fire of this kind. In this way the build up of dense ground cover can be prevented, and the chances of a severe fire avoided.

6.7.4 Option 5.4: Explore institutional links and other ways that will allow principal downstream beneficiaries of river flows (people and organisations involved with irrigation, livestock, fisheries, environment, wildlife, and hydropower) to support practical measures preventing degradation of the high catchment

This was an idea that was raised and extensively discussed at the SMUWC workshop on the Water Resources of Usangu, held at Mbeya in June 1999. The principle is that those people and organisations located downstream, who would most benefit from protection of the headwaters of the high catchment area, should in some way contribute towards the expense of introducing land husbandry and other measures upstream. It was stated that villagers living in these regions did not have the incentives or resources to protect those areas under threat, particularly when they could see no immediate benefit to their own livelihood.

Participants felt that parastatal organisations such as TANESCO, which possessed large revenues, should be persuaded to set aside a small amount of money to facilitate suitable catchment protection measures in the headwaters. Not only would these measures be of direct benefit to TANESCO by safeguarding their long term water supply, but that organisation would gain from the good public image garnered from this action.

It is not clear which of the other downstream users would have surplus resources to set aside for these protection measures. For example, several of the irrigators have difficulty even now raising resources to pay their annual water right fees. Existing fishing and livestock are subsistence livelihoods. Wildlife organisations have incomes from the issue of hunting concessions and park entry fees, and with their interest in the environment, might be persuaded to support such an initiative.

6.7.5 Option 5.5: Encourage active management of the grasslands in the high catchment, including controlled burning, to maintain their status as historical grasslands

The land resources of the high catchment in the project area have been intensively studied by the SMUWC project. Rather than agreeing with current thinking that substantial clearance by deforestation has occurred over recent decades, it is thought that these extensive grasslands have existed since historical times. Trees would be marginal competitors to the grasses due to poor soils, lack of soil moisture on convex slopes, exposure to wind and irregular burning, and have only gained a foothold in the more sheltered gullies which tend to attract more reliable soil moisture. There are other locations in this region of Africa, such as the Nyika Plateau in Malawi and the Inyanga Highlands in Zimbabwe, which have similar characteristics.

It is suggested that active management of these grasslands should be introduced to preserve their status as historical grasslands. It is noticeable that if they are fully protected, then trees are able slowly to gain a foothold. A better policy might be to allowed regular controlled burning, which would discourage trees, and promote healthy grass growth. The growing of potatoes and other vegetables should be discouraged on the steeper slopes, which would otherwise initiate soil erosion.

6.7.6 Option 5.6: Continue to monitor extent of valley floor cultivation in the headwaters of rivers on the eastern edge of project area

The cultivation of swampy areas in the headwaters of rivers, called *vinyungu*, is a traditional technique which allows crops to be grown throughout most of the dry season. The area of the swamp in the bottom of the river valleys is enhanced by cutting of ditches which improve the water supply and drainage.

This cultivation technique is particularly prevalent in the headwaters of the Ndembera, Kyoga and eastern Mbarali subcatchments (Figure 6.7). The western headwaters of the Mbarali, and the other rivers originating from the high catchment to the south of the project area possess only minor pockets.

If the valley bottom swamp is directly converted into an equivalent size of vegetable garden, then the consumption of water is unlikely to change. This is because the evapotranspiration from the vegetables is approximately equal to that of the swamp vegetation, since both are short growing varieties. (On the other hand, if the swamp was converted to a forest, then evapotranspiration would increase). The difficulty comes if small irrigation channels are used to increase the size of the *vijaruba* well beyond the valley bottom swamp’s original size. Then the water consumption will increase, and will inevitably lead to a reduction of streamflow downstream.

It seems likely that this is happening on the three subcatchment areas with the greatest concentration of *vinyungu*. But the consumption will be modest, and only increase slowly. Eventually a noticeable effect on downstream irrigators and other users will happen towards the end of the dry season. But the positive results of the increased production of dry season vegetables will probably be of greater benefit than trying to reverse this slow increase of area being put under cultivation. Communities may consider that cultivation of vegetables may have equal or greater priority to that of paddy rice.

It will be prudent for the Rufiji Basin Water Office to continue in future to monitor the total area under *vinyungu* cultivation.

Figure 6.1 Location of existing and proposed channels in the vicinity of Madibira Smallholder Agriculture Development Project

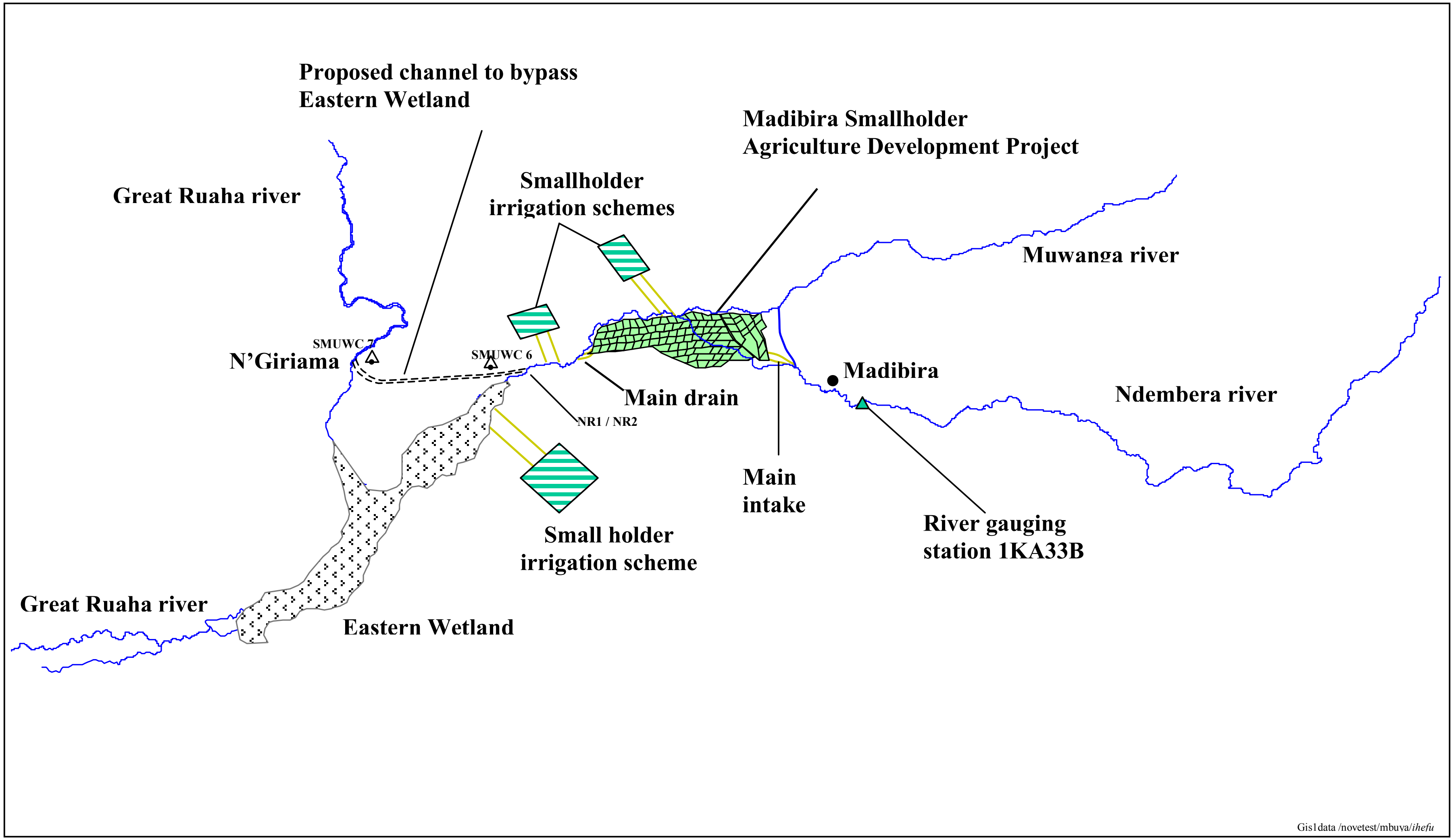


Figure 6.2 Sketch map of complex network of channels at outlet of the Eastern Wetland at N'Giriama

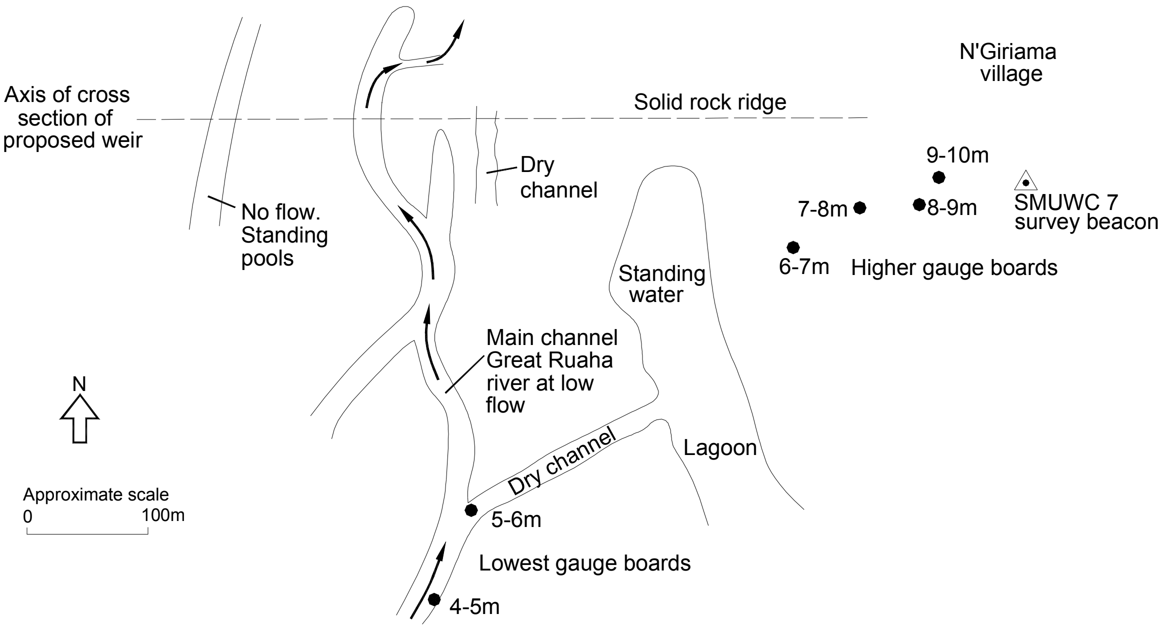
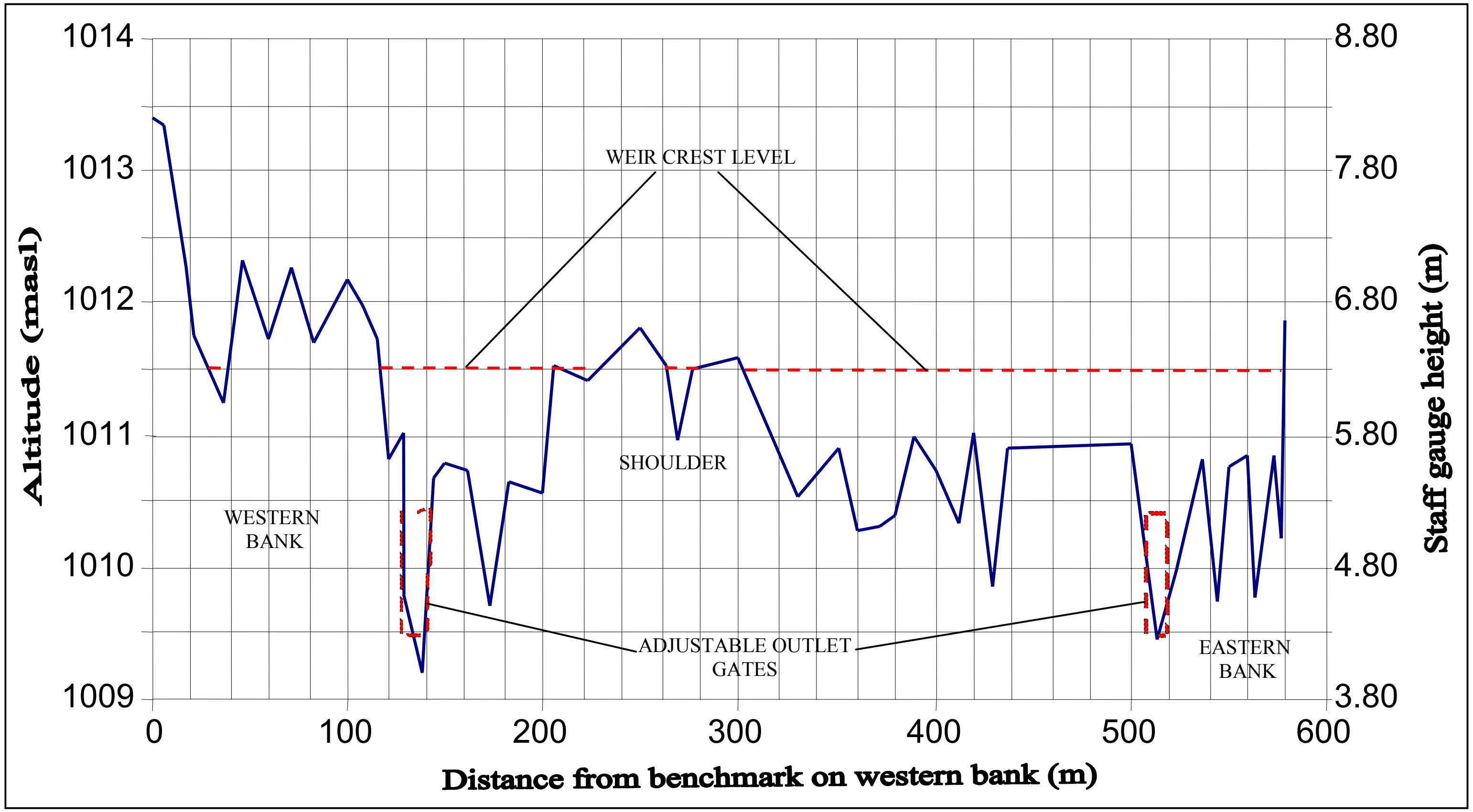


Figure 6.3 Cross section of Great Ruaha river at outlet of Eastern Wetland at N'Giriama showing crest level of possible weir



GIS2DATA/D/smuwc2000db/st/Nick/fig3.1FN_graph

Figure 6.4 Topographic profile between SMUWC8 control beacon and perennial swamp

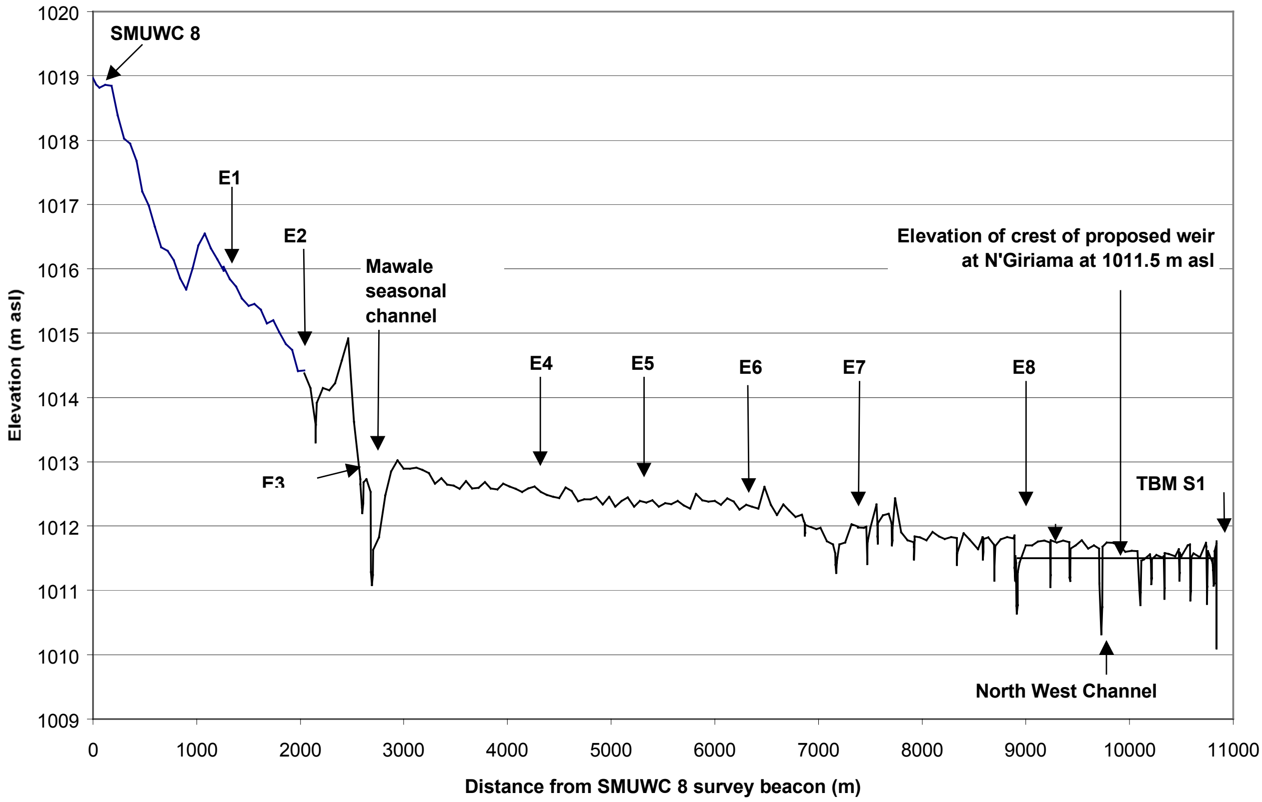


Figure 6.5 Blocked channels in the Eastern Wetland

Figure 6.6 Longitudinal profile along North West Channel to N'Giriama, October 2000

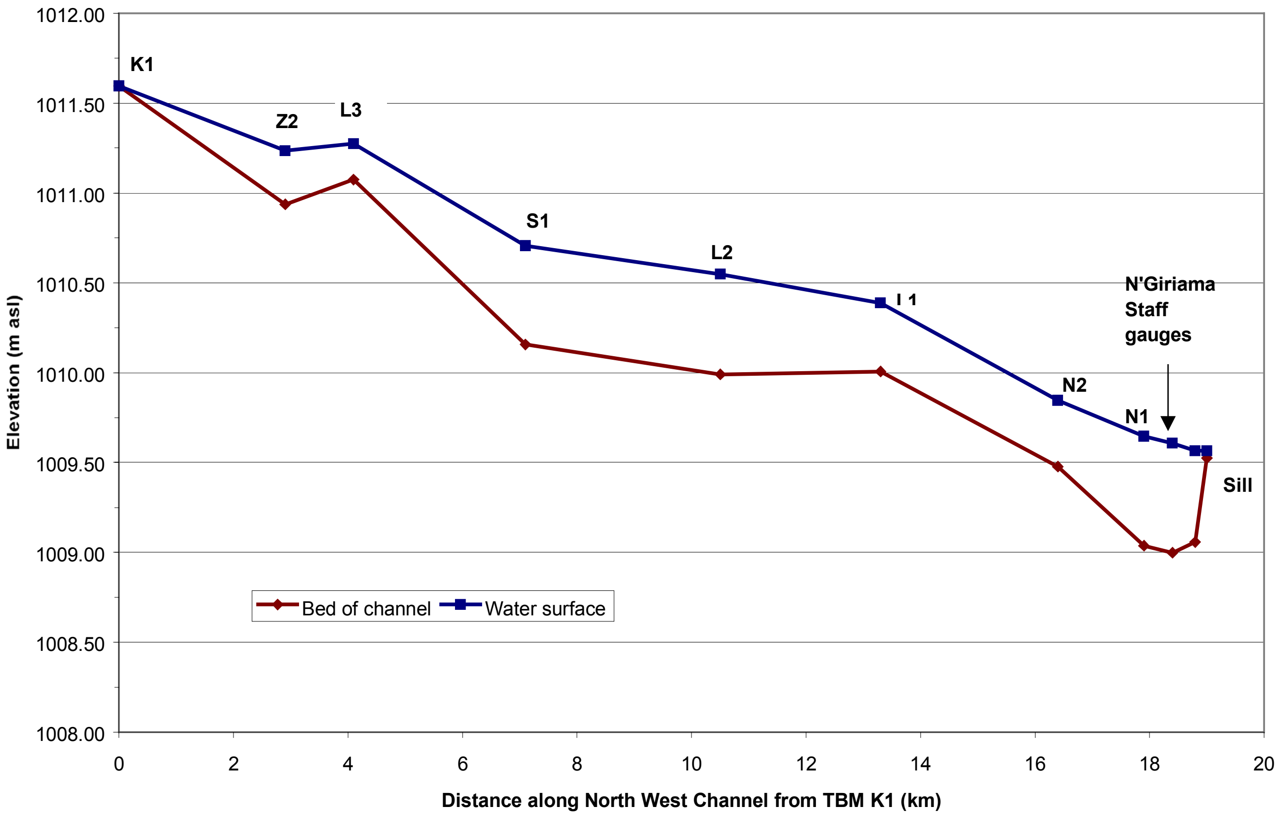
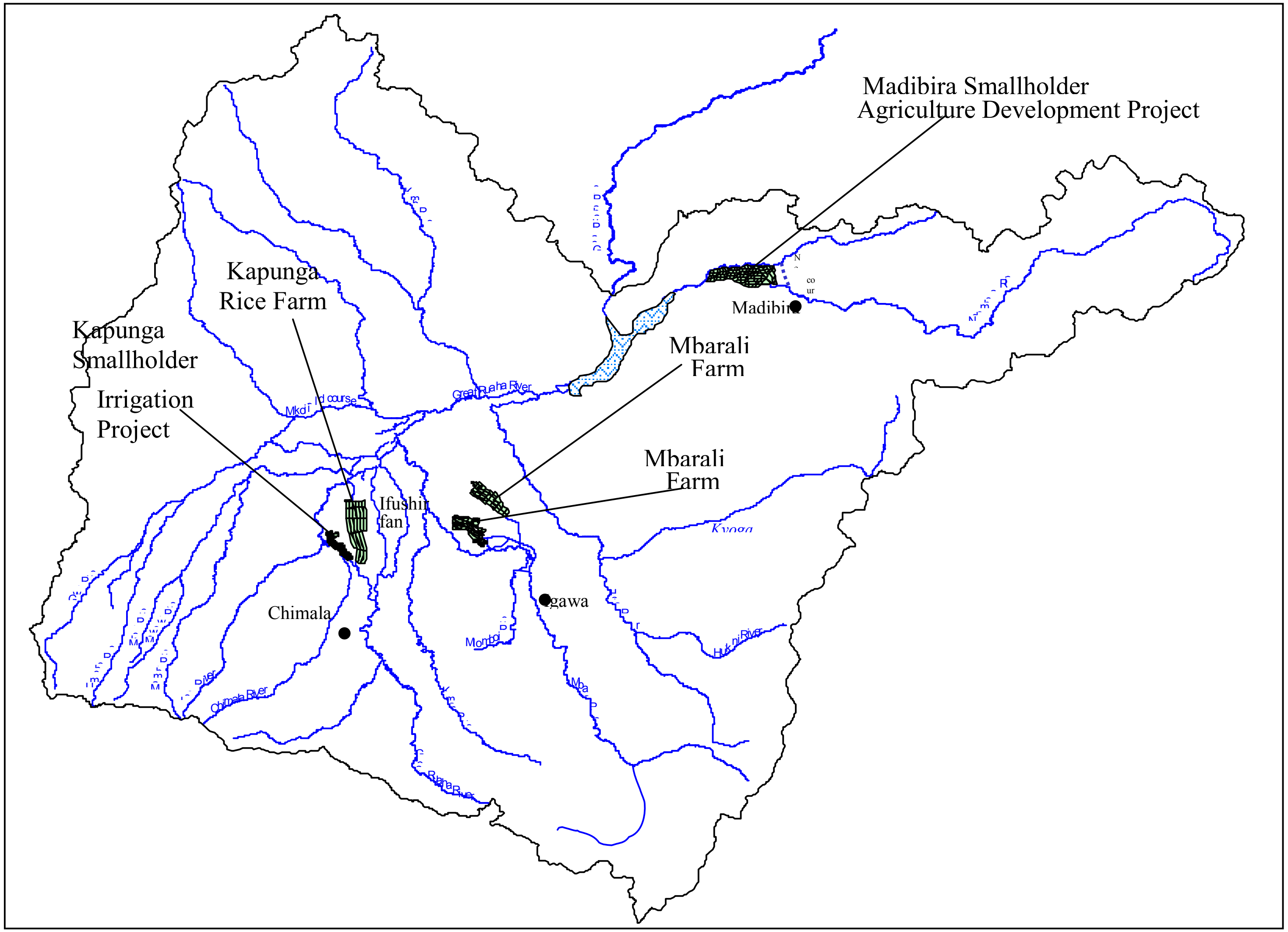


Figure 6.7 Location of large state irrigation schemes



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APPENDIX A

DRY SEASON WATER DEMAND SURVEY IN IRRIGATION AREAS

A.1 Introduction

An average of 87% of river flows is diverted into irrigation areas during the dry season in Usangu. This has been identified as a major cause of the reduction in river flow downstream of the irrigation areas. Most of the flow is diverted by large irrigation schemes such as Mbarali, Kimani and Kapunga schemes from the Mbarali, Kimani and Great Ruaha rivers respectively. Typically, these rivers are dry downstream of the intake points during the dry season. The diminished river flow reduces inflow to the Eastern Wetland in the dry season and leads to the cessation of outflow into the Great Ruaha river (Section 4.3.5 of Supporting Report No. 7)

Despite the abstraction, relatively little irrigation takes place during the dry season. Canal water is used by people living in a number of villages in and around the irrigation areas. Uses include domestic supply, for livestock watering and for making bricks. One of the management options for increasing water availability in rivers downstream is to reduce abstraction in the dry season by partially closing the intake gates of the main irrigation schemes and, ideally, providing alternative water supplies from other sources, e.g. wells and boreholes. Before plans can be made to reduce dry season abstraction and provide alternative supplies, it is necessary to know what the net and 'reasonable' gross demand for water is in the irrigation areas in the dry season.

This appendix presents a summary of the results of a survey of water use carried out in the dry season of 2000 in three irrigation areas: Mbarali NAFCO rice farm, Kimani smallholder rice scheme and Hassan Mulla farm.

The survey involved determining:

- the level of dry season water abstractions
- the area under rice irrigation in the 1999/2000 dry season
- the area under non-rice in the same dry season
- other water uses, their respective proportion and their location of abstraction.

A.2 Methodology

A.2.1 Abstractions and return flows

Abstractions were measured at each intake at intervals of approximately two weeks using a current meter. The return flow back to the river system after irrigation, if any, was also measured in each drain.

A.2.2 Irrigation water use

To gain an impression of the amount of water used for irrigation three transects were made across each scheme to get a good representation of the entire farm. These transects were visited every 9-14 days although omissions did occur. The following parameters were determined along each transect:

- Size of the field; this was categorised as small (<50m^2), medium (≅150m^2), large (≅250m^2) and very large (>400m^2)

- The approximate planting and harvesting date in each plot

- Return flows to the drains (if any)

- Actual field situation; this was classified according to the following:
  - Small holder
    A: Rice with water
    B: Harvested field with water
    C: Rice with moist soil
    D: Harvested field with moist soil
    <u>E: Rice with dry soil</u>
    F: Harvested field with dry soil
    NC: Non-cropped field
    SW: Swamp
    HL: Highland
    P: Ploughed

  - Large scale farms (e.g. Mbarali)
    W: Wet
    M: Moist
    D: Dry
    P: Ploughed

- Nature of plot at harvest; either wet or dry
- Depth of standing water layer (if any)
- Other water uses within the fields.

The actual rice cropped area for the 1999/2000 season was determined by taking GPS points along the perimeter of the harvested fields. The points were then inserted into a geo-referenced map of the study area. Dry season cropping was estimated by interviewing farmers.

A.2.3 Water used for domestic purposes, livestock watering and brick making

The various villages were visited and villagers were interviewed on their water needs, sources and their daily net demand. Information on alternative water sources and water quality problems were also gained. Villagers were also asked about their cropping calendar, field water management and agronomic activities in the fields. Livestock numbers and locations of drinking points were established. The amount of water consumed by livestock was estimated. Water used for construction purposes was also determined.

A.2.4 Net demand and reasonable gross water demand

These terms are very important and need explaining. Net water use is that arising from normal use at the point of use (e.g. in the field or home). However water is also lost in arriving at those points of use. This additional water, added to the net water, is the gross water used. However, currently very large amounts of water are used leading to unwarranted waste; this level of gross water use is clearly unnecessary. Instead a *reasonable* gross water demand level should be considered, enough to provide for the net demand, and for reasonable losses in conveyance and distribution. This report distinguishes therefore between the current excessive gross water use and a future 'managed' reasonable gross water use.

A.3 Mbarali rice farm

A.3.1 Villages

The villages identified in the Mbarali system are Ihanga, Ibara, Isisi, Rujewa, Mwakaganga, Nyeregete, Ubaruku, Mwanavala (Maongole) and Imalilo Songwe (Figure A.1).

A.3.2 Water abstraction and return flow

Mbarali river has one major abstraction (NAFCO main canal). Other abstraction points include the Hassan Mulla furrow and the Old British intake. There is a proposed intake at Ibohora village to convey water to Itamba village. If constructed in 2000, it will be in use in the 2000/2001 season.

Table A.1 gives a summary of the discharge measurements made at all abstraction points along the Mbarali river.

Table A.1 Flow measurements along Mbarali river

System/section		17/07/00	25/07/00	08/09/00	13/09/00
Mbarali	Above intake	4.194	3.41	2.94	
	Hassan furrow	0.115	0.23	0.178	
	Old British intake	0	0	0	
	Ibohora village	3.738	2.56	0.461	
	Warumba bridge	3.85	2.5	-	
	Nyaluhanga	4.607	4.23	0.956	

During the study period, Hassan Mulla furrow, Lyangegele and Shule intakes abstracted water continuously. The Mbarali NAFCO offtake was closed on 22 July 2000 for cleaning. Mbuyuni intake abstracted water on prescribed days of the week, ie, Saturday till Wednesday.

Mbarali NAFCO farm 2 drains had some flow that did not get back to the river system since residents of Mwanavala village utilised it.

A.3.3 Village water needs and sources

The Mbarali river and the NAFCO main canal are the main sources of water for each village for domestic use, livestock watering and for brick making. There is an intake for domestic water supply at Igomelo about 10 km above the Igawa gauging station (1KA11A) with a pipe network to several villages. However, this supply is unreliable.

Flows in the NAFCO main canal also generate hydropower for Rujewa and the farm.

The following summarises sources of water used by each village:

<u>Ihanga village</u>

This village is situated close to the hydropower station. Its main water uses include water for household needs, brick making and watering livestock. They obtain this water from Mbarali NAFCO main canal, Hassan Mulla furrow and directly from Mbarali river downstream of both intakes.

<u>Ibara village</u>

Similarly, water needs include domestic water requirements and water for making bricks. The water from the pipe network is supplemented by water from Mbarali river and Mbarali NAFCO main canal.

<u>Isisi village</u>

The village entirely depends on canal water for its water needs which include domestic water, livestock water consumption, horticultural irrigation and water for making bricks. Three quarters of the village fetches its water from Mbarali NAFCO main canal, a distance of about 2 km, while the remainder obtain their water from Hassan Mulla furrow.

<u>Rujewa</u>

The Mbarali NAFCO main canal and the piped network meet its water requirements. However, the Mbarali main canal supplies about 70% of the daily consumption since the piped water is rationed and is only available in the early morning and in the evening.

<u>Wakaganga village</u>

Mbarali NAFCO farm 1 canal supplements the unreliable piped water system. Mbarali river also provides water for some residents of this village. The Mayota canal, the Mission canal and the canal taking water back to the river through Jangurutu hamlet distributes water to different points of the village.

<u>Ubaruku village</u>

Water needs in Ubaruku village include that for domestic consumption, horticultural irrigation, making bricks and for livestock numbering 600 animals. There are two major water sources viz. Mbarali Farm 1 main canal which supplies 80% of the water and piped water. The water supplied by the pipeline is inadequate and untimely despite having 17 watering points. There are three traditional (hand-dug) wells, which are very useful during critical times especially when Mbarali intake is closed. One of the wells has a culvert casing supplemented with bricks; the water level is constant at 6 m below ground surface throughout the year.

The village is in advanced consultation with the office of the District Water Engineer for the drilling of a borehole close to their domestic water tank.

Nyeregete village

Water needs of this village are met from four sources namely: Mbarali Farm 2 drains, Hassan Mulla farm drains, piped network and a number of shallow wells. Sometimes when flow in Mbarali farm 2 main canal is high, some of it serves Nyeregete directly through the flashout gates.

Mwanavala (Maongole) village

With a population of 3 222 people and about 8 000 cattle, this village entirely relies on water from Mbarali Farm 2 drains. There are two personal shallow hand-dug wells, about 1.5 m deep from which the villagers cue for water when NAFCO drains are not flowing. However, one of the wells has salty water. Domestic water needs is approximated at 40 l/person/day. Making of bricks is often hampered by water scarcity.

Imalilo Songo village

This is another peri-NAFCO village. It has a population of about 3 800 people. Water needs include water for domestic use, livestock, brick making, and water for irrigation. There are approximately 12 000 cattle in the area during the wet season. However, due to scarcity of fodder, only a quarter of the animals are within the village during the dry season. Water needs are met from a number of sources: piped water, NAFCO farm 1 drains which supplies 75% of the water requirements during the dry season, and a few shallow hand-dug wells (0.5-2 m deep). However, only one out of the 19 watering points is operational. When there is no flow in the NAFCO drains, apart from the few shallow wells whose quality has not been ascertained, the villagers obtain water from Great Ruaha river which is about 10 km away.

'All villages' water use

Table A.2 presents estimates of the demand for water for domestic purposes, livestock watering and brick making in each of the villages in the Mbarali irrigation area. This partly includes villages supplied by the Hassan Mulla Furrow. Per capita rates of water use shown are based on field observation. The per capita demand assumed for livestock is 30 l/person/day. Six litres of water per brick are assumed for the calculation of the demand for brick making. This value is based on field observation.

Table A.2 Non-irrigation water demand in Mbarali system

Village	Popn. relying on surface water	Daily water demand (l/capita/day)	Domestic water demand (m3/day)	Livestock numbers	L'stock water demand (m3/day)	No. of bricks made daily	Water demand for bricks (m3/day)	Total water demand (m3/day)
Iyanga	490	80	39	1700	51	1200	7	97
Ibara	1480	80	118	700	21	800	5	144
Isisi	2312	60	139	300	9	400	2	150
Rujewa	7200	80	576	250	8	1000	6	590
Mwakaganga	1500	50	75	1200	36	600	4	115
Ubaruku	9600	80	768	600	18	2200	13	799
Nyeregete	1800	40	72	4612	138	400	2	213
Mwanavala	3222	40	129	8000	240	400	2	371
Imalilo Songwe	3800	15	57	3000	90	200	1	148
	31404	**58**	**1973.2**	**20362**	**68**	**7200**	**43**	**2627**

The overall water demand of 2 627 m^3/day together with an assumed twelve hour water gathering time gives a required flow in the canal of 152 l/s per 24 hours for domestic use, livestock watering and brick making.

A.3.4 Irrigation activities and water use

A total of 738 ha were cultivated on Mbarali Farm 2 during the last wet season (1999/2000). This value was obtained from records in the farm manager's office.

Dry season cropping (which establishes the reasonable gross water demand for Mbarali intake) is estimated at 100 ha for the whole Mbarali intake command area, based on surveys carried out by the SMUWC project.

The reasonable net irrigation demand arising from 100 ha of cultivation is estimated to be 120 l/sec. This arises from the supply to meet a total depth equivalent of 930 mm over a growing period of 120 days. This depth in turn arises from a net ETo of 4.8 mm/day, a seepage loss of 2.0 mm/day and an initial field wetting dose of 100 mm. If a canal loss of 75% is assumed (conservative) the reasonable gross flow required to meet 100 ha is approximately 120 l/sec.

A.3.5 Wastage of water in the Mbarali system

Transects of the Mbarali system reveal that almost all water is utilised within the larger command area, with no water returning to the river drainage system. Most of this water is used in wetting non-cropped rice fields within the NAFCO farm, and it is this practice that represents the greatest wastage.

A.3.6 Total dry season water demand in the Mbarali system

The reasonable gross demand (domestic, livestock and irrigation) for water in the Mbarali system would appear to be about 250 l/sec. A further 100 l/sec should be added to ensure delivery of water to the further reaches of the system where water is required by villagers, and a further 100 l/sec to ensure reasonably minimum levels of water in reaches of the canal where water is collected by villagers. This means that, without boreholes being added, reasonable water use within the Mbarali system is around 450 l/sec (or below 500 l/sec). If boreholes could be placed in villages, then surface water flow could drop to about 350 l/sec.

A.4 Kimani irrigation scheme

A.4.1 Villages

The villages identified in the Kimani system are Mbuyuni, Mabadaga, Msesule, Itamba, Uturo and Ukwavilla.

A.4.2 Water abstraction and return flow

The Kimani river has five offtakes: Mbuyuni, Mayota, Shule, Lyangegele, and Isenyela. All others, except for Mbuyuni, are traditional intakes that are controlled using local materials such as logs, stones or sacks full of soil/sand. Makambalala canal behaves as a tributary to Kimani river bringing water from the Great Ruaha river. Mayota and Isenyela offtakes ceased abstracting from mid July. Table A.2 gives the measurements made in intakes along the Kimani river on the 13th September.

Table A.2 Flow measurements, Kimani irrigation system

System/section		7/17/00	7/25/00	9/8/00	9/13/00
Kimani	Mbuyuni intake				0.574
	Below intake				0.414
	Mayota intake				0
	Shule intake				0.067
	Lyangegele intake				0.227
	Isenyela intake				0
	Makambalala				0.728
	Below all abstractions				0.417

There was no flow back to the river in any of the drains. This means that all of the water abstracted was consumed in some way in or downstream of the irrigation scheme. This situation has been observed by the other surveys conducted by SMUWC (see Supporting Report No. 8)

A.4.3 Village water needs and sources

All six villages are well served by piped water which is adequate and timely. The intake of the domestic water system is situated in Kimani river approximately 10 km upstream of the gauging station (1KA9). In spite of this there are a number of pastoralists that migrate to seek pasture below Msesule village and obtain their domestic water from field canals served by Mbuyuni intake. There is one designated livestock drinking point served by Mbuyuni intake. Otherwise livestock get their water directly from the Kimani or Mbarali river depending on their grazing ground. Table A.3 provides estimates of the demand for water for non-irrigation uses in the Kimani system.

Table A.3 Non-irrigation water demand from Kimani river

Village	Popn. relying on surface water	Domestic water demand (l/capita/day)	Domestic water demand (m3/day)	Livestock numbers	L'stock water demand (m3/day)	No. of bricks made daily	Water demand for bricks (m3/day)	Total water demand (m3/day)
Mabadaga	0	0	0	1700	51	300	2	53
Itamba	0	0	0	700	21	100	1	22
Msesule	200	60	12	300	9	100	1	22
Mbuyuni	0	0	0	250	8	300	2	9
Uturo	0	0	0	1200	36	200	1	37
Ukwavila	0	0	0	600	18	200	1	19
	200	**60**	**12**	**4750**	**24**	**1200**	**7**	**162**

The overall water demand of 162 m^3/day together with an assumed twelve hour water gathering time gives a required flow in the canals of just 9 l/s for domestic use, livestock watering and brick making.

A.4.4 Irrigation activities and water use

Figure A.2 shows the layout of the cropped area in the Kimani irrigation scheme in the dry season of 2000. A total of 805.3 ha were irrigated from the Kimani-Mbuyuni canal during the wet season, but 24 ha of dry season crops during the dry season (based on the SMUWC survey of furrows)

An area of 24 ha of non-rice crops translates into a reasonable gross flow of 30 l/sec at the intake. This is derived from an initial dose of 100 mm, 4.8 mm ETo, 2.0 mm seepage, conveyance losses of 25% and a growing season of 120 days.

A.4.5 Wastage of water in the Kimani system

Excessive water flows are used in creating small areas of swamp within the command area and in wetting up of fields (about 5-10% of fields or about 100 ha remain damp because of this).

A.4.6 Total dry season water demand in the Kimani system

The realistic water demand from the Kimani abstraction point should be in the region of 40 to 50 l/sec. Whereas the usual flow abstracted is in the region of more than 90% of river flow (or 200 to 500 l/sec depending on the flow in the river).

It is clear that the partial closure of the Kimani river intakes is possible down to a total of about 50 l/sec. Added boreholes further downstream might mean further closure to perhaps zero. Kimani farmers would also like to close the intake to rest their fields from constant watering.

A.5 Hassan Mulla Farm

A.5.1 Water abstraction and village water use

Table A.1 presents flows measured in the Hassan Mulla furrow. During the dry season the flow for this furrow fluctuates around the 150 to 200 l/sec level. Some of this water is used by nearby villages of Ihanga, Isisi and Nyeregete for domestic, livestock and brick-making activities. Demand for non-irrigation water is estimated at about 26 l/sec (taken from a total of 460 m^3/day for these three villages).

A.5.2 Irrigation activities and water use

This section describes only the irrigation activities and water used by the Hassan Mulla Farm during the dry season in 2000. Figure A.3 shows the layout of the cropped area in the Hassan Mulla Farm during the rice-growing season. Hassan Mulla Farm is located close to Rujewa and Ihanga Village.

During the dry season, small gardens of vegetables and trees are cultivated, amounting to no more than approximately 12 ha in total. This area does not account for more than 30 l/sec reasonable gross demand.

Second ratooning of rice takes place until mid-July, it is estimated that this accounts for no more than 30 l/sec, gross.

Field preparation for October transplanting begins in early September, the same time as nursery preparation. It is probable that all canal water is then used to wet up fields.

Reasonable irrigation demand is therefore approximately 60 l/sec.

A.5.2 Wastage of water in the Hassan Mulla farm

Reasonable gross use of water (domestic and irrigation) amounts to about 90 l/sec in the Hassan Mulla farm. This translates into an abstraction flow of 106 l/sec, assuming losses of about 15% with the smaller, well-defined channels found here. Abstraction of water above this level is not necessary and is considered as wasteful. For example the survey did see that there was some flow in the drains of Hassan Mulla farm; however, this did not get anywhere far as it was utilised by livestock from Kioga numbering about 600 animals. Since the Kioga river is seasonal in nature, it might be argued that the Hassan Mulla furrow is providing an important watering function outside its command area. Excess water is sometimes put into four small dams around the farm.

A.5.3 Total dry season water demand in the Hassan Mulla

In summary, flows for various demands are 26 l/sec for domestic, livestock and brick-making, 30 l/sec for non-rice crops and 30 l/sec for various field demands, plus about 15 l/sec for conveyance losses. If the reasonable gross abstractable flow of water in Hassan Mulla is 106 l/sec during the dry season, then any flow above this could be seen to be wasteful. Certainly, flows above 150 l/sec seem to be excessive, unless water for residents of Kioga is taken into account. Without boreholes in the Hassan Mulla command area it is recommended that the Hassan Mulla furrow be partially closed down during the dry season to 110 l/sec. If boreholes can be introduced, and relatively unnecessary watering of fields can be reduced then the Hassan Mulla furrow could be closed down to about 40 l/sec during the dry season. The water would be used to irrigate non-rice dry season cropping only.

A.6 Kapunga system

A.6.1 Introduction

This part of the report is taken from the Irrigation Efficiency Studies conducted in the Kapunga rice farm.

A.6.2 Village domestic water needs

Water abstracted during dry season is used for domestic purposes, livestock watering, brick making and other allied activities. The demand due to these activities is increasing each year. This is mainly due to increase of the population in an irrigation system; the number of households has increased by 90 in one year to over 200 in the year 2000. And according to interviews, the average number of people in each household is about 4. The estimation of water requirement per household was done by interview of women. The average numbers of buckets required per day was estimated to be 5. The requirement per household was then estimated to be 80 l/day. The calculation of the system requirement is 223 households will require 80 = 18 000 l/day.

A.6.3 Livestock water needs and sources

It was reported that most of the livestock are taken to the *Ihefu* swamp during dry season. However those animals which are old and sick remain at home. Sometimes the milked cows are maintained at home for milk production for the family members who do not go to *Ihefu*. It was therefore estimated that, during dry season, the livestock number in the Kapunga scheme is about 300 cattle and 200 goats and sheep. During the dry season, it was estimated that on average cattle would require 30–40 l/day while sheep and goats require 4-5 l/day. Thus, the livestock water requirement is; Cattle: 300 x 35 = 10 500 l/day. Goats and sheep: 200 x 4.5 = 900 l/day. Total livestock requirement is 11 400 l/day

A.6.4 Brick-making water needs

Brick making is an activity which requires water during dry season. The water requirement for bricks was estimated in collaboration with the brick maker at Kapunga. It was estimated that, to make 400 bricks of 16 cm x 30 cm x 7 cm (width x length x height) would require 1 000 litres. The number of bricks required to make a medium size house is about 2 000. If 400 bricks require 1 000 litres, 2 000 bricks will require 5 x 1 000 = 5 000 litres. If 40 houses of this type are built each season, the water requirement will be 40 x 5 000 litres. The period of brick making is in August and September, a period of 60 days. Thus, brick making will require 40/60 x 5 000 = 3 300 l/day.

A.6.5 Irrigation activities and water use

Dry season cropping in the Kapunga scheme is rare, but a conservative estimate of less than 10 hectares in total is assumed. This area would require less than 25 l/sec. Therefore, most dry season water use is required for domestic use in NAFCO and peri-NAFCO villages around Kapunga.

A.6.6 Wastage of water in the Kapunga system

Wastage of water in the Kapunga system has been studied quite closely. Most of the water that is taken through the intake is used up in wetting of empty harvested rice fields. The following is a list of the ways in which this can happen:

- Wilful flooding of harvested fields by duck hunters and fishermen in the schemes and subsequent evaporation of water.
- Pond creation in canals by fishermen enhancing evaporation and percolation losses to the ponded water.
- Naturally developed swallow holes in canals leading to losses estimated to be up to 30 l/s, which continuously irrigate harvested fields.
- Deep percolation losses in fields, which are estimated to range from 2-4 mm/day.

A.6.7 Total dry season water demand in Kapunga

Total net water use is domestic + livestock + brick making = 32 700 l/day (equivalent to 0.4 l/sec). To this can be added an irrigation requirement of about 25 l/sec. The gross reasonable use also depends on meeting conveyance losses of water to villages, which without boreholes might be a further 200-300 l/sec. With boreholes, water demand in Kapunga could be cut considerably. In summary, reasonable gross water use at the abstraction point is about 200-300 l/sec without boreholes. This contrasts to the current abstraction of between 600 to 1200 l/sec during the dry season.

A.7 Conclusions

Table A.4 presents comparisons of possible future intake settings (based on current reasonable gross water use) against current settings. In all cases, current intake settings are about two to four times larger than need be.

Table A.4 Summary of current use against possible future abstractions

Irrigation system	**Current abstraction l/sec**	**Estimated reasonable gross use l/sec**	**Recommended intake setting without boreholes l/sec**	**Recommended intake setting with added boreholes ** l/sec**
Mbarali (Mbarali river)	2000 to 4000	350	500	300
Kimani various intakes (Kimani river)	200 to 500	40 to 50	50	0-40
Hassan Mulla (Mbarali river)	150 to 200	110	110	40
Kapunga	600 to 1200	200 to 300	300	100

(Ruaha River)		
Total saving	2 000 + 150 + 75 +700 =2 925 l/sec	2 300 + 160 + 140 + 900 = 3 500 l/sec

** This water would be used for irrigating crops only and for meeting some domestic supply that boreholes would not meet in a cost effective manner.

From a survey of three of the four red route rivers (excluding the Ndembera), it is concluded that partial closure of intakes (with added boreholes in downstream villages) would save about 3 000 to 3 500 l/sec from being take out of the rivers. The accuracy of these figures needs to be checked as averages have been taken on the basis of spot measurements of fluctuating river and canal flow rates.

In addition to meeting water supply needs, it is advantageous to keep some flow passing down canals so that they do not dry out, causing cracking and the formation of swallow holes.

Figure A.1 Mbarali river system and villages along the canals

Figure A.2 Irrigated area under rice, Mbuyuni intake, Kimani river, 1999/2000

Figure A.3 Irrigated area under rice, Hassan Mulla Farm, Mbarali river, 1999/2000

APPENDIX B

AREAL VARIATIONS OF RAINFALL OVER THE SMUWC PROJECT AREA, 1998-2000

B.1 Introduction

This appendix examines the areal rainfall distribution over the Usangu basin for the two rainfall years over which the SMUWC project operated; 1998/1999 and 1999/2000. Tables B.1 to B.5 present monthly totals for the rainy season months December to April for the raingauges that were establishedor rehabilited by SMUWC. A summary of the rainfall distribution is given in Section 3.2.5 and the rainfalls are mapped in Figure 3.4 of the main report.

B.2 Rainfall over the Eastern Wetland

Observations were collected from five raingauges located around the Eastern Wetland. Four of these stations were installed by the SMUWC Project in December 1998: N'Giriama, Upagama, Ikoga and Igava. The raingauge at Madibira is an historical station operated by the Ministry of Water. After an automatic weather station was installed at Madibira in October 1998 this raingauge was closed down in April 1999. However to ensure continuity of this important station SMUWC reinstalled a separate manual raingauge there in September 1999.

There were some observational problems at Igava during the 1999/00 season, so this record should be treated with caution for just that year. As a consequence it is recommended that to estimate the areal rainfall falling over the Eastern Wetland priority should be given to using a combination of the three stations N'Giriama, Upagama and Ikoga.

The monthly rainfall totals for the 1998/99 and 1999/00 wet seasons are given in Table B.1. Considering the total rain falling within the five month period 1 December-30 April, the majority of stations fall within the range 437-565 mm during 1998/99 and within the range 367-464 mm during 1999/00. Only the N'Giriama station recorded a value above the maximum of this range in both years, 626 mm in 1998/99 and 532 mm in 1999/00.

Inspection of the table does not show much correspondence between the stations of the monthly distribution of rainfall. Ikoga and Madibira shows some similarities for the 1998/99 season, but not so much for 1999/00. During 1999/00 N'Giriama recorded values about 30% higher than Madibira in each month; but this pattern was not found in 1998/99. The individual sequence for Madibira was very similar in both seasons to that of the mean of the 5 stations, except for the month of February.

B.3 Rainfall over the Western Wetland

Observations were collected from seven raingauges located in and around the Western Wetland. Four of these were historical stations operated by different agencies: those at Mbarali and Kapunga Farms are operated by NAFCO, while that at Kimani Resthouse is operated by Ministry of Water. The raingauge at Igurusi was initially established by FAO but fell into disuse when that project finished ; subsequently the institution there was taken over by the Ministry of Agriculture Training Institute (MATI), and with assistance from SMUWC the station was restarted in November 1999.

The remaining three stations were all established by the SMUWC project: Upagama in December 1998, Ukwaheri in November 1999, and Kapunga Drain in January 2000. The aim of this last station is to assist in studies of irrigation efficiency over the Kapunga Rice Project.

The monthly rainfall totals for the 1998/99 and 1999/00 wet seasons are shown in Table B.2. The observations are missing at Kapunga Farm for January 2000.

The table shows that the monthly distribution of rainfall is very similar at Mbarali and Kapunga Farms in 1999/00, and quite similar also in the 1998/99 season. What is most noticeable during the 1999/00 season is that the rains essentially failed at Mbarali and Kapunga Farms, with totals over the 4 month period January-April 2000 of only 176 mm and 169 mm respectively. The total at Kapunga Drain of 277 mm also appears low.

The table shows that the rainfall distributions for 1999/00 are similar at the three stations of Kapunga Farm, Kapunga Drain and Ukwaheri, but with a gradual increase in individual monthly values moving northwards across the Western Wetland.

There are also some similarities during 1999/00 between the Igurusi and Kimani Maji stations, and between the Igurusi and Upagama stations, but in general the Upagama and Kimani Maji records do not match up over the two seasons taken together. Additional years of rainfall observations need to be collected to confirm these patterns.

Considering the total rain falling over the five month period 1 December-30 April, the majority of stations fall within the same ranges as that for the Eastern Wetland, namely 437-565 mm for 1998/99 and 367-464 mm for 1999/00. The only exceptions are the high value of 634 mm at Kimani in 1998/99 and the three exceptionally low values at Kapunga Drain, Kapunga Farm and Mbarali Farm, mentioned above. This means that, in general, the rainfall is extremely uniform over the whole of the Usangu Plains, which encloses both the Eastern and Western Wetlands.

B.4 Rainfall along the Ruaha National Park riverine reach

The riverine reach follows the valley of the Great Ruaha river as it passes through the Ruaha National Park from N'Giriama down as far as the park headquarters at Msembe. Records from four rainfall stations located in this reach were collected. Two of these, at Jongomeru and Msembe Park, are operated by the Ruaha National Park rangers. The Msembe Ferry raingauge is a Ministry of Water station, with a long record stretching back to 1967. The station at Stolberger camp is observed by a private individual. Of these four stations it is thought that only the Msembe Ferry submits its records to the Directorate of Meteorology. There are other rainfall stations operated by the Ruaha National Park, but, except for Magangwe (Section 3.2.8), they lie even further away from the project area, so were not included in this analysis.

From Table B.3 it can be seen that rainfall over this riverine reach is less than the Eastern Wetland, and decreases moving downstream in a northeasterly direction.

B.5 Rainfall over the high catchment in the north west

Observations from five rainfall stations were collected from the north west of the project area. Two historical stations were already in existence, one at Chunya operated by the Ministry of Agriculture, and the other at Magangwe operated by the Ruaha National Park. Other than these two stations, there was a general lack of information about the rainfall distribution in this part of the project area. To rectify this, three further stations were installed by the SMUWC project. The first at Msangaji Primary School in the high catchment commenced in mid-January 1999. The following season two further stations commenced at Sangambi and Idunda Primary Schools in November 1999. Sangambi was located on the top edge of the Chunya escarpment, while Idunda was located at the foot of the rising ground, half way between Upagama and Msangaji.

The monthly rainfall totals for the 1998/99 and 1999/00 wet seasons are shown in Table B.4. The monthly distributions at the two stations of Magangwe and Chunya possess some similarities, while Idunda and Sangambi are also quite similar to each other. What is most noticeable are the high totals for March recorded at Msangaji in both 1999 and 2000, namely 397 and 393 mm respectively. This is not reflected in any of the other four stations in this north west part of the project area. In fact, the record at Msangaji bears more resemblance to the records at Allsa (Uyole) or Mbeya Maji in the south west part of the high catchment (Section 3.2.9).

Independent evidence collected by SMUWC staff suggests that the rainfall may be quite high in the area around Msangaji in the north west of the project area. First, there is miombo forest growing there, which requires rainfall in the range 700-1200 mm to flourish. Growth of miombo is vigorous in this area and it is therefore thought that 900 mm would be the minimum expected. Second, there is cultivation of good quality maize on sandy soils; normally the rainfall requirements of maize are in the range 600-900 mm, so again a rainfall in the upper range, 900 mm, is expected. Finally, there are a number of springs in the area which do not dry up.

B.6 Rainfall over the high catchment in the south west

Observations were collected from four historical stations in this part of the project area. They are all operated by different agencies: Mbeya Met is a synoptic station at Mbeya airport operated by the Directorate of Meteorology; Mbeya Maji is operated by the Ministry of Water at their regional office; Shantlya is a primary school; and Allsa Farm is operated by the Ministry of Agriculture at their Uyole agriculture research station. In fact it was found that the raingauges variously called Allsa Farm and Uyole Research station are exactly the same station.

Monthly totals for the 1998/99 and 1999/00 wet seasons are shown in Table B.5. Monthly distributions for the four raingauges were quite similar in 1998/99, the main differences occurring during the months of January and April 1999. Values at Shantlya raingauge recorded for the 1999/00 season had not yet been received at the Directorate of Meteorology. The three remaining raingauges had very similar monthly distributions for this second wet season.

B.7 Rainfall over the high catchment in the north east

Observations were collected from four stations in this part of the project area. Three of these were long standing historical stations, Mafinga Bomani and Sao Hill Livestock operated by the Ministry of Agriculture, and Irundi Hill North operated by the Department of Forestry. The fourth station, Sadani Primary School had been an historical station for a period of years until closed, but was restarted by SMUWC staff in November 1999, so it did not possess any observations for the first year of the project.

Observations for the 1998/99 and 1999/00 wet seasons are shown in Table B.6. Considering that Sao Hill Livestock gauge is located between Mafinga and Irundi, and has a slightly higher altitude, it is surprising that it values are substantially lower than either of its neighbours; this will need further investigation.

Table B.1 Rainfall observations (mm) over the Eastern Wetland

Month	N'Giriama	Upagama	Ikoga	Igava	Madibira	Mean of 5 stations
Dec 98	16.5	32.3	46.5	21.0	27.2	28.7
Jan 99	156.1	129.5	89.0	79.5	78.8	106.6
Feb 99	137.0	163.0	57.0	93.0	60.4	102.1
Mar 99	284.5	198.0	224.0	222.9	223.2	230.5
Apr 99	31.5	42.5	80.0	25.1	47.6	45.3
Total December 1998 – April 2000	**626**	**565**	**497**	**442**	**437**	**513**
Dec 99	115.0	30.0	74.0	64.5	85.0	73.7
Jan 00	197.3	94.0	97.0	79.5	130.5	119.6
Feb 00	54.3	120.0	83.0	139.0	48.8	89.0
Mar 00	124.6	96.5	166.2	57.0	94.0	107.7
Apr 00	40.4	90.0	43.5	26.5	48.3	49.8
Total December 1998 – April 2000	**532**	**431**	**464**	**367**	**407**	**440**

Table B.2 Rainfall observations (mm) over the Western Wetland

Month	Upagama	Mbarali Farm	Kimani Maji	Kapunga Farm	Igurusi FAO/MATI	Kapunga Drain	Ukwaheri Primary School	Mean of 4 stations
Dec 98	32.3	9.3	17.8	48.9	No record	No record	No record	27.1
Jan 99	129.5	165.1	116.6	116.3	No record	No record	No record	131.9
Feb 99	163.0	88.6	114.0	45.6	No record	No record	No record	102.8
Mar 99	198.0	139.1	295.9	152.7	No record	No record	No record	196.4
Apr 99	42.5	69.7	90.0	87.0	No record	No record	No record	72.3
Total Dec 1998 – Apr 1999	**565**	**472**	**634**	**451**	**No record**	**No record**	**No record**	**531**
								Mean of 5 stations
Dec 99	30.0	6.4	100.5	Missing	67.8	No record	29.7	46.9
Jan 00	94.0	61.6	96.8	67.9	113.0	74.3	124.2	97.9
Feb 00	120.0	49.4	56.7	47.9	100.9	76.2	93.7	84.1
Mar 00	96.5	54.0	116.0	52.7	115.4	81.9	75.6	91.5
Apr 00	90.0	11.4	41.8	0.0	63.3	44.1	50.0	51.3
Total Dec 1999 – Apr 2000	**431**	**183**	**412**	**>169**	**460**	**>277**	**373**	**372**

Table B.3 Rainfall observations (mm) along the Ruaha National Park riverine reach

Month	**Jongomeru**	**Stolberger Camp**	**Msembe Ferry**	**Msembe Park**	**Mean of 4 stations**
Dec 98	6.5	11	9.7	7.2	8.6
Jan 99	126.0	131	53.8	91.9	100.7
Feb 99	35.0	7	93.4	63.5	49.7
Mar 99	213.4	223	189.1	180.3	201.5
Apr 99	52.5	66	57.9	48.0	56.1
Total Dec 1998 – Apr 1999	**433**	**438**	**404**	**391**	**417**
Dec 99	89.0	110	62.5	56.7	79.6
Jan 00	39.0	82	64.0	63.6	62.2
Feb 00	60.6	65	44.0	43.4	53.3
Mar 00	165.6	188	138.0	128.9	155.1
Apr 00	71.2	44	20.3	31.8	41.8
Total Dec 1999 – Apr 2000	**425**	**489**	**329**	**324**	**392**

Table B.4 Rainfall observations (mm) over the high catchment in the north west

Month	Magangwe	Idunda Primary School	Msangaji	Sangambi Primary School	Chunya Agriculture	Mean of 2 stations
Dec 98	42.5	No record	No record	No record	64.7	53.6
Jan 99	73.5	No record	>123.1	No record	141.2	107.4
Feb 99	80.0	No record	168	No record	72.6	76.3
Mar 99	264.5	No record	397	No record	239.6	252.1
Apr 99	94.5	No record	280	No record	70.1	82.3
Total Dec 1998 – Apr 1999	**555**	**No record**	**>968**	**No record**	**588**	**572**
						Mean of 5 stations
Dec 99	205.5	77.9	58.0	59.3	176.1	115.4
Jan 00	108.4	152.9	195.7	133.0	111.6	140.3
Feb 00	154.0	155.2	181.3	140.8	206.5	167.6
Mar 00	116.3	96.2	392.5	160.9	155.9	184.4
Apr 00	45.0	70.2	84.3	65.5	37.7	60.5
Total Dec 1999 – Apr 2000	**629**	**552**	**912**	**560**	**688**	**668**

Table B.5 Rainfall observations (mm) over the high catchment in the south west

Month	Mbeya Maji	Mbeya Met	Allsa Farm (Uyole)	Shantlya	Mean of 4 stations
Dec 98	53.4	76.6	30.9	70.0	57.7
Jan 99	244.8	331.2	220.7	108.0	226.2
Feb 99	106.5	121.8	145.1	134.0	126.9
Mar 99	328.7	329.7	323.2	322.0	325.9
Apr 99	174.7	169.7	303.0	163.0	202.6
Total Dec 1998 – Apr 1999	**908**	**1029**	**1023**	**797**	**939**
					Mean of 3 stations
Dec 99	117.3	144.7	85.4	Missing	115.8
Jan 00	130.0	150.9	134.7	Missing	138.5
Feb 00	157.3	181.5	149.0	Missing	162.6
Mar 00	262.8	217.5	237.6	281.0	239.3
Apr 00	52.0	64.6	64.6	Missing	60.4
Total Dec 1999 – Apr 2000	**719**	**759**	**671**	**Missing**	**717**

Table B.6 Rainfall observations (mm) over the high catchment in north east

Month	Irundi Hill North	Sao Hill Livestock	Mafinga Bomani	Sadani Primary School	Mean of 3 stations
Dec 98	75.4	67.2	129.0	No record	90.5
Jan 99	99.1	97.7	171.5	No record	122.8
Feb 99	99.3	82.4	96.0	No record	92.6
Mar 99	256.4	187.2	291.5	No record	245.0
Apr 99	61.9	53.6	96.5	No record	70.7
Total Dec 1998 – Apr 1999	**592**	**488**	**785**	**No record**	**622**
					Mean of 3 different stations
Dec 99	70.2	89.8	111.0	163.3	114.8
Jan 00	111.1	72.9	186.0	119.9	139.0
Feb 00	118.5	Missing	184.0	67.8	123.4
Mar 00	205.7	143.2	243.0	218.3	222.3
Apr 00	65.2	90.5	87.0	85.6	79.3
Total Dec 1999 – Apr 2000	**571**	**Missing**	**811.0**	**655**	**679.0**

APPENDIX C

DATA USED IN THE ANALYSIS OF ONSET OF RAINS

Table C.1 Grouping of Stations for the Analysis of the Shift of the Onset of Rainfall

Group A	Group B	Group C	Group D	Group E	Group F
09933033	09933028	09733002	09733000	09833003	09933020
09934049	09934011	09735014	09734000	09834002	
	09935004	09833000	09734001	09834004	
		09833001	09735003	09834005	
		09834001	09735008	09835007	
		09834016	09735013	09835021	
		09835002	09735015	09835022	
		09835010	09833002	09835023	
		09835011	09833010	09835030	
		09835024	09833015	09933023	
		09835025	09833020	09934029	
		09835033	09833025	09934034	
		09835036	09834000		
		09835039	09834003		
		09835042	09834006		
		09835044	09834008		
		09933000	09834010		
		09933002	09834011		
		09933004	09834012		
		09933005	09834013		
		09933007	09834018		
		09933011	09835005		
		09933013	09835009		
		09933024	09835013		
		09933029	09835016		
		09934014	09835017		
		09934018	09835019		
		09934019	09835026		
		09934020	09835034		
		09934021	09835040		
		09934023	09933010		
		09934024	09933022		
		09934027	09933031		
		09934032	09934001		
		09934039	09934008		
		09935002	09934013		
		09935003	09934022		
		09935005	09934025		
		09935006	09934026		
		09935007	09934038		
		09935009			

Table C.2 Rainfall statistics abstracted from analysis of records from 100 stations

Nr	File/Station	Decads from 1 January Onset	Cessation	Duration	Onset to 20 Feb (mm)	Long rainfall total (mm)	Mean Annual Rainfall (mm)
1	09733000	33	12	16	498.02	875.15	957.34
2	09733002	32	11	16	572.60	883.09	950.00
3	09734000	33	12	16	334.85	602.50	665.60
4	09734001	33	11	15	349.46	547.83	604.74
5	09735003	33	12	16	352.59	594.13	656.50
6	09735008	33	12	16	326.80	572.93	620.34
7	09735013	33	12	16	351.45	576.01	621.09
8	09735014	32	12	17	407.98	681.52	734.09
9	09735015	33	12	16	439.83	701.67	767.24
10	09833000	32	12	17	322.70	537.33	584.49
11	09833001	32	12	17	552.02	871.76	938.72
12	09833002	33	10	14	530.71	781.45	866.68
13	09833003	34	12	15	542.81	965.73	1103.07
14	09833010	33	13	17	941.93	1864.46	2073.70
15	09833015	33	12	16	696.95	1152.13	1271.58
16	09833020	33	12	16	542.13	862.03	964.22
17	09833025	33	13	17	520.15	942.42	1046.10
18	09834000	33	12	16	392.64	648.79	724.81
19	09834001	32	10	15	472.62	733.98	805.31
20	09834002	34	11	14	441.93	722.24	825.86
21	09834003	33	11	15	392.10	588.91	632.59
22	09834004	34	10	13	386.31	616.73	695.34
23	09834005	34	12	15	425.25	759.79	832.23
24	09834006	33	11	15	432.75	675.93	730.98
25	09834008	33	11	15	389.95	585.29	634.10
26	09834010	33	11	15	460.00	719.63	793.17
27	09834011	33	11	15	433.52	668.98	721.23
28	09834012	33	10	14	435.73	584.44	658.52
29	09834013	33	12	16	508.51	887.70	1036.06
30	09834016	32	10	15	325.15	459.81	489.94
31	09834018	33	13	17	250.90	463.36	502.13
32	09835002	32	12	17	455.48	785.94	842.70
33	09835005	33	13	17	505.40	984.36	1082.15
34	09835007	34	14	17	581.47	1764.99	2011.38
35	09835009	33	14	18	515.01	1254.68	1421.49
36	09835010	32	10	15	452.34	710.80	787.70
37	09835011	32	11	16	541.98	891.20	987.10
38	09835013	33	12	16	545.98	981.84	1134.61
39	09835016	33	10	14	388.43	614.72	711.85

Table C.2 Rainfall statistics abstracted from analysis of records from 100 stations (continued 1)

Nr	File/Station	Decads from 1 January Onset	Cessation	Duration	Onset to 20 Feb (mm)	Long rainfall total (mm)	Mean annual rainfall (mm)
40	09835017	33	12	16	512.63	882.58	966.87
41	09835019	33	13	17	629.93	1151.64	1293.78
42	09835021	34	14	17	473.32	1240.04	1461.17
43	09835022	34	15	18	817.23	2238.13	2634.58
44	09835023	34	14	17	519.82	1484.62	1730.71
45	09835024	32	14	19	638.66	1537.64	1711.64
46	09835025	32	14	19	1088.85	2669.03	2942.55
47	09835026	33	13	17	550.38	1078.38	1228.63
48	09835030	34	13	16	493.79	912.17	1045.48
49	09835033	32	11	16	532.83	876.75	954.09
50	09835034	33	15	19	514.82	1190.70	1331.88
51	09835036	32	12	17	505.91	846.46	905.33
52	09835039	32	12	17	494.19	806.57	852.46
53	09835040	33	11	15	458.31	733.39	828.70
54	09835041	-999	-999	36	445.14	-124.90	-356.40
55	09835042	32	13	18	430.69	744.24	826.52
56	09835044	32	11	16	746.56	1236.42	1339.25
57	09933000	32	15	20	655.17	1996.28	2395.46
58	09933002	32	15	20	702.94	2025.98	2432.94
59	09933004	32	14	19	818.85	1727.29	2071.94
60	09933005	32	15	20	604.23	1927.05	2290.15
61	09933007	32	15	20	700.22	1969.24	2394.25
62	09933010	33	15	19	481.98	2317.94	2721.91
63	09933011	32	15	20	708.94	2117.75	2419.79
64	09933013	32	15	20	774.97	1661.13	1916.54
65	09933020	35	15	17	338.77	1686.80	2144.10
66	09933022	33	13	17	274.28	604.03	753.64
67	09933023	34	13	16	560.45	2031.10	2546.19
68	09933024	32	14	19	761.51	1588.27	1885.57
69	09933028	31	15	21	500.05	989.33	1145.87
70	09933029	32	15	20	911.68	1898.48	2166.18
71	09933031	33	12	16	571.98	912.30	1017.43
72	09933033	30	12	19	1139.54	2017.47	2254.95
73	09934001	33	12	16	550.32	980.84	1078.92
74	09934008	33	12	16	848.43	1544.86	1766.58
75	09934011	31	13	19	912.92	1471.86	1586.87
76	09934013	33	12	16	595.78	1121.94	1275.30
77	09934015	32	12	17	610.06	1079.93	1170.14
78	09934018	32	13	18	555.48	1050.91	1132.30
79	09934019	32	12	17	522.66	943.25	1027.20

Table C.2 Rainfall statistics abstracted from analysis of records from 100 stations (continued 2)

Nr	File/Station	Decads from 1 January Onset	Cessation	Duration	Onset to 20 Feb (mm)	Long rainfall total (mm)	Mean annual rainfall (mm)
80	09934020	32	12	17	499.90	911.45	988.43
81	09934021	32	12	17	557.76	1004.33	1078.66
82	09934022	33	11	15	549.49	912.98	1026.54
83	09934023	32	13	18	1096.53	2080.96	2281.33
84	09934024	32	12	17	666.53	1239.09	1355.49
85	09934025	33	12	16	1033.41	1965.17	2160.24
86	09934026	33	13	17	623.93	1255.29	1399.32
87	09934027	32	13	18	652.41	1248.28	1360.11
88	09934029	34	13	16	996.01	2053.69	2294.47
89	09934032	32	11	16	640.93	938.29	1051.36
90	09934034	34	13	16	375.22	772.66	911.75
91	09934038	33	12	16	504.19	914.17	1013.36
92	09934039	32	12	17	535.06	920.82	992.37
93	09934049	30	13	20	929.76	1545.19	1659.70
94	09935002	32	13	18	470.95	1013.82	1115.12
95	09935003	32	13	18	1032.79	1932.06	2078.25
96	09935004	31	13	19	872.71	1638.85	1825.74
97	09935005	32	13	18	766.17	1454.80	1580.66
98	09935006	32	13	18	585.36	1220.54	1294.30
99	09935007	32	13	18	519.36	1213.15	1366.83
100	09935009	32	13	18	960.98	1990.18	2295.28