LAND-OCEAN INTERACTIONS IN THE COASTAL ZONE (LOICZ)

Core Project of the International Geosphere-Biosphere Programme (IGBP) and International Human Dimensions Programme on Global Environmental Change (IHDP)

AfriCat

LOICZ - Global Change Assessment and Synthesis of River Catchment - Coastal Sea Interactions and Human Dimensions in Africa

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Cover: The cover design shows the continent of Africa (www.motherplanet.com/images/continent/africa.jpg) and the graphic represents the need for combined natural and socio-economic approaches to the D-P-S-I-R concept in both research and wise management of people and their activities in the coastal zone.

The LOICZ Reports and Studies Series is published and distributed free of charge to scientists involved in global change research in coastal areas.

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1 INTRODUCTION

This report is an outcome from a Workshop held in Mombasa 16 - 18 February 2004. The workshop included representatives from the African science community working on river catchment issues and agencies concerned with the funding and dissemination of science to support and contribute to the sustainability and development agenda in Africa. The report outlines the background to the AfriCat studies, the rationale and structure to the studies, and the results of the individual catchment studies. Essential results of the AfriCat studies have meanwhile been published (Snoussi et al., 2007).

1.1 Background

Effects on the hydrological cycle and sea-level rise have been identified to be the key issues generated by global change that impact the environmental functions of riverine and coastal systems. Coastal zones respond to global changes by various measures that affect horizontal material and water flows which, in turn, affect human society that is largely concentrated along this water cascade. Parallel changes in demography increase the pressure on the environmental system largely through demands for high quality water and space. Global change science is challenged to provide a sound underpinning analysis of the natural and human dimensions of changes along the water cascade, including scenarios of strong and weak sustainability options.

Land-Ocean Interactions in the Coastal Zone (LOICZ), a core project of the International Geosphere-Biosphere Programme (IGBP) and International Human Dimensions Programme for global environmental change (IHDP), has conducted studies in order to assess the linkages between anthropogenic activities in African catchments and issues of management concern at the coast. The results of these AfriBasins workshops, which were held in Nairobi in 2000-2001 under the auspices of START, LOICZ, IOC/UNESCO, UNEP-ROA, and RIKZ (The Netherlands), have been published (Arthurton *et al*. 2002).

A major result of the AfriBasins network has been the conclusion that damming and water abstraction in the catchments are amongst the most important anthropogenic drivers/ pressures, leading to coastal impacts that will be exacerbated by societal responses to global change pressures. The impoundment of water by damming and its abstraction largely for irrigation purposes were recognized above all in the case of the River Nile, but are also common practices within most of the other catchments studied – large, medium or small - in the Africa region. Construction of dams is driven by increasing demands from urban and rural communities for reliable freshwater supply, agricultural irrigation and hydro-electric power. As these practices become more widespread, they are leading to significant reductions in the fluxes of water and river-borne sediment that are discharged from catchments to coastal sea systems. These flux reductions are contributing to changes in the state of the coastal environment, and these changes are in turn impacting coastal communities and their livelihood through issues including coastal erosion, estuarine salinisation including impact on coastal groundwater aquifers, and the depletion of nutrients in coastal seas.

1.2 The AfriCat studies

Through the inclusion of both natural scientists and socio-economists, AfriBasins achieved an overview of the linkages between anthropogenic drivers in the catchments and coastal impacts and issues. While indicative but still not exhaustive, the study provided a basis for proposing a project that aimed to investigate in greater detail the catchment-coastal sea linkages with human dimensions that were identified relating to damming and water impoundment. This project – 'AfriCat' (African Catchment Studies) – was envisaged as an umbrella for a number of catchment-specific case studies around Africa to be carried out in African institutions under the leadership of experts identified in the AfriBasins process and beyond. Based partly on the model developed for EuroCat (http://www.iia-cnr.unical.it/EUROCAT/project.htm), a pilot project for AfriCat was initiated in November, 2002, funded by START with support from the Intergovernmental Oceanographic Commission (IOC of UNESCO). The chosen theme of the AfriCat pilot phase – The coastal impact of water impoundment and abstraction in catchments, past, present and future – reflects the high level of importance that was

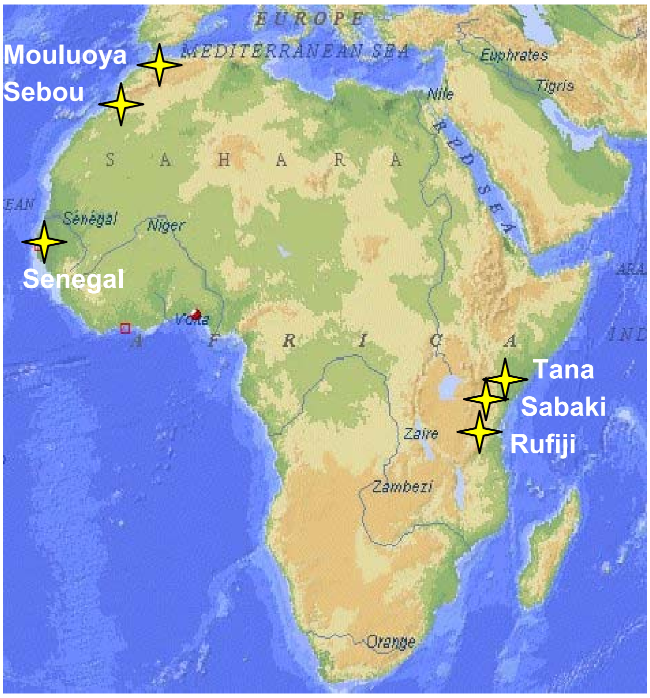

Figure 1. AfriCat Pilot sites

attached by the AfriBasins process to an understanding of this linkage.

AfriCat comprised four country sub-projects (Morocco, Senegal, Kenya and Tanzania) covering six catchments in total. An assessment of the contributions that climate-related and socio-economic changes have made, and are predicted to make under a range of scenarios, to downstream and coastal state changes and their environmental and socio-economic impacts was a key element of the project. Five of the catchments studied include large dams, and one (the Athi-Sabaki system in Kenya) is free from significant damming, thus serving as a control system (Figure 1).

As with AfriBasins, LOICZ-AfriCat has employed the DPSIR (Driver-Pressure-State-Impact-Response) analytical and response framework (Figure 2) to these studies, assessing the linkages between environmental and socio-economic impacts and issues at the coast and drivers – including their human dimensions – in catchments, with a view to informing appropriate management and policy responses at local to global scales.

1.2.1 AfriCat Structure

Focusing on the linkages between water impoundment/abstraction in catchments and the impacts and issues at the coast, the study provided a pilot for detailed case studies to be carried out. The objectives of each study were to explore the strengths and weaknesses of the assessment, appraisal and response approach, drawing attention to important information gaps and, importantly, to the essential links for effective information transfer between scientists, managers and stakeholders. Each study was structured around a series of work packages (Table 1). The project reviewed the impacts of past climate change and documented extreme events as well as considering the consequences of predicted future climate and socio-economic changes. The case study sites represented four contrasting catchment types and the project culminated in a regional workshop discussion between all the contributors, the outcomes of which are presented here.

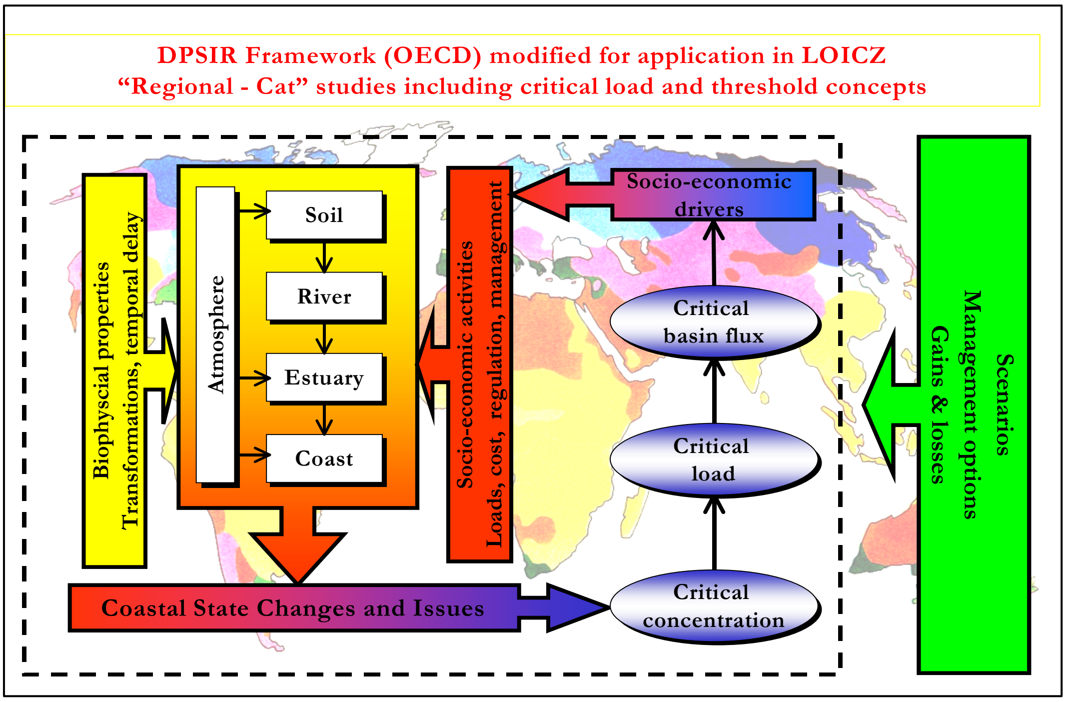

Figure 2. The LOICZ-Basin approach and the DPSIR approach. Modified after Turner et al., 1998

Table 1. The AfriCat work packages.

Work Package	Description
1	Databases and tools
2	Impacts, indicators and critical loads
3	Scenarios and response/management options
4	Past, Present and Future changes in catchment fluxes
5	Integration at the African level

The catchments chosen for this study were:

The Sebou and Moulouya – the two largest rivers in Morocco – both of which have been dammed. This study achieved a detailed synopsis of the history, current status and future development plans (to 2020) of impoundment and abstraction in the semi-arid Moulouya and Sebou catchments. It included information on the socio-economic drivers (present and future) – the needs for irrigation water, drinking water, etc.

The late Holocene evolution of the Moulouya coastal environment is described, then in more detail changes over the last 50 years, including the time when the largest dam, Mohamed V, was commissioned (1967). The environmental impacts of those changes are discussed, though socio-economic impacts are yet to be addressed. The roles of other possible drivers are being appraised, e.g. climate change. Also, the possible impacts at the coast of further long-term changes in water and sediment flux due to the programme of damming in the Moulouya catchment to be commissioned between 2003 and 2014 are assessed.

For the Sebou catchment, the project has compiled the history of damming development as well as the development possibilities and water budget needs to 2020. Changes in the fluxes of water and sediment in the Sebou system form a key part of the background information. Current work includes consideration of the impacts of flux changes (past, present and future) on the coastal environment and its communities – sedimentation, erosion, fisheries impacts, etc., with reference to indicators of change. The study also analysed other possible drivers and pressures (climate change, urbanisation) of coastal change around the mouth of the Sebou and considered future scenarios (25, 50 years) for this catchment, including the important concerns over the consequences of siltation in reservoirs.

The Senegal – a large West African river, dammed in its upper reaches (Manantali Dam) and seasonally dammed at the head of its estuary (Diama Dam). This is a study of the impacts of the Diama Dam on the river's delta/estuary and its littoral. A key aim was to distinguish between changes that are due to damming and those due to the highly dynamic littoral processes that affect this shoreline, notably the morphodynamics of a major sand spit – the Langue de Barbarie – constraining the estuary mouth (Figure 9).

The study prepared a thorough account of the physical setting based on published work. There is a focus on the delta (including Holocene history) and estuary, and the ocean shore with a strong emphasis on the coastal spit morphology and associated beach changes. It also details the urban development of the town of St Louis located on the estuary. Hydrological data and flux changes due to damming are yet to be compiled. The study includes systematic database and GIS-related work to document the available data. The data listed includes many topics that are, or may be, dam-related, including climate change as a driver and how this may impact on flow regimes, wave climate and sea-level rise.

The Tana and Sabaki (also known as Athi) in Kenya, the former having been dammed. This study is a comparative approach between the two basins (dammed and undammed respectively) using relevant time series of hydrological and sediment data. It has shown the main changes that have occurred in the Tana and Sabaki during the last 50-60 years. In the case of the Tana, flow and sediment reductions relate mainly to the construction in 1982 of the largest of the headwater dams (Masinga). In the case of the Sabaki, a dramatic increase in sediment load in the 1990s is ascribed to major deforestation in the catchment. Some 10% of the Tana's flow is 'lost' by abstraction, partly by transfer to the Sabaki system.

In the Tana, impacts in the lower basin and at the coast include a reduction in peak flows and related flooding that have seriously impaired rice cultivation and increased estuarine saline intrusion. The reductions in mean flow and (suspended) sediment discharge do not appear to have had a particular impact, although fisheries in Ungwana Bay are said to have become degraded. In the Sabaki, the main impacts are major shoreline progradation in Malindi Bay and the degradation of fisheries through the siltation of seagrass and reef nursery areas.

The study has successfully demonstrated the linkages over a 50-year time span between human activities in the catchments and coastal impacts though a full integration of the socio-economic aspects has yet to be included.

The Rufiji in Tanzania, one tributary of which is already dammed and for which damming of the main river is proposed. The Rufiji study provides a detailed review of published work relating to the Rufiji basin and its potential development. An inventory of the basin has been compiled including its physical setting, ecology and socio-economics.

The study aimed to consider future damming and abstraction development plans in order to provide a forecast of the flux changes and their impacts that may be anticipated if dam construction and commissioning proceeds. There are clearly major local socio-economic pressures in the Rufiji delta and the possibility of climate change and its impacts (including possible sea-level rise). It is against this background that any coastal state changes due to future dam construction must be appraised. In particular there is a need to develop suitable indicators that are specific to the impacts of river flux changes.

While the catchments differ in the state and scale of their damming and in the nature of the impacts and issues at the coast, a standardized approach to the research was used based on the Driver-Pressure-State-Impact-Response (DPSIR) framework developed by the OECD in the early 1990s and adapted for use in LOICZ (Figure 2). This approach places a strong emphasis on consultation with catchment and coastal managers, and, where appropriate, coastal stakeholders, building on a comprehensive review of the literature and relevant unpublished information as well as the scientists' own observed data. An important aim was to draw attention to information gaps and to review effective information transfer between scientists and managers/stakeholders. The studies considered the impacts of past climate change and documented extreme events, as well as the possible consequences of predicted future climate and socio-economic changes. This synthesis provides an overview of the case studies and synthesises their main findings. The original papers that were the output from the four country sub-projects are included as appendices.

2 DRIVERS AND PRESSURES

2.1 Damming and water abstraction

The principal direct socio-economic drivers of damming and water abstraction in the catchments studied in AfriCat are agriculture and land-use change, urbanisation and industry – all related to demographic change and indirect drivers such as national governance and global economics. Urbanisation and industry have led to an increasing demand for electric power, while urbanisation and industry and, in particular, the development of agricultural irrigation schemes have created a huge demand for water. By far the greater part of these increased demands in the catchments studied has occurred over the last 50 years. Forecasts show that the trends of these demands will continue to increase for the foreseeable future.

Data from the Moroccan basins illustrate the regional trends in water demand (Ministère des Travaux Publics 1997). In the Moulouya basin, with a projected increase of the population from 1985 to 2020 (respectively 65% for the urban and 19% for the rural population), the water demand for domestic and industrial uses in the basin will increase from 77 Mm^3/yr in 1985 to 274 Mm^3/yr in 2020, an increase of 255%. In the adjoining Sebou basin, where the population is expected to rise from 4.5 million in 1990 to 7.5 million in 2020, the demand for drinking water will rise from 229 Mm^3/yr to 663 Mm^3/yr in 2020, an increase of 189%. The needs for irrigation water in the Moulouya, 723 Mm^3/yr in 1985, are forecast to rise to 1460 Mm^3/yr, i.e. by 102% by 2020. In the Sebou, needs estimated at 1550 Mm^3/yr in 1990, are expected to increase to 3398 Mm^3/yr by nearly 119% by 2020. Data from Kenya are less specific but show similar overall trends, based on the assumption that the present rate of population growth will be maintained (GOK 1979a, b; 1992).

In most countries of the region, the demand for power is expected to increase considerably over the next 50 years (Figure 3). The regional response to the increasing demand for water and electric power has been the construction of dams – many incorporating hydro-electric power facilities – and by the abstraction of water from reservoirs and water courses, notably

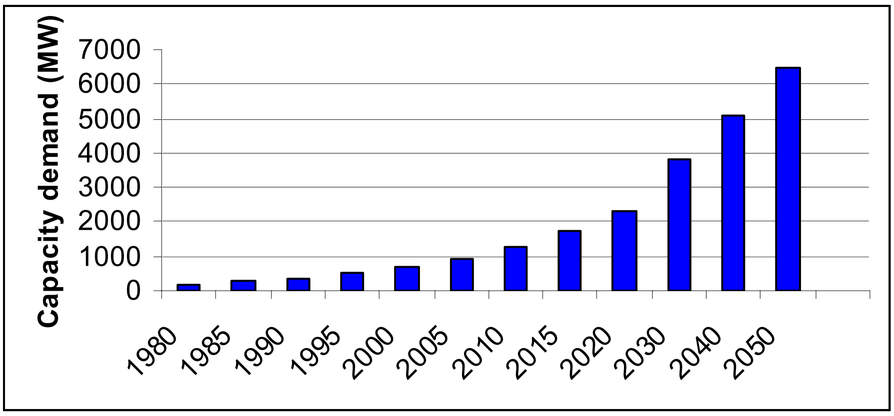

Figure 3. Basic power demand and forecast (megawatts) for extended Grid network in Tanzania. Source: Hafslund (1980). Extrapolation beyond 2015 by Shaghude *et al.* (2004).

for agricultural irrigation. Most large dams in Africa have been constructed over the last 50 years, notably in southern Africa, but also in Egypt, Morocco, Senegal, Nigeria, Ghana and Kenya. Many more dam and abstraction schemes, including some in the AfriCat catchments, are in their planning stages or under consideration. Taken together, the onset over the last 50 years of these human-generated pressures represents a major change from the pre-development condition of the water cascades in African catchments. Indications are that the magnitude of this change will continue to increase over the next 20-50 years.

2.1.1 Damming

The damming of principal drainage courses for power generation, water supply and flood control has been an important factor in the economic development over the last few decades of three of the four countries included in AfriCat.

Table 2. Main characteristics of existing dams in the Sebou and Moulouya basins, Morocco. (T: Transfer; PI: Potable and industrial water; I: Irrigation; HE: Hydro-electricity).

	River	Dams	Year of completion	Surface area of basin. (km²)	Capacity (Mm^3)	Water supply (Mm^3)	Uses
Sebou	Sebou	Garde	1991	27,000	40	200	I
	Sebou	Allal Fassi	1990	5400	82	750	T.HE.I
	Ouerrha	Al Wahda	1996	6190	3800	2564	HE.I.PI.T
	Inaouène	Idriss 1st	1973	3680	1800	700	HE.I
	Beht	El Kansera	1935	4542	266	372	HE.I.PI
	Mikkès	Sidi Chahed	1996	680	170	200	I
Moulouya		Mohamed V	1967	49,920	490	900	I.HE.PI

In Morocco, the Sebou basin includes 6 large reservoirs (Table 2) and more than 10 small ones built over a period of 70 years. These reservoirs are now a major source of irrigation and drinking water and strongly regulate the flow in the upper, mid- and lower catchments. The Al Wahda dam, constructed between 1991 and 1996 on the (tributary) Ouerrha river, is the second most important dam in Africa after the High Aswan dam. It will generate a potential hydroelectric capacity of 400 GWh/year. In the Moulouya basin, the largest reservoir – Mohamed V – as well as a number of small reservoirs of local interest, assures the irrigation of the lower Moulouya plain. The Mohamed V dam is also equipped with a hydro-power station.

In Senegal river basin, there are two large dams – the Manantali in the upper reaches, commissioned in 1987, and the Diama at the head of the estuary, commissioned in 1985. The

Diama dam is an anti-saline barrage and that of Manantali has the roles of flood regulation and hydroelectric power generation. The Diama dam operates as a seasonal barrage, emplaced in November following the flood season and raised in April. Its principal role is to prevent the ingress of seawater into the lower valley of the Senegal River. The dam provides a flood discharge while allowing the creation of a reservoir between the levels of 1.5m and 2.5m IGN. It also provides a navigation lock 175m long and 13m wide. The embankments constructed on the two banks of the river allow the creation of an important freshwater reservoir, filling the tributary depressions of the Lac de Guiers, the Lac R'kiz and the depression of Aftout es Saheli. Thus upstream of the dam, a lake is created with a surface area of 435 km^2 with a storage capacity of 585 Mm^3.

In Kenya, there has been a programme of damming on the upper reaches of the Tana river since the 1960s (Table 3; GOK-TARDA 1976a, b). Power generated from the hydro-stations forms 78% of the total electricity output in Kenya. Out of this, 65% is produced in the Seven Forks scheme (Masinga, Kamburu, Gitaru, Kindaruma and Kiambere power stations). The total installed capacity is 598.5 MW of which 458.4 MW comes from the five Seven Forks dams.

In Tanzania there are two reservoirs – Mtera and Kidatu – on the Great Ruaha River, a tributary of the Rufiji. The Mtera reservoir, with a live storage capacity of about 3,200 Mm^3, was formerly used as a storage and flood control facility for the downstream Kidatu reservoir (live storage = 125 Mm^3, with a power generating capacity of 204 MW) but a hydropower station of 80 MW was later installed at Mtera. There are no reservoirs of significant importance in the other two tributary catchments (Kilombero and Luwegu rivers).

Table 3. Characteristics of existing and potential reservoirs in the Tana basin, Kenya.

Reservoir	Gross volume ($M m^3$)	Surface area (km^2)	Catchment area (km^2)	Mean river discharge (m^3/s)	Year of completion
Masinga*	1,560	113	7,335	97.2	1981
Kamburu*	147	15	9,520	149.5	1975
Gitaru*	20	3.1	9,520	120.9	1978
Kindaruma*	16	2.4	9,807	155.9	1968
Kiambere*	315	13	11,975	121.8	1988
Karura	74	8			Planned
Mutonga	1,580	46			Planned
Grand Falls	3,600	119			Planned
Usueni	330	26			Planned
Adamson's Falls	1,730	102			Planned
Kora Hills	3,800	190			Planned

Source: GOK-TARDA (1982a, b, c) * One of the Seven Fork scheme dams.

Both Morocco and Kenya have planned programmes for the construction of additional dams to cope with the anticipated future demands for water and power. In the Sebou basin (Morocco), 9 new dams are planned between now and 2020. The realization of this suite of dams would allow access to a surface water volume of 4,467 Mm^3/yr in 2020, on a basis of 5,600 Mm^3/yr supply, i.e. a usage rate of 80% (Conseil Supérieur de l'Eau 1992). In the Moulouya basin at least 4 new dams are planned to assure the limitation to 6000 m^3/s of the flood discharge from the Mohamed V dam; to satisfy the demand for drinking and industrial water (300 Mm^3/yr in 2030); and to meet the demand for irrigation (920 Mm^3/yr) (Conseil Supérieur de l'Eau 1990). Within Kenya's upper Tana basin, sites have been identified for the construction of six additional dams for hydropower generation. These are Mutonga, Grand Falls, Karura, Adamson's Falls, Korah and Usueni (Table 3; GOK 1979a, b; GOK-TARDA 1982a, b, c).

On the Senegal river, large schemes continue to be developed. There are dam projects at three sites in the upper basin – Gouina, Gourbassi and Félou on the principal tributaries of the Senegal. In Tanzania there are plans under consideration for the damming of the Rufiji River at Stiegler's Gorge, some 200 km upstream from the coast.

2.1.2 Water abstraction

The pumping or discharge of water from reservoirs, water courses and aquifers to meet the needs of the public, of industry and, particularly, agricultural irrigation is another crucial factor in the economic development of the AfriCat countries.

The Senegal river has several irrigation schemes along its course. The schemes should allow the irrigation of 120,000 ha in the delta for the development of rice cultivation by private farmers and village cooperatives under the supervision of SAED, a state body. Thus, for example, in the rural community of Ross-Béthio, 16,644 ha were effectively improved in 2000 (SAED 2000). Projects such as POAS (Plan of occupation and use of soils) in the rural community of Ross-Béthio and the Charter of Land Irrigation, besides their effects on the organization of the local farmers, should equally allow harmony between the management of the scheme, the use of the water and the agricultural activities *sensu stricto*.

In both of the Moroccan catchments studied, there has been a great expansion in irrigated agriculture over the last few decades. The Sebou basin is one of the most populated regions of Morocco and it represents the country's most important agricultural region with 19,200 km² of irrigated lands, including the large-scale irrigation schemes of the Rharb plain. In Kenya several irrigation schemes were commissioned in the Tana basin in the early 1960s and early 1980s, covering an area of 54,676 ha (Table 4; GOK 1992). However, some of these schemes have since collapsed. According to existing estimates, the basins have a potential of 132,000 ha for irrigation. Traditional irrigation using seasonal floodwaters formed the basis of rice cultivation in floodplain of the lower Tana and the Tana delta before these floods were controlled by damming.

Seasonal flooding still underpins the agriculture of the lower Rufiji river in Tanzania, where the principal water course remains free from damming. Significant abstraction of water due to large-scale irrigation activities occurs in the Great Ruaha tributary catchment, especially along the Usangu plains (Jensen *et al*. 2000), where the net abstraction is reported to be as high as 22%.

2.2 Other drivers and pressures affecting the catchments

In Africa, as elsewhere, the development of damming and water abstraction has taken place – and is taking place – against a background of other, mostly human-generated catchment drivers and pressures. These latter include climate and demographic changes, deforestation and land-use change, urbanisation and industrial development.

Table 4. Major irrigation schemes in the Tana and Athi-Sabaki* basins, Kenya.

Scheme	Potential (actual) area (hectares)	Water abstraction (Mm^3/m'th)	Water diversion system	Major crop	Ownership & Current status
Mwea-Tebere Irrigation Scheme		17	Gravity-fed canal	Rice	NIB, Fully operational
Bura Irrigation and Settlement Scheme	6,700 ha (2500 ha)	16.6	Diesel pumps to canal	Cotton	GOK, Partially collapsed
Hola Irrigation and Settlement Scheme	12,000 ha (2185 ha)	12	Diesel pumps to canal	Cotton	GOK, Collapsed
Tana Delta Irrigation Project	12,000-16,000 ha (1,200 ha)	10	Inflatable Rubber	Rice	TARDA, Partially collapsed
Lower Tana Village Irrigation Schemes	1,000 ha	1.0	Diesel pumps	Rice	Community, Partially operational
Garissa Projects	50-200 ha	0.01	Diesel pumps	Hort. produce	Private, operational
*Kibwezi Irrigation Scheme		1	Diesel pumps	Hort. produce	UON, Fully operational

NIB=National Irrigation Board, TARDA=Tana and Athi Rivers Development Authority, GOK=Government of Kenya, UON=University of Nairobi; * a scheme on the Athi/Sabaki river.

2.2.1 Climate change

Climate change is an indirect driver of damming in that the amounts and patterns of precipitation are changing, with increases in temperature and a higher incidence of extreme climatic events. The changes in climate encompass natural variability as well as the responses to human-induced pressures (notably 'greenhouse gases') at the global scale.

The impacts of climate change in Africa were reviewed by the Intergovernmental Panel on Climate Change (IPCC 2001). According to a model developed by Hulme *et al.* (2001), future annual warming across Africa ranges from 0.2°C to more than 0.5°C per decade. This warming is greatest over the interior of semi-arid margins of the Sahara (including the Senegal catchment) and central southern Africa. Future changes in mean seasonal rainfall in

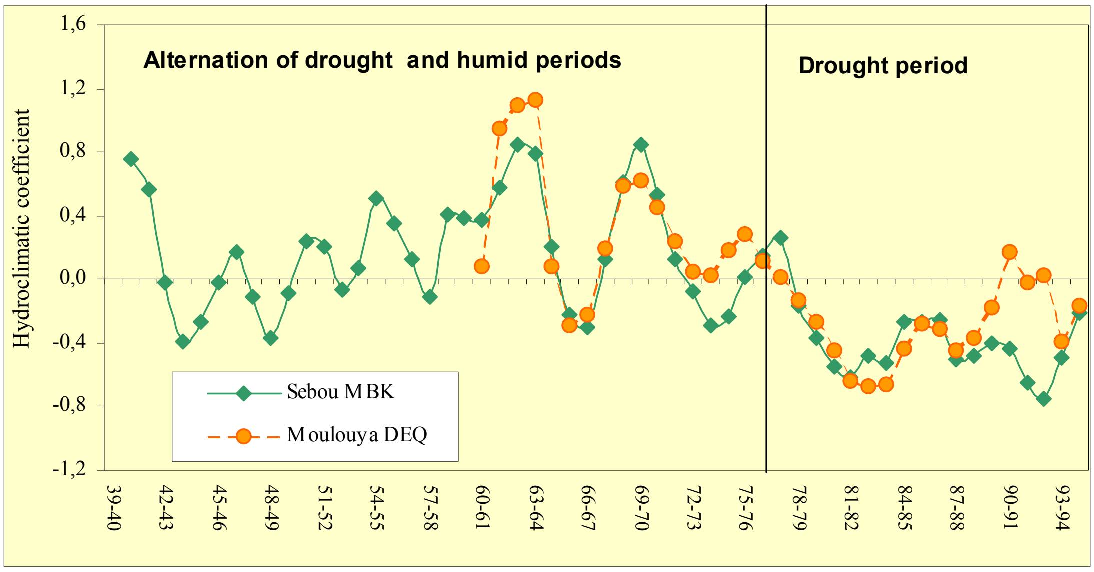

Figure 4. Variation of Hydroclimatic coefficients (Hc*) for the Moulouya and Sebou systems 1939-1994 at Mechra Bel Ksiri (MBK) and Dar El Qaid (DEQ) gauging stations. (Snoussi *et al.* 2002).

*Hc(%) = [Q_{ma} - Q_{mi}) / Q_{mi}] x 100, where Q_{ma} is mean annual flow and Q_{mi} is mean inter-annual flow.

Africa were less well defined and differed according to the warming scenario. Under the lowest warming scenario, parts of equatorial east Africa (including the Kenyan and Tanzanian catchments), rainfall increases by 5-20% in the months DJF and decreases by 5-10% in JJA. Under intermediate warming scenarios, significant decreases (10-20%) in rainfall during March to November are apparent in North Africa (Moroccan catchments) in almost all models by 2050. Under the most rapid global warming scenario, there are increases in DJF rainfall of 50-100% over parts of eastern Africa (Kenyan and Tanzanian catchments), and some JJA rainfall increases for the Sahel region (Senegal catchment).

In Morocco, where the rainfall occurs mostly as short and heavy storms, flood events contribute extensively to the water fluxes (Figure 4). For example, during the 1963 floods, the maximum water discharge of the Sebou river reached 8000 m^3 s^{-1} (approximately 61 times greater than the mean annual value) and that of the Moulouya, 5200 m^3 s^{-1} (nearly 240 times greater than the mean annual discharge). The projections for 2020, conducted according to the IPCC methodology (Secretariat d'Etat chargé de l'Environnement 2001), foresee a general decrease of about 4% of the annual volume of precipitation. They also forecast a 15% reduction of the surface waters and an increase in the frequency of extreme events (floods and drought).

Figure 5. Southerly migration of isohyets in Senegal during the period 1931-1990 (Source: Cartographic databanks of the IRD).

In Senegal, the southerly migration of the isohyets for the periods 1931-60 and 1961-90 presents clear evidence of the severity and length of the drought (Figure 5). It is, moreover, one of the principal causes of the degradation of the environment and the mobility of the Senegalese people. The southern movement of the 400mm isohyet by nearly 100km has caused the breakdown of cultivation, especially in the north of the country.

Most of the rainfall in the Senegal catchment occurs in the wintry period – May to October-November (Figure 6). The spatio-temporal distribution of the rainfall is closely linked to the position of the monsoon front, to the behaviour of the lines of squalls and consequently is in part dependant on the whole of the West African climate system. The Senegal basin is subject

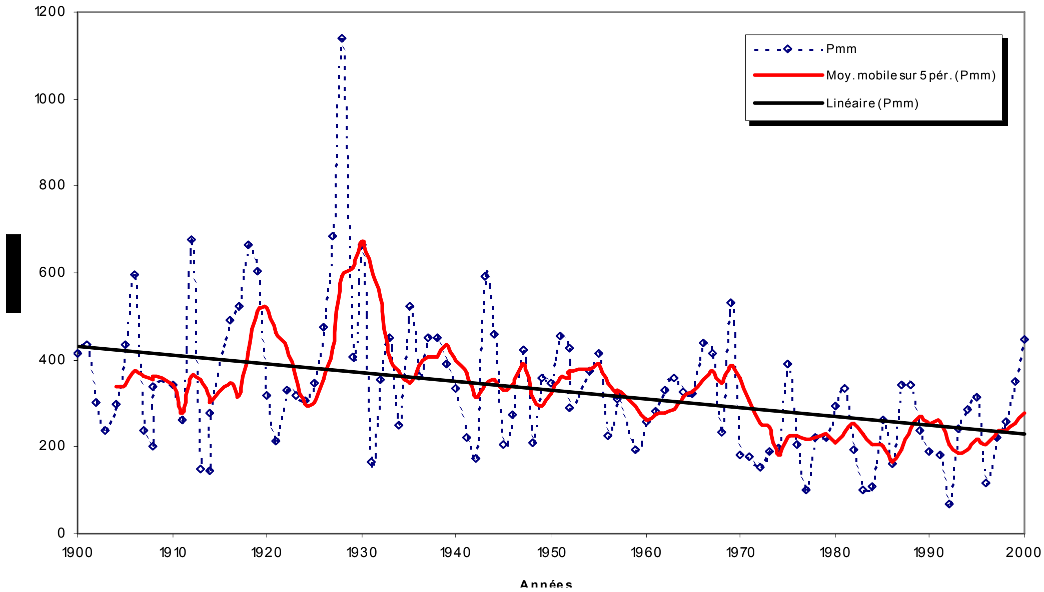

Figure 6. Rainfall measurements at St Louis on the Senegal River estuary, 1900-2000 (Source: Direction de la Météorologie Nationale du Sénégal). Pmm: Rainfall in mm per year, red line: five year running mean, solid line: linear regression.

to large variations in average annual precipitation. The climatic gradient is characterised by a consistent decrease in rainfall from 1650mm at Labé and 1900mm at Mamou in the upper basin, to 500mm at Bakel in the middle basin, to 350mm at St Louis in the estuary. Generally the rainfall in the low delta and estuary have been characterised by a uniform decrease since the beginning of the 1970s. The scarcity of rainfall and its corollary, the large variability of flows, are elsewhere the reasons behind most of the development schemes – the dams of Diami and Manantali, for example. Since the mid-1990s some rainy episodes seemed to question the alarmist theses of persistent drought. Nevertheless, there is nothing to indicate a return to normal (pre-1970s) rainfall.

Rainfall data in the headwater catchment of the Tana river in Kenya reveals significant changes in rainfall conditions over the last few decades (Figure 7). Data for the Nyeri station, upstream of the dams, showed that a significant shift occurred in 1975-76. Extreme conditions

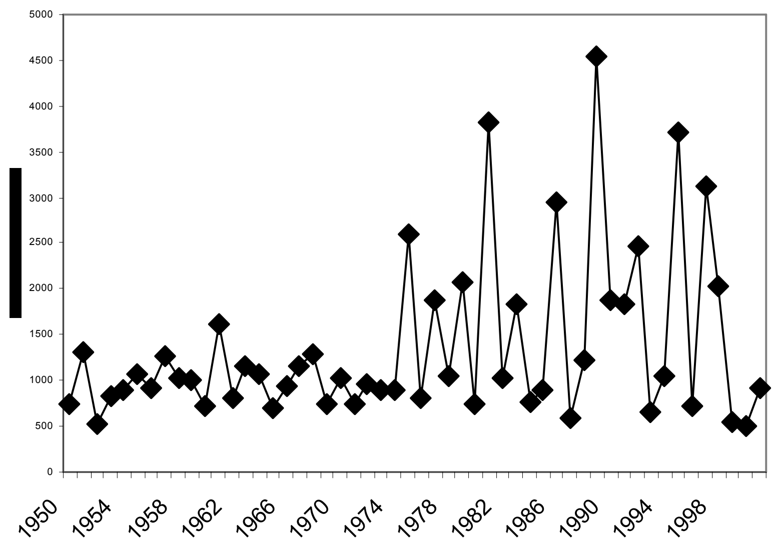

Figure 7. Annual total rainfall at Nyeri in the upper Tana catchment (Source: Kenya Meteorology Department, 2003).

have become more frequent, implying that the risks for flooding and drought are high (cf. Odingo *et al.* 2002). The increased frequency of occurrence of both flood and drought conditions has also increased in the headwaters of the Athi-Sabaki river (Odingo *et al.* 2002).

In the Rufiji study in Tanzania, trend analyses have been conducted on historical rainfall data (Figure 8). In general, the stations on the upper Rufiji indicate increasing rainfall trends. There was no evidence of either increased or reduced rainfall indicated by the stations from the lower Rufiji. Scenarios of climate change in Tanzania have been discussed by Mwandosya *et al*. (1998) and Agrawala *et al*. (2003). Using the General Circulation Model (GCM), Mwandosya *et al*. (1998) and Agrawala *et al*. (2003) compared the baseline climatic pattern of Tanzania with the expected climate due to doubling of CO_2 which is anticipated at the beginning of the next century (IPCC 2001). The two studies project that, as a consequence of doubling the greenhouse gas concentration in the atmosphere (which is projected to be the case at the beginning of the next century), there would be associated changes in temperature, rainfall and river run off. The mean annual temperature is projected to increase by about 2.2°C throughout the country. This will be associated with an increase in rainfall in some parts of the country (including the higher catchments of Rufiji Basin in south-eastern Tanzania) and an increased runoff of at least 5% in the Rufiji River.

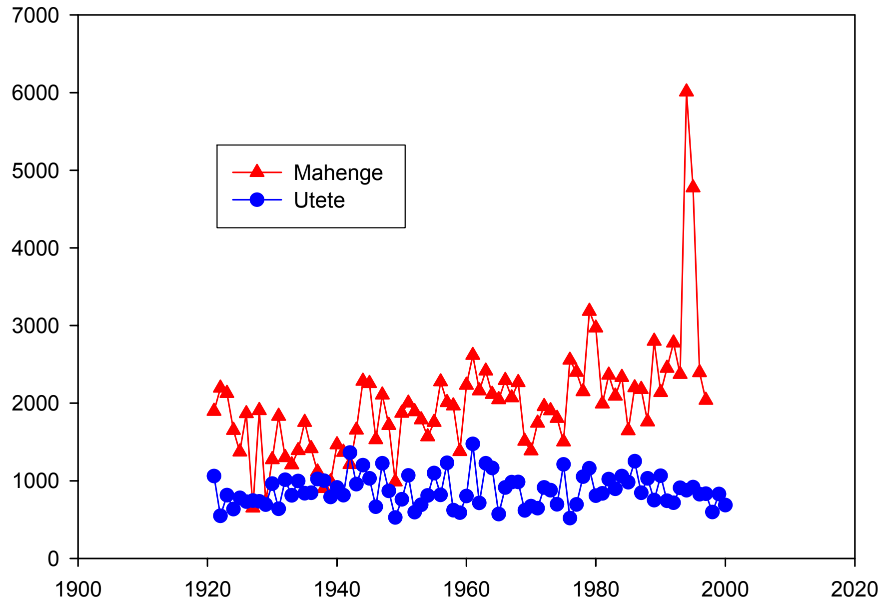

Figure 8. Annual rainfall patterns at two stations – Utete in the lower Rufiji and Mahenge in the upper Rufiji, Tanzania (Shaghude *et al.* 2004).

The different historical and predicted changes noted for each of the AfriCat river catchments emphasise the regional aspect of climate change. This is especially hard to assess using coarse resolution GCMs (which previous assessments have been based upon) and projects are underway to provide regional assessments of climate change using regional climate models and empirical techniques (http://www.aiaccproject.org/). These data will allow climate change estimates at higher spatial resolution, which in turn will allow catchment-scale assessments of expected future change.

2.2.2 Deforestation and land-use change

The underlying socio-economic drivers of deforestation and changes in land use are largely related to population growth, but many factors of economics and governance are also relevant. In the Athi-Sabaki and Tana basins of Kenya, large changes have occurred over the last 50 to 80 years as a result of the developing market in tea and coffee. Large areas of forestland have been cleared for farmland, mostly in the high rainfall highlands of central Kenya, so that the total area of the country under forest cover has reduced from 3.5% in the 1950s to about 1% at present, representing a clearance of nearly 60,000 ha (600 km^2). The present study, based on extrapolation from data of previous deforestation rates, estimates that by 2050 the area under forest will be less than 0.5% of the total.

Besides the economic motives for land-use change (including international trading patterns and the changes from subsistence to commercial systems), the underlying drivers of land-use change include population growth, poverty, weak ownership rights, and governance and institutional failures. In Kenya, government policies have played an important role in inducing changes in land use in the Tana and Athi-Sabaki river basins (cf. GOK 1999a, b). The creation of settlement schemes through the excision of forestlands and the expansion of rural roads in the catchment areas of central Kenya have altered the patterns of land use and accelerated the degradation of catchment areas (see Ongwenyi 1985). Soil conservation initiatives have been voluntary and farmers have not been compelled to apply erosion control measures. Where attempts have been made to apply the basic soil conservation strategies, the failure rate has been quite high. Government policies of particular significance include those geared towards the promotion of the expansion of total land under crop production, particularly for tea, coffee and maize cultivation and the provision of water to rural and urban centres. The other indirect socio-economic drivers of change include land tenure system and weak ownership rights, as well as economic motives where emphasis is put on profit maximization at the expense of environmental conservation. Another significant factor is a lack of long-term data and information. Climate variability and change in the Tana and Athi-Sabaki river basins also act as indirect drivers of change (Mogaka *et al*. 2002).

2.2.3 Urbanisation and industrial development

Rapid urban development and industrialization are impacting on the water resources in the Tana and Athi-Sabaki river basins and consequently the coastal zone. This is occurring mainly through increased inter-basin transfer of water from the Tana to the Athi river basin and the subsequent discharge of effluents from the city of Nairobi to the Athi River. Also, the presence of impermeable urban surfaces in the city of Nairobi limits the extent to which rain water can percolate or infiltrate into the soil. This results in rapid generation of surface runoff and hence rapid rise of peak flows during the rainy seasons. The discharge of municipal and industrial effluents from the city also reduces the water quality status of the river and forms a potential threat to the downstream and coastal ecosystems.

2.2.4 Locally generated (coastal) pressures

The aggregated impacts of all the catchment pressures described above must be assessed against a background of local pressures – pressures generated by coastal communities themselves in their use of local resources, by coastal urbanisation and industrial development – as well as the pressures of (mostly climate-driven) marine forcing and possibly also changes in land level due to tectonism or sedimentary consolidation, for example.

In the delta and adjoining floodplain of the Rufiji in Tanzania, many of the changes presently occurring are the consequences of local socio-economic pressures on the use of coastal resources associated with activities such as agriculture, fisheries and various local and external commercial trades such as the harvesting of mangrove poles, fuelwood collection and charcoal production.

Before 1969, the agriculture system in lower Rufiji was totally dependent on the natural interaction of rainfall and river flooding. However, after the so-called ‘villagization’ policy which took place between 1969 and 1973 (Cook 1974; Bantje 1979, 1980; Kajia 2000; Ochieng 2002), most households moved from their settlements in the river valley to drier upland areas of cleared forest or woodland. The villagization policy also affected the delta islands. Mangrove forest clearing has been undertaken as an alternative to the former subsistence floodplain agriculture, clearing mangrove forest in areas not permanently flooded by salt water. Activities in the Rufiji concerned with wood products include the production of fuelwood, charcoal, timber and poles. While fuelwood and woodland pole harvests are generally considered as subsistence activities, charcoal and timber production and mangrove pole harvest are often regarded as commercial activities. The latter activities require licences, but studies in the area indicate that the illegal harvesting of these resources is rife (Kulindwa *et al*. 2001).

Climate-forced marine pressures are a feature of the coastal zones of all the basins studied. These are particularly dominant in the Senegal river estuary. Coastal geomorphological changes there are the product of catchment pressures effective *via* the river (particularly in times of flood and extreme tidal conditions) and pressures from wave-induced currents affecting the littoral zone of the ocean-facing shore. The dominant littoral current on this shore flows from north to south. Estimates of the rates of sand transport there range from 223,000 to 1,500,000 m^3/yr, the process causing the accretion of a sand spit – the Langue de Barbarie – extending recently as much as 30 km from the town of St Louis, with the consequent southward diversion of the mouth of the Senegal river (Figure 9). In October 2003, local socio-economic pressures contributed to coastal geomorphological change; a channel was artificially excavated across the spit about 5 km south of St Louis with the aim of reducing the risk of flooding in the town.

While all of the AfriCat studies acknowledged the occurrence of (eustatic) sea-level rise resulting from global warming as a pressure on the coastal zone, none cited specific evidence of contemporary sea-level change.

3 STATE CHANGES

The physical state changes in the water cascades in the study catchments are described below in relation to the respective pressures:

Figure 9. The sand spit of the Langue de Barbarie, Senegal. The main estuarine channel of the Senegal river to the right of the picture is viewed upstream, towards the town of St Louis (Source: http://www.saintlouisdusenegal.com/35a.htm).

3.1 Damming and abstraction

- Reduced annual water discharge to the sea;
- Reduced peak water flows or flooding events downstream of the dams;
- Possible increased mean rate of river flow downstream of the dams due to controlled discharge;
- Reduced sediment flux downstream of the dams and annual discharge to the sea, due to the trapping of sediment in reservoirs.

In the Moulouya basin of Morocco before construction of the Mohamed V dam, the total annual average volume of water carried by the Moulouya to the Mediterranean was close to one billion cubic metres, though with a marked variability. Comparison between the water flows at Melg El Ouidane gauging station upstream of the dam and Saf Saf station downstream shows a reduction of 89%. In this case, water is diverted to a subsidiary dam (Mechra Homadi) for use in irrigation. The flux of suspended sediments shows a similar reduction between these gauging stations, with a 94% reduction in the sediment discharge downstream. Thus only 6% of the sediment supply of the Moulouya is currently discharged to sea.

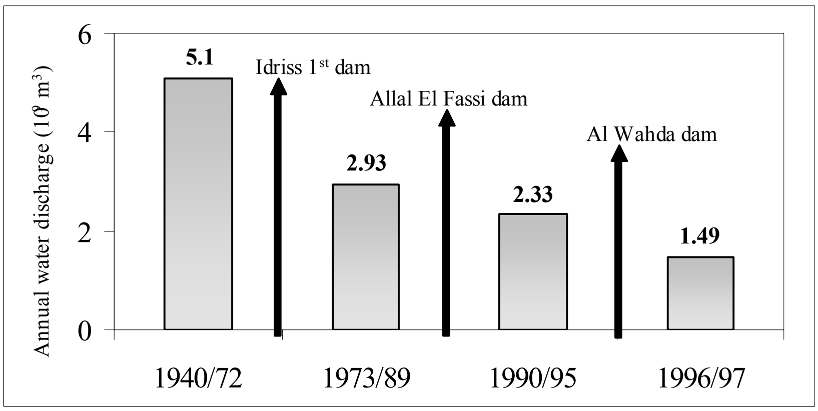

Figure 10. Reductions in the Sebou water discharge at Mechra Bel Ksiri following the construction of the dams (Haida 2000).

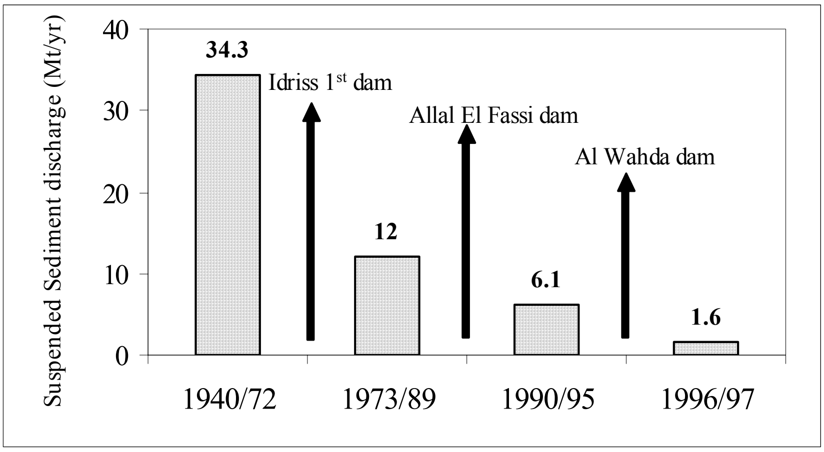

Figure 11. Variation of the Sebou suspended sediment discharge at Mechra Bel Ksiri before and after the construction of the dams (Haida 2000).

In the case of the Sebou basin, analysis of changes in the water discharges before and after the construction of dams (Figure 10; Haida 2000) shows that the flow at Mechra Bel Ksiri, the gauging station nearest to the mouth, has been reduced by 71%. Applying this reduction to the whole basin, the Sebou would currently carry less than 2 billion m^3/yr to the coastal zone compared with an estimated 6.6 billion before damming.

Comparable cumulative reductions in suspended sediment flux have occurred, indicating that at Mechra Bel Ksiri, 95% of the sediment load have been trapped within the dams (Figure 11). For the whole basin, about 6% of the total sediment discharge of the Sebou river reaches currently the estuary.

In the upper Tana basin in Kenya, damming has played a significant role in the regulation of the river flow. The construction of the Masinga dam, in particular, led to a major change in the flooding pattern of the river with a reduced frequency of occurrence of 100-year floods in the lower basin. The reduced frequency of flooding of the Tana River can be attributed to damming since flood water is stored or retained in the reservoirs before it is released downstream. Small flood events are absorbed effectively, but high floods such as those associated with El-Nino are not because of the limited capacity of reservoirs. The sediment

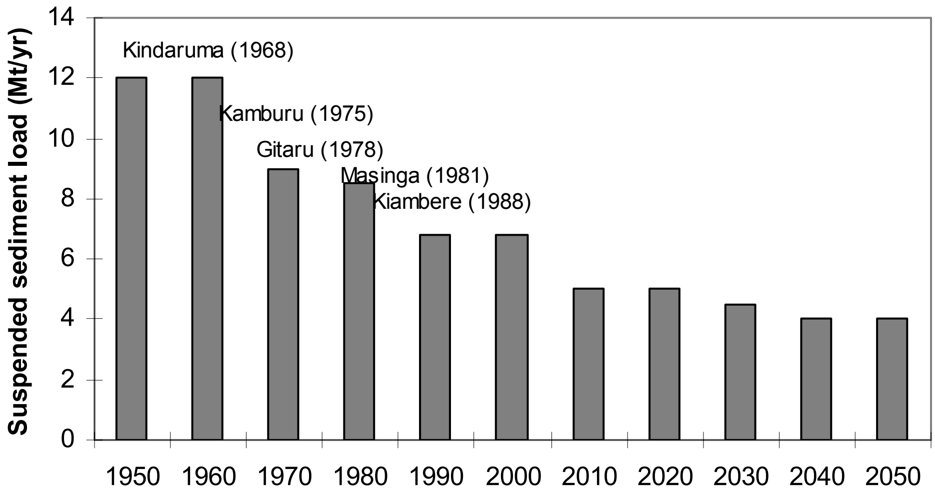

Figure 12. Changes in annual suspended sediment load of the Tana river, in relation to the commissioning of dams in the upper Tana basin. Extrapolations 2010-2050 are by Kitheka *et al.* 2002.

load has also declined due to damming (Figure 12) from a 1950s' recorded rate of 12 Mt/yr to the present value of 6.8 Mt/yr (Kitheka *et al*. 2003b). It is expected that there will be a further decline to less than 4 Mt/yr if further large dams are constructed as planned.

In contrast to the Tana system, records indicate a marked increase in both water flow and sediment discharge in the adjoining, but undammed, Athi-Sabaki system (Figure 13).

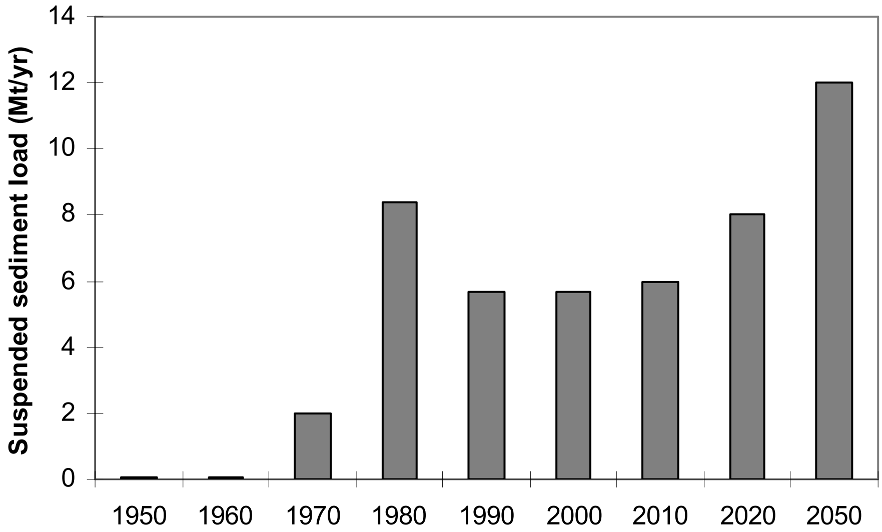

Figure 13. Mean annual suspended sediment load of the Athi-Sabaki river. Extrapolations to the years 2010-2050 are by Kitheka *et al*. 2003a.

In the Tana basin in Kenya, the total irrigation water demand was estimated to be 60 Mm^3/month before the partial collapse of the schemes in 1989 – this is roughly 6% of the total annual flow measured at Garsen in the lower Tana basin. If all the existing irrigation schemes were to operate at their optimum levels, the total abstraction would be equivalent to about 20% of the total annual discharge.

The commissioning of the Diama and Manantali dams on the Senegal river and the resulting new hydrodynamic conditions have introduced changes in the regime of fluctuating levels and flows. The present Senegal estuary is marked by two special characteristics of tidal dynamics:

- the effect of the tide that was felt up to 450km, to the vicinity of Diouldé Diabé, is now restricted to about 50km; current measurements show that maximum velocities now occur at mid-tide;
- in this short estuary, the tide wave is reflected from its upstream limit at the Diama dam then propagated towards the mouth; the study of the tide records at St Louis post-damming shows many abnormal peaks – the discharge from the Diama dam clearly influencing the water levels in the estuary.

The important deficit (32%) in the flow of the Senegal river in the lower basin since the commissioning of the Diama dam has been reduced by artificial floods produced by release from the Manantali dam (today the average deficit is 20%). The raising of the low water level of the river resulting from the emplacement of the dams has translated to a rise in the water table in the lower basin by an average of 200-500mm (Thiebaux *et al*. 1993).

3.2 Climate change

The contributions to water cascade state changes due to climate change are difficult to isolate and quantify, particularly in dammed systems. Much research is needed in this field.

Increases in temperature are likely to affect the cascade states by increasing rates of evaporation, both from land and reservoir surfaces. Run-off rates from land surfaces are likely to be reduced with reduced water flows in rivers as a consequence. While such reductions in dammed systems might reduce the volume of water stored, any state change at the coast would depend on the regimes of water abstraction and discharge from the dams. In the undammed systems of the Athi-Sabaki and Rufiji, any reductions might be expected to affect the coastal state, though the distinction of these effects from changes due to rainfall variation, for example, may not be feasible. In the Moroccan catchments the effect of increased extreme climatic events reported is to increase soil wash and the mobilization of sediment; this exacerbates the serious problem of sedimentation in reservoirs, reducing their volume efficiency and lifespan.

The changes in mean annual rainfall and rainfall patterns, including extreme events, that have been documented in Section 2 are reflected in overall annual discharges, and peak and mean river flows of undammed systems. In dammed systems any contribution to changes at the coast due to catchment rainfall patterns are likely to be masked by the damming and abstraction regimes, though the effect of changes in annual rainfall over the long-term may be detectable. For Moroccan rivers such changes are not very evident. There the long-term trend of the water discharges before damming shows a very slight decrease.

3.3 Land-use change and deforestation

The state changes in the water cascade due to land-use change are a response to a range of socio-economic pressures including population growth, as well as climate change.

The largely undammed system of the Rufiji and the undammed Athi-Sabaki (Figure 13) respectively provide evidence of the changes in water run-off and sediment load due in large part to land-use change. Evidence of increased rainfall in the upper Rufiji comes from the present analyses of long-term rainfall data and the projected climatic scenarios (Mwandosya *et al*. 1998). There is however no documented evidence for increase in water flow to the sea. On the other hand, there are documented evidence to support increased flooding frequency of the Rufiji which are linked to the landuse changes of the upper catchment (Savile 1945; Bantje 1979). According to Savile (1945) and Bantje (1979), prior to 1935, recorded serious floods with serious crop damage in the lower Rufiji floodplain occurred approximately once every 12-15 years. After 1935, serious floods with damaging effects to crops occurred at a much higher frequency, about once in every three years. Both Savile (1945) and Bantje (1979) linked the increased flood frequency with the land-use changes associated with the deforestation in the upper Rufiji catchment for creating agricultural land.

However, while there is a general perception that forest clearance and the spread of cultivation has led to increases in the rate of water run-off, the mobilisation of sediment in catchments and sediment loads being discharged, it may prove difficult to distinguish any such changes from those due to increased rainfall, including extreme events. The recorded changes in the Athi-Sabaki system are particularly striking, but here both land-use changes and increased rainfall, including extreme events, have occurred over the last few decades (Figure 13). In Morocco, there is concern that increased sediment flux due to land-use change will exacerbate the already serious problem of sedimentation in reservoirs noted above. This is another topic area where more research is needed to clarify the role of land-use change in the changes to catchment fluxes.

Another relevant aspect of land-use change is its effect on climate. Two of the main physical realisations of land-use change are to change the albedo (reflectivity) of the earth's surface and the Leaf Area Index (LAI, amount of vegetation contributing to plant transpiration).

Regional climate modelling work in southern Africa has shown that over arid regions, changes in LAI can affect rainfall by changing the moisture available for evaporation at the surface (M. Tadross, *pers. comm.*). Also, changes in albedo of the order of 20% (within the bounds of natural variability) could lead to rises in temperature of 3-4^{o}C and a drying of the continental interior. While no evidence of these effects was presented within the AfriCat case studies, as land-use change accelerates, the effect on local climates and the hydrological cycle may become significant.

3.4 Distinguishing the contributions to state change from different pressures

The contributions that are made to flux changes through different pressures (e.g. land-use and damming) may tend to either reinforce or neutralise each other. If management and policy responses at local to global scales are to be appropriate and effective, it is important that the causes of specific state changes in the water cascade to the coastal sea are correctly identified and evaluated. In many cases, as described above, it is likely that such state changes have more than one contributory cause. Some of those causes may add to the magnitude of the change while others may have a reducing effect. This is another area that requires more detailed research.

In the Sebou and Moulouya coastal zones, in addition to the strong reduction of river sediment discharges to the coasts due to dams, coastal drivers such as sand extraction and coastal planning, marine forcing and probably sea level rise have all aggravated the beach erosion.

A summary of the main state changes within the water cascades of the AfriCat catchments, at present and forecast over the next 25 years, is given below (see also Table 5).

Morocco:

- Increased damming and water abstraction leading to major reductions in water flow (including flood events) downstream to the coast, with reduced flushing and, at the Moulouya estuary, an increasing influence of marine forcing;
- Increased damming and water abstraction leading to major reductions of sediment flux downstream and coastal discharge due to sediment trapping;
- Reduced annual precipitation leading to reduced water flow in rivers (undammed or supplying reservoirs);
- Increased frequency of extreme climatic events leading to increased sediment flux to reservoirs.
- Increased deforestation and land-cover clearance leading to greatly increased sediment flux to reservoirs.

Senegal:

- Diama dam causing a seasonal reduction in freshwater flow in the estuary of the Senegal river;
- Dominance of marine forcing (supplemented by local human intervention) causing coastal geomorphological change.
- Stronger influence of saline waters in the delta and estuary due to the emplacement of the barriers; dilution of the waters not normally assured, the land rapidly becomes saline;

- Sedimentation at the foot of the works and in the different reservoirs, and a modification of the minimum depth level due to water generally highly charged with suspended material;
- Fresh occurrences and aggravation of floods due in part to the new hydrodynamic conditions created by the dams and in part to poor planning of urban development, notably in muddy and swampy neighbourhoods.

Kenya:

- Increased damming and abstraction in Tana leading to reduced peak flow flood events downstream;
- Increased damming and abstraction in Tana causing major reductions in annual sediment discharge to the sea;
- Increased damming with controlled discharge in Tana leading to increased mean discharge rates;
- Land-use change in Athi-Sabaki catchment causing greatly increased sediment flux and discharge to sea.

Tanzania:

- Increased flooding frequency due to land-use changes in upper catchment.

Table 5. Changes in the states of water and sediment discharges at the coast in the AfriCat systems over the last 25 years.

River catchment	Damming objective(s)	Annual water discharge	Mean water flow	Incidence of peak water flow	Annual sediment discharge
Moulouya	Irrigation & Power	Major reduction	Major reduction	Major reduction	Major reduction
Sebou	Irrigation & Power	Major reduction	Major reduction	Major reduction	Major reduction
Senegal	Irrigation, Power & Flood control	Major reduction	Major reduction	Major reduction	Minor reduction
Tana	Power mainly	Minor reduction	Minor increase	Medium reduction	Medium reduction
Athi-Sabaki	Undammed	No significant change	Medium increase	Medium increase	Major increase
Rufiji	(Gt. Ruaha trib.) Power	Minor /medium reduction	Medium reduction	Medium increase	Medium increase

In the system where the impounded water mainly serves power generation – the Tana in Kenya – there has been only a minor reduction in water discharge, though with major reductions in sediment discharge and the incidence of peak flows.

In the systems where irrigation as well as power has been a priority, notably the Moulouya and the Sebou in Morocco, both sediment and water discharges have shown major reductions, as well as mean water flows and the incidence of peak flows.

The largely undammed systems have both shown medium increases in the incidence of peak flows and in the case of the Athi-Sabaki a major increase in sediment discharge, all apparent consequences of climate and, particularly, land-use change in the upper catchments.

4 ENVIRONMENTAL AND SOCIO-ECONOMIC ISSUES AND IMPACTS

The environmental and socio-economic issues in the downstream and coastal areas are summarised in Table 6. This section describes the issues and their trends, and addresses their validation as representative of the impacts of specific catchment pressures and drivers that are transmitted to the coast through changes in the states of the water cascade including the principal material fluxes. In particular, it attempts to appraise the specific importance of damming and water abstraction as pressures of change affecting the coast amongst the full suite of pressures, both natural and human, including those in the catchment and those at the coast.

In its Synthesis Workshop, AfriCat included a review of the downstream and coastal impacts and issues for the various catchment to coastal sea cascades in historical, present and predictive perspectives. In each case the issues were ranked according to their perceived importance or severity and, where feasible, an indication was given of the present trends of these impacts. The results of this science-based ranking process are included within Table 6. One non-coastal impact – sediment trapping in dam reservoirs – is also shown in this table.

A key part of this scientific review process was an assessment of the validity of the perceived causal linkages that connect the downstream and coastal impacts and issues to specific pressures and drivers in the catchments. Consideration of the information derived from the non-dammed systems was an important element of this assessment, as was a knowledge of climate and land-use pressures in the catchments, and socio-economic and marine pressures acting directly (locally) on the coastal zone.

4.1 Environmental and socio-economic impacts linked to catchment pressures

The principal impacts of the state changes affecting downstream parts of the river basins and the coastal areas (including the coastal seas) are:

- Changes (mostly reductions) in the supply of freshwater to the downstream and coastal environments and their communities;
- Loss or reduction of seasonal flooding of floodplains and associated reduction in the siltation of floodplains and mangrove forests – consequent negative socio-economic impacts on e.g. agricultural production;
- Enhanced saline intrusion of estuaries and salinisation of estuarine groundwaters affecting mangroves and agriculture;
- Changes in estuarine and coastal geomorphology – channel modification, shallowing, deepening; dominance of littoral processes leading to mouth restriction; coastal erosion and accretion, siltation – consequent impacts on e.g. tourism and navigation.

All of these impacts imply risks to biodiversity.

In addition to these downstream impacts, a particularly serious issue relating specifically to dammed systems is that of the entrapment in the dammed reservoirs of sediment eroded from the upper catchments.

Table 6. AfriCat synthesis of downstream and coastal issues. Rankings (3=high; 0=low; n/a=not applicable) indicating the perceived importance of issues according to a) AfriCat scientists and b) for proxy policy- and decision-makers. Arrows indicate increasing ⇑ or stable ⇒ trends. * indicates river without significant existing dams.

<table>
<tr><th>ISSUES</th><th></th><th>Morocco Sebou</th><th>Morocco Moulouya</th><th>Senegal Senegal</th><th>Kenya Tana</th><th>Kenya Athi-Sabaki*</th><th>Tanzania Rufiji</th></tr>
<tr><td>1. Changes in water discharge</td><td>Policy and decision makers</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>3. Downstream flooding</td><td>Policy and decision makers</td><td colspan="2">1</td><td>3</td><td colspan="2">1</td><td>2</td></tr>
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<tr><td>4. Salt water intrusion</td><td>Policy and decision makers</td><td colspan="2">3</td><td>3</td><td colspan="2">2</td><td>1</td></tr>
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<tr><td>5. Coastal morph. change</td><td>Policy and decision makers</td><td colspan="2">2</td><td>2</td><td colspan="2">1</td><td>1</td></tr>
<tr><td>Coastal erosion</td><td></td><td>1 ⇒</td><td>3 ⇑</td><td>2</td><td>2</td><td>0</td><td>0</td></tr>
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<tr><td>River course change</td><td>AfriCat scientists</td><td>1</td><td>3</td><td>2</td><td>2</td><td>1</td><td>2 ⇑</td></tr>
<tr><td>Estuary deepening</td><td></td><td>0</td><td>0</td><td>0</td><td>2</td><td>0</td><td>0</td></tr>
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<tr><td>6. Socio-economic impacts</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Downstream health effects</td><td></td><td colspan="2">0</td><td>0</td><td colspan="2">1</td><td>2</td></tr>
<tr><td>Coastal water quality</td><td></td><td colspan="2">1</td><td>1</td><td colspan="2">1</td><td>1</td></tr>
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<tr><td>Wood resources</td><td>AfriCat scientists</td><td>1</td><td>1</td><td>1 ⇑</td><td>1</td><td>2</td><td>3 ⇑</td></tr>
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<tr><td>7. Loss of biodiversity</td><td>Policy and decision makers</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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<tr><td>8. Sediment trapping in dams</td><td>Policy and decision makers</td><td colspan="2">3</td><td>2</td><td colspan="2">2</td><td>n/a</td></tr>
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<tr><td>9. Adaptation strategies</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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4.1.1 Water and sediment discharges

The science-based rankings for most of the coastal issues show considerable variation among the catchments assessed. However, two consistently reported major issues in the AfriCat systems are the reductions in water and sediment discharges to the sea. The studies have demonstrated that these issues are predominantly the impacts of damming and water abstraction, with, in the case of the Moroccan catchments for example, step changes occurring at the coast as consequences of specific episodes of dam construction. Knowledge of climate and land-use change in the catchments in the undammed systems has shown that both of these pressures are making contributions to changes in water and sediment fluxes, the Athi-Sabaki in Kenya providing an extreme example of increased rainfall and extreme events combined with deforestation and agricultural expansion causing an increasing sediment load being discharged to the sea. A similar increase in both sediment and water discharge is observed in the Rufiji in Tanzania.

In Morocco, the construction of dams has promoted investment in hydraulic schemes for irrigation along both the Sebou and the Moulouya rivers. This increased consumption of water has improved the standard of living of the population and generated employment. In addition, the control of floodwaters by damming is regarded as having considerable economic benefit. In the Moulouya basin the floodwaters are controlled by the Mohamed V and Mechra Homadi dams, and in the Sebou basin mainly by the Al Wahda dam. The latter can reduce the flood volumes at the Gharb plain by more than 95%, avoiding economic losses estimated at close to 27M US$/yr (Ministère de l'Agriculture 1994).

In the Senegal river basin, despite the construction of the Diama dam, which now forms the head of the Senegal river estuary, there is a recurrent problem of flooding affecting the town of St Louis near the estuary mouth. In fact the town has long known serious inundation from exceptional floods, the most remarkable ones being in 1827, 1843, 1854, 1855, 1858, 1866, 1871, 1890 and 1950. The town of St Louis is situated in a relatively flat zone which has always been subjected to floods during winter, but since the middle of the 1990s there are reports of fresh occurrences of flooding which could be linked with the discharges from the Diama dam in periods of flood. However, several other causes have been invoked to account for the fresh occurrences and aggravation of the flooding – illegal occupation of swampy areas formerly forming part of the main river bed, embankment of the right bank, etc.

The delta and its adjoining floodplains of the Tana river in Kenya were similarly subject to seasonal inundation until the time of construction of the dams in its upper catchment. The capture of floodwaters and sediment by the dams effectively eliminated the peak flows through the lower catchment and greatly reduced the sediment discharge so that the traditional patterns of agriculture on those floodplains, notably rice cultivation, have been disrupted, forcing adaptation in farming practice and reportedly leading to local conflict.

The lower reaches of the Rufiji system in Tanzania illustrate the benefits to agriculture and fishery due to seasonal flooding which irrigates the floodplains, provides the nutrients for the agricultural crops and recharges the floodplain lakes. The planned dam at Stiegler's Gorge is expected to effectively reduce the nutrients (due to sediment trapping in the reservoir) and the flood peaks. The reduction of the flood peaks, particularly of the Luwegu tributary would have positive impacts to the lower Rufiji agriculture as most of the damaging floods in Rufiji have been associated with this tributary. However, the elimination of silt sediments will negatively affect the traditional floodplain agriculture. Also the reduction of peak floods will negatively affect the floodplain lakes and its associated fishery.

4.1.2 Salinisation and salt water intrusion

Salinisation linked to damming is perceived as a major, or potentially major, issue in all of the AfriCat catchments. In Morocco, the coastal wetlands of the Moulouya no longer receive river floods, which would assure the recharge of the coastal water table with freshwater used for irrigation. This situation at first facilitated the reclamation of the wetlands for agriculture. However, the waters and soils have since become increasingly saline due to irrigation, and the cultivated lands are becoming abandoned, with the emigration of agricultural workers.

This problem is acute in the Senegal estuary, where the increasing salinisation of the delta lands is regarded as a direct consequence of the construction of the Diama dam. Since the construction of the Diama dam with the seasonal impoundment of freshwater, there has been increasing degradation in the agriculture of the Senegal delta area through salinisation. For example, in the Gandiolais area, between the dam and the estuary mouth where market gardening is an important activity, there has been an expansion of salt marsh, a progressive loss of cultivated land and the degradation of relic mangrove. The changes in the freshwater flow regime following the construction of the Diama dam on the Senegal River have had a major impact on the seasonal salinity and temperature variations in the estuary, with consequent effects on fisheries

Similar degradation has affected the Tana delta in Kenya. The influx of seawater has contaminated freshwater supplies and has also affected crop production within the delta, despite an increase in dry season freshwater baseflow through regulation of discharge from the dams.

4.1.3 Coastal geomorphological change (includes erosion, accretion and siltation)

Geomorphological change is another issue with complex linkages. Damming and water abstraction are considered to be responsible pressures in the estuaries and littorals of the Moulouya and Sebou in Morocco, for example. Reduced freshwater and sediment discharge have modified the river and estuary channels and altered the regimes of littoral sediment transport with an increased influence of marine forcing.

The Moulouya shoreline in Morocco underwent remarkable adjustments after construction of the Mohamed V dam. Indeed, given the weak fluvial hydraulic power, the marine influences have been reinforced, leading to the reworking of the shoreline sediments, the narrowing of the mouth, and the accretion of mouth bars. According to Zourarah (1994), the most effective waves and the induced sand transport are directed westwards. The net littoral transport was estimated at approximately 165,000 m^3/yr. The transported sand was responsible for the accretion of the west coast, while the east coast shoreline, starved of fluvial input, retreated. It is more difficult to link the evolution of the Sebou shoreline to the river damming activities, since there have been many local contributions. These include the port construction and related defensive structures which have interfered with the river basin processes and altered the natural evolution of the coast. However, the reduced flushing of the estuary mouth by the now much diminished floodwaters necessitates dredging to keep the port entrance navigable.

The shoreline at the estuary of the Senegal river is the most dynamic of all the study sites. However, the forces of coastal geomorphological change there are dominantly marine, though driven by climate. The geomorphological evolution of the river mouth is largely controlled by the littoral transport of sand from the Mauritanian coast to the north. The impact of the dams on the changes of coastal morphology has not actually been proved but remains hypothetical, seen simply in consideration of the recent evolution of the coastal spit – the Langue de Barbarie. At the present time, there is no clear linkage between the damming and the coastal geomorphological changes. In Kenya, the reduction in sediment load and the increase in mean flow of the Tana River have caused significant geomorphological impacts at the coast (Figure 14). At the mouth of the Tana delta, the rate of coastal erosion has recently increased. While this appears to be caused by reduced sediment discharge, the observed erosion could also be partly due to sea-level rise and intensification of wave activity at the coast. Reduction in sediment discharge in the delta has triggered the erosion of the channel bed, leading to general deepening of the estuary.

In the Athi-Sabaki system, the increased sediment load is responsible for several coastal impacts. Coastal accretion is a major issue on the littoral extending southwards from the estuary to the town of Malindi, with strongly negative socio-economic impacts, in particular on the development of the town as a tourist resort. The linkage there is with climate and land-use change in the catchment. At the estuary, situated near Malindi, there is very heavy siltation which has caused accretion and progradation of beaches between Ngomeni and Malindi. The increased siltation has considerably reduced the water depth in Malindi Bay, thus rendering difficult the continued use of Malindi as a port. The plume of sediment laden water from the Sabaki outflow has also increased the turbidity of water in Malindi Bay, reducing its aesthetic value and impacting on the use of beaches for recreational purposes. Deposition of silt has adversely impacted sensitive coral reef and seagrass habitats in the northern part of the Malindi Marine National Park (see below). This process of siltation is particularly important during the North-east monsoon, when the silt laden discharge plume is driven southward by the coastal currents.

In the Rufiji, the shoreline has shifted seawards, protruding some 15 km into the Mafia channel (euroconsult 1980) as a result of deposition of the sediment load carried by the Rufiji towards the coast, with strong positive impacts to the prawn fishery. Incidences on changes of river courses at the delta during extreme flood events are also reported (Kajia 2000; Shaghude 2004), with associated potential negative impacts on biodiversity.

4.1.4 Loss of biodiversity

Biodiversity loss at the coast is recognized as a moderately important issue in all of the AfriCat catchments whether dammed or not. In cases such as the Moulouya estuary in Morocco, the loss is partly a consequence of the draining of the coastal wetlands made possible by the great reduction in freshwater discharge at the coast due to damming and water abstraction.

Figure 14. One of the mouths of the Tana river, Kenya, flanked by sand dunes (Photograph courtesy of UNEP).

The Diama dam on the Senegal River prevents the migration of fish between the estuary and the other parts of the basin which serve as their spawning grounds. The same cause has been cited for the disappearance of certain species of mollusc downstream of the dam. Altogether, the whole fishery dynamics of the estuarine zone has been modified.

In the Tana delta in Kenya the loss is ascribed to saline intrusion resulting from the damming-related reduction in freshwater discharge. Similar linkages are proposed for the Rufiji delta, where reduced discharge due to construction of the proposed dam at Stiegler's Gorge is likely to impact negatively on the biodiversity of the mangrove forests. In the case of the Senegal basin, salinisation and associated loss of biodiversity in the estuarine land is due to seasonally reduced freshwater discharge from the Diama dam. The problem of loss of biodiversity described from the undammed Athi-Sabaki system is different. The threat there is to the sensitive marine ecosystem in the Malindi Marine National Park affected by the sediment plume discharged from the Sabaki estuary. In that case, the issue is linked to the pressures of land-use and climate change, with increasing discharges of sediment.

4.1.5 Sediment trapping in reservoirs

The evidence from the Moroccan catchments shows that reductions in water and sediment discharge are major issues at the coast, but these are associated with the serious management problem of siltation in reservoirs through their trapping of sediment delivered from the upper catchments. The high rate of soil erosion is mainly due to natural drivers. However, in the Moulouya basin, the clearance of extended areas of Alfa for industrial use has exacerbated this phenomenon. It is forecasted that, by the year 2030, the Mohamed V dam will be completely filled with sediment. In the Ouerrha sub-basin where the slopes are steep and the rocks easily erodible, the slightest removal of vegetation has had serious impacts like landslides and mudflows. The trapping efficiency calculated for the different dams range from 85 to 99%. Sediment trapping is also recognized as a problem in the Tana reservoirs in Kenya.

The enhancement of sediment delivery of from catchments to rivers through land-use and climate change affects dammed and undammed rivers alike. In dammed systems, sediment delivered to the cascade above the dams is likely to be trapped, while that delivered below the dams can be expected to be transported to the coast, the rates of discharge being dependent on rainfall in the lower catchments and on the regimes of discharge from the dams.

4.2 Impacts of local pressures

Local socio-economic pressures may have a considerable negative impact on downstream and coastal communities and the sustainability of their coastal resources. The impacts of changes brought about by human activities in the lower Rufiji basin and Rufiji delta, including the 'villagization' policy of the late 1960s – early 1970s and the current poor regulation of charcoal production and the harvesting of fuelwood and mangrove poles are examples. Although villagization was intended to protect the people against flood risks (Bantje 1979; Ochieng 2002), it had a number of negative effects. The agriculture relocated in the uplands away from the river is entirely dependent on rainfall (Ochieng 2002) and, because the land there is generally less fertile than in the floodplain (Cook 1974; Ochieng 2002), it is usually abandoned after few years. This leads to shifting cultivation which has a strong negative impact on biodiversity. Further pressure on the environmental degradation is contributed to by poverty, resulting from farming of the less fertile uplands. In the delta, the clearance of mangrove through pole harvesting or for agriculture also has a negative impact on biodiversity as well as increasing the vulnerability of the mangrove areas to erosion. The use of pesticides by farmers in the delta to kill crabs in the rice fields leads to localized pollution in the mangroves, with associated negative impacts to the biodiversity.

The impacts of marine forcing on the estuary of the Senegal river are referred to above. In the case of the Tana and Athi-Sabaki systems, climatically monsoon driven waves have determined the alongshore redistribution of the sand bedload discharged from the estuary mouths. The principal effect has been the formation of barrier beaches, with sand being deflated from the backshores to build prominent sand dunes. The position of the mouth of Athi-Sabaki estuary at Malindi changes on a seasonal basis, partly due to alongshore transport of sediments along the coast. During south east monsoon, the alongshore drift southward leads to growth of a sand spit which extents northward. As a result, the mouth of the estuary shifts northward. During the northeast monsoon, the reverse is true.

5 RESPONSES

The DPSIR framework (Figure 2) provides an avenue for a consideration of remedial action, addressing the linkages that have been established between issues/impacts and pressures/drivers through prioritised management and policy responses, which are designed to feed back into beneficial state changes. The prioritisation of the responses reflects the level of importance attached to the issue in question. The science-based ranking applied to the various AfriCat issues is supplemented and compared, where appropriate, with a corresponding ranking compiled at the AfriCat Synthesis Workshop (held under the auspices of the NePAD Coastal and Marine Secretariat) by a group representing policymakers and funding agencies familiar with the African situation. The findings of this group are incorporated in Table 6. They include rankings of issues not considered by the scientific assessment such as downstream health effects and coastal water quality, as well as rankings of issues relating to adaptation strategies. Their assessments of coastal geomorphologic issues are generalised by country, as compared with the more detailed science-based assessments.

For some of the key issues, particularly downstream flooding, saltwater intrusion and sediment trapping, there is close agreement between the scientific and the policymaking perspectives. The policymakers did not rank the issues of changes in water discharge and water supply, while they placed much less emphasis on sediment discharge than did the AfriCat scientists. Such differences illustrate that, in this African situation, there are still significant perception gaps between scientists and policy-oriented advisers.

Recommendations for, and the anticipated benefits of, management and policy responses that address the principal issues and impacts affecting the downstream and coastal areas (including the coastal seas) of the AfriCat study catchments are set out by country in Tables 7-10.

Table 7. Moroccan catchments responses.

Issue	Response action	Comment on presumed benefit
Salinisation of soils	Drainage and leaching of soils with high salinity.	Limited and dependant on the availability of rainfall.
Saline intrusion	Construction of dams (barrage de Garde) at the limit of marine intrusion.	Limitation of the salinisation of coastal aquifers.
Coastal morphological changes	Dredging of channels (Sebou).	Improvement of navigation but would have to be done frequently (costly).
Socio-economic	Promote awareness among farmers to combat soil erosion, water pollution (fertilizers) and water loss (irrigation).	Improvement of quality of life.
Biodiversity loss – Coastal ecological changes	Medwetcoast Project for the conservation of the coastal wetlands of the Moulouya. Planning environmental flows downstream of the dams.	Rehabilitation of the ecological values and biodiversity.
Sediment trapping	Re-forestation of important areas in the Sebou and Moulouya basins. Dredging of a Mechra Homadi reservoir (Moulouya).	Decreased run-off and soil erosion Costly and inefficient.
Adaptation strategies – Integrated management	Creation of the Basin Agencies which coordinate different sectors dealing with the natural resources within the basins.	Improvement of communication and cooperation between the policy-makers.

The key policy actions for the Moroccan catchments are:

- the creation of the Basin Agencies and
- the improvement of awareness among the population.

Recommendations and suggestions:

- It is necessary to elaborate management models in order to cope with the strong irregularities of precipitation, satisfy the population and agricultural needs and preserve the ecological functions of the coastal wetlands. Scientific research is needed for this.

- It is necessary that the communication between decision-makers and the users work properly, notably in extreme climatic periods.

- It is necessary that the Basin Agencies cooperate with the coastal managers in an integrated vision of the systems.

Table 8. Senegal catchment responses.

Issue	Response action	Comment on presumed benefit
Water discharge	Releases from the dam to maintain freshwater flows to the estuarine zone.	Recharge of the coastal water table with freshwater.
		Restoration of mangrove ecosystems.
Sediment discharge	Limit the effect of the marine sedimentation within the estuary by dredging.	Possibility of river navigation.
Downstream flooding	Creation of diversion zones and canalization of the estuary.	Reduction of flood risk in the town of St Louis.
Salinisation of soils	Increased dry season freshwater discharge from the Diama dam.	Enhanced fresh groundwater flux through the delta area, improving agricultural potential.
Coastal geomorphological changes	Monitoring the regime of littoral sediment transport from Mauritania and assessing the possible impacts on that regime of continuing climate change.	Improved ability in managing and forecasting the evolution of shoreline change at the mouth of the Senegal river.
	Monitoring the impacts of engineered changes to the Senegal river mouth.	
Socio-economic issues	Improved planning and regulation of urban development at St Louis.	Reduced impact on urban areas of river flooding.
Biodiversity loss – Coastal ecological changes	Adoption of measures to facilitate fish migration between the Senegal estuary and river basin.	Arresting a decline in the state of estuarine fisheries.
Adaptation strategies	Rationalisation of scope of OMVS management in association with SOGEM and SOGED.	Improved integration of water management in the Senegal river basin and its coastal zone.
	Planning adaptive measures for continuing climate change, including provision for the effects of sea-level rise.	Improved ability to cope with increasing drought conditions, coastal erosion and marine induced flooding.

OMVS is an international body charged with the management of the Senegal river basin. It comprises different decision-making organizations such as the conference of the heads of state, the council of ministers and the high commissariat. Two private bodies – SOGEM (Société de Gestion de Manantali) and SOGED (Société d'exploitation des eaux de Diama) – are in charge of the operational management of the works and are equally charged with overseeing the licencing of the water.

For the transboundary Senegal river system decision procedures within OMVS are theoretically comparatively simple. In reality they are complex because in each country other bodies also have responsibility for water management leading to problems from a lack of a true water management system for the coordination, organization and planning of the various water uses. To that is added an important partitioning between the different decision-making bodies which maintain little or no contact.

Since the emplacement of the large dams of Diama in the estuary and of Manantali in the upper basin, institutional questions have become more crucial. Different approaches have been tried in the frameworks of various projects such as an Integrated Coastal Area and River Management pilot programme, which seeks to integrate the coastal zone and the river basin in the same management unit. But establishment of GILIF (Gestion Intégrée du Littoral et des bassins Fluviaux) was effected late so that the institutional arrangements between the different interests have yet to be realized. At the level of OMVS also one notes a growing interest in what happens in the coastal zone, notably because of the start of a river navigation programme in partnership with COSEC (Conseil Senegalais des Chargeurs). This means that from now on OMVS is positioned as a potential authority in charge of the coastal zone that is under the influence of the Senegal river basin. This scheme would offer the advantage of dealing with the problems of the coastal zone and those of the basin together.

Table 9. Kenyan catchments responses.

Issue	Response action	Comment on presumed benefit
Water discharge	Implementation of effective dam water release plan in order to maintain critical flows necessary for maintaining the downstream ecosystems/environment.	Security of freshwater supply to coastal communities and lower basin/deltaic environments; related improvements in agriculture and biodiversity.
	Plan for possible increased rainfall variability as forecast in regional Climate Change scenarios.	Implementation of water conservation strategies.
Sediment discharge	Implement re-forestation programmes in the upper Tana and Athi-Sabaki catchments through projects that address the socio-economic drivers of land degradation.	Surface runoff will reduce due to increased infiltration.
		Decreased soil erosion and improved agriculture in the catchment areas.
	Implement soil conservation measures in cultivated and non-cultivated areas.	Reduced sediment load at the coast and reduced turbidity of river and marine waters.
Downstream flooding	Implementation of environmental flows in discharges from the upper Tana dams.	Improved agriculture through partial reinstatement of seasonal flooding in the lower Tana basin.
Saltwater intrusion	Regular release of water from dams during dry season to flush saltwater in estuaries.	May be incompatible with hydro-power generation and water supply plans.
	Construction of barrages in the Tana delta.	Reduced influx of saltwater in the delta (costs likely to outweigh benefits).
Coastal geomorphologic changes	Implementation of sediment load reduction measures in the Athi-Sabaki system.	Reduced the degree of shoreline change and improved tourism amenity at Malindi.
		Reduced siltation of Malindi harbour.
Biodiversity loss – Coastal ecological changes	Creation of Tana Delta Conservation Area.	Improved or conserved biodiversity.
	Re-forestation of degraded mangrove wetlands.	Sustainability of livelihood systems.
		Sustainability of marine fisheries.
	Maintain critical dry season discharge.	Reduced negative impact of Sabaki sediment plume on sensitive marine ecosystem.
	Implementation of sediment load reduction measures in the Athi-Sabaki system.	
Sediment trapping	Implement reforestation of upper Tana and Athi-Sabaki catchments.	Increased vegetation cover will facilitate infiltration of surface runoff and decrease soil erosion.
	Implement soil conservation measures.	
	Construction of sediment traps and small sacrificial dams.	Reduced sediment load at the coast.
	Dredging of the upper Tana Basin reservoirs.	Increased lifespan of hydroelectric power dams - dredging is a costly option.
Adaptation strategies – Integrated management	Creation of Regional integrated river basin-coastal management authority.	Improved coordination between catchment and coastal management authorities.
	Strengthening the capacity of Tana and Athi Rivers Development Authority (TARDA) and Catchment Boards.	Improved implementation of soil and water conservation programmes in the Tana and Athi-Sabaki river basins.
	Full implementation of the National Environment Coordination Act (1999).	Reduced degradation of land and water resources in catchment areas.
	Implement or re-instate routine hydrological monitoring of principal water courses.	Improved hydrological data for planning and policy-making.

The key policy responses for the Kenyan situation are:

- the creation of a Regional integrated management authority and catchment boards;
- the promotion of environmental discharge regimes in the Tana system and
- the implementation of measures to arrest the rate of land degradation through soil erosion in both the Tana and the Athi-Sabaki catchments.

Table 10. Rufiji catchment responses.

Issue	Response action	Comment on presumed benefit
Water discharge	Maintain the seasonal flooding regime. Plan for possible increased rainfall as forecast in regional Climate Change forecasts.	Maintain the productivity of floodplain and deltaic agriculture; also lake and prawn fisheries.
Sediment discharge	Implementation of re-forestation and soil conservation measures to arrest land degradation and soil erosion in the upper catchment.	Less shoreline change through reduction in sediment accretion on the delta front.
	Maintenance of suspended sediment discharge.	Positive impact on prawn fisheries and floodplain agriculture.
Downstream flooding	Damming the Rufiji at Stiegler's Gorge. Consider an alternative site (upstream on the Luwega tributary) to that proposed at Stiegler's Gorge.	Dangers from serious flooding reduced without eliminating beneficial impacts of seasonal flooding and sediment discharge on the lower floodplain and delta areas.
Saltwater intrusion	Need to maintain freshwater flow through the lower basin/delta.	Promotion of healthy mangrove forest.
Coastal geomorphologic changes	Restriction and regulation of mangrove clearance.	Reduced vulnerability to shoreline erosion.
Socio-economic issues	Re-appraise the policy of 'Villagization' in the lower Rufiji catchment. Reduce the harvesting of woodland resources in the lower Rufiji floodplain and delta.	Improve the sustainability of agriculture and harvesting forest products.
Biodiversity loss – Coastal ecological changes	See Adaptation strategies (below).	(see below)
Adaptation strategies	Reform the 'Villagization' policy of 1969.	Arresting the negative environmental and socio-economic impacts of this policy.
	Reform policy related to the utilisation of woodland resources in lower floodplain and delta through e.g. promotion of fuel switching opportunities, tree planting, improving efficiency of fuelwood and charcoal utilisation.	Improving the sustainability and biodiversity of woodland and delta forest resources.

The key policy responses for the Rufiji system in Tanzania are:

- Maintaining the seasonal flooding regime and associated suspended sediment discharge to the lower Rufiji floodplain and delta
- Reviewing the 'Villagization' policy and making appropriate reforms to promote the sustainability of floodplain agriculture.
- Reforming policies related to the utilization of woodland resources in the lower Rufiji floodplain and delta.

6 SUMMARY OF PRESSURES AND RESPONSES

6.1 Pressures and impacts of damming and water abstraction

The impoundment of water principally for power generation and agricultural irrigation (but also domestic supply) since the 1960s in four of the six catchments studied in AfriCat has enabled major urban and industrial growth, with considerable socio-economic benefits at the national scale. The dams have also allowed control of the water cascade so that the damage and loss of life and livelihood caused by flooding episodes have been greatly reduced. The demands for power and irrigation water are set to continue their increases of the last few decades, with new schemes being commissioned or planned with the aim of satisfying these demands.

As well as the obvious socio-economic benefits of damming at the national or even sub-regional scale, the pressures from damming and water abstraction have caused, and will continue to cause, changes in the natural flow of water and sediment within catchment water cascades affecting the downstream and coastal environments and their dependent or associated communities. Some of the impacts have been beneficial, but many have had, or are having, adverse effects. The changes include not only reductions in the quantities of water and sediment transported to the coast (and coastal sea) but also changes in the patterns of delivery, with, for example, consequent reductions in the incidence of peak water flows which, though in the past have constituted a threat of flooding, have been a key element in the sustainability of floodplain agriculture and the deltaic ecosystem.

The impacts of the changes due to the pressure from damming and water abstraction are of particular significance considering the timescale of their occurrence. All of the dams in the AfriCat catchments studied have been constructed and commissioned within the last 50 years. Within this brief time-span, some major reductions in the availability of freshwater at the coast have taken place as dams have been built – mostly with immediate effect. Secondary effects of these reductions – notably the salinisation of soils and the intrusion of seawater into estuarine groundwater tables affecting agricultural productivity and the health of mangrove forests in estuaries for example – have been slower in their manifestation. The impacts of reduced sediment transport are also slower to be manifest, whether the progressive impoverishment of downstream floodplains, the adjustment of river beds, or the changes in coastal geomorphology caused by a diminished sediment supply from the catchments to estuarine beaches.

The current trends of change in all of the dammed catchments suggest that the physical adjustments to the water cascades are by no means complete and that the downstream and deltaic environments will continue to be subject to changing conditions as a result of damming. Little is known of the likely consequences of the existing damming and water abstraction over the long-term – say the next 50 years – let alone the ways in which catchment systems may respond to further damming and abstraction.

6.2 Land-use and climate change pressures and their impacts

While damming and water abstraction are major contributors to many of the downstream and coastal environmental and related socio-economic issues, there are other contributors at the catchment and at the local, coastal levels. Of particular importance are land-use and climate changes and their effects on water and, particularly, sediment fluxes. As with damming, land-use changes have become increasingly evident over the last 50 years or so, with deforestation, the clearance of agricultural land for subsistence agriculture and the changes in agricultural practice. The pressures of land-use change are driven by a complex suite of local to global socio-economic drivers, including, for example, national development policies and external trading agreements. The consequence of increased sediment flux on the sustainability of dam reservoirs because of sediment trapping reducing the effective volume of water storage is a matter of real concern to catchment managers. Climate change pressures are also apparent in the AfriCat catchments, with observed long-term increases or decreases in rainfall or the increased frequency of extreme events, themselves exacerbating soil erosion and sediment run-off. The changes due to these pressures are likely to continue to be important factors in catchment management. All catchments lie within areas for which climate change is forecast – increased temperatures and changes in rainfall – according to the various global warming scenarios of the IPCC, while land-use changes, whether related to agriculture, urbanisation or simply the poverty of rural communities, are likely to result in significant impacts at the coast.

AfriCat has drawn attention to the importance of human-related pressures created in the coastal zone itself, irrespective of human activities in the catchments. The use of coastal resources is a major issue in some of the lower catchment and estuarine areas. For example, the pressures of over-harvesting the woodland and mangrove resources for fuelwood, charcoal production and construction poles, and the clearance of mangrove in favour of agriculture are impacting adversely on the sustainability of those resources and on the biodiversity that those environments support.

6.3 Responses

The responses that are appropriate to the management of the pressures and their impacts described in this study of AfriCat catchments (Section 5) may be categorised into three main types:

- Institutional frameworks
- Catchment management
- Information and skills gaps

6.3.1 Institutional frameworks

As in most coastal countries, catchment and coastal management responsibilities in the AfriCat countries are divided among many different organizations, often focused to specific sectoral goals and lacking effective linkage between environmental and developmental objectives. The studies recognize the need for the integration of catchment and coastal management by agencies that take into account the whole water cascade and its human dimensions – those *affecting* the cascade within the catchment as well as those *being affected by* the cascade in downstream and coastal environments. The development authorities with responsibilities specifically for damming and irrigation supply, as well as other key stakeholder groups, should be represented within those agencies. The agencies would provide the essential interface with government policymakers. In the case of the transboundary Senegal basin, an international management body already exists though its remit is currently restricted to the river basin, excluding the coastal zone.

6.3.2 Catchment management

The responses tabled for the AfriCat basins (Section 5) include a wide range of tasks, most of which can be carried out at the catchment level of management. Within the context of the AfriCat studies, the key achievable management tasks relate to the operation of existing damming and abstraction schemes and the planning of future schemes.

- Firstly, there is a need to consider further ways in which water discharges could be adjusted to provide improvements in downstream and coastal environmental and socio-economic conditions, while still providing protection against damaging floods.
- Secondly, the problem of sediment trapping impacting on the sustainability of dam reservoirs needs to be addressed jointly with the rigorous application of soil erosion measures in upper catchments.
- Thirdly, the downstream and coastal impacts of future planned schemes in catchments that are already dammed, as well as those presently undammed, need careful assessment, particularly in the light of climate change forecasts.

Beyond the context of damming, the studies have highlighted the urgent need to tackle the root causes of land degradation and soil erosion, and the over-harvesting of estuarine or coastal resources. A range of practical and policy options and recommendations is tabled in Section 5 (Tables 7-10).

6.3.3 Information and skill gaps

A shortage of trained scientists and administrators is a feature of all the AfriCat countries. There is an urgent need to redress this shortcoming if the aims expressed above are to be achieved. Given an improvement in the availability of these human resources, a priority at the national level is to enhance the knowledge base upon which management and policymaking decisions are made. Observational monitoring networks should form the bases of the physical and socio-economic information required for catchment management. For example, there is a case for the re-establishment of many former river gauging stations that have ceased to operate, and a need to enhance the observational meteorological network to provide a control for climate change models. Greater capacity in all AfriCat countries to forecast the impacts of climate and demographic changes is another priority.

7 AFRICAT OUTPUTS AND CONCLUSIONS

The project provided an opportunity to study individual catchments in a wider African context alongside representatives from regional agencies with a view to looking for common outcomes and needs as well as to look into future research aimed at framing the mutual agendas of scientists, agencies and policy makers that rely on science for informed decision-making. The results of the AfriCat studies, as well as other African catchment studies show that there is considerable potential benefit from linkage between rivers and coasts at the scientific, policy and management levels. Improving management is a crucial goal and the challenge for scientists is to produce a sound information base that is accessible and understandable to the management community at local as well as more regional levels.

These outcomes formed the basis for looking towards the future needs for African catchment studies that would maximise ownership and flexibility in addressing key scientific questions along the water cascade, generating networks including institutions that help address all the stakeholders. The underpinning consideration is that changes in environmental parameters along the water cascade, whether due to natural or anthropogenic causes, produce changes in human activities that modify the water cascade to produce environmental, economic and social changes in the coastal zone (Figure 15).

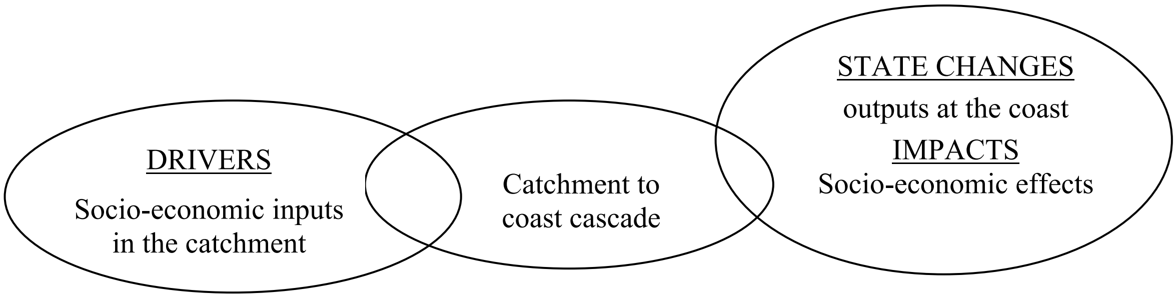

Figure 15. The linking of watershed drivers through the water cascade to the coastal zone.

Future research needs should address not only methodologies and tools, but also structures and management; organisation and institutional arrangements; and funding needs and mechanism criteria that would be needed for a research programme. Critically, future research should aim to improve linkages between socio-economic drivers and impacts as well as biophysical and biogeochemical fluxes in order to analyze the human dimensions of major biophysical and biogeochemical changes in catchments. It has to have both retrospective and future-oriented parts, which in the end should cater for the development of scenarios for strong vs. weak sustainability options. Specific areas that should have a high priority in future research agenda should be:

- Identification of indicators/thresholds for state changes in the coastal zone.
- Assessment of the validity of the socio-economic linkages to change.
- Understanding the functioning of environmental systems .

Future research should have an emphasis upon defining system components along the whole water cascade to the coast and the fluxes that drive coastal biogeochemical processes including catchment drivers (human/natural) and coastal drivers (human/natural) that allow assessment of current systems in order to lead to forecasting potential. The general methodological framework that could support such a structure is given in Figure 16.

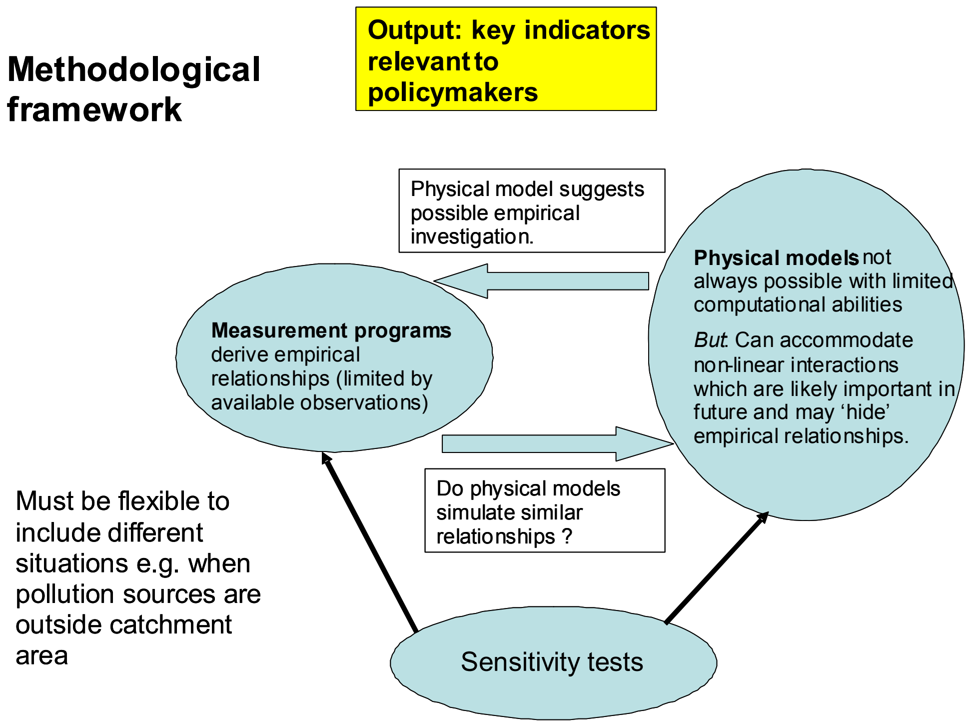

Figure 16. General methodological framework for future AfriCat studies.

An approach that defines the need to consider the spatial and temporal scales at which problems originate is necessary that addresses four spatial scales - local, country, regional and global as well as short, medium and long-term. Scientists are often working at the local level whereas problems at local level may originate at national, regional or global level and the solution should be sought at the appropriate level. To achieve this, a number of sequential and mutually supporting work packages are required to address the source to sink issues of the water continuum (Figure 17). A focal institute should be identified for each work package that has expertise to provide services, advice and training.

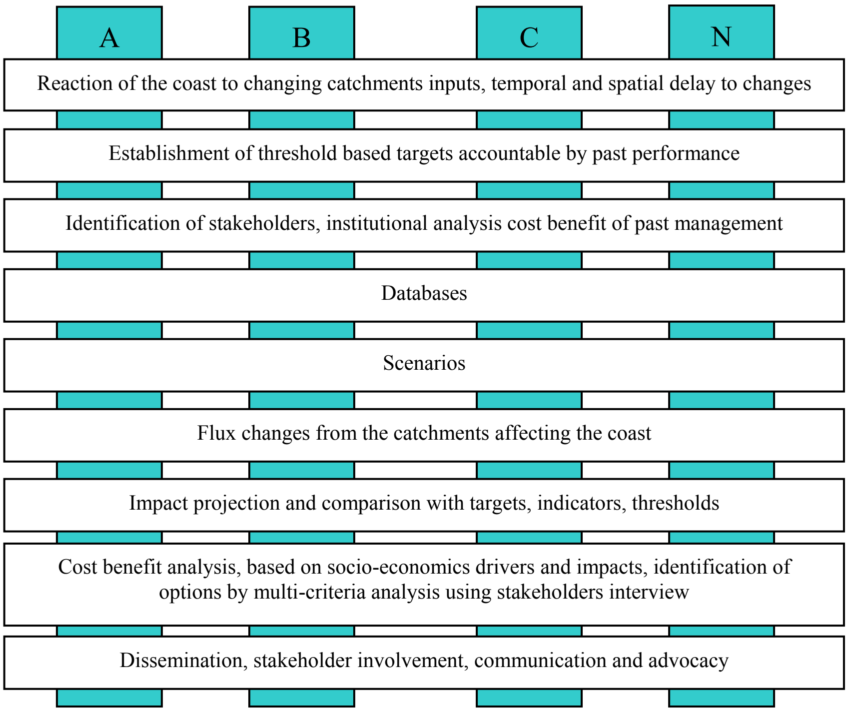

Figure 17. Sequential work packages (horizontal blocks) for the exploration of source to sink issues in the water continuum of catchment to coast. Each work package might require co-ordinated inputs from a number of institutions (vertical blocks). Retrospective and future perspective should be the foundation for scenario development.

8 ACKNOWLEDGEMENTS

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IMPACT OF DAMMIMG ON THE SEBOU AND MOULOUYA RIVER BASIN - COASTAL ZONE SYSTEMS (MOROCCO)

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Abstract

The present study discusses the impact of the construction of dams and other drivers/pressures on the water and sediment discharges of the Sebou and Moulouya - the two largest rivers of Morocco - and examines the associated impacts on the estuarine and coastal zone. The need for the impoundment of water by damming is driven by a rainfall deficit and growing demands for reliable freshwater supplies to urban and rural communities, for agricultural irrigation and for hydro-electric power. It is estimated that the construction of dams has reduced the water discharge of the Sebou and the Moulouya rivers by 70% and 47% respectively. The projections for 2020 show increases in of all these drivers.

Concerning sediment abstraction, it is recognized that in the Sebou and Moulouya basins the high rate of natural and man-induced soil erosion is responsible for the high sediment yields of the rivers. Recently the construction of dams has reduced the sediment fluxes that are discharged through the catchment to the coastal seas by nearly 95% for the Sebou and 93% for the Moulouya. This high rate of sediment abstraction has been responsible for rapid siltation of the reservoirs and had serious environmental and socio-economical impacts by reducing reservoir capacity and lifespan.

The investigation of other drivers such as climatic variability showed that during the last decades, recurrent droughts have exacerbated the reduction of water flows both into and below the reservoirs. Other anthropogenic pressures/drivers associated with the socio-economic activities such as agriculture, industry, tourism, port development, etc. have generated impacts such as pollution and salinization of groundwater, disruption of the hydro-sedimentary functioning of the Sebou estuary, retreat of the Moulouya delta, erosion of sandy beaches, and degradation of ecosystems. These changes are in turn impacting coastal communities who either migrate or change their type of activities. Predicted global warming will lead to the construction of additional dams and could aggravate these impacts. It is therefore recommended that the future water needs and planned dam activities are assessed and analysed on a scientific and socio-economic basis, as well as the linkages between these activities and coastal equilibrium.

Introduction

The study was conducted within the framework of the AfriCat (African Catchment) pilot project, initiated by LOICZ and funded by the International System for Analysis Research and Training (START). The Sebou and Moulouya – the two largest rivers in Morocco – were chosen as case studies. As semi-arid regions with contrasting climatic seasons, the two basins periodically face a rainfall deficit caused by recurrent droughts. In order to improve the management of these shortages and to satisfy the increasing water needs, a large-scale program for the construction of dams has been carried out over the last decades for drinking water, irrigation, and hydroelectric power. The Sebou is heavily dammed and characterized by important land use changes both within the basin and along the coast, while the Moulouya has only one large dam and the estuarine zone is undeveloped.

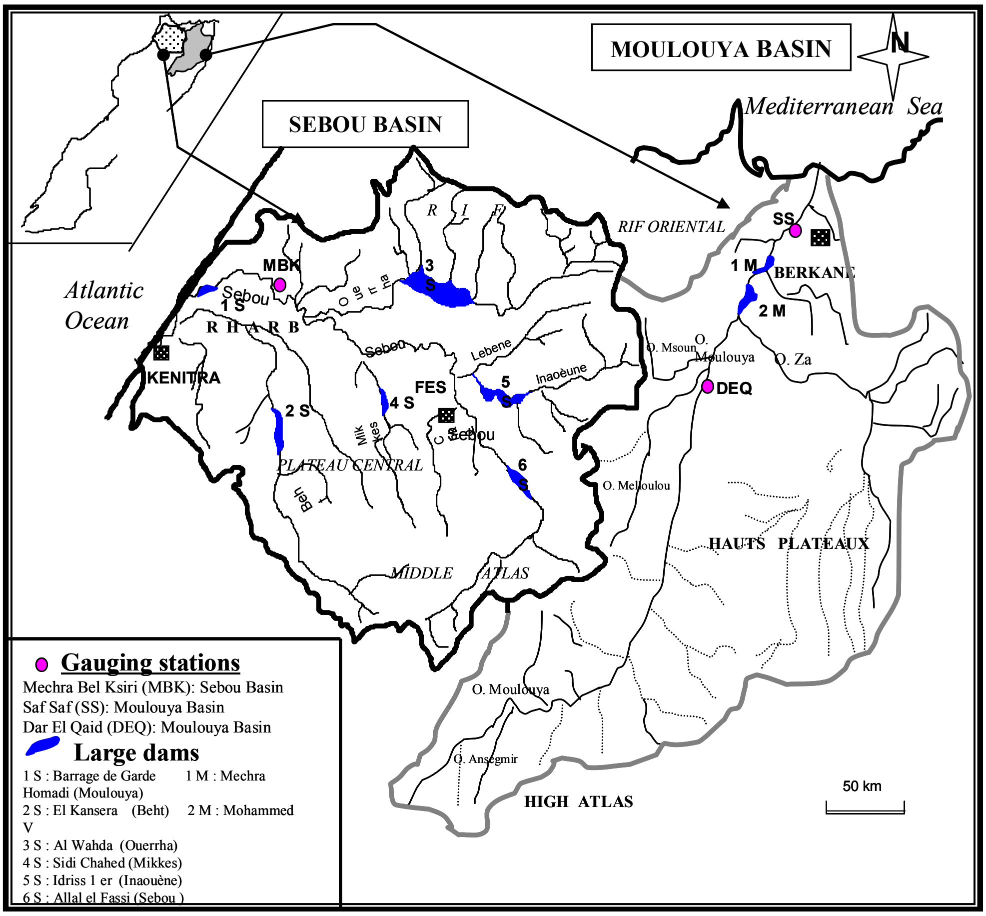


Figure 1. Situation of the Sebou and Moulouya basins, showing major dams and the main gauging stations.

The main objective of this study is to assess the linkages between water impoundment / abstraction in catchments and the impacts and issues at the coast. It will also review the impacts of others drivers/pressures such as climate change, and will consider the consequences of predicted future climate and socio-economic changes.

Description of the river basins

The Moulouya

The Moulouya basin (Figure 1) is the largest river basin in Morocco, draining approximately 53,500 km^2 in the eastern part of the country. It rises in the Atlas Mountains and flows into the Mediterranean Sea. The upper basin is separated from the lower floodplain by the large Mohammed V reservoir, which traps most of the sediment delivered from the upstream region. The bedrock consists mostly of sedimentary rocks (limestone, marl, sandstone, conglomerate). Downstream of the dams, the Moulouya follows a commonly sinuous course in a wide plain before discharging to the sea. On either side of the river mouth, sand deposits form a system of parallel littoral bars representing positions of the past shorelines.

The estuary zone with its complex marshes represents a Site of Biological and Ecological Interest over about 3,000 hectares. It is a refuge for many birds of worldwide or national interest. It is also a national protected habitat for diversified wildlife and rare plants. The project MedWetCoast-Morocco (2003), which includes the mouth of the Moulouya, has as its principal objective the conservation of these coastal wetland ecosystems.

The climate is typically Mediterranean with the average precipitation ranging from 200 mm to 600 mm (DGH 1988). Most of the rainfall is concentrated in only a few days. The run-off is estimated at 16mm for an average precipitation of 300mm (Laouina 1987). The mean annual temperature ranges between 9°C and 20°C.

The population represents about 8% of the total population of Morocco in 1994. The main human activities are agriculture (138,000 km² of irrigated lands), industry, mining and grazing. Agriculture is developed mainly in the lower Moulouya, where the soil is fertile and water sufficient. The main crops are cereals, horticulture, and sugar beet. In the more arid zones, the land is used mainly for livestock grazing. Forests are developed on the slopes of the Atlas and Bni Znassen mountains.

The Sebou

The Sebou River is also one of the largest Moroccan rivers (Figure1), draining approximately 40,000 km^2 between 33° and 35° north and 4° and 7° west. It stretches about 600 km from its source in the Middle Atlas to the Atlantic Ocean. The morphology of the watershed reflects the difference in relief between the north and the south. The Sebou basin can be divided into three distinct geomorphic regions: the upper, mid-, and lower Sebou. The upper Sebou rises at over 2800 m in the Middle Atlas mountains and is underlain mainly by calcareous rocks. The mean annual precipitation is over 1000 mm with snow at high elevations in winter. The mid-Sebou basin lies within the Rif and Prerif Mountains, characterized by an average altitude of 2000 m, very steep slopes, a strong rainfall gradient across the basin averaging 2000 mm, and bedrock composed of shale, marl and sandstone. The Ouerrha and the Inaouene are the major tributaries of the Sebou draining the Rif and Prerif mountains. In its lower basin, the Sebou opens into a wide valley – the Rharb – where it meanders through a floodplain. There the mean annual rainfall is about 600 mm in the west and 450 mm in the southeast.

The Sebou basin is one of the most populated regions of Morocco. By 1994, its population totalled about 5 million of which 61% live in rural areas. It represents the country's most important agricultural region (19,200 km² of irrigated lands) and has a relatively developed social and economic infrastructure. Natural vegetation covers only 25% of the total basin area. Because the lower basin consists of a coastal plain, large-scale irrigation schemes have been developed in the Rharb plain.

Assessment of catchment impoundment and water abstraction

Current Status:

Table 1 shows the main characteristics of existing dams in the Sebou and Moulouya basins. The reservoirs are managed by the Water Planning and Research Directorate (DRPE) and the Basin Agencies: ORMVAG for the Sebou and ORMVAM for the Moulouya.

The Sebou basin encompasses 6 large reservoirs (Figure1) and more than 10 small ones built over a period of 70 years. These reservoirs are now a major source of irrigation and drinking water and strongly regulate the flow in the upper, mid- and lower catchments. The Al Wahda dam, constructed between 1991 and 1996 on the Ouerrha River, is the second most important dam in Africa after the High Aswan dam. Its storage capacity will irrigate 100,000 ha, generate a potential hydroelectric capacity of 46 MW, transfer a water capacity of 600 10^6 m^3 towards the south regions, and protect the Gharb plain from major floods.

In the Moulouya basin, the largest reservoir – Mohamed V – as well as a number of small reservoirs of local interest, assures the irrigation of the lower Moulouya plain through the waters released and diverted to the Mechra Homadi dam. The Mohamed V dam is also equipped with a hydro-power station.

Table 1. Main characteristics of existing dams in the Sebou and Moulouya basins. (T: Transfer; PI: Potable and industrial water; I: Irrigation; HE: Hydro-electricity).

	River	Dams	Year of completion	Surface area of basin (km²)	Capacity (10^6 m^3)	Water supply (10^6 m^3)	Uses
Sebou	Sebou	Garde	1991	27,000	40	200	I
	Sebou	Allal Fassi	1990	5400	82	750	T.HE.I
	Ouerrha	Al Wahda	1996	6190	3800	2564	HE.I.PI.T
	Inaouène	Idriss 1er	1973	3680	1800	700	HE.I
	Beht	El Kansera	1935	4542	266	372	HE.I.PI
	Mikkès	Sidi Chahed	1996	680	170	200	I
Moulouya		Mohamed V	1967	49,920	490		I.HE.PI

Future plans

In the Sebou basin, 9 new dams are planned between now and 2020, in response to the demand for water in fulfillment of the Guiding Plan for the Integrated Development of the Basin (Conseil Supérieur de l'Eau 1992) (Table 2). The realization of this suite of dams would allow access to a surface water volume of 4,467 Mm^3/yr in 2020, on a basis of 5,600 Mm^3/yr supply, i.e. a usage rate of 80%.

Table 2. Programme of commissioning of dam projects until 2020.

River	Dam	2003	2006	2007	2005	2008	2012	2014	2016	2020
Sebou	Ouljet Soltane				X					
	Mdez					X				
	Aïn Timedrine					X				
	Mechra Hajar					X				
	Tafrant						X			
	Sidi Abbou							X		
	Rhafsaï								X	
	Bab Ouender									X
Moulouya	Sidi Saïd	X								
	Ansegmir		X							
	Targa ou Madi			X						
	Tilidanine							X		

In the Moulouya basin, the important objectives of the future plans, such as presented in the Guiding Plan of development of the Water Resources of the Moulouya Basin (CSE 1990) are:

- to assure the limitation to 6000m^3/s of the flood discharge from the Mohamed V dam;
- to satisfy the demand for drinking and industrial water (300Mm^3/yr in 2030); and
- to meet the demand for irrigation (920 Mm^3/yr).

To attain these objectives, a timetable for the construction of at least 4 new dams is presented in the Plan. These reservoirs will compensate the reduction of the regularization of the Mohamed V - Mechra Homadi complex and will increase the rate of regularization of surface waters to 87% in the year 2020. According to this plan, the socio-economic impact is widely positive since the updated advantages surpass the updated costs by 200% to 260%. The plan foresees the avoidance of the loss of 16,000 to 18,000 jobs in the lower Moulouya.

Socio-economic drivers of water abstraction and future trends (Figure 2)

1- Water demand for domestic and industrial use:

Moulouya:

In response to the increase of the population from 1985 to 2020 (respectively 65% for the urban and 19% for the rural population), the water demand for domestic and industrial uses in the basin will increase from 77 Mm^3/yr in 1985 to 274 Mm^3/yr in 2020, an increase of 255%.

Sebou:

The population of the basin was 4.5 million inhabitants in 1990, and will rise to 7.5 million in 2020. The water demand of the main conurbations such as Fès, Meknès, Kénitra and Taza has long been essentially assured by groundwater resources. Nevertheless, with the socio-economic development that these towns are experiencing, groundwater is no longer sufficient to meet the increase in demand for drinking water. Thus recourse to surface waters was accentuated during the decade 1980-90. Overall in 1990 the demand for drinking water was 229 Mm^3/yr; it will reach 663 Mm^3/yr in 2020, an increase of 189%.

2- Demand for irrigation:

Moulouya:

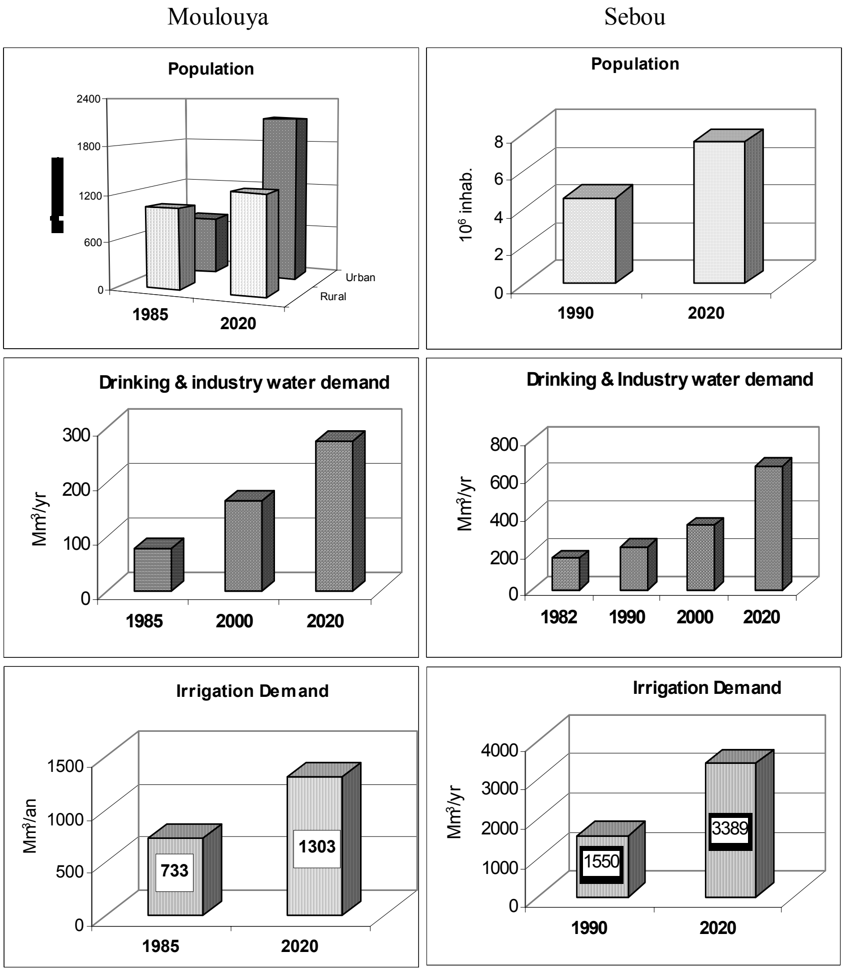


Figure 2. Evolution of the socio-economic drivers in the Moulouya and Sebou basins.

According to the Guiding Plan (1990), while there was a need in 1985 of 723 Mm^3 for the hydro-agricultural equipment of the Moulouya, the need for water in 2020 will rise to 1303 Mm^3, an increase of about 80%.

Sebou:

The water resources in the basin have so far allowed the irrigation of the large plains of the Beht and the Gharb and the small plains alongside the valleys in the Meknès-Fès Plateau. The needs for water, estimated at 1550 Mm^3/yr in 1990, will increase of nearly 54% by 2020.

Climatic variability and river flow changes

Data on water flows used in this study were obtained from the gauging stations operated routinely by the Water Planning and Research Directorate (DRPE), which also kindly provided us with information on the status of dams.

Seasonal variation:

As with most Mediterranean rivers, because the rainfall occurs mostly as short and heavy storms, flood events contribute extensively to the water fluxes. For example, during the 1963 floods, the maximum water discharge of the Sebou river reached 8000 m^3s^{-1} (approximately 61 times greater than the mean annual value) and that of the Moulouya, 5200 m^3s^{-1} (nearly 240 times greater than the mean annual discharge).

While the maximum flows of the Moulouya occur in October, November and December (Figure 3), seasonal distribution of the Sebou flows is marked by peaks in winter and spring, thanks to the supplies from its numerous triburitaries and of the melted snows.

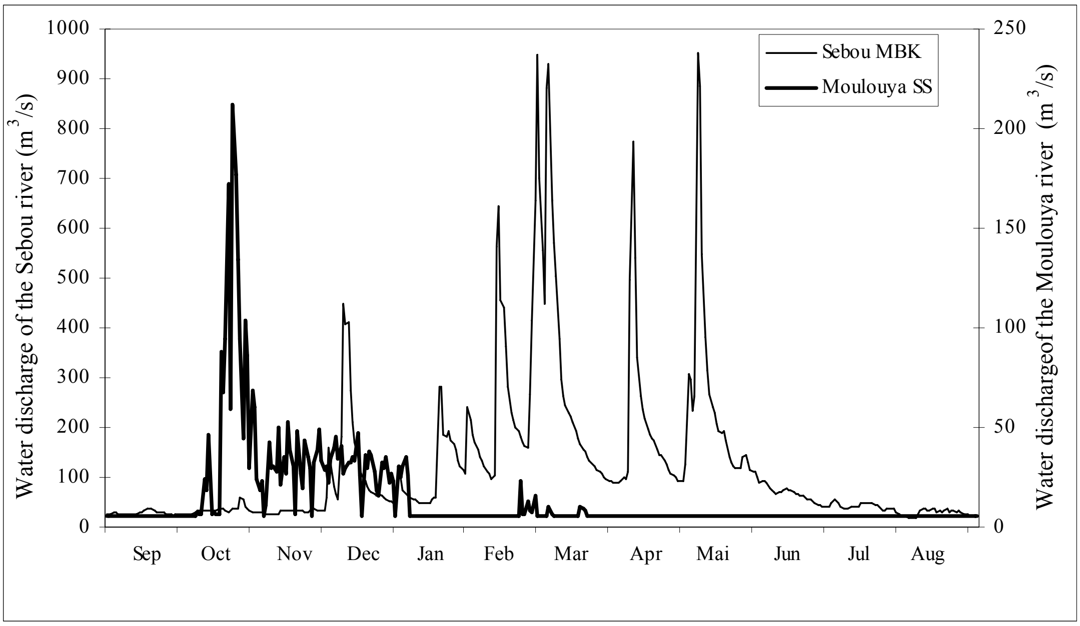
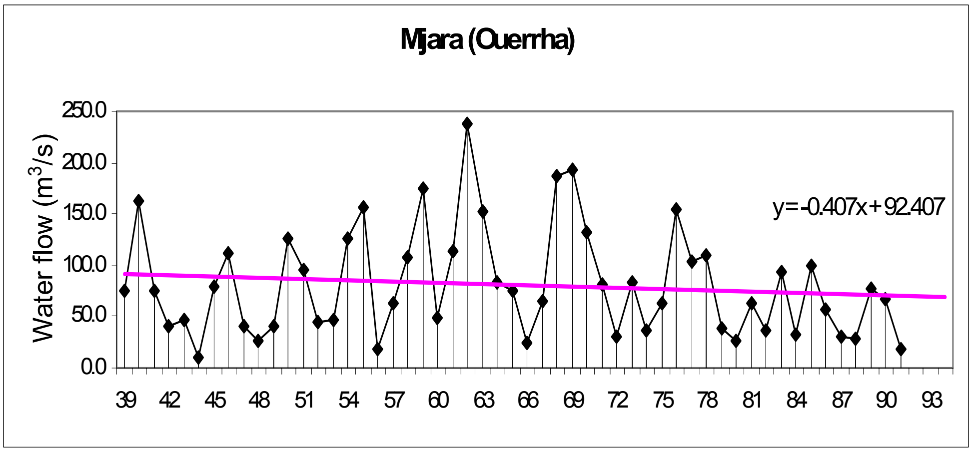


Figure 3. Water discharge variations in the Moulouya (at Saf Saf) and the Sebou (at Mechra Bel Ksiri). (Source: Snoussi *et al.* 2002).

Long-term variation

The long-term variability of water flows has been examined from the available hydrological data (1939 to 1993 for the Sebou, and 1963 to 1995 for the Moulouya). In order to capture only the climatic change effect without the damming impact, the stations chosen are Melg El Ouidane located upstream of the Mohamed V dam in the Moulouya, and Mjara on the Ouerrha, a tributary of the Sebou, before its damming in 1996.



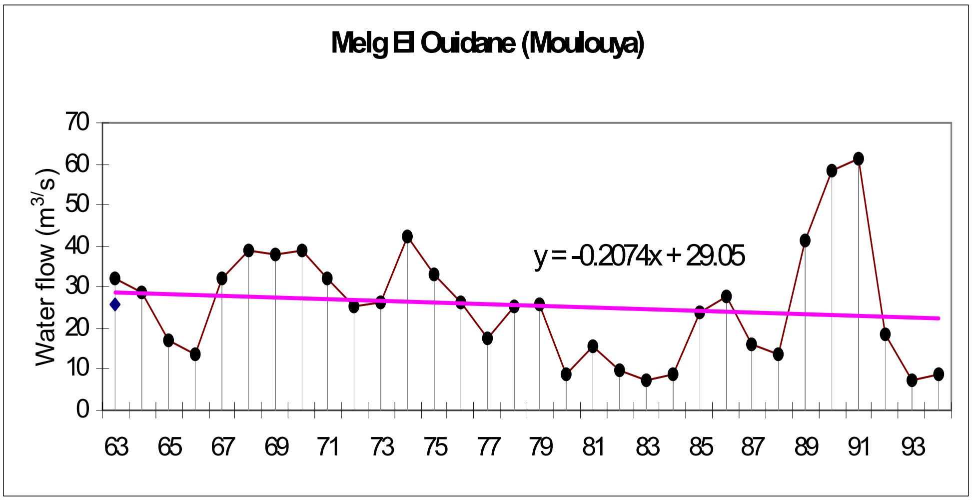


Figure 4. Variation of the mean water flow of the Moulouya at Melg El Ouidane (downstream of the dam) (above) and of the Ouerrha (not yet dammed) at Mjara (below).

Figure 4 shows for both basins a slight downward trend and a decrease between 1975 and 1990. This decrease reflects the dryness that Morocco faced during that period.

Future trends

The projections (for Morocco in 2020) of the impact of climatic change on water resources, conducted by the State Secretary for the Environment (2001) according to the IPCC methodology, foresee a general decrease of about 4% of the annual volume of precipitation. They also forecast a 15% reduction of the surface waters and an increase in the frequency of extreme events (floods and dryness). The demand for water would therefore be higher, and the proposed development would not be able to satisfy this demand. It is therefore necessary to take global warming into account in the planning of all future works.

State changes due to dam construction

Water discharge

Moulouya

The mean recorded flow at the gauging station of Melg El Ouidane, which represents the total flow of the upstream basin controlled by the Mohamed V dam, was 316m^3/s between 1963 and 1995. The supply to the dam is estimated by the General Directorate of Hydraulics to be 915 Mm^3/yr (Zarki 1999), 1650 Mm^3/yr (in Irzi, 2002) and 768 Mm^3/yr (Boumeaza 2002).

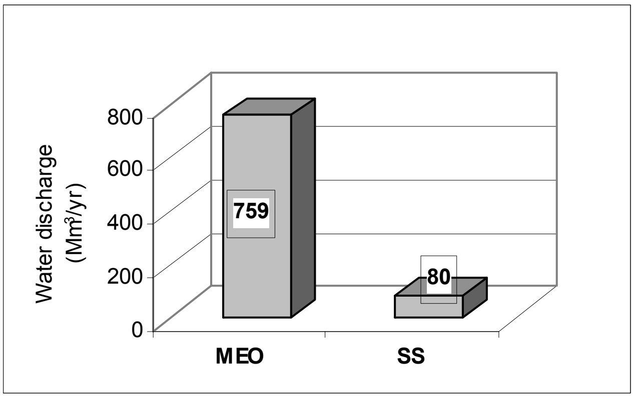


Figure 5. Comparison of the Moulouya water discharge upstream (Melg El Ouidane: MEO) and downstream (Saf saf: SS) of the Mohamed V dam.

But one can say that, before the construction of the dams, the total annual average volume carried by the Moulouya to the Mediterranean was close to one billion cubic meters with a marked variability.

Comparison between the water flows at Melg El Ouidane station upstream of the dam and Saf Saf downstream of the dams (Figure 5) shows a reduction of 89%.

To show that this reduction is due to the construction of the Mohamed V dam and not simply to the drought, Snoussi *et al*. (2002) compared annual rainfall and annual water discharge at Saf Saf before and after the construction of the dam. Figure 6 shows that before the construction of the dam the correlation was very good ($R^2 = 0.94$), meaning that the flow of the river strongly depended on the rainfall. After the construction, the correlation no longer exists because of the control of the water reserves in response to floods and/or extended droughts.

Sebou

The changes of the Sebou discharge have already been analyzed by Mignot (1992) and Haida (2000). Haida (2000) has estimated the water and sediment discharges at Mechra Bel Ksiri gauging station, which is located 75 km from the mouth and covers an area of 26,100 km² (65% of the total area of the Sebou basin). Mignot estimated the water and sediment fluxes

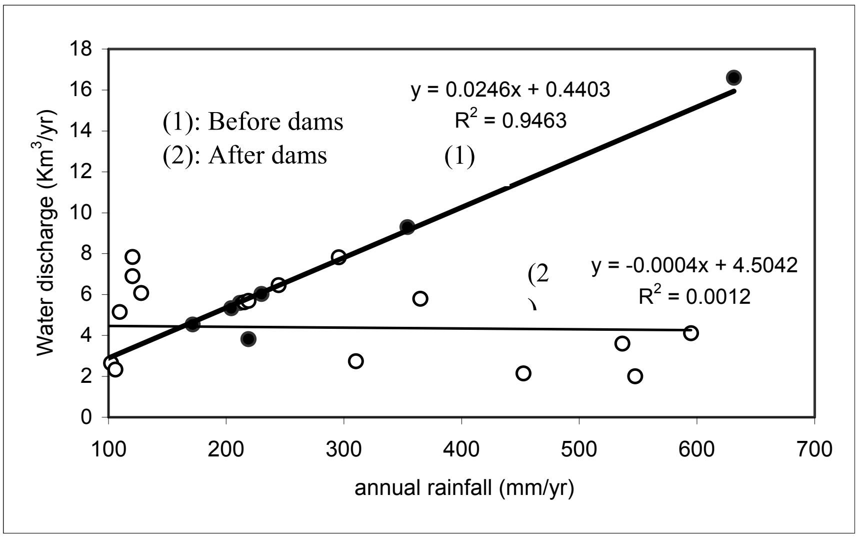


Figure 6. Relationship between rainfall and the water discharge of the Moulouya at Saf Saf before and after the construction of the Mohamed V Dam. (Snoussi *et al*. 2002).

discharging from the whole Sebou basin to the ocean. According to Mignot's estimates, before the construction of the dams (Allal El Fassi, de Garde and Al Wahda), the Sebou brought to the ocean an average of 6.6 billion m^3/yr of water with peak discharges from January to May. The comparison of the water volume that flows in and out of the estuary under the influence of the tides (about 10 billion m^3/yr) and the water volume brought by the river Sebou (6.6 billion m^3/yr), shows that the Sebou estuary before the construction of the dams was clearly river dominant (ratio of 1.5).

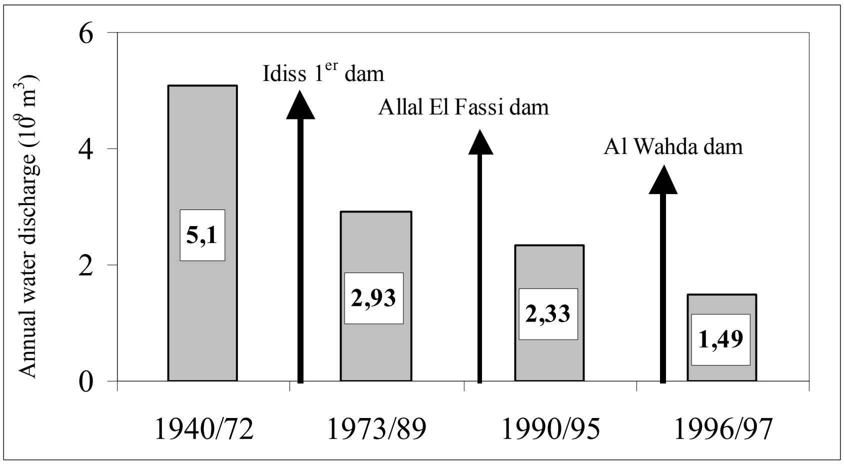


Figure 7. Reductions in the Sebou water discharge at Mechra Bel Ksiri following the construction of the dams (Haida 2000).

Haida (2000) analysed the changes of the Sebou discharges before and after the construction of dams. The flows at Mechra Bel Ksiri (Figure 7) show a reduction of nearly 43% after the construction of Idriss 1st dam, 20% after the construction of Allal El Fassi dam, and 36% following the construction of the Al Wahda dam. As in the Moulouya basin, there is a better relationship between the rainfall and the water flow before the construction of the dams than after (Figure 8). Therefore, while neglecting the impact of the Sidi Echahed dam (commissioned in 1996) because of its very small catchment (680 km²), one can say that the current water flow of the Sebou at Mechra Bel Ksiri have been reduced by 71%. Applying this reduction to the whole basin, the Sebou would currently carry less than 2 billion m^3 yr^{-1} to the coastal zone instead of the estimated 6.6 billion before damming.

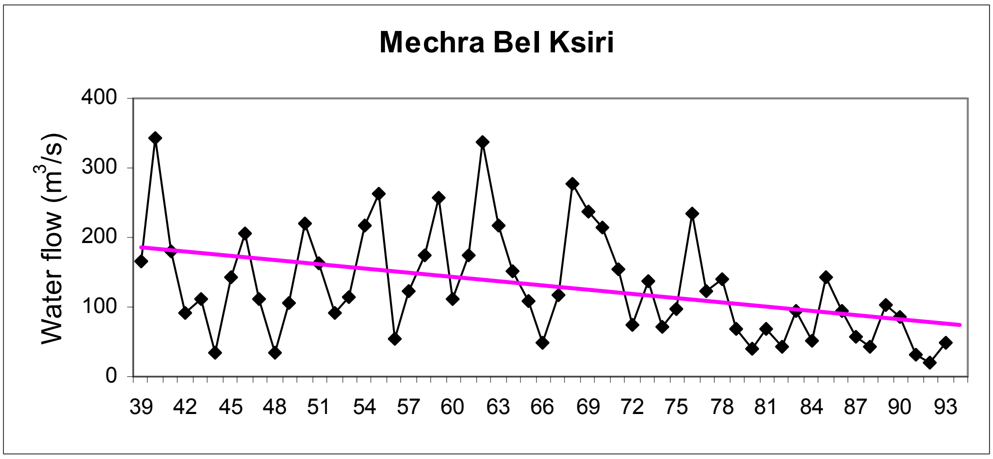


Figure 9. Variation in the water discharge of the Sebou at Mechra Bel Ksiri.

Mignot (1992) had also noted a reduction of the water flow of the Sebou of about 56%, while comparing the annual mean flows at Mechra Bel Ksiri for the period 1939-1973 with the period 1973-1986. He attributes this reduction to a combination of a reduction in rainfall and the growth of irrigation of the Rharb plain during the two last decades. Agoumi et al. (1998) also found that from 1973 the trend of the rainfall and water flows at Mjara showed a net decrease compared with the preceding period. According to these authors, the decrease was due not to the increase of irrigation but probably to the impact of the global warming on the flow system. Therefore, at Mechra Bel Ksiri, the most downstream gauging station, the decline in the Sebou water discharge could be attributed to the dams, drought and also to an increase of stream abstraction for irrigation. It is difficult to prioritize these drivers. However, when comparing the dammed river (Sebou) (Figure 9) and the (not then) dammed one (Ouerrha) (Figure 3) for the same period, one can say that damming and the related agricultural activities are more responsible of the decrease of the water discharge than climate variability.

Suspended sediment discharge

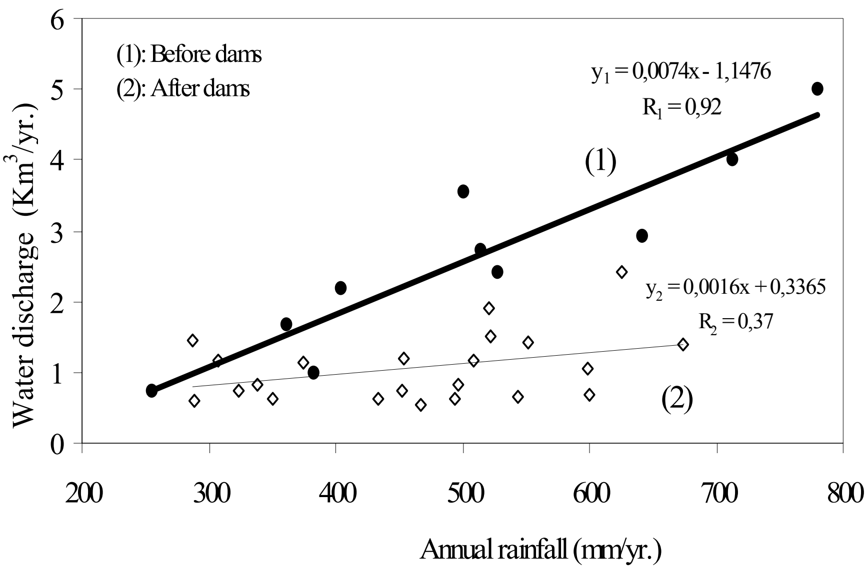


Figure 8. Relationship between annual rainfall and annual water discharge of the Sebou at Azib Es Soltane before and after the construction of the dams (Haïda *et al*. 1999).

Moulouya

The estimated suspended sediments transported at Melg El Ouidane upstream of the Mohamed V dam and at Saf Saf downstream of the dams are presented in Table 3.

Table 3. Estimation of the suspended sediment transport upstream and downstream of the dams (Source: Conseil Supérieur de l'Eau 1990). * originating from dam releases.

Station	Concentration (g/l)	Water volume (Mm^3/yr)	Suspended sediment transport (10^3 t/yr)
Melg El Ouidane	11.3	759	8600
Saf Saf	6	80	500 (+500 to 1000)*

This table shows that, without taking into account the releases from the Mohamed V dam, there is a 94% reduction in the sediment discharge downstream of the dams. This value is very close to the Trapping Efficiency estimated by Snoussi *et al*. (2002) at 93% and means that only 6 to 7 % of the sediment supply of the Moulouya is currently discharged to sea. Taleb (1988) had estimated a rate of 10%.

Sebou

According to Mignot (1992), the mean sediment discharge of the Sebou at Kénitra is 28,000,000 tons per year. Snoussi *et al*. (1990) had estimated the total suspended load brought by the Sebou to the estuary to 26 10^6t/yr (of which 58% was brought by the Ouerrha tributary). The sediment flux can also be crudely estimated from the specific erosion rate of the whole basin. This rate being 600 t/km²/yr, the sediment supply would be 24 10^6 t/yr. All these values are very close to one another, but we will take the mean estimated value of 25 10^6 t/yr.

According to Haida (2000), the successive construction of the Idriss 1st, Allal Al Fassi and Al Wahda dams induced a decrease of 95% in the downstream suspended sediment flux of the Sebou (Figure 10).

Therefore, 93% of sediment would be subtracted from the total downstream flux of the Sebou. If one takes the value of 25 10^6 tons as the load carried before the construction of the dams, the Sebou sediment discharge would have undergone a reduction of 94%.

Environmental and socio-economic impacts of damming and water abstraction

Positive

Development of the irrigated perimeters and urban, industrial and touristic development:

Protection against floods:

The floodwaters are controlled by the Mohamed V and Mechra Homadi dams in the Moulouya basin, and mainly from the Al Wahda dam in the Sebou basin. The latter can reduce the flood volumes at the Gharb plain by more than 95%, avoiding an economic loss estimated at close to 27 million US$/yr (Ministère de l'Agriculture 1995).

Improvement of surface water quality:

An improvement of the quality of waters flowing downstream of the dams is predictable thanks to the discharge operated during the summer to satisfy the water needs and support the environmental flows. According to the Sebou Guiding Plan, a water flow downstream of the Al Wahda dam of 3 m^3/s in summer can be increased to more than 30 m^3/s thanks to the releases (Conseil Supérieur de l'Eau 1992).

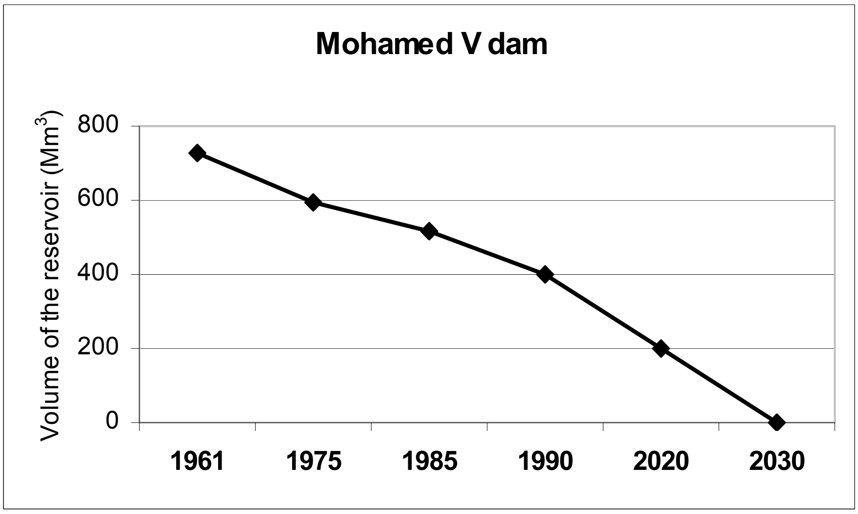


Figure 11. Trend evolution of the volume of Mohamed V reservoir due to siltation.

Development of the fishery resources and touristic activities:

The construction of dams has allowed the creation of water plans likely to favour the development of fish-farming resources, and stimulate the development of tourism. The dams will have to be equipped with fish ladders to facilitate their migration, as is already the case for the Garde de Sebou dam.

Negative Effects

Loss of the useful capacity of the reservoirs by siltation:

The rapid siltation of Moroccan reservoirs, due to the high rate of natural and man-induced soil erosion, was identified by the Ministry of the Public Works (1997) as being critical from the standpoints of volume and lifespan respectively. Indeed, the trapping efficiency calculated for the dams built on the Sebou and the Moulouya (Table 4) ranges from 85 to 99%, and their lifespan 42 to 540 years (Haida 2000; Snoussi *et al*. 2002).

The volume of the Mohamed V reservoir had reduced from 726 Mm^3 to 400 Mm^3 by 1990, a loss of 45% of the initial capacity. According to the Guiding Plan for the Development of the Water Resources in the Moulouya basin (Conseil Supérieur de l'Eau 1990), the useful capacity of the reservoir would be reduced to nothing by 2020, and the reservoir completely filled by 2030 (Figure 11), 64 years after commissioning. Snoussi et al. (2002) estimated its lifespan at 59 years, 5 years less than the projection of the Guiding Plan. The siltation of this dam has led to important losses of agricultural production, employment and energy production. According to a report of the Ministry of the Public Works (1997), it is estimated that, by the year 2030, 70,000 ha of irrigated land and 300 million kWh of electricity will be lost. The corresponding economic losses would be of 95 million US$.

Table 4. Trapping Rate and lifespan calculated for the reservoirs (Snoussi *et al*. 2002).

Rivers	Dams	Year of completion	Surface area of catchment (km²)	Sediment flux (10^6 t/yr)	Rate of trapping (%)	Lifespan (Years)
	Allal Fassi	1990	5400	2.6	85	42
	Al Wahda	1996	6190	16	96	374
Sebou	Idriss 1er	1973	3680	2.6	99	540
	El Kansera	1935	4542	1.9	94	195
Moulouya	Mohamed V	1967	49,920	12	93	59

Salinization and d*eterioration of water quality:*

The development of irrigation has raised the water table and led to salinization of groundwater and pollution by nitrates because of the excessive use of fertilizers. This can constitute a real threat for the biodiversity. According to Benkaddour (1997), the salinity of the Moulouya superficial waters varied in 1996 between 1.12 and 3.74 g/l and three-quarters of the Triffa wells were considered saline and unsuitable for irrigation. To fight against this salinization, drainage works and rationalization of groundwater pumping were undertaken. Besides, several farmers have been obliged to change their type of agriculture, because of the strong salinity of the water.

Modifications/losses of the ecological values of the coastal wetlands of the Moulouya:

The evaluation of the state of the Moulouya wetlands downstream of the dams (Dakki *et al*. 2003) revealed a number of malfunctions and threats directly or indirectly linked to the water abstraction of the Moulouya such as:

- *A decrease in the hydrological function of the wetlands*

The coastal wetland no longer receives river floods, which would assure the recharge of the coastal water table with freshwater used for irrigation. This situation at first facilitated the reclamation of the wetlands for agriculture. However, the waters and soils became increasingly saline due to irrigation, and the cultivated lands are becoming abandoned.

- *Loss in biodiversity*

Among the *invertebrates*, the two species *Venus gallina* and *Cardium edule* recorded a strong decrease. These types probably suffered at the same time strong pollution and changes of habitat (silted-up sediments and shallower depth). With regard to fish, the analysis shows a very strong regression of the stocks of migrant and estuarine fish. The *Great Alose* in particular has disappeared from the site. This is due in part to the construction of the dams but also to excessive fishing at sea, and maybe to the degradation of the spawning fish due to pollution from the discharge of the Zaïo sugar refinery and the release from the Mechra Homadi dam.

- *Loss of the economical values of the wetlands*:

The suspension of activities such as fishing, aquaculture and the gathering of the shellfish in the lower course of the Moulouya, translates to a loss of income (Khattabi 2002). This has led to emigration abroad or to other Moroccan cities, or sometimes the conversion of fishermen to farmers or agricultural workers.

Assessment of coastal state changes in relation to human development in the basin

Moulouya:

The study of the historic evolution of the lower course of the Moulouya and coastline from the diachronic analysis of the aerial photos and satellite images has been realized by several authors (Zourarah 1995; Boumeaza 1998; Zarki 1999; Boumeaza 2002; Imassi and Snoussi 2003). It shows that for more than half a century, the lower course of the Moulouya, its delta and the adjacent beaches east and west of the mouth have undergone important changes (Figure 12):

- Before the dam was constructed (1958), the lower Moulouya river pattern was sinuous to meandering and the river mouth was much wider than it is today (Figure11). The fluvial load was significant enough to lead to the progradation of deltaic deposits in the eastern part of the mouth.

- After construction of the Mohamed V dam, the river mouth and the coastline reacted with remarkable adjustments. Indeed, given the weak fluvial hydraulic power, the marine influences have been reinforced, leading to the reworking of the shoreline sediments, the narrowing of the mouth, and the accumulation of mouth bars. According to Zourarah (1994), the most effective waves and the induced sand transport are directed westwards. The net littoral transport was estimated at approximately 165,000 m^3/yr. The transported sand was responsible for the accretion of the west coast, while the east coast, starved of fluvial input, retreated.

- In 1963: The Moulouya suffered an historic flood that caused disastrous flooding of the plain and caused the channel to erode a rectilinear passage more directly towards the sea.

- In 1980: The lower course suffered only small changes to its banks, probably occurring, according to Boumeaza, at the time of the great floods of 1976 spring. The delta showed minor progradation that could be explained by regressive erosion of lower course, which, though deprived of supply from upstream, re-established its long profile while incising its bed, thus generating enough sediment to prograde the delta.

- In 1988: The delta shows a net decline in comparison with 1958. Boumeaza (2002) estimated an average of 10m/yr. Snoussi *et al*. (2002) thought that this recession was certainly due to the reduction of the sediment supply due to trapping behind the dams, but probably also to the decrease of flows after the drought period between 1980 and 1990. These weaknesses of the fluvial influence induced a strengthening of the marine influence that has been responsible for the readjustment in the coastal profile.

- In 1995: While the lower course records no modification, the delta continues to recede.

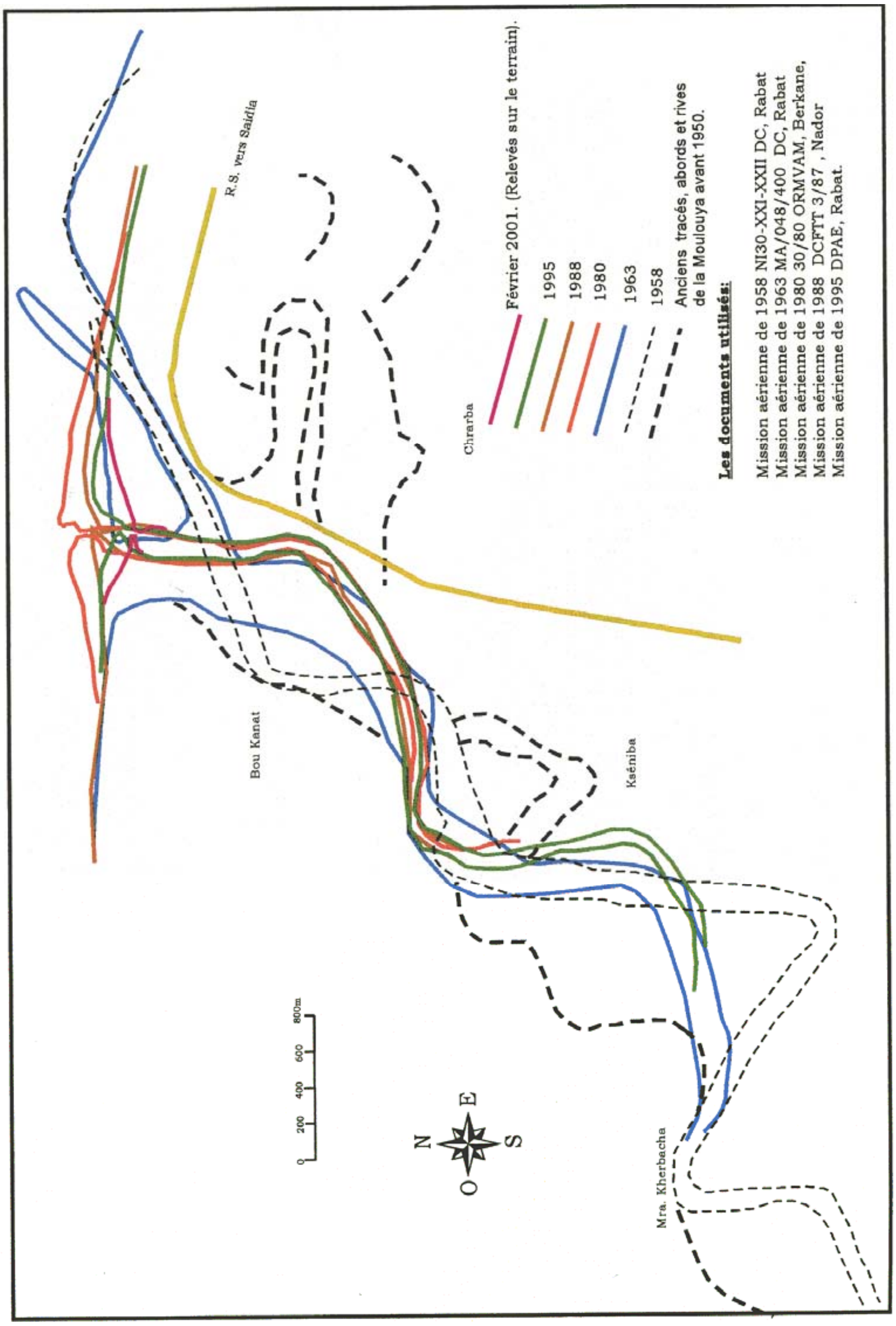


Figure 12. Evolution of the delta and the lower course of the Moulouya (after Boumeaza 2002).

Sebou:

Concerning the evolution of the Sebou coastal plain, it is more difficult to link the evolution of the shoreline to the river damming activities, since the causes of this evolution are manifold and affect the coast at different rates and times. The causes include the following: the Sebou river is heavily regulated (78%), there is a large movement of the population from the country to the coastal towns and there is development of beach tourism. There is sand extraction for construction purposes, and the construction of the ports and related defensive structures have interfered with the river basin activities and deeply altered the natural evolution of the coast.

From the oceanographic and hydraulic point of view (Mignot 1992), the estuary of the Sebou is subjected:

- to tides reaching an amplitude of 3.20m in spring tides, and causing an oscillating volume of 20 Mm^3. This volume passes to 9 Mm^3 in neap tides. Maximum speeds of current of 1.2 to 1.5 m/s can be measured in low water allowing the maintenance of depth in the estuary.
- to riverine water flows that range from 6.6 billion to currently only 2 billion m^3/yr. The estuary of the Sebou has become wave dominated. The sediment fluxes that were very important before the construction of the main dams (25 Mt/yr) are now reduced to less than 2 Mt/yr. The major part of the suspended matter is transported towards the open sea, leaving a small fraction that deposits itself in front of Kénitra. The coarse sand fraction that represents about 10% is found within and in front of the mouth in the form of a cone associated to the marine sediments.
- to wave action, particularly strong on this part of the coastal zone, since for nearly one month, the wave heights surpass 3m and can reach 7m. These strong waves induce an important redistribution of sediments with sands re-entering the mouth, forming an extensive bank on the right shore prejudicial to the navigation.

The most important activities that are responsible of the current state of the coastal zone are as follow:

- *Construction of ports and dykes:*

The estuary of the Sebou includes the port of Kénitra 17 km from the mouth and a commercial harbour 3 km from the mouth. The two harbours are linked by a navigable channel having a natural depth of 2.50 m below chart datum, being about 4 m at mean level.

The mouth of the Sebou is protected by two jetties, north and south, constructed between 1921 and 1932, in order to facilitate navigation. However, despite these structures, the mouth often silts up, necessitating frequent dredging. During the last ten years, dredging of 640,000 $m^3 yr^{-1}$ was necessary to maintain access to the Kénitra-Mehdya harbours. In fact 80 % of the dredging carried out of the mouth concerned sandy sediments. Only dredging from Kénitra harbour (100,000 m^3) concerned muddy sediments. The construction of the jetties has led to an important erosion of the beaches to the south of mouth and accretion of the beaches to the north (Allouza 2002).

With constant reshaping due to floods, storm waves and dredging, it is very speculative to link the decrease of the sediment supply from the Sebou to the morphological evolution of the estuary. But one can say that, despite the sharp reduction of fluvial sediment input, the estuary is silting up and necessitates frequent dredging. This could be explained by weak fluvial competence and a relative strengthening of marine influence, with marine sediment entering the estuary. Moreover, as some of the dams were constructed for flood control, the estuary is not flushed as frequently as before. The estuary has become a site of enhanced siltation, increasing the residence time within the estuary of pollutants coming from Kénitra and agricultural lands within the basin. These pollutants could be discharged to sea only during major floods.

- *Seaside urbanization:*

The Sebou littoral zone has recorded important urbanization since the 1980s (Madouni 1997). This has overlapped into the coastal domain, leading to an imbalance of the sediment budget between the bordering dunes and the sea shore, degradation of the vegetation cover and in turn a migration of wind blown sand.

- *Exploitation of sand:*

Zaoui (2002) considered that the main cause of the degradation of the Sebou coastal zone is the exploitation of the sand from the beaches and dunes. Currently there are 34 pits in the zone of which each furnishes 300 m^3 of sand per day. Altogether, 5600 m^3 are exploited daily: 4000 m^3 from private quarries and 1600 m^3 from common quarries. This extraction, added to the retention of sediment by the dams and to the exhausting of the current stock of sand, will aggravate the retreat of beaches.

Conclusion

The construction of dams obviously has many socio-economic benefits in the Sebou and the Moulouya basins since rainfall is scarce and concentrated in only a few days and agriculture constitutes a large percentage of the Moroccan economy. However, damming activities have generated important negative impacts, notably a sharp reduction of the water and sediment fluxes of rivers to the coastal seas. It is estimated that the water discharges of the Sebou and Moulouya rivers have been reduced by 89% and 71% respectively, and their sediment fluxes by nearly 95% and 94%. These major state changes within the two basins have occurred largely within the last 40 years.

The abstracted sediments are trapped within the reservoirs, causing their rapid siltation, compromising their storage capacity and shortening their lifespan (an estimated 59 years for the Mohamed V reservoir). By reducing the river discharges, the dams have also affected the morphological equilibrium of the shoreline. It seems that, for the two rivers, coastal erosion and sedimentation are due not only to the reduction of sediment discharge, but also to the reduction of water discharge, the latter strengthening marine influence in the estuarine zones.

The investigation of climate variability as a driver showed that, during the last few decades, recurrent droughts have reduced water flows above the reservoirs and exacerbated the dam-related reductions below the reservoirs. Future projections indicate a reduction of 15% in surface waters by 2020 due to global warming, and an increased demand over the same period of water for domestic, industrial and agricultural purposes due to population growth. Because of the critical scarcity of water in the basins and the expected future human related pressures – the rising costs of investment, growing competition between the water users, and aggravation of environmental problems – the existing damming strategy could become unsustainable. The major challenge is to reconcile meeting freshwater needs at the basin scale with the minimization of negative impacts on the environmental and socio-economic functions of the downstream and coastal zones.

Human related pressures/drivers associated with activities downstream from the dams and in the coastal zone itself, such as agricultural practice, industrial and port development, sand extraction and tourism, have also generated negative environmental impacts. These include pollution and the salinisation of groundwater, disruption of coastal habitats, the siltation of the Sebou estuary, the retreat of the Moulouya delta, erosion of sandy beaches and the degradation of ecosystems, particularly in the coastal wetlands.

The future research effort should be focused on establishing and demonstrating the clear linkages between human activities in the catchments and the changes and their impacts downstream to the coastal seas; determining the relative magnitude of changes that are attributable to human activities such as water and land use, and to environmental factors such as climate variability and change.

Acknowledgments

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HYDROLOGICAL AND MORPHO-SEDIMENTOLOGICAL MODIFICATIONS IN THE ESTUARY AND COASTAL ZONE OF THE RIVER SENEGAL

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Introduction

Since the construction of large dams on the Senegal River, the estuarine and coastal zones have undergone numerous changes in key aspects of their hydrology, morphology and sedimentology.

The general features of the coastal oceanography on the continental shelf adjoining the estuary of the Senegal river are described in the works of Guilcher (1954), Rochette (1964), Rebert (1983), Sall (1983), Bbl-Sw (1985), Gac *et al.* (1990), Cecchi (1993), Kane (1985, 1997), among others. These authors were able to show that the oceanographic factors have a big influence on the hydrodynamic system of the estuary of the Senegal River.

Diop (1990), for his part, believed that it was the elements of the oceanography (essential in the placing of certain deposits) that largely controlled the sedimentological and morphological evolution of the estuarine environment, as is the case in the delta of the Senegal and elsewhere.

The zone of study

The Senegal River is one of the large hydrographic features of the Atlantic face of Western Africa. It extends between 10º 30' and 17º 30' of northern latitude and between 7º 30' and 16º 30' of western longitude. The Senegal River discharges into the Atlantic Ocean after a traverse of 1700 km including a varied range of rich and picturesque countryside from southern Soudan to the Sahel (Figure 1). Its catchment is divided between four countries: Guinea, Mali, Mauritania, and Senegal. The catchment of Senegal is subdivided into three big hydrogeographic zones differing widely in their topography, geology, hydrography and climate:

- the upper basin upstream of Kayes;
- the lower basin or alluvial valley that extends 630 km from Kayes to Dagana, scattered with fluviodeltaic levees;
- the delta, situated downstream from Richard Toll and extending to the estuary, from which the river discharges to the sea by a unique mouth.

Before the construction of the Diama barrage in 1986, saline intrusion was perceptible, during periods of low water, as far as Podor, about 300 km from the mouth. During extreme years, the tidal influence could reach Diouldé Diabé, 150 km upstream from Podor. The estuarine zone was then much larger than these days; the river then supplying extensive flood zones occupied by mangrove swamps.

This position has changed considerably since the construction of the barrage, which has become the artificial upstream limit of the estuary. The downstream limit is formed by the mouth, unique outlet through which marine waters flow back up the river (Figure 1). The estuary of the Senegal River therefore is restricted to the zone between the Diama barrage and

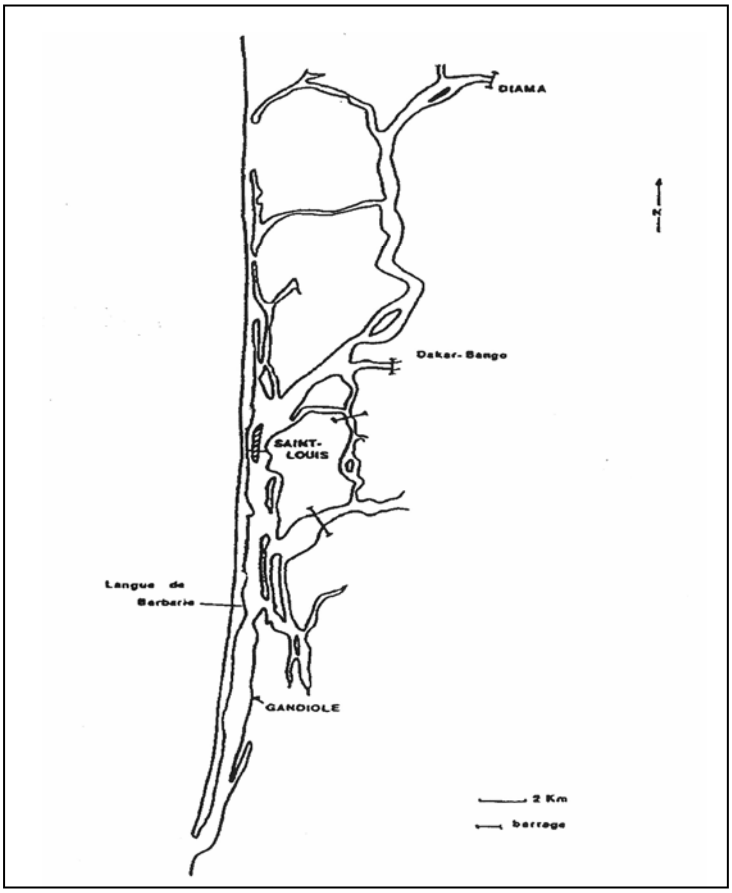


Figure 1. The estuary of the Senegal river.

the mouth, and constrained laterally between the sandy spit of the Langue de Barbarie to the West and the zone of dunes to the East.

Ocean circulation and coastal dynamics in the vicinity of the estuary

The circulation of the masses of ocean water alongside the Senegalese coast is subject to the influence of the system of winds and barometric distribution. Locally, the topography of the continental shelf and the orientation of the coast induce modifications to the course of superficial marine currents, which depend in fact on the climatic seasons (Diop 1990). The Senegalese coast is bathed by important "upwellings" of water from the deep ocean that originate in the region of central South Atlantic Ocean.

Two large surface currents are observed:

- The North Equatorial current that transports westwards the cold waters of the Canaries current,
- The Counter-Equatorial current that transports eastwards the warm, saline waters formed on the southern edge North Atlantic gyre.
- At the beginning of the wet season, masses of southern waters push back the front of the upwelled cold waters, the surface current flowing from south to north to a velocity between 5 and 15 $cm.s^{-1}$ with peaks of 30 $cm.s^{-1}$

The waves

All the observations carried out on the continental shelf by various authors such as Guilcher (1954), Rochette (1964), Rebert (1983), Sall (1983), and Gac *et al*. (1990), confirm that there exist large wave types in this domain:

- The northwest swell, of boreal origin, with an induced littoral drift from north to south.
- The southwest swell, of southern origin, linked to a littoral drift from south to north.

The NW swell predominates throughout the dry season from October to June and has its origin in the distant storms of the North Atlantic NW quadrant (N 320° to N 360°). This swell reaches the coast in the form of trains of long wave-length (an average of 190 to 300 meters), its amplitude is generally stronger (the average values are understood to be between 1 m and 1.60 m) and it propagates itself at a speed of the order of 22 $m.s^{-1}$. The average direction of propagation for this swell of northern origin is from the northwest. Approaching the Barbarie coast, the swell is subjected to refraction on the bottom at the level of the continental shelf; it loses much of its energy and breaks more or less obliquely to the coast. The NW swell causes a mobilization then important transport of sand in the direction north-south (longshore drift).

The SW swell occurs from June to October and has its origin in the strong westerly winds of the South Atlantic: they are linked in their direction and their frequency to the flow of the monsoon coming from the St Helena anticyclone. Their amplitude is lower (average values understood to be between 0.80 m and 1.20 m) and their period shorter (between 5 and 10 seconds). Their action is also less marked: they lose much of their energy as a consequence of diffraction suffered at the peninsula of Cape Verde, forming a screen whose shelter includes all the Langue de Barbarie. The period of the southern swell corresponds to the impoverishment "*thinning down*" of the beach following the reduction in the transport of sandy material.

The alongshore drift

On the coast, both of the swells, especially the northwesterly one, generate alongshore drift. This is a coastal current, parallel to the shore, and is the resultant of the obliqueness of the swell in comparison with the shoreline. It has a direction N-S along the Langue de Barbarie; its velocity varies between 0.13 and 0.57 $m.s^{-1}$ Barusseau *et al*. (1993) indicate measured values of 0.30 $m.s^{-1}$.

The alongshore drift transports and deposits the sand on the beaches, periods of acceleration and of slowdown being closely related to the nourishment and denourishment phases of the beach (GAC *et al*. 1982). The estimates of sediment transport carried out by this alongshore drift along the Langue de Barbarie, calculated according to various methods, are variable following the authors: Minot (1934) values it at 550,000 $m^3.yr^{-1}$ by the method of the cubatures; according to Surveyer-Nenninger-Chenevert (1972) "the preliminary calculations based on the houlometric relief indicate that the littoral transport towards the south on the Barbarie coast is on average 900,000 $m^3.yr^{-1}$", Pinson-Mouillot (1980) advanced a figure of 1,500,000 $m^3.yr^{-1}$, while Barusseau (1981) gave understood values between 223,000 and 495,000 $m^3.yr^{-1}$ and finally Sall (1983) estimated it at 365,000 $m^3.yr^{-1}$. This transportation has the effect of constraining the mouth of the Senegal River and to cause it to migrate towards the south.

The tides

The impacts of the tide on the extent of the Senegal River estuary have been largely described by Guilcher (1954), Rebert (1983) and Cecchi (1993). The oceanographic manuals of the harbour master of Saint Louis stipulate that the tide wave that affects the north coast comes from south with a delay of three-quarters of an hour compared with Dakar (40 minutes in American and British directories, 48 minutes in the French annual, according to Bbl-Sw 1985). The peninsula of Cape Verde, oriented east-west, causes disruption to the advance of the tide wave coming from south.

The twice daily movement of water does not occur at uniform intervals, but with important gaps: "the tide rises much more slowly than it descends". In fact, the time that separates a low tide from the following high tide is 7 hours, while the descent from this high tide to the low tide that follows lasts for 5 hours 45 minutes (Louise 1919).

In the absence of a tide gauge on the ocean side, the amplitude of the tide at sea is not known with precision. The works of Surveyer-Nenninger-Chenevert (1972) give the following fluctuations:

- maximum = 1.8 m;
- mean of spring tides = 1.20 m;
- mean of neap tides = 0.6 m.

During spring tides, the sea level at the mouth can range between –0.75 m and +0.75 m IGN (amplitude of 1.50 m). The mean amplitude, after correlation with Dakar, would be 1.15 m during spring tides and 0.55 m during neap tides.

Bbl-sw (1985) gives the following values for its measurements in the open sea recorded between October 1982 and August 1983:

- annual minimum = 0.3 m;
- annual mean = 0.9 m;
- annual maximum = 1.65 m.

In the estuarine part of a river, the tide wave that is produced in front of the mouth produces a diverted wave that enters the river upstream: this is the river tide coming from the ocean tide. This river tide is a hydraulic phenomenon more complex than the ocean tide for the flows of freshwater, the slope and the form of the intervening water course.

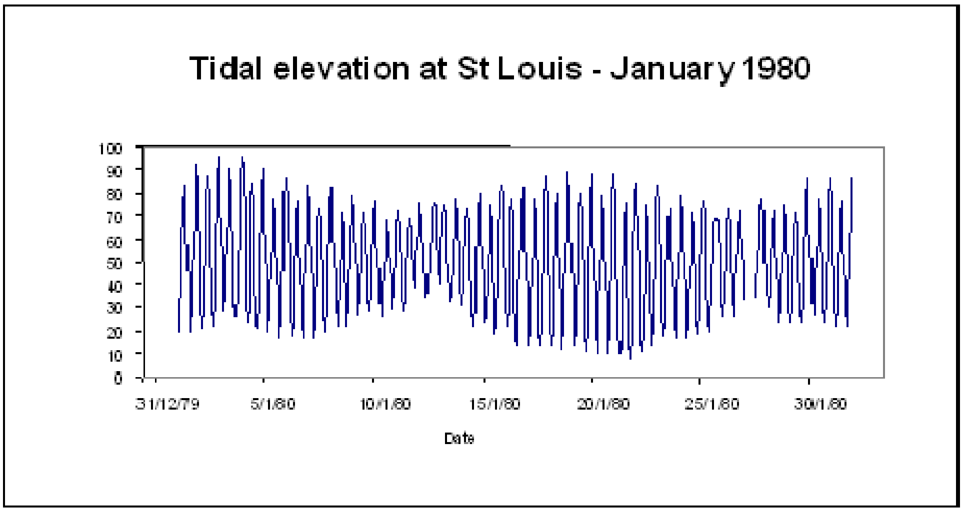
At the time of upstream propagation, the characteristics of the tidal signal change noticeably, with notably a significant increase of its propagation speed and a net reduction of its amplitude.

The rate of propagation of the tide wave (that is not the speed of the tidal currents) is at a maximum at high tide and minimal at low tide; within the estuary of the Senegal River it is between 7 and 10 m/s, according to Bbl-sw (1985). The variation of the rate of propagation is explained by the fact that the tide wave, while distorting itself at the time of its advance upstream induces a perceptible increase in the length of the ebb in comparison with that of the flood. Rochette (1964), quoted by Kane (1997), asserted that rate of propagation increases abruptly upstream of Saint-Louis, an effect probably linked to the reduced section of the river; the rate of propagation of the high tide is always quicker than that observed of the low tide, the time difference being again more important when the flows of the river are not negligible.

Table 1: Propagation times for the tides (before the barrage), Rochette (1974) cited by Cecchi (1993)

Station	PK	Time of propagation		Rate of partial propagation ($m.s^{-1}$)	
		High tide	Low tide	High tide	Low tide
Gandiole	2.5	20 minutes	25 minutes	2.1	1.7
Saint-Louis	18	1h 35	1h 45	3.4	3.2
Diama	51	3h 05	3h 20	6.1	5.8

Before construction of the barrage, the dominance of the ebb over the flow increased with the decrease in tidal amplitude. This asymmetry of the marine tidal cycle is sometimes marked by a net half-monthly periodicity, with a marked gap during the spring tides. The reduction in the river section (670 m² downstream of Saint Louis, 360 m² upstream) is in addition responsible for the net increase in the propagation speed of tide wave (Cecchi 1993).



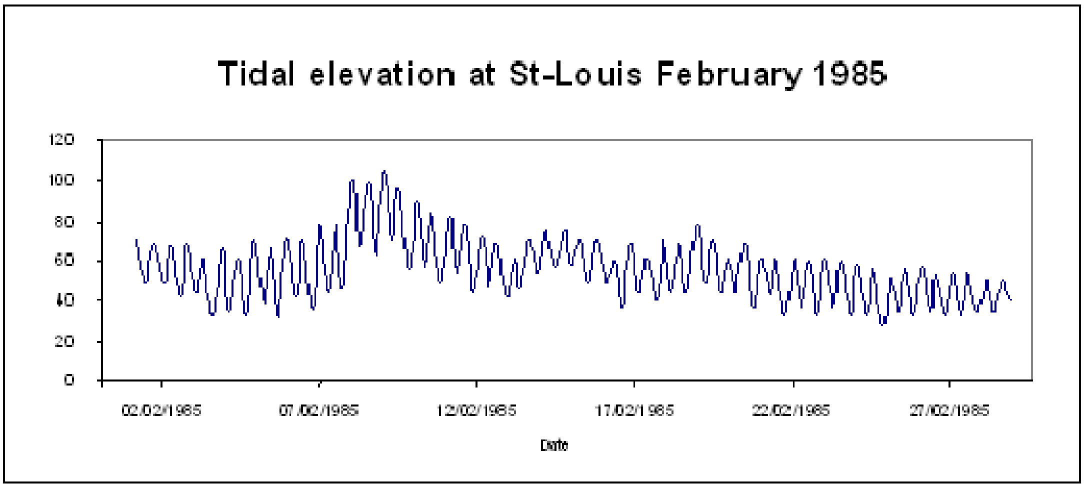


Figure 2. Propagation of the tide at Saint Louis over two periods (1980 and 1985)

At the mouth, the mean amplitude is 1.15 m for spring tides and of 0.55 m for neap tides, and, according to Rochette (1964, 1974), during low water, the reduction of amplitude is at a maximum between the ocean and Gandiole (about 33% for the mean spring tides and 20% for the mean neap tides, the change explained by the major loss of energy produced at the level of the bar). This reduction in amplitude is weaker between Gandiole and Saint Louis, and reduces again upstream of Saint Louis.

The tidal conditions can vary from one year to next (Figure 2). The cause is certainly linked to modifications at the level of the mouth. Barusseau *et al.* (1998) noted that the coast of the Senegal is subject to marine erosion that creates a dynamic environment, with transport and deposition of sand on the coast. That gives rise, at the level of the mouth, to a constriction that is released by the floods.

The position and the state of the mouth have an important influence on the variations in river level. The tidal range is much reduced through the mouth, according to Bbl-sw (1985) the reduction of the tidal range in the estuary is due to an interaction between the littoral transport and the tidal currents, and the natural formation of a wide, shallow mouth.

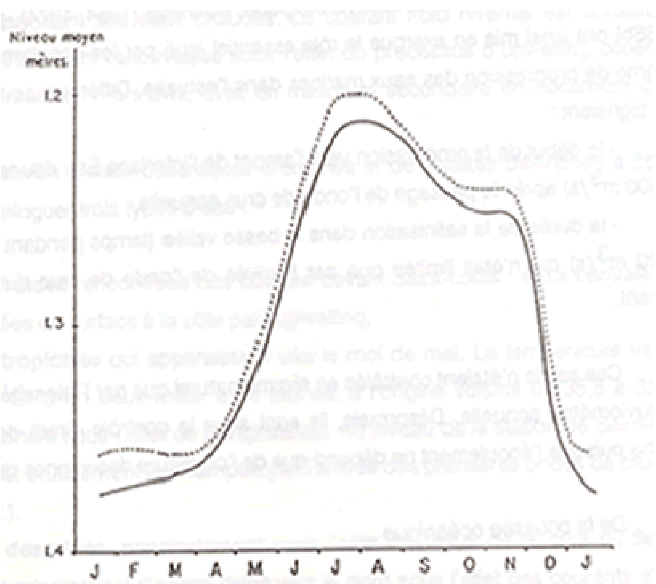


Figure 3. Mean level of the ocean at Dakar 1958-1965 (Rebert 1983 in Cecchi 1993)

The water quality in the estuary

Salinity

The intrusion of the salt wedge (saline tongue) in the estuary of the Senegal River has been the object of numerous important studies justified essentially by the entire agricultural infrastructure commissioned or in the planning stage in all the low valley of the Senegal. Rochette (1964, 1974); Gac *et al.* (1986, 1993), Kane (1985, 1997), and Cecchi (1993) have widely described the principal aspects of the salinity in the lower Senegal. Moreover it is from these various authors that we borrow the results that we present here.

The salinity of the waters in the lower estuary is generally dependent on the supply of sea water, the quality of which changes according to the masses of ocean water pressing against the mouth. Cecchi (1993) believed that the rise in salinity in the estuarine reaches is directly dependent on the advection of ocean waters. Seasonal oscillations of the mean level of the ocean were superimposed on the periodic variations of the tide (Figure 3).

The variations of mean sea level are perceptible on the whole length of the maritime reaches. The effects of fluctuations of the sea level on the evolution of the saline intrusion are therefore of great importance. The mean level at the mouth produces, following the sense of its change, an advance or a retreat of the salinity that has repercussions on the whole length of the maritime reaches. Thus Rochette (1964) studied the influence of this flow that propagates and superimposes itself on the river flow. He noted that a variation of 1 cm per day determines at the mouth a flow of 22.3 $m^3.s^{-1}$. The estimates, carried out as well by Orstom as by Sogreah, show that the influence of the tide plays a role determining salinisation especially in the first 20 or 30 km of the estuary (Kane 1997).

Figures 4 and 5 show the variations in surface salinity at Saint Louis before and after construction of the Diama barrage. Downstream of the barrage, the discharge of water, outside of the flood periods, strongly disrupts the annual cycle of salinisation - dissolution.

Figures 4 and 5 demonstrate the importance of seasonal variability of the salinity of the estuary of the Senegal River. The study of seasonal change (Corbin and Cecchi 1991) shows thus important variations during the sequence of the annual cycle that allow the identification of several sequences. After the episode of the flooding during which the whole of the river up to the mouth becomes occupied by continental waters (dilution), the tide wave begins propagating itself in the estuary until the superficial salinity at Saint Louis attains a value near to that of the ocean. The saline intrusion resumes thus as early as at the beginning of December and continues until about the months of May.

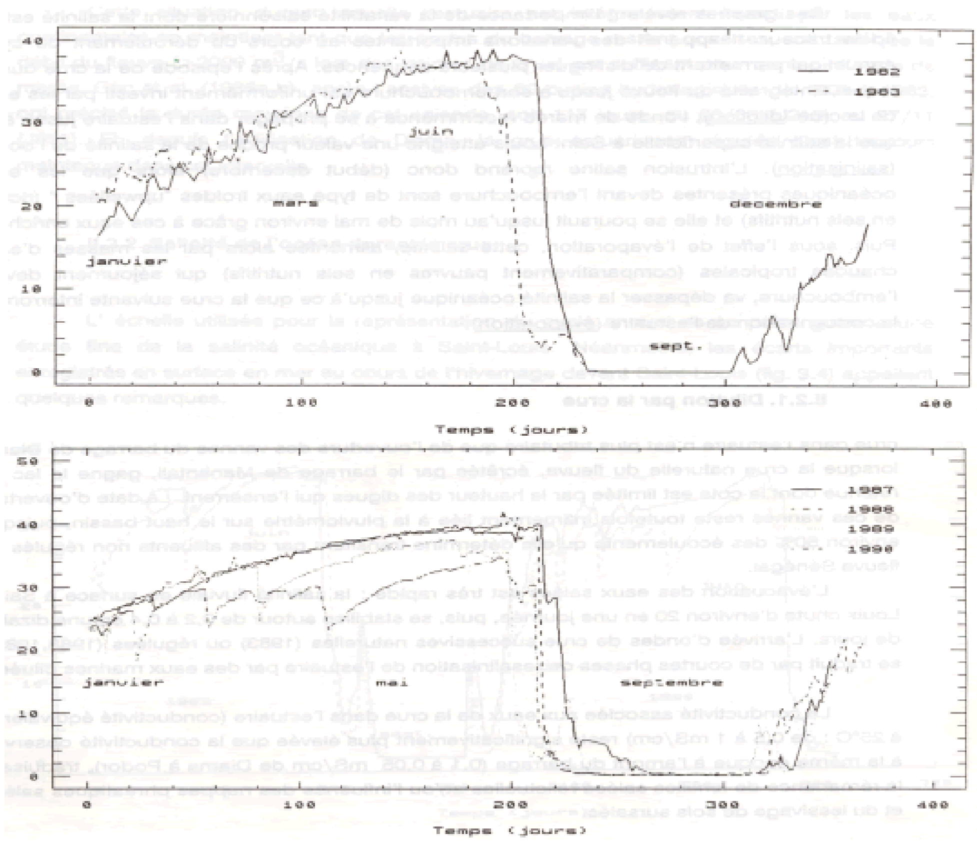


Figure 4. Surface salinity in the estuary at Saint Louis before and after the Diama barrage (Cecchi 1993 after Kane 1985)

Nevertheless, the release of freshwater carried out for technical reasons at the barrier in the dry season induces a dilution of sea water. The longitudinal variations of salinity almost always show a decrease upstream during the low tide period.

The dilution by the floods is also an important fact that deserves to be underlined. According to Rochette (1964), as soon as the volume of the flood wave surpassed 900 Mm^3, the retreat of

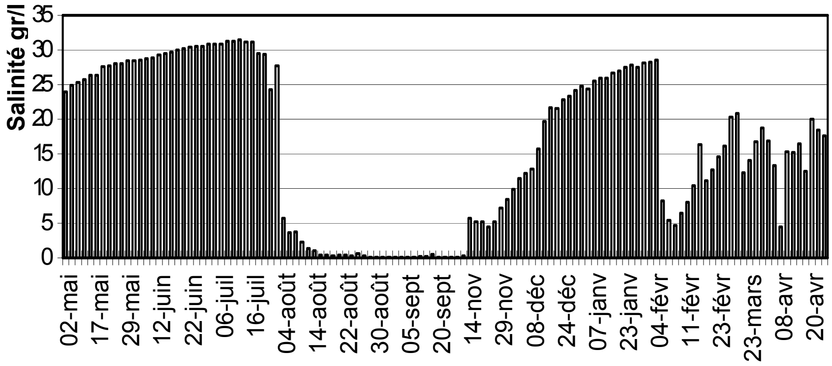


Figure 5. Surface salinity at Saint-Louis in 1990-1991

the saline water to the mouth was total. Henceforth, the flood wave in the estuary is strictly dependent on the sluice operations at the Diama barrage. Therefore, the estuary is completely under the dominance of the continental freshwaters. Such a situation is maintained so long as the barrage sluices remain open, as long as the flow of the river is sufficient to contain the tide wave.

One witnesses more and more a modification of the salinity conditions of the estuary of the Senegal River. Since the start of the energy program of the OMVS, the dam at Manantali that has a hydroelectric role tends to operate continually for the production of electricity, inducing surplus water to be released in the valley. The management of the Diama barrage, which is in a certain liable measure affected by the conditions that prevail upstream, has in consequence to be appropriate to the new conditions which affect Manantali. Periodic releases are therefore operated from Diama in accord with the needs of management, this inducing a strong dilution of the estuarine water during a good part of the year.

The temperature of estuary waters

The measurements carried out at Saint Louis by Cecchi (1993) and Kane (1997) show that the water temperature of the Senegal River in the estuary is subject to very significant seasonal variation (Figure 6). The estuary is always warmer than the ocean, notably during the beginning of the salinisation phase (January-April).

The temperature of the salt water varies from a minimum of 16 °C to a maximum of about 28-30 °C. Freshwater that flows into the estuary from August to October is generally 4 to 5 °C

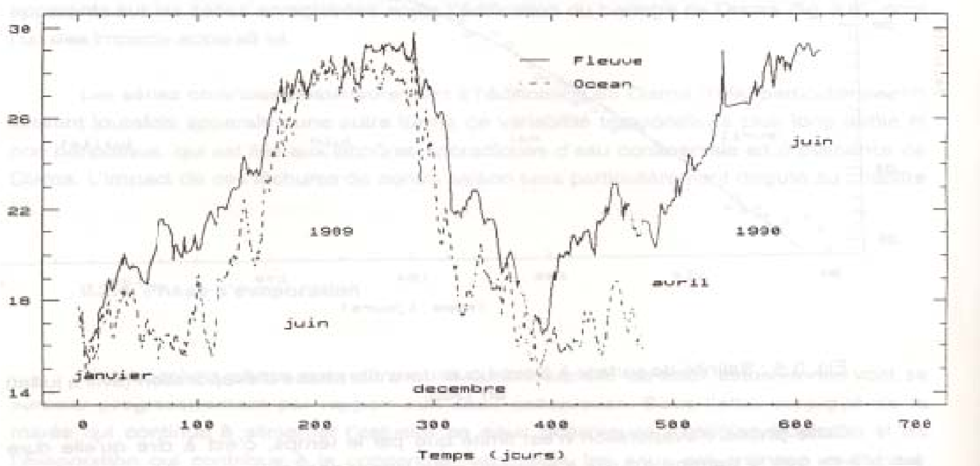


Figure 6. Seasonal temperature variations in the river and the ocean in 1989 and 1990

warmer than the salt water.

The annual thermal range, of the order of 15 °C in the estuary, records its minimum in December-January, and its maximum at the heart of the high-water season; it is in the same order of magnitude as that of the sea, according to Bbl-sw (1985).

The estuarine waters evolve during the dry season depending on the succession of the ocean water masses circulating alongside the Saint Louis coast. Cecchi (1992) distinguished several phases in the evolution of the temperatures:

- From the month of October, cold South Atlantic waters show their effects at the surface by the well known phenomenon of upwelling; also the temperature of water in the estuary subsides, and attains its seasonal minimum in January. At this time of year, solar radiance is minimal (about 210 W m^{-2}), and insolation is reduced to about 8 hours.

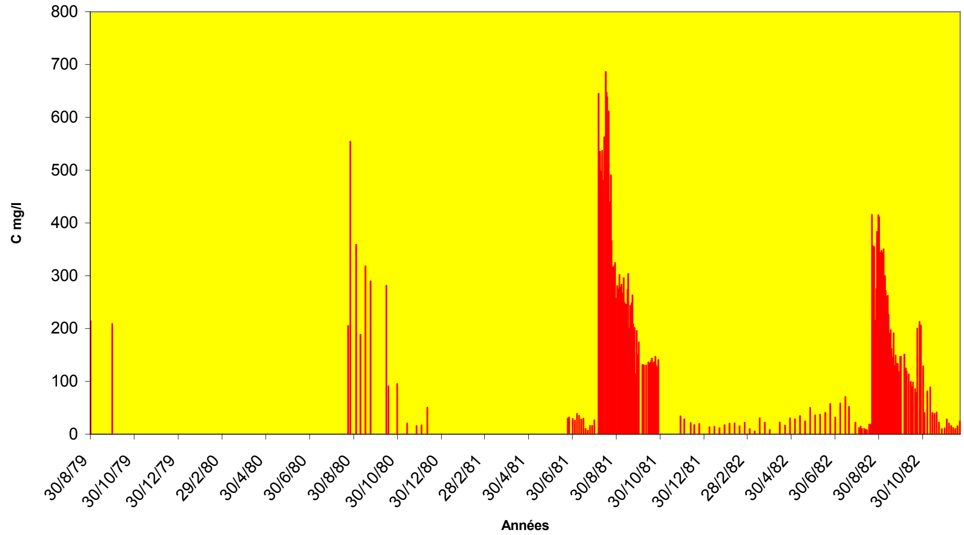


Figure 7. Changes in the concentration of SPM at the station of Saint Louis (1979-1982)

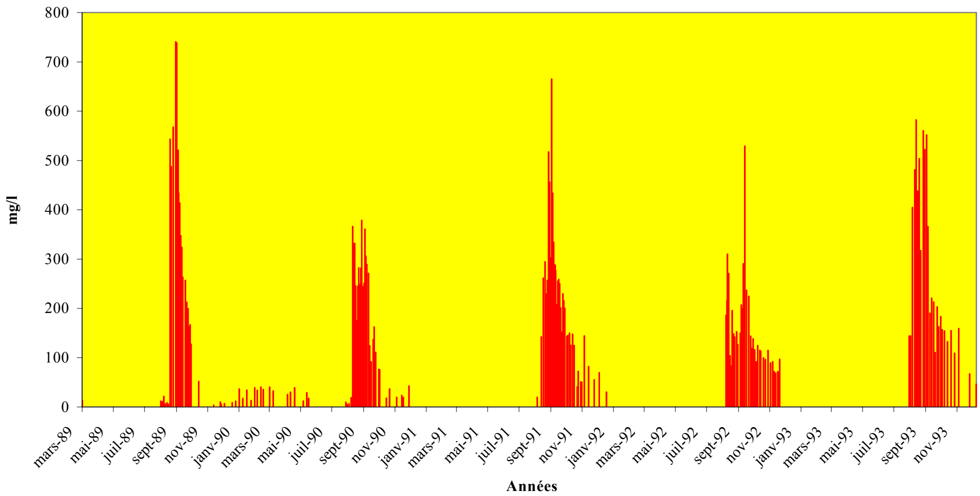


Figure 8. Changes in the concentration of SPM at the station of Diama-Amont (1989-1993)

- In the months March and April, estuarine waters become progressively warmer, solar irradiance is at a maximum (about 290 W m^{-2}) and the insolation time attains 10 hours per day. Nevertheless, ocean waters in the open sea at Saint Louis still remain cold.

- From May onwards, cold ocean waters withdraw from the shore of the northern coast giving way to warm tropical waters, and during the whole rainy season, they are almost the same temperature as the fresh floodwaters.

Transport of suspended material in the estuary

The riverine supply of suspended matter (SPM) in the estuarine zone and at the mouth of the Senegal river have been principally studied by Gac and Kane (1986), Kane (1985, 1997) and the project Equesen (1993) (Figures 7 & 8). Other researches on SPM have been conducted in the upper part of the basin.

Episodic measurements were carried out before 1980 at certain stations of the river. Riou (1936) signals measurements done at Bakel and Saint Louis in 1908 and 1934-1935. From these measurements he concludes that, with a given flow of 39 billion m^3, the Senegal transports 4 Mt of suspended matter of which 30% would be deposited in the floodplain and 70% would be discharged to the sea.

The measurements carried out by Seguy (1935) and Mandin (1957) at Dagana, Bakel and Fadougou reveal that the average load of SPM at the beginning of the flood is estimated at 250 mg l^{-1} at Dagana and 170 mg l^{-1} at Bakel. While resuming the measurements of the SPM, Michel (1970) considered that the annual detrital supply varies between 2,800000 tons and 1,000000 tons. Senegal-Consult (1970) valued at 1.4 and 2.9 Mt the annual SPM flows at Manantali and Bakel. The mission Surveyer-Nenniger-Chenevert (1972) for its part estimated at 1 Mt the quantity of suspended matter carried by the Senegal River towards its mouth.

It is necessary to underline that the true measurements of suspended matter on the estuarine part was not truly begun until the start of the 1980s notably with a vast ORSTOM program that allowed Kane *et al*. (1985) to follow the changes of the MES in the estuary during the years 1981-1982 and 1982-1983. The results obtained at the time of these two years of measurements allowed estimation of the supply respectively to 2,850000 tons and 1,185000 tons.

The data treated and presented here come from the measurements of the EQUESEN project (1993) and Kane (1997). These measurement campaigns were carried out at the start of the 1980s at the station of Saint Louis and towards the 1990s at the Diama-Amont station. Unfortunately, the concentrations of suspended matter were no more made the object of a systematic follow-up in the estuarine part, and this explains why we do not present any more recent data.

The observation of seasonal variations in the turbidity shows a central maximum in the period of high water and a minimum that coincides with the period of low water. One notes a rapid increase of the MES with the arrival of annual floodwaters that transport the sediments originating in the erosion of the basin. The concentrations remain comparatively high (close to 200 mg.l^{-1}) until the end of September-beginning of October. From the month of October, the solid loads diminish very quickly and the supply soon becomes non-existent.

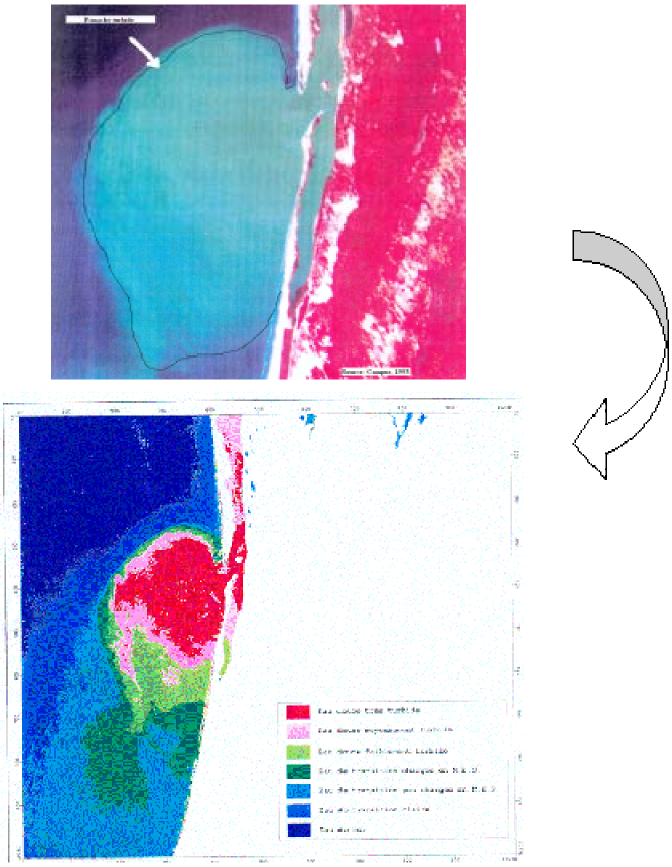


Figure 9. Turbid plume in the open sea at the mouth of the Senegal River (Classification used by Campus 1993)

The strongest daily concentrations observed during the successive cycles of artificial floods at the Diama-Amont station (Figures 8) were 740.6 mg.l^{-1} (01/09/1989), 378.9 mg.l^{-1} (30/08/1990), 665.5 mg.l^{-1} (04/09/1991), 529.4 mg.l^{-1} (15/09/1992) and 582.6 mg.l^{-1} (15/08/1993). To the station of Saint Louis stronger daily concentrations observed during the two successive cycles between 1980 and 1982 were 686.4 mg.l^{-1} (15-08-1981) and 415.8 mg.l^{-1} (20/08/1982).

The annual averages calculated by Kane (1997) are 218.32 mg.l^{-1} in 1989-90, 90.49 mg.l^{-1} in 1990-91, 187.45 mg.l^{-1} in 1991-92, 125.28 mg.l^{-1} in 1992-93, and 190.31 mg.l^{-1} in 1993-94; they are completely comparable (except for the year 1990) with the ones obtained at Saint Louis which were established as 252 mg.l^{-1} in 1981-82 and 156 mg.l^{-1} in 1982-83. This classifies the Senegal, according to the terminology of PARDE, as strongly turbid. Gac and Orange (1993) measured an average for the station of Bakel 221 mg.l^{-1} of 1979-80 to 1986-87 and 222 mg.l^{-1} of 1987-88 to 1992-93.

In the downstream reaches, continental waters push back marine waters and expel them outside the estuary. The mouth discharges to the sea a turbid plume that penetrates deeply into the ocean. At sea, on the littoral and the continental shelf, a turbid plume develops from the beginning of the month of August. On the image of the 01/10/1986, a turbid freshwater plume is particularly well developed around the mouth of the Senegal River Figure 9).

Having regard to the different recent modifying interventions on the estuary, it would be necessary to realize a new campaign of measurements of the sedimentation from the ocean side into the riverine part.

Dynamic evolution of the coastal zone

The evolution of the coastal zone has been a subject followed since 1989 by different research projects: Campus, Equesen, Gilif, Sidibe (2002) in the framework of the studies conducted by the Chair UNESCO/UCAD on the coastal zones and the small islands, and recently by START.

Measurements were made from the topo-bathymetric monitoring stations established on the Langue de Barbarie to the right of the lighthouse of Gandiole. This monitored zone corresponds to the base of the Gandiole ODC installed in 1989 in the framework of the Campus project.

Figure 10. Topobathymetric monitoring station on theLangue de Barbarie.

Each of the stations is represented by a boundary indicator formed by a tube of PVC, about 60 cm long, sunk to 50 cm depth and set in concrete (Figure 10). An iron rod extending 5 to 10 cm is placed in the center of the cemented tube. It is used as a fixed marker for the operations concerning topobathymetric relief. It is all painted in blue for a better recognition. The topographic measurements are carried out with the assistance of a laser beam geodimeter carried by a tripod placed at the level of the boundary indicator and of a reflector.

The topobathymetric profiles carried out between 1989 and 1991 (Figure 11) on the seaward shore of the Langue de Barbarie and of its foreshore on the base of Gandiole show three sections: the beach with its dune belt, the near foreshore and the slope. The first two are subject to important variations; the slope presents modest transformations that, usually, lead only to weak overall translations of the profile.

The general evolutionary tendency during this period shows a high beach presenting soft slopes – between 0.15 % (profile 10) and 2.19 % (profile 6); as for the low beach, its slopes are comparatively steep and vary between 8.33 % (profile 6) and 3.62 % (profile 8).

Table 2. Variation (in m) in the position of the shoreline in relation to the situation of June 1989 (Kane 1997)

PROFILE	1-10-1989	1-06-1990	1-10-1990	1-06-1991	1-11-1991
P1	31	41	123	41	31
P5	41	51	72	72	-31
P6	00	20	41	82	51
P7	62	51	82	82	72
P8	72	41	72	51	62
P9	00	-10	00	00	-10
P10	-1000	31	-10	00	41
P11	-5	123	93	93	113
P12		10	00	-10	-5
P15		41	20		51
P16		00	-31	-82	

Table 3. Morphological variations between 1990 and 2002 (Sidibé 2002)

Profile	High beach	Low beach	Sediment budget	Rate of annual retreat
5 M	+27.47 m^3	-62.91 m^3	-35.44 m^3	1.71 $m.yr^{-1}$
6 M	+23.84 m^3	-63.29 m^3	-39.45 m^3	3.45 $m.yr^{-1}$
7 M	+24.99 m^3	-78.15 m^3	-53.16 m^3	2.39 $m.yr^{-1}$
8 M	+12.6 m^3	-14.80 m^3	2.2 m^3	0.48 $m.yr^{-1}$
9 M	+24.1 m^3	-4.39 m^3	19.71 m^3	0.44 $m.yr^{-1}$
10 M	+19.55 m^3	-26.85 m^3	-7.51 m^3	1.12 $m.yr^{-1}$
11 M	+35.30 m^3	-41 m^3	-5.7 m^3	2.26 $m.yr^{-1}$
12 M	+36.78 m^3	-58.62 m^3	-21.84 m^3	3.38 $m.yr^{-1}$
Mean	+25.58 m^3	-43.75 m^3	-17.65 m^3	1.90 m/yr^{-1}

The shore has advanced, until October 1990-June 1991, in the northern part of the zone. In the southern half of the base, a retreat was established to the contrary in this period but the tendency for inversion followed again. Opposition is clear, in this regard, between the profiles P9 and P10. One must note as well that, between October 1989 and June 1990, the growth of the beach width undergoes a slowdown or even inverses (P9) such that one can imagine the existence of a transfer of material from the northern zone towards the southern. At the southern extremity (P15 and P16), the evolution is contrasted as well. Along the length of the shore, there are some sectors that are eroding while others are accreting.

The measurements carried out more recently by Sidibe (2002) have shown that the slopes of the high beach are comparatively slight comprised between 1.10 % (profile 5) and 5 % (profile 10) and the low beach presents stronger slopes comprised between 1.99 % (profile 7) and 8.5 % (profile 12). Comparison of the profiles of morphological evolution of the coastal zone between 1990 and 2002 (Figure 12), show almost the same evolution between 1990 and 2002 (Sidibe 2002). The observed changes generally affect both the low and the high beach.

The general aspect of the profiles is of a concave - convex type, just as well in 1990 as in 2002.

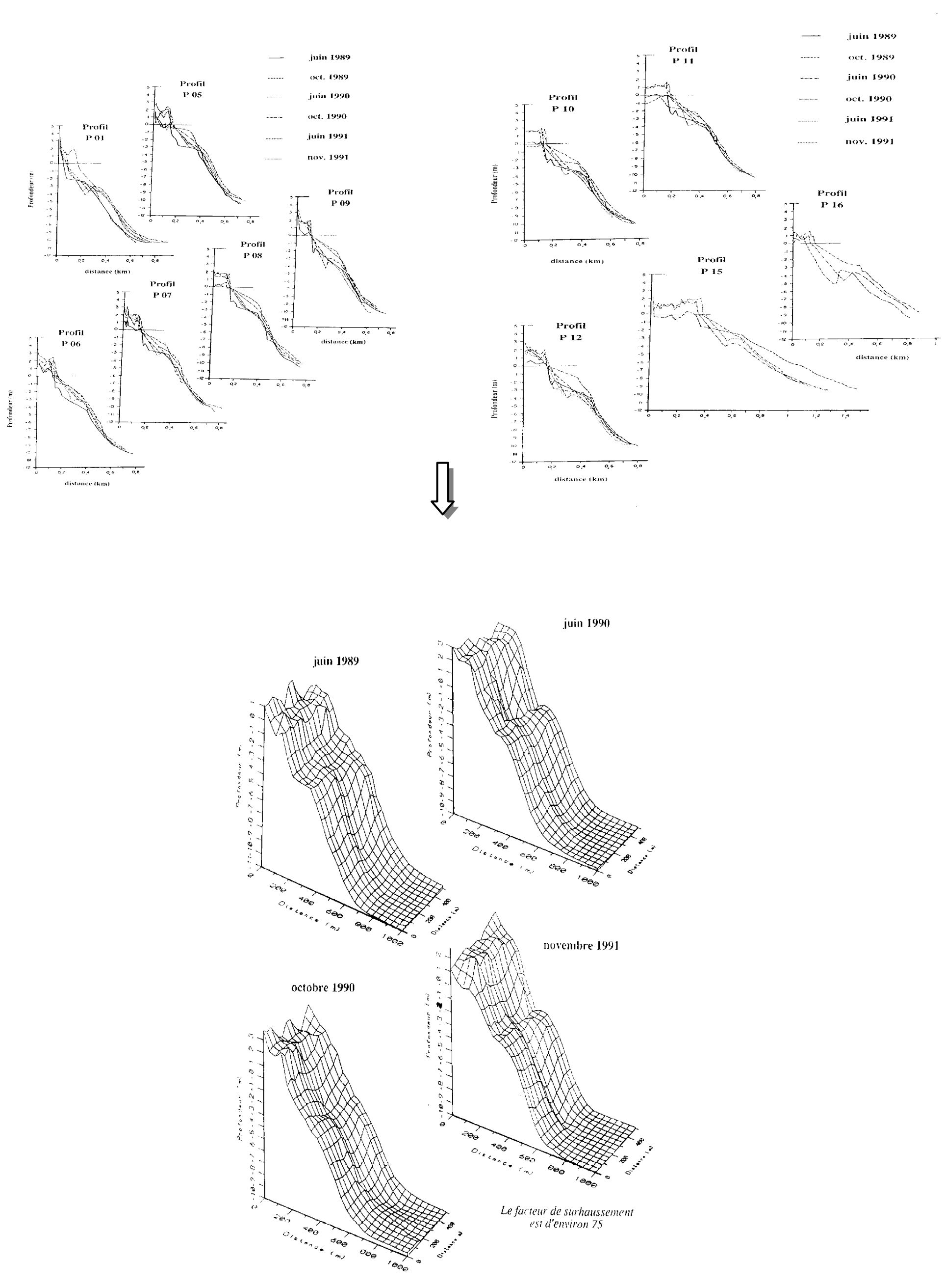


Figure 11. Morphological variation of the littoral belt and the open sea foreshore at Gandiole, between 1989 and 1991 (Kane 1997).

Considering all of the profiles, one notes between 1990 and 2002 an erosion of the low beach and a nourishment of the high beach (Table 3). The overall sediment budget, always negative, translates a general erosive tendency that shows itself besides by a general retreat of the shore line.

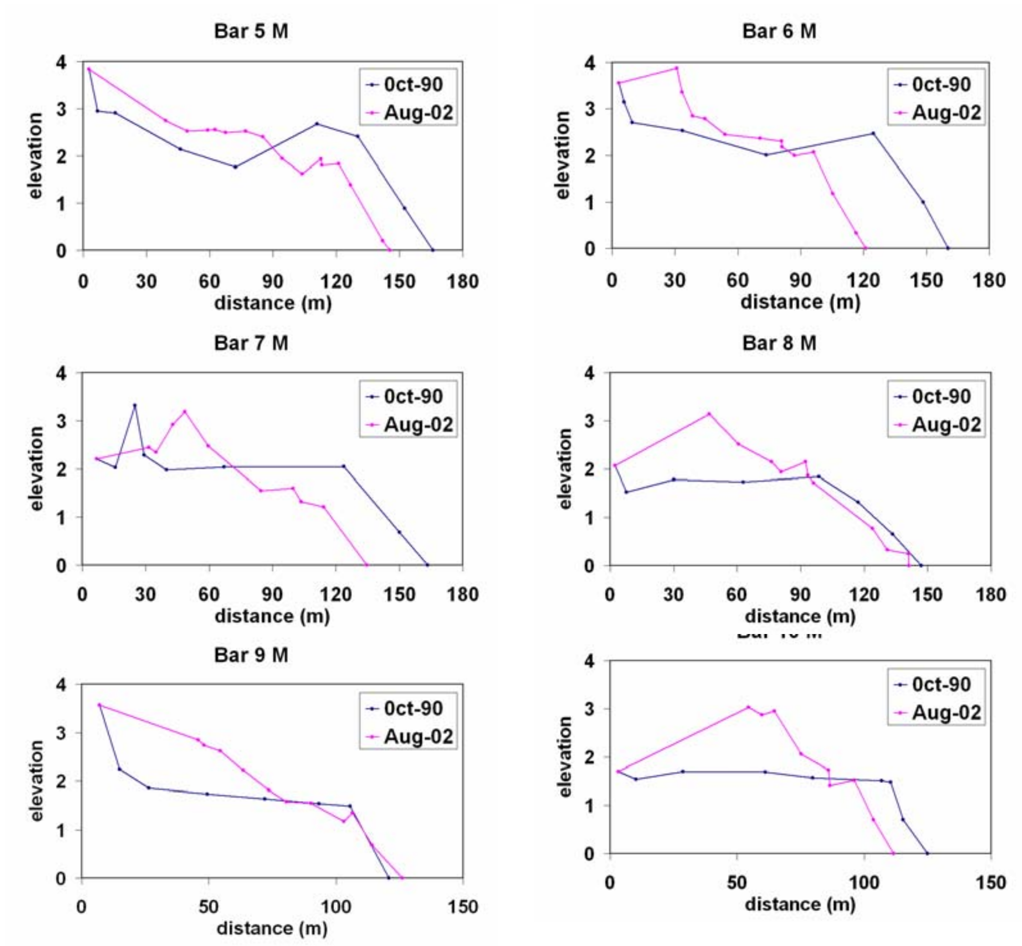


Figure 12. Comparison of topobathymetric profiles between 1990 and 2002 (Sidibé 2002)

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INTER-LINKAGES BETWEEN THE SOCIO-ECONOMIC DYNAMICS AND CLIMATIC VARIABILITY ON LOWER RUFIJI CATCHMENT, TANZANIA.

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ABSTRACT

This study considers the interlinkages between climatic variability and the socio-economic dynamics in the Lower Rufiji catchment. The major anthropogenic pressures on the Lower Rufiji catchment are associated with socio-economic activities including agriculture, fishing, hunting and various local and external commercial trades of the woodland resources. Historically, the traditional agriculture system, which depended much on the interaction between the natural (wild) floods of the Rufiji river and rainfall, has to a great extent been affected by the national villagization policy of 1969, which forced the people to move out of the flood plain to upland areas and delta islands. Two main factors have promoted the importance of the local fishery – agriculture is below subsistence level, and fishery is the major source of animal protein. Apart from the shrimp fishery which is for export, most of the other fishery is either for subsistence demand or local trade. There is an increasing user pressure on the woodland resources that are harvested to provide fuel wood, charcoal poles and construction timber.

The lower Rufiji generally receives insufficient rainfall, and, because of this, the agriculture system depends on both rainfall and flooding of the river. While floods are considered to be the main protection against famine for the lower Rufiji farmers, the short rains provide a safety net against famine. Despite their negative effects (mainly on agriculture), floods are important in the long-term sustainability of the fish resources in the lakes.

Spectral analyses of the long-term rainfall and river discharge data in the low frequency spectrum revealed cycles of 1.5-3 years (for the rainfall), 2-3 years (for discharge data) and 3-8 years (rainfall), 3-5 years (discharge). The shorter cycles (<3 years) were associated with Quasi-Biennial Oscillation (QBC) and the longer cycles (>3 years) were associated with the ENSO oscillation. Impacts of the planned impoundment of the Rufiji River at Stiegler's Gorge are likely to include river bed degradation, sediment trapping and saline intrusion in the delta, with negative effects on agriculture and fisheries.

Introduction

The present study is a short-term study on the Rufiji (Figure 1), the largest river basin in Tanzania, with a total area of 177,000 km^2 (20% of the area of the country). In the Rufiji, damming is confined to a tributary river (Great Ruaha, Figure 1), providing an opportunity to analyze the changes that are currently taking place, and can be expected to take place within the lower basin and coastal environment if further damming takes place.

The specific goal of this work is to synthesize the existing, currently widely scattered information on the Rufiji to provide a comprehensive understanding and to forecast the effects of river impoundment by the multipurpose dam planned at Stiegler's Gorge, some 180 km upstream from the coast, on the structure and functioning of the downstream and coastal

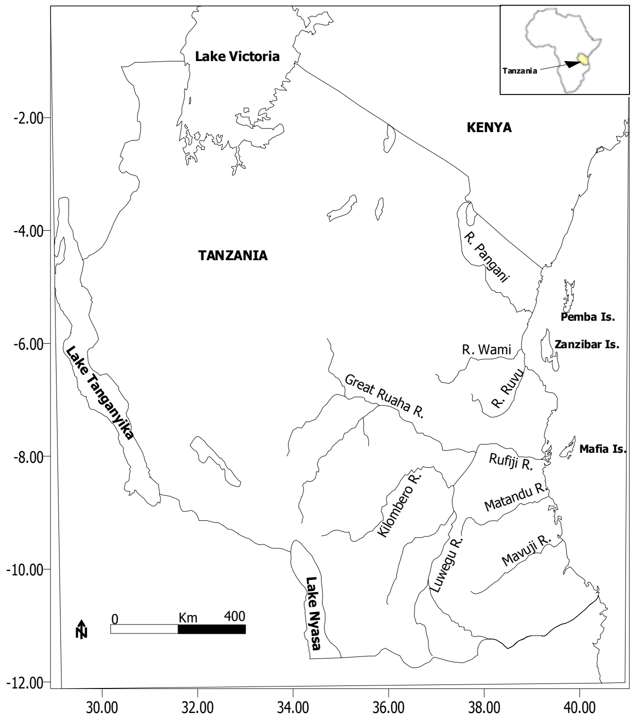

Figure 1. Map of Tanzania showing the Rufiji River (with its main tributaries) and other coastal rivers.

socio-economic dynamics. Priority is accorded to the impacts on agriculture and fisheries; the two major socio-economic activities, whose long-term sustainability has been maintained by the 'wild' (natural) floods of the Rufiji River. The historical information on climate change and recent events is analyzed, including the frequency and severity of major floods.

The study area

The study is on the lower Rufiji River (with a catchment area of about 19,215 km^2), its flood plain and delta, and the adjoining coastal waters (Figure 2). However, relevant linkages drawn from the upper Rufiji river catchment are also considered. The geomorphology of the area has three main units:

- The Rufiji floodplain, with recent alluvial soils, and where flood inundation occurs
- The delta which constitutes a prolongation of the floodplain, but where, in addition to flood inundation by land-derived water, sea-water intrusion has become significant.
- The terrace area, which borders the floodplain to the north and south, and which is developed on sandstone bedrock.

The floodplain itself can be further subdivided into zones (Figure 2), reflecting the depositional pattern of the sediments, with the coarser, less fertile material being predominant in the upper reaches and finer material occurring in the lower reaches. The zones are the upper, middle and lower floodplain, which, together with the Delta, form four agro-economic zones (Agrar-und Hydrotechnik GmbH 1982).

The Rufiji river, with a mean annual discharge of about 30 x 10^9 m^3 (euroconsult 1980a) is fed by three main tributaries, Luwegu, Kilombero and Great Ruaha, supplying respectively 18%, 62% and 15% of the total inflow to the Rufiji (Figure 2). There are two reservoirs – Mtera and Kidatu – on the Great Ruaha River. The Mtera reservoir, with a live storage capacity of about 3,200 Mm^3, was formerly used as a storage and flood control facility for the downstream Kidatu reservoir (live storage = 125 Mm^3, with a power generating capacity of 204 MW) but a hydropower station of 80 MW was later installed at Mtera. There are no reservoirs of significance in the other two tributary catchments (Kilombero and Luwegu rivers). From its start at the confluence of the Kilombero and Luwegu rivers, the Rufiji flows for about 100 km to the Pangani Rapids , where the river cuts through a low ridge, forming the steep-sided narrow Stiegler's Gorge, about 8 km long. The lower Rufiji river catchment extends from Stiegler's Gorge for about 180 km downstream to the shore of the Indian Ocean.

From Stiegler's Gorge (elevation about 65 m above sea level), the river runs into a deep alluvial flood plain that is contained within a low and relatively narrow valley with width varying from 7 - 30 km (Turpie 2000). The flood plain, which is seasonally inundated, covers approximately 1450 km^2. It comprises a mosaic of former river channels, levees and shallow depressions supporting sparse shrub, intensive cultivation, scattered tree crops or tall grasslands, palm trees and *acacia* woodlands (Ochieng 2002). Another important feature of the lower Rufiji flood plain is the presence of permanent lake system. There are altogether 13 permanent lakes on the flood plain (Hogan *et al*. 1999), giving a total area of 2850 ha – more than 50% of the surface of standing water bodies in the valley (Mwalyosi 1990; Ochieng 2002). These permanent water bodies are surrounded by forests and are connected to the river via small inlets or channels. Seasonal discharges of fresh water enter the lakes through these inlets/channels. Hippos and crocodiles are common in most of the lakes as well as the river.

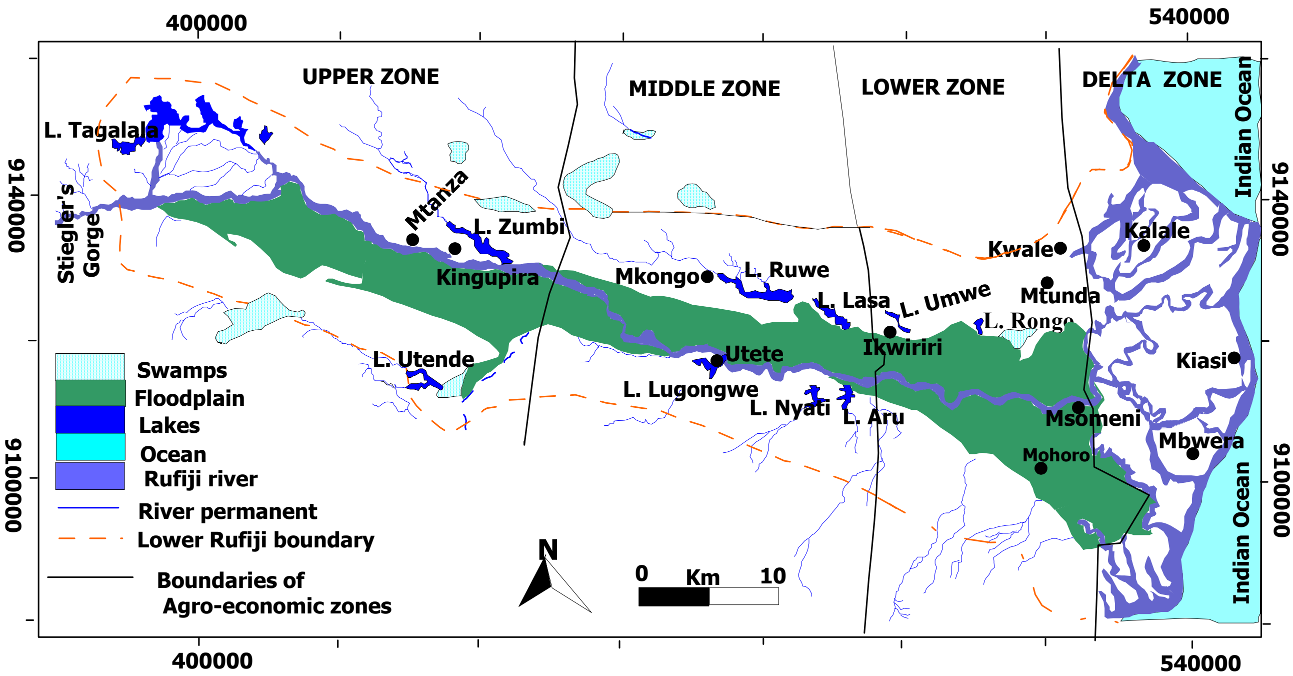

Figure 2. Map showing the Lower Rufiji catchment, with the four agro-economic zones (Upper, Middle, Lower and Delta).

The Rufiji delta is crescent shaped, 23 km wide, 65 km long and protrudes 15 km into the Mafia channel in the Indian Ocean, covering an area of about 1200 km^2 (Kajia 2000). The delta coastline is approximately 90 km long. The delta is formed by seven main distributary channels (Figure 3) interwoven with smaller channels and creeks (Kajia 2000). The most ecological important feature is its mangrove forest, the largest in East Africa, with an estimated coverage of 559 km^2 or 53,200 ha (Semesi 1991; Kajia 2000). The Rufiji delta mangrove forest constitutes of about 46% of the total mangrove forest coverage in Tanzania. It is linked by ocean currents to coral reefs surrounding Mafia Island to the east and it influences fisheries production in the islands of Zanzibar to the north through the northerly flow of marine currents.

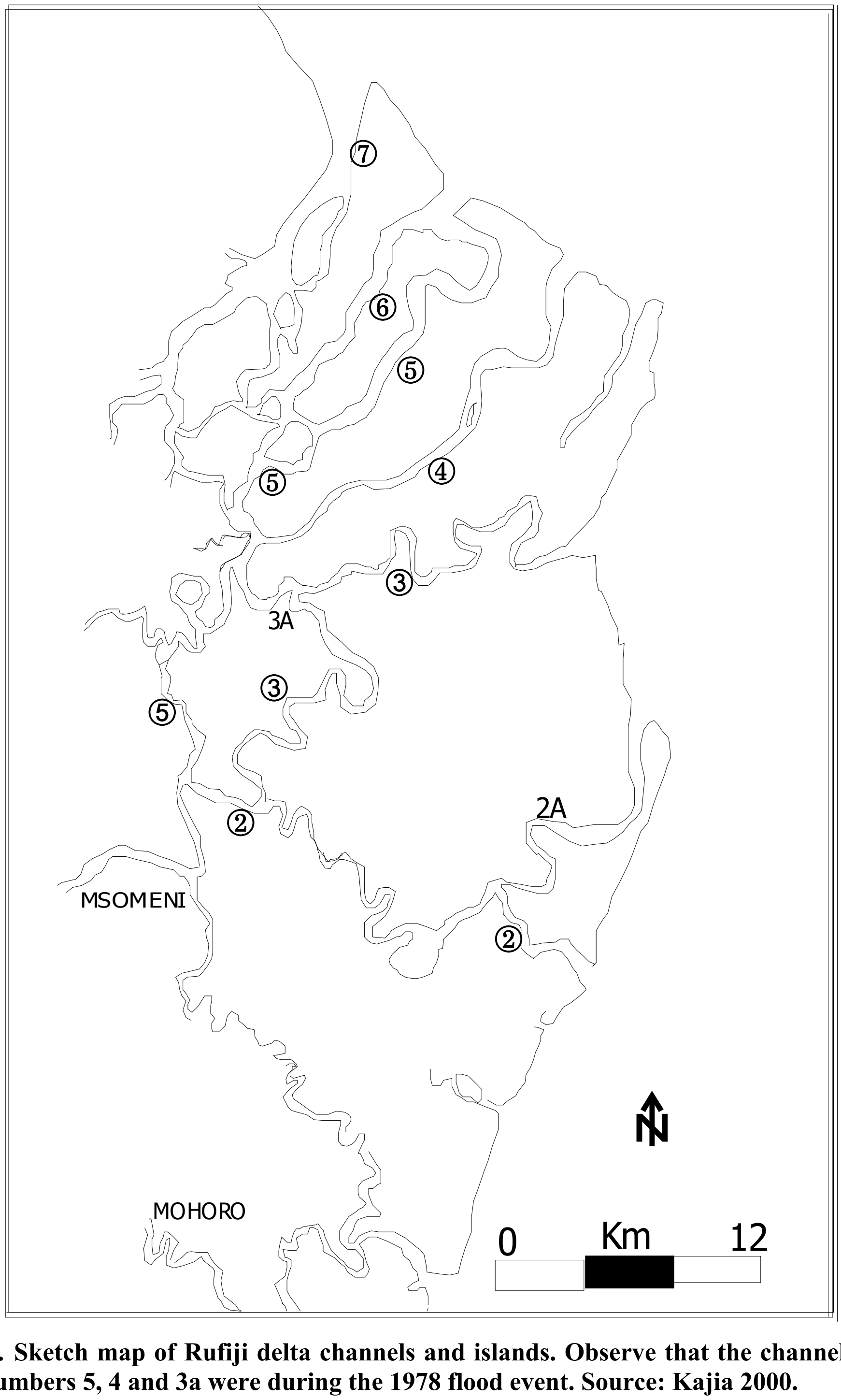

Figure 3. Sketch map of Rufiji delta channels and islands. Observe that the channels shown by the numbers 5, 4 and 3a were during the 1978 flood event. Source: Kajia 2000.

Major socio-economic activities on the lower Rufiji

The major anthropogenic pressure on the lower Rufiji catchment is associated with the socio-economic activities such as agriculture (farming), fishing and various local and external commercial trades. Most of these activities have taken different shapes during the course of time and are currently causing significant negative effects to the future sustainability of the natural resources present in the catchment. The future trends of these activities are related to demographic and climatic changes (Figure 4).

Agriculture

The agriculture system in the lower Rufiji catchment has been changing gradually through time (Cook 1974). Its evolution has been influenced by the interplay of natural, ecological and

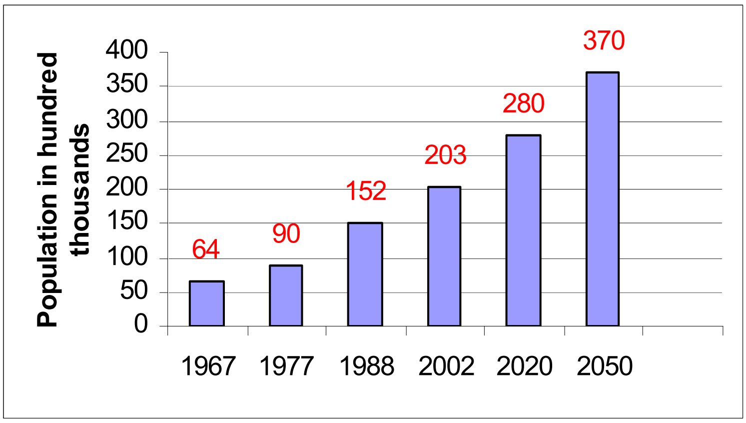

Figure 4. Population statistics for lower Rufiji since 1964 to 2050. Note that the statistics for 2020 and 2050 have been estimated using the growth rates indicated from the available statistics (1964 and 2002).

anthropogenic factors. The natural factors include rainfall, floods and droughts. Ecological factors include issues such as locust invasion, pests and weeds, and anthropogenic factors include demographic changes, political decisions, and lifestyle. A significant number of studies reveal that the lower Rufiji catchment has been and is still an area of great agricultural potential (Cook 1974; VHL 1979; Bantje 1979, 1980, 1981; Ngana 1980; euroconsult 1980a-d; Kajia 2000; Turpie 2000; Ochieng 2002).

According to Bantje (1979, 1980) and Ochieng (2002), large quantities of foodstuffs (beans, maize, rice and sesame seeds) and livestock (sheep, cattle and goats) used to be exported to areas as far north as Zanzibar and occasionally even to India. While the historical record reports more than 20 occasions of serious food shortages and famines between 1880 and 1980 (Bantje 1980), it is generally believed that the export of agricultural products was probably the dominant trend during the 19th Century. During those “good old days”, the agricultural production in most villages produced beyond self-sufficiency to create surplus for export outside tribal boundaries (Ochieng 2002).

Today the old trend has significantly changed. The present agricultural production in Rufiji is not even enough for subsistence. For instance in 1997, the food balance sheet for Rufiji District showed that, while the total amount of food requirements in terms of cereals and legumes was 33,548 and 4,793 tons respectively, the balance was 30,761 and 605 tons, indicating deficits of 2,787 and 4,188 tons. Ochieng (2002) notes that today no export of foodstuffs is reported and food remains the main expenditure item as quantities of food crops produced are inadequate to cover all the household needs of food and cash.

Despite the dwindling trends of agriculture, various studies indicate that it is still the main occupation of many households in the lower Rufiji. It is estimated that more than 90% of households in the floodplain and the delta consider agriculture as their main occupation (Ochieng 2002). The agricultural system of the lower Rufiji catchment has long been influenced by a combination of rainfall and flooding. (Marsland 1938; Cook 1974; Bantje 1980; Kajia 2000; Ochieng 2002).

While flooding of the Rufiji has generally been considered to be one of the most important factors for the agricultural surplus in the lower Rufiji, it has at times threatened the agriculture system. The seasonal floods which inundate most parts of the floodplain and the delta, compensate for a shortage of rainfall, help to control vermin, regenerate soil fertility with fresh silt deposits and create opportunity for second crop season (Bantje 1980). Apart from sustaining agriculture, floods also stimulate fish production and also sustain mangrove production in the delta. However, excessive floods, especially when they occur in January, have been attributed to serious damage of crops and famine.

Prior to 1969, the agriculture system in lower Rufiji was totally dependent on the natural interaction between rainfall and flooding of the river. However, after the villagization policy which took place between 1969 and 1973 (Cook 1974; Bantje 1979, 1980; Kajia 2000; Ochieng 2002) the agriculture system in the lower Rufiji took a new shape. The policy forced most households to move from their settlements on the wet lowlands of the river valley to drier areas on uplands away from the flood plain. Although the policy was formulated as a safeguard measure to protect the people against flood risks (Bantje 1979; Ochieng 2002), the policy had a number of negative effects:

1. The upland farm fields are generally less fertile than the floodplain fields (Cook 1974; Ochieng 2002).
2. The agriculture on the upland farm fields is entirely dependent on rainfall (Ochieng 2002).
3. Households which needed to maintain farmland on the floodplain had to travel far to their fields (Cook 1974). Due to this inconvenience, most households have small houses (*madungu*) in their floodplain farm fields (Turpie 2000) used as temporary homes during the farming season. The whole family stays in the temporary houses, except children in school (who stay with the father in the village). The long-time separation of families due to the division of labour has a negative impact on the social well-being of households. This may have corresponding multiplier effects on agriculture and other economic activities.
4. Due to the fact that settlement on the floodplain is not permanent, pest damage is reported to have increased significantly (Cook 1974; Turpie 2000).
5. Due to their lower fertility, the upland farm fields are usually abandoned after few years. Shifting cultivation is therefore the common type of farming on the uplands (Ochieng 2002). This type of cultivation has a devastating effect on the conservation of biodiversity as most of the farmlands are formed from cleared forests and woodlands.

The villagization policy did not only affect the agriculture system on the floodplain, but also affected the agriculture system on the delta islands. Prior to villagization, the inhabitants of the delta had their rice fields in the floodplain upstream from the mangrove areas where they established temporary settlements during the farming season (Ochieng 2002). After the farming season, they would return to their permanent settlements on the delta islands for other activities such as fishing and pole trading. During the villagization campaigns people were moved away from the floodplain. Mangrove forest clearing was taken-up as an alternative to the former subsistence agriculture on the floodplain, starting to clear the more emergent mangrove forest to establish their farms. The agriculture system in the delta islands continued to be flood dependent.

The changing nature of flood regime and the ecological characteristics of the delta have controlled the subsequent evolution of the *mlau* cultivation on the delta islands. It is reported that in 1978 the river created a new inlet to the delta (Figure 5) bringing more fresh water to some areas of the mangrove forest. Consequently the cultivation of rice in the mangroves increased. Shifting cultivation is also a common practice in the delta agriculture. The rice seedlings are often affected by crabs, and farmers respond by using DDT to kill the crabs (Semesi 1991) and incidentally other species (Kulindwa *et al*. 2001). The mangrove farm fields are usually abandoned after few years because of colonization by weeds. Since the regeneration of mangroves in those areas does not take place spontaneously, this type of cultivation is considered to be a threat to the conservation of biodiversity (Ochieng 2002).

Fishing

Fishing is another important economic activity in the lower Rufiji catchment. Although at a local level there are some villages (around some of the permanent lakes) where fishing may be ranked as the first important activity (Hogan *et al*. 1999), it is on average ranked 2nd to farming (in terms of labour time spent). There are two main factors which make the local people consider fishing to be of importance: 1- agriculture is generally below subsistence level, and 2- fishing is the main source of animal protein needs. In the three eco-regions - floodplain, transition zone and delta - surveyed by Turpie (2000), approximately 56%, 52% and 61% households, respectively, are involved in fishing. In these eco-regions, the household effort was estimated at 86, 56 and 123 days per year. In the floodplain and transition zone, fishing is exclusively regarded as men's activity, but in the delta eco-region both men and women are involved. In the latter case, women participate in shrimp, octopus and squid fishing, but not generally in finfish fishery. The majority of the fishers in all three eco-regions use nets, although traditional traps and hooks are also used.

Within the floodplain, fishing is mainly done in the freshwaters of the permanent lakes which provide suitable breeding habitats for fish and are regularly replenished by the seasonal floods (Turpie 2000). Fishing is not carried out in the river for fear of crocodiles and hippopotamus as well as the fast flow of the river (Hogan *et al*. 1999). It is carried out throughout the year but with a strong seasonal change in effort corresponding to periods of flooding (Turpie 2000). It is reported that the freshwater fishing in the area is generally unselective in terms of both species composition and size. The negative effect of this practice is that the fish resources have little opportunity to regenerate. In the delta, fishing is carried in the estuaries and in shallow inshore waters along the coast.

The marine catches are generally constant throughout the year as the fishers have the options of fishing finfish as well as prawns. Prawn fishing is cyclic due to the fact that it is tide dependent, most fishing being carried during the neap tides. Estimates indicate that over 80% of all prawns caught in Tanzania come from Rufiji delta; of these 90% are exported (Mwalyosi 1990; Kulindwa *et al*. 2001). The biggest cause of biodiversity loss related to fishing in the delta is caused by the fishing gear commonly used (Kulindwa *et al*. 2001). It is reported that the local people use stake traps made from the roots of *Rhizophora mucronata* so that the fish are stranded during low tide. This process damages the roots of the plant, and, because the traps are woven tightly together, even the juvenile fish cannot escape. Besides traps, fishnets with smaller meshes are commonly used, with similar destructive effects. The use of poison extracted from locally available plants also contributes to loss of fish. Signs of stock depletion are currently being experienced. Traditionally it is reported that fishers used to catch fishes using the "Kukiricha" practice - striking the oars on the water so that fish would jump into the boat, a sign of their abundance (Kulindwa *et al*. 2001).

Firewood, charcoal, timber and poles

Economic activities related with wood products include firewood, charcoal, timber and poles. While firewood and woodland pole harvest are generally considered as subsistence activities, charcoal and timber production and the harvest of mangrove poles are often regarded as commercial activities. The latter activities require licenses, but studies in the area indicate that illegal harvesting is rife. Few available historical data allow projections of the long-term trends because of two major shortcomings 1- The data are of short duration (5 – 10 years), 2- They relate to the licensed trade which is considered to be far lower than the un-licensed trade (Kulindwa *et al*. 2001). While more reliable data is found from specific studies (e.g. Turpie 2000; Kaale *et al*. 2000; Kulindwa *et al*. 2001), these studies give only the present situation. Using the data from the latter studies which estimated the present harvest of the various natural resources in the area using households surveys, here we estimate the *per capita* harvest of various resources using the 2002 population statistics (203,000 people) (Table 1). On the basis of these data, we are attempting to reconstruct the historical trend (from 1964) and future trends (to 2050) using the population statistics available (and projected population of Rufiji for the years 2020 and 2050). The reconstructed long-term trend annual harvest of various woodland resources is presented in Figure 5.

Firewood and charcoal

Firewood and charcoal are the main sources of fuel in the lower Rufiji catchment (Kaale *et al*. 2000; Turpie 2000; Kulindwa *et al*. 2001). Fuel wood is by far the major source of fuel contributing 80-85% of the total household energy used, while charcoal contributes 10-15% of the total (Kaale *et al*., 2000).

Table 1. Estimated *per capita* and reconstruction of annual harvest of various woodland resources (expressed in tons for fuel wood, charcoal and timber and in scores for mangrove poles) in lower Rufiji. The annual population statistics used to estimate these trends are: 1977 (90,000), 1988 (152,000), 2002 (203,000), 2020 (280,000) and 2050 (370,000).

Resource	*Per capita* harvest	Estimated harvest				
	(At present)	1977	1988	2002	2020	2050
Fuel wood	625 kg	56,250	95,000	126,875	175,000	231,250
Charcoal	32 kg	2,880	4,864	6,496	8,960	11,840
Mangrove poles	n.a	-	-	126,464	-	-
Timber	n.a	-	-	12,600	-	-

In the floodplain, fuel wood is collected from the farm fields, woodlands and to a lesser extent in the forest reserve; and in the delta from the mangrove forests. Mangrove wood reputedly makes better fuel wood than woodland wood (Turpie 2000). Fuel wood harvest from the mangrove forest has been singled out as one of the root cause of the loss of biodiversity (Kulindwa *et al*. 2001).

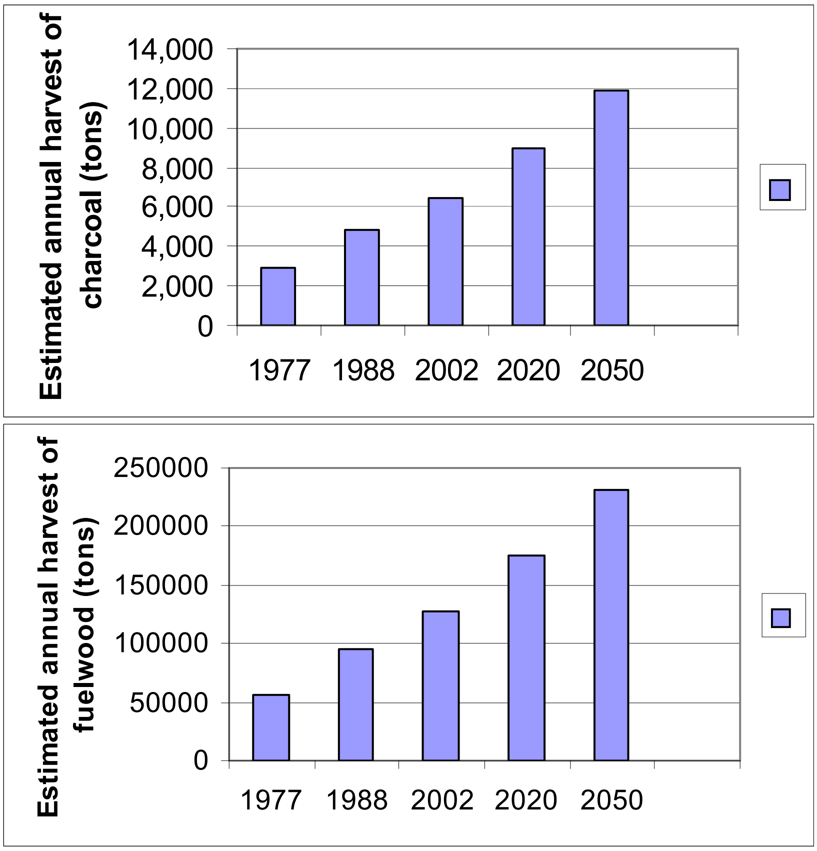

Figure 5. Estimated annual harvest of fuel wood (a, upper panel) and charcoal (b, lower panel) in Lower Rufiji.

In the lower Rufiji catchment, charcoal is often made, generally for commercial purposes, not from the mangrove forests (Turpie 2000), but from miombo woodlands from the floodplain. Most types of miombo woodlands are suitable for charcoal (Chidumayo 1991 in Turpie 2000). The activity requires a license, but illegal harvesting is reported to be extremely high, accounting to as much as 90% of the total (Kulindwa *et al*. 2001). Estimates of the annual production of charcoal are generally unreliable. Although the commercialization of wood resources provides tangible monetary benefits to rural communities, it also contributes to the resource depletion that will ultimately threaten their long-term survival (Luoga *et al*. 2000). The present study notes that to a large extent the growth of charcoal trade from the lower Rifiji floodplain to Dar es Salaam and other urban centers is influenced by the higher electricity tariffs. People in urban centers already served by electricity prefer to use charcoal and kerosene for cooking rather than electricity. Unless measures are undertaken to significantly reduce the cost of electricity, the growth of this charcoal trade is expected to be higher than the projections shown in Figure 5b.

Poles

Harvest of poles from the woodlands and mangroves is another economic activity taking in the area. In the floodplain villages, poles are usually cut from the woodlands within 1.5 to 3 hours of a village (Turpie 2000). Most of the pole harvest is to meet local demand, mainly house construction. Thus, although some pole cutters use the activity as an alternative source of income, the pole trade is generally between households in the area. Much pole cutting is carried out illegally. It is estimated that the annual harvest of poles in the area is about 1.3 million poles with a gross volume of 5000 m^3 (Turpie 2000). Due to the fact that some two-thirds of the harvest is withies (very thin poles), the sustainability of this activity is uncertain.

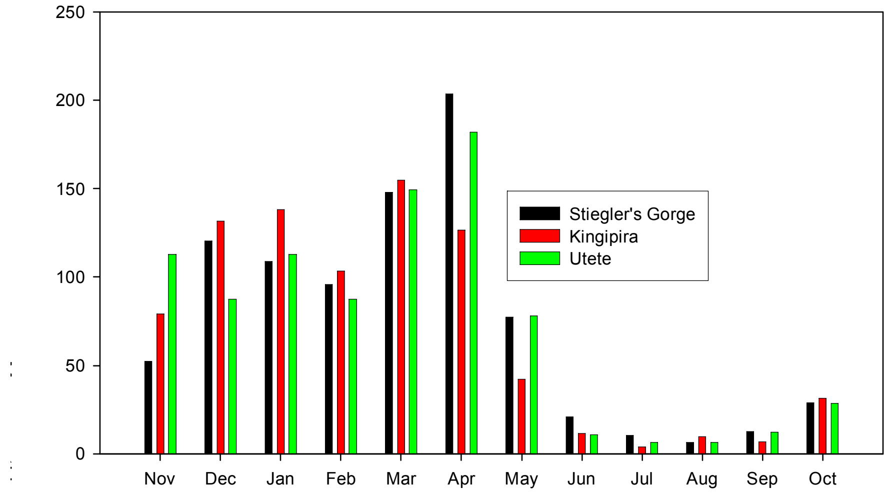

Figure 6. Mean monthly rainfall at three meteorological stations (Utete, Kingipira and Stiegler's Gorge) on Lower Rufiji catchment. (Source: Tanzania Meteorological Agency).

Cutting of mangrove poles is a major activity in the delta. A mangrove management plan has been instituted in places (Semesi 1991) to control the harvest of mangrove products (including poles). Although the management plans hinges around joint management with active participation of local communities, it has side effects which make legal cutting rather complicated (Turpie 2000). Because of the capital required for permits, most permits are in the hands of traders from large centers outside the Rufiji delta who employ local people to do the cutting. Most harvesting is reported to be illegal, unselective and unsustainable (Kulindwa *et al.* 2001). The future trends of this trade are likely to be influenced by demographic changes in the delta as well as its external demand.

Timber

Timber cutting is an economic activity taking place in all villages with access to the woodland resources. This excludes the residents of the delta. Like the charcoal and mangrove pole trade, the timber trade is externally driven by its demand from business traders from Dar es Salaam and other major centers for the export market. The activity requires a license whose cost varies from species to species. The most preferred hardwood species from the area at the moment are *Afzelia quanzensis* (mkongo) and *Dalbergia* (mpingo). Significant transport costs are also involved to transport the product to the market center. Because of the large capital needed for such costs, the trade is also controlled by external traders who operate on a large scale (Turpie 2000). During field visits for the present study, logging activities were observed in all the villages from Mtanza to Mloka. The logging operations employ strong people and therefore often involve young men. Our interview to villagers revealed that most of the logging traders were Chinese business men. There is presently no control by the forest department over the location and extent of timber harvesting (Wells *et al*. 2000). This raises doubt on the future sustainability of the resource.

The pattern of long-term climatic variability

General climatic setting

The climate of the lower Rufiji river catchment is tropical with narrow variation in monthly temperature and day length. Like most parts of eastern Tanzania, the rainfall pattern is controlled by the Inter-Tropical Convergence Zone (ITCZ) and the monsoon winds from the Indian Ocean. According to Nyenzi *et al*. (1999) the rainfall in Tanzania is characterized by

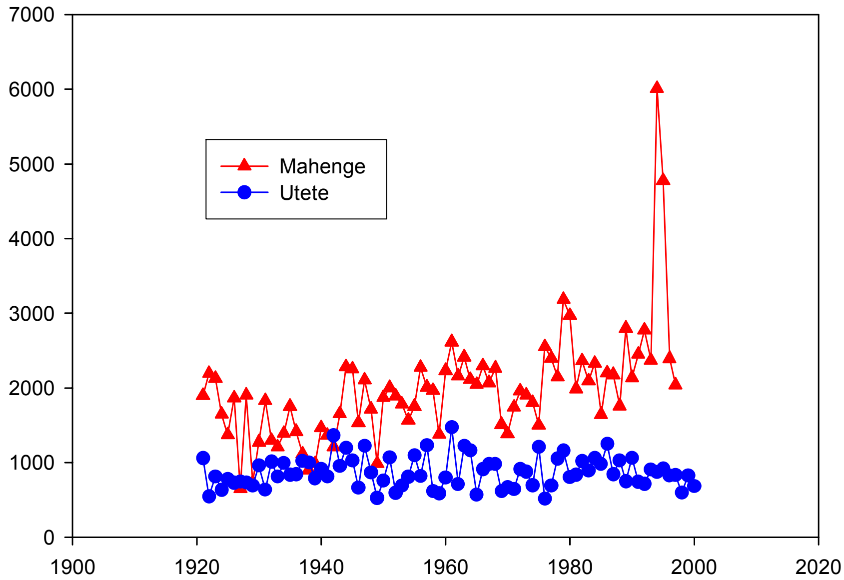

Figure 7. Annual rainfall patterns at two stations; one taken from lower Rufiji (Utete) and the other taken from Upper Rufiji (Mahenge). Observe that Mahenge receives much higher precipitations than Utete.

two main regimes: 1) the unimodal regime with continuous rainfall from October to April/May, and 2) the bimodal regime with a short rain season from October to December and a long rain season from March to May.

In the present study, rainfall data from three meteorological stations (Stiegler's Gorge, Kingupira Wildlife and Utete Agriculture Centre) were analyzed (Figure 6). For each of the three stations, the data consist of monthly precipitation for different time periods. Utete station has the longest historical data (1921 – 2000). The Stiegler's Gorge data range from 1955 to 1990 with a gap in 1959 and the Kingupira data from 1968 to 2000 with gaps in 1980, 1996 and 1997.

The mean monthly rainfall for all three stations shows that the rainfall season starts in October/November through May, with peak in March/April (Figure 6). The data are similar to those reported from other stations in lower Rufiji (e.g. Sørensen 1998 in Turpie 2000). The rainfall pattern of lower Rufiji catchment thus conforms to the unimodal regime in common with most parts of the eastern coast of Tanzania, south of Dar es Salaam (Ogallo 1980 cited in Nyenzi *et al*. 1999). The mean annual precipitations are generally similar for each of the three stations (Stiegler's Gorge = 884.4 mm, Kingupira = 839.4 mm and Utete = 872.0 mm). They all show that the area does not receive abundant rainfall. This is one of the major climatic factors, which has historically shaped the agriculture system in the lower Rufiji catchment. Because the rainfall is generally not abundant, the agriculture in the area does not depend solely on rainfall, but rather on both rainfall and flooding. While the former is generally controlled by the local geographic regime, the latter is largely influenced by the 'external' geographic regime, in particular that of the upper Rufiji which receives much higher precipitation (Figure 7). In the present study, rainfall data from three stations (Mahenge, Kilombero and Ifakara) of upper Rufiji were analyzed. Mahenge, like Utete (from lower Rufiji) has the longest historical data (1921-1997). The Kilombero data range from 1962-2002 and those from Ifakara from 1958 –2002. Here we present the data for Mahenge and Utete for comparison. The data show that Mahenge receives much higher precipitation than

Utete. The precipitation in the other two stations (Kilombero and Ifakara) is slightly lower than that at Mahenge, but generally higher than at Utete.

Unlike most parts of Tanzania which have either one or two agricultural seasons, Rufiji District is peculiar in that its agriculture year is characterized by three seasons (Bantje 1979; Hamerlynck, 2003): 1- the short rain season (*Vul*i), which involves planting of maize in November/December and harvest in February/March; 2- the flood season or long rains season (*Masika*), which involves planting of rice in December/January and harvest in June/July; and 3- the flood recession season (*Mlau*), which involves planting of maize and pulses in May/June and harvest in August/September (maize) and October/November (pulses).

Interlinkages between rainfall, flooding and agriculture

Rainfall and flooding are the two dominant environmental factors in lower Rufiji catchment which control agriculture and the livelihood of people. In good years, they complement each other so as to create favorable conditions (especially for rice cultivation). In bad years, their interaction may result in either drought or disastrous flooding. According to Bantje (1979), a good or a poor harvest is determined by the quantity, timing and duration of both rainfall and flooding, and these conditions vary from year to year. A failure of short rains may cause food shortage unless rainfall and flooding in the flooding season are favourable. Thus, if the failure of short rains is followed by no floods (i.e. prolonged draught), poor harvest of both maize and rice will result, leading to serious famine. However, if the failure of short rains is followed by adequate floods, good mlau harvest with poor maize harvest would result, leading to less serious famine. The other scenario of a good short rain season followed by poor flood season would lead to a more serious famine than the scenario of poor short rain season followed by good flood season. Several studies in the area recognize that the exceptional potential of lower Rufiji lies in the floodplain (rather than the upland areas), which has its fertility regenerated yearly by the river flood (e.g. Cook 1974; Bantje 1979, 1980, 1982; Kajia 2000; Ochieng 2002).

Using a 23-year series (1979 – 2003) of daily rainfall data at Utete, Hamerlynck (2003 and personal communication) discusses the seasonal risks of crop failure under different combinations of rainfall and floods (Table 2). From his analyses, he notes that the likelihood of having no floods is 0.60 (i.e. 6 years out of 10), the likelihood of having adequate floods is 0.25 (i.e. once every 4 years), etc. By multiplying the different probabilities, the likelihood of a combination can be calculated if the events in themselves are not correlated. For example, no flood and inadequate short rains will occur in 0.60x0.65 = 0.39, thus in about 4 years out of 10. He also notes that different types of crop failure have different impacts on the duration of food shortages and therefore on the risk of famine (Table 3).

Table 2. Probabilities of different flood and rainfall events on the lower Rufiji floodplain farming in any single agriculture year (Source: Hamerlynck 2003, personal communication)

Flood	None	Adequate	Excessive
	0.60	0.25	0.15
Short rains		Long rains	
Inadequate	0.65	Inadequate	0.35
Adequate	0.35	Adequate	0.65

Table 3. Number of months of potential food shortage in lower Rufiji catchment for different combinations of short rains and floods (Source: Hamerlynck 2003, personal communication).

	No flood	Adequate flood	Excessive flood
Inadequate short rains (<400 mm)	15	7	10
Adequate short rains (>400 mm)	9	0	4

As can be seen from Table 3, the worst case scenario is a failure of the short rains, followed by a year without flood, which is associated with 15 months of potential food shortage. The frequency of occurrences of such a combination is once every seven years. The second longest food shortage risk occurs in a year with inadequate short rains and excessive floods, which is associated with a ten month potential food shortage period. This combination occurs

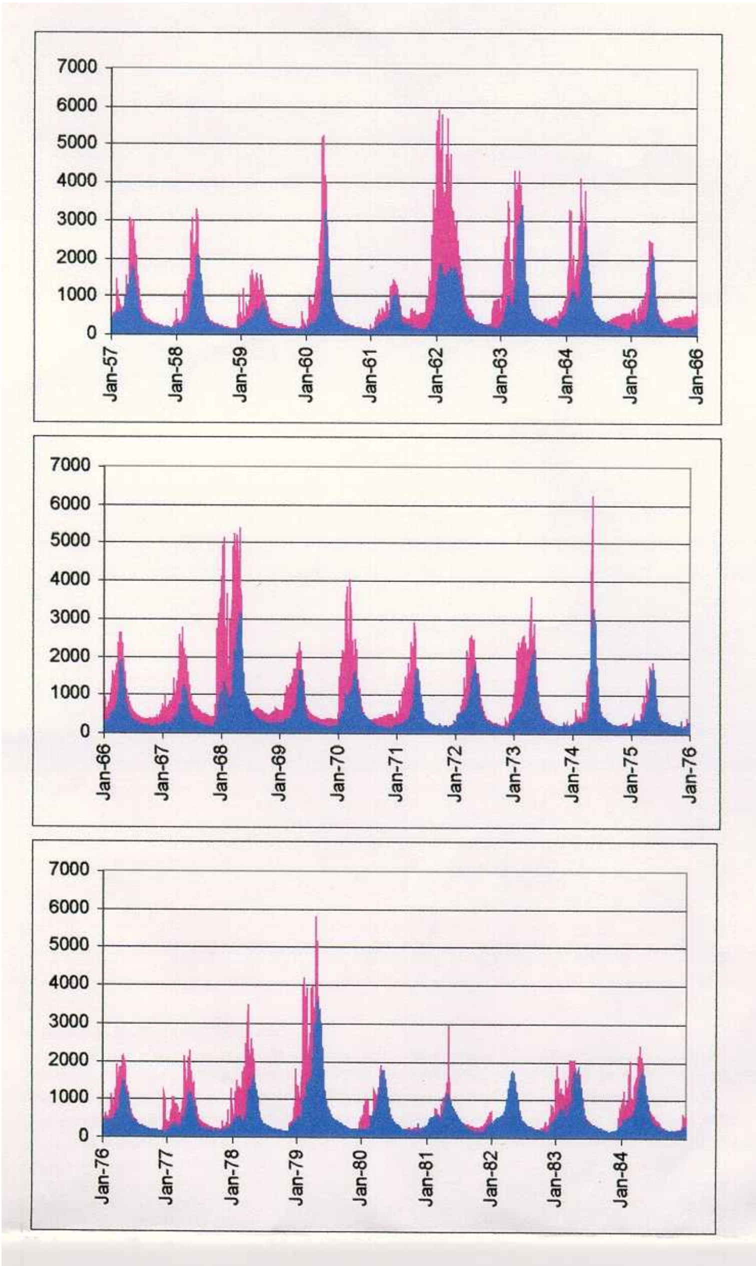

Figure 8. Hydrograph of the Rufiji River between 1957 and 1985 (flow in m^3s^{-1}). The contribution of the Kilombero tributary are shown in blue, characterized by regular fluxes with late flood (April) peaks (1000 – 3000). The contribution of the Luwegu tributary are shown in red, characterized by irregular early (January – February) flood peaks (2000-4000 m^3s^{-1}). Source: Hamerlynck (2003)

in about one year out of ten. The famine risk is however relatively low because of the compensatory high fish yield (Hamerlynck 2003, Duvail and Hamerlynck, 2007). The third longest food shortage risk period occurs in a year with adequate short rains in combination with the absence of a flood, which is associated with a 9-month long potential food shortage period. Here again the famine risk (especially before the villagization program) is considered to be relatively lower because of the interdependence of floodplain and hill dwellers. The adequate short rains would lead to good harvest on the hills, which would support the floodplain dwellers. In case of failure of short rains and adequate floods, the potential food shortage period is seven months, which occurs once every 6 years. Due to the interdependence of floodplain and hill dwellers, this also would lead to relatively low famine risk. A combination of adequate short rains and excessive floods leads to a relatively short food shortage period (4 months). A review of relationship between food shortages and flood/draught events using a 100-year (1880 – 1980) series of historical records (Bantje 1980) shows that drought and floods as single causes of food shortages are both listed eight times, while the combination of flood and draught is also reported to occur eight times. The above results emphasize two main points, 1- the floods are the main protection against famine for the lower Rufiji farmers and 2- short rains are another safety net against famine for them.

Analysis of the pattern of long-term climatic variability

Investigation on the nature of the long-term climatic variability, namely rainfall and flooding in the lower Rufiji catchment has been and is still a subject of interest by many workers. Understanding the long-term climatic variability and how it interacts with the physical environment is considered to be one of the key elements needed in the future management of the agriculture system, as well as other economic activities (e.g. fisheries) and future planned projects (such as damming) in the area. Despite a general understanding, little is known about this subject.

Our investigation of the temporal and spatial rainfall data from the three stations cited above (Utete, Stiegler's Gorge and Kingupira) shows that, although the mean annual precipitation is broadly similar, local variation exists, particularly in the annual total precipitation. Bantje (1979), who used monthly rainfall records from other stations (Utete, Mtanza and Mohoro), reports significant differences in annual precipitation for the three stations investigated (Utete = 868 mm, Mtanza = 700 mm and Mohoro = 1100 mm) and concluded that the total amount of rainfall in the catchment decreases rapidly when going inland from the coast. Thus, while rainfall records for Utete may be considered to represent the average rainfall precipitation for floodplain areas, the data might not be representative of the delta. Mohoro data could best represent this area, but like other rainfall records in the lower Rufiji catchment it is of shorter duration (Bantje 1979). Thus, we use the long-term temporal rainfall data for Utete for interpretation of the average climatic conditions of the lower Rufiji catchment with this caution.

It is also worth noting that the long-term historical rainfall data are characterized by peaks of different amplitudes (Figure 7). Table 4 shows spectral analyses to investigate the periodicity of the long-term rainfall data from three stations on lower Rufiji catchment and three other stations on the upper Rufiji catchment. Initial analysis of the data revealed that spectral amplitudes of high frequency overshadowed low frequency signals. Therefore the data were filtered into two frequency bands; high (period 2-12 months) and low (period above 12 months) and the upper limit was restricted by the rainfall sample length. The graphs showing the position of various spectral bands and their respective spectral heights for Mahenge (upper Rufiji) and Utete (lower Rufiji) are presented in Figures 9-10.

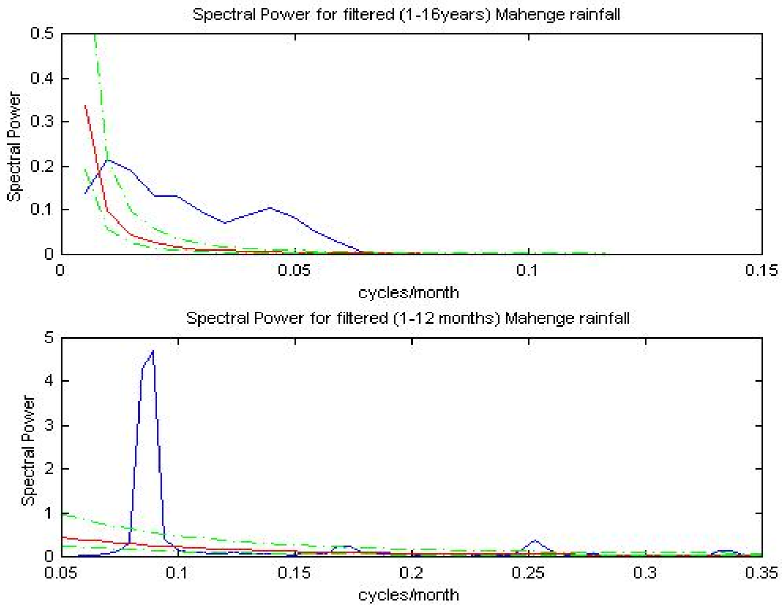

Figure 9. Low (Upper panel) and high (lower panel) frequency spectral bands of the filtered (1-16 years) and 1-12 months, respectively rainfall spectrum for Mahenge .

Table 4. Stations from upper and lower Rufiji whose historical rainfall data were investigated for spectral analyses.

	Station	Latitude	Longitude	Duration
	Kilombero	7.40°S	37.00°E	1962 -2002
Upper Rufiji	Mahenge	8.41°S	36.43°E	1921-1997
	Ifakara	8.90°S	36.39°E	1958-2002
	Stiegler's Gorge	7.48°E	37.55°E	1955-1990
Lower Rufiji	Kingupira	8.23°S	38.37°E	1968-2000
	Utete	8.10°S	38.45°E	1921-2000

Table 5. Rainfall spectrum in the low frequency band

Station	Cycles in Years for the Peaks		
Mahenge	8.4	3.4	1.9
Kilombero		2.8	1.7
Ifakara	7.4		
Kingupira		2.1	
Stigler's Gorge			1.7
Utete	8.4	4.2	2.8

Table 6. Rainfall spectrum in the high frequency band

Station	Cycles in months for the Peaks		
Mahenge	12	6	4
Kilombero	11	5.7	4
Ifakara	11	5.7	4
Kingupira	11	6	4
Stigler's Gorge	11		4
Utete	11	6	4

The spectral characteristics for all six stations are summarized in Tables 5 and 6. They all suggest a similar climatological pattern. They demonstrate that rainfall spectral amplitudes in the Rufiji basin are similar. It is here suggested that rainfall in the Rufiji basin is associated with QBO (Quasi Biennial Oscillation) and ENSO (El Niño Southern Oscillation) in the spectral bands 1.5-3 years and 3-8 years respectively. High frequency spectral bands are associated with annual and seasonal cycles, e.g. 12 months, 6 months and 4 months.

Spectral analysis was also carried out for river flow data for three stations, Sanje (7.36°S 36.54°E), Hagafiro (9.23°S 34.49°E) and Mpanga (8.56°S 35.48°E), in the upper Rufiji. The results are summarized in Table 7.

Table 7. River flow rates spectrum in the low frequency band

Station	Cycles in years for the peaks	
Mpanga	3.8	2.1
Sanje	4.2	2.1
Hagafiro	3.3	

Like the rainfall data, the river flow spectral analysis shows cycles for 2-3 years, which are associated with QBO (Quasi Biennial Oscillation) and 3 – 5 years, which are also most likely associated with ENSO events. The similarity in pattern between the rainfall data and

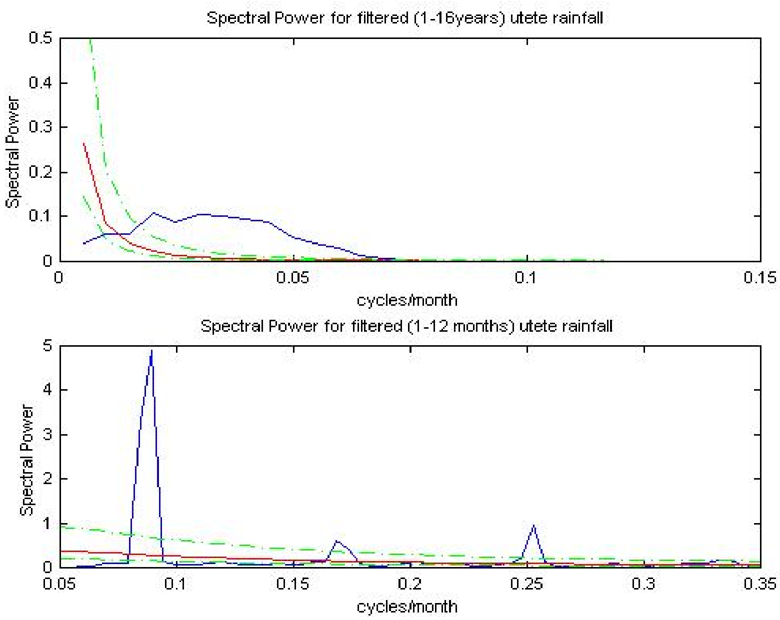

Figure 10. Low (Upper panel) and high (lower panel) frequency spectral bands of the filtered (1-16 years) and 1-12 months, respectively rainfall spectrum for Utete.

discharge data suggests a positive association between river flow and rainfall.

Further investigation of the relationship between rainfall and river discharge data was made using correlation analyses. Thus, monthly rainfall data of the six stations was correlated with monthly river flow rates of the three stations (with flow duration in brackets), Sanje (1962-1980) Hagafiro (1980-1991) and Mpanga (1957-1977). Very low correlation coefficients were obtained, suggesting that monthly averages of rainfall precipitation are not good in estimating river discharges. The correlation coefficients were also poor when the correlation analyses were done using daily rainfall and flow data (January – May 1965). All in all there should be a significant relationship between flow and rainfall if good quality data are used. The poor correlation obtained is therefore probably data reflection of poor data quality (particularly the river flow data which had significant gaps).

Fitting of the long-term rainfall pattern with other climatic models

In recognition of the current increasing rate of global warming due to greenhouse effects, the development of climatic change scenarios has been an interesting theme of research. In the case of Tanzania, the existing climate change scenarios have been discussed by Mwandosya *et al.* (1998). In this model, the climate change scenarios compare baseline climate with the climate that could be expected if anthropogenic greenhouse gases in the atmosphere increased to twice the baseline concentration (which is projected to take place at the beginning of the next century), and the associated changes in temperature and rainfall. The model suggests an increase in temperature of between 2.5 – 4.5 ^{o}C under the doubling effect of CO_2 throughout the country. The model also suggest a decrease in the amount of rainfall of up to 15% in the central, southern and southwestern sectors of the country and a decrease of up to 10% in the long rains season in the eastern bimodal sector. The remaining sectors would have rainfall increases ranging from nil to 45%. The Rufiji basin (upper and lower) in general lies within the sector projected to be associated with an increase in rainfall.

In the present study trend analyses have been conducted in the historical rainfall data to investigate whether they reveal increasing trends. The trends indicated for two stations from upper Rufiji (Mahenge and Ifakara) are presented in Figure 11. The results of other stations are as summarized in Table 8. With the exception of Kilombero, the other two stations on the upper Rufiji indicate increasing rainfall trends. There was no consistent trend indicated by the stations from the lower Rufiji; one of the stations (Stiegler's Gorge) indicated a decreasing trend, another one (Utete), a constant trend and the third (Kingufiro), an increasing trend.

Table 8. Summary of analyses of rainfall trends

Station	Rainfall trend
Ifakara	Increasing
Mahenge	Increasing
Kilombero	Constant
Stiegler's Gorge	Decreasing
Kingupira	Increasing
Utete	Constant

Future damming, flooding and people's livelihood

The proposed future impoundment of the Rufiji at Stiegler's Gorge was planned during the late 1970s. The proposed reservoir was designed to cover approximately 1250 km^2 at high-regulated water level, and 550 km^2 at low regulated water level. The difference between high and low regulated levels was estimated at 30 m with a typical annual drawdown of eight meters. The Stiegler's Gorge project has been envisaged as a multipurpose project with several expected long-term benefits, of which two were considered to be the most important 1- its high hydropower potential (2100 MW) would facilitate the pursuit of Tanzania's policy for industrialization and further electrification (Figure 12), which would in the long run enable Tanzania to become less dependent on expensive imported energy, 2- flood control would facilitate agricultural development on the lower Rufiji flood plain as wild (natural) floods had been posing considerable limitation on the advancement of agriculture during the past. The purpose of this section is to consider the nature of the expected interlinkages between the proposed river impoundment, the flooding of the Rufiji and the people's livelihoods.

One of the major physical impacts associated with the proposed river impoundment at Stiegler's Gorge is the problem of "river bed degradation", a consequence of reducing a river system's supply of sediment. The resulting effect is that the lower riverbed equilibrium would change and it would begin to erode its bed. In principle, erosion would continue until a new equilibrium with a flatter slope (Hafslund 1980). Studies have shown that strong degradation of the riverbed will occur. Under the present conditions, the wild flood irrigation in the

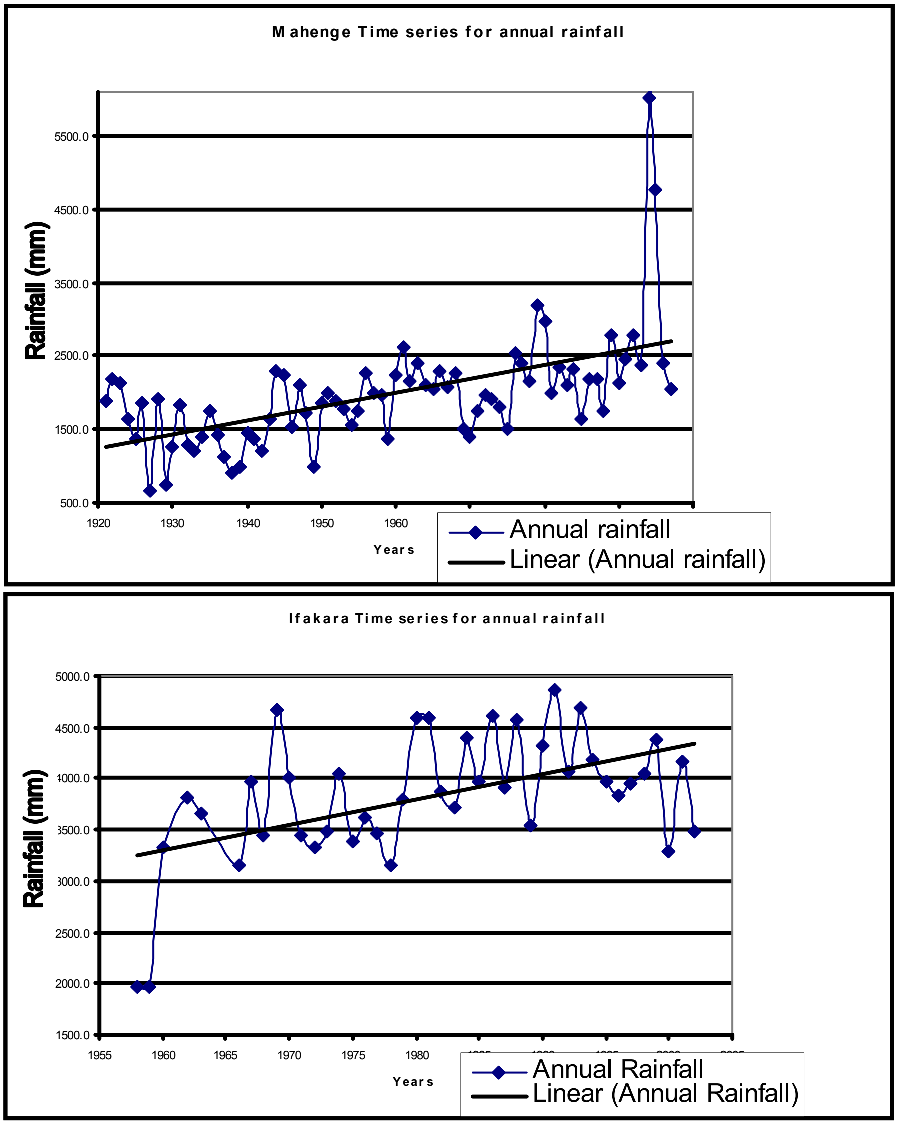

Figure 11. Estimated long-term linear rainfall trends for Mahenge (Upper panel) and Ifakara (lower panel).

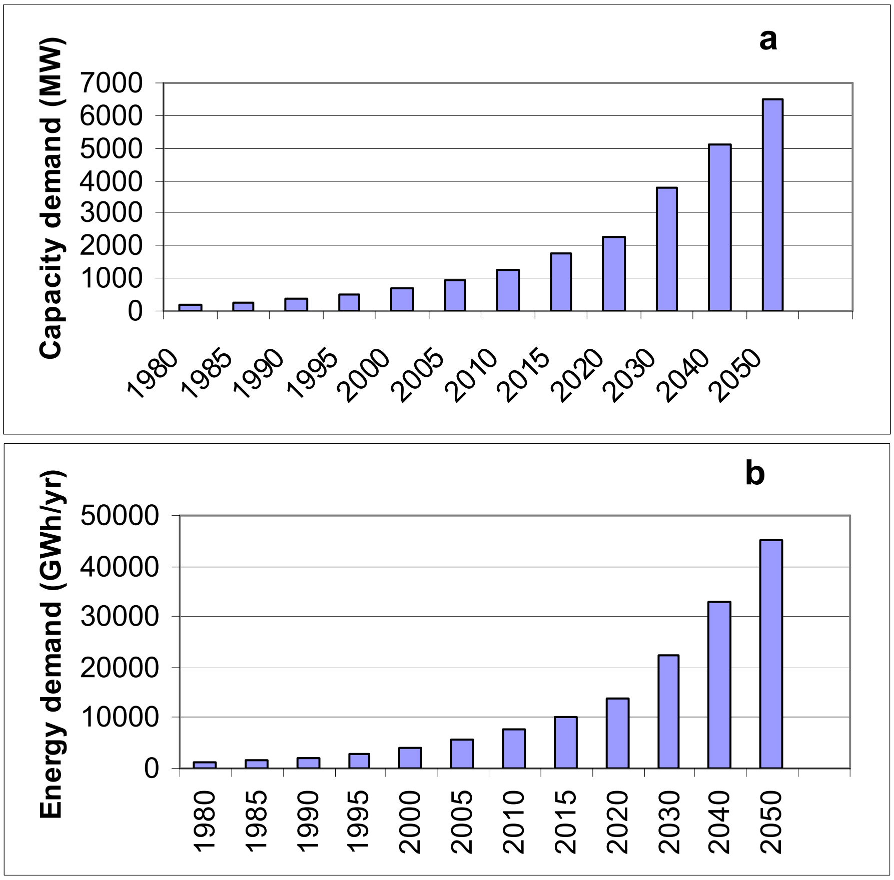

Figure 12. Basic power forecast for extended Grid network in Tanzania - modified after Hafslund (1980).

downstream area requires a discharge of at least 2500 m^3/s at Stiegler's Gorge for three to four weeks annually. Excessive floods (floods exceeding 3000 m^3/s) cause significant damage to crops. The resulting deepening of the main river channel would demand higher controlled irrigation floods with potential negative consequences to both agriculture and fisheries in the downstream areas. Furthermore, groundwater levels in the floodplain are likely to fall, which would have direct effects on vegetation and agricultural activities in the floodplain. The total result of such processes is that the present production systems in agriculture and fisheries will after some time have to be replaced by other systems.

Pumped irrigated agriculture has been planned for the long-term future development of the lower Rufiji floodplain (Mwalyosi 1982). Due to the complex nature of the floodplain and the obvious differences in soil types, climate, accessibility and engineering requirements, the floodplain and delta has been delineated into 9 blocks. During our present study, a field visit was conducted to one of the pilot irrigation farm projects (Segeni) which is located within the Ikwiriri block. The Segeni pilot farm covers a gross area of 60 ha. The farm is maintained by three pumps (two of which are 25 Hp and the third pump is a 16 Hp). Currently the farm has been donated to the Segeni Farmers Union, consisting of 53 farmers. Our interview to one of the farmers revealed that, during the early years of its existence (early 1990s), the farm used to be very productive, yielding optimum production of 40–60 bags of rice per acre. However, in the course of time, the production has fallen to less than 10 bag of rice per acre. Management of the pumps was reported to be one of the major causative factors for the poor yields as the farmers need working capital which is usually higher than they can afford. This casts doubts on the sustainability of the proposed future mechanized pumped irrigation over the entire floodplain and delta.

Another major consequence of the proposed river impoundment at Stiegler’s Gorge is associated with sediment trapping in the reservoir. The studies (Hafslund 1980) indicate that most of the coarse sediments would be trapped in the reservoir and some of the suspended sediments and organic particles. Apart from the river degradation problem discussed above, trapping of the coarse sediments is expected to have considerable consequences on the downstream sedimentation patterns - on the beach, the migration pattern of the meanders and delta distributary channels). Reduction of the suspended sediments and organic matter means reduction in the average supply of nutrients to the floodplain, with negative consequences to agriculture.

Another major consequence of the proposed river impoundment at Stiegler's Gorge is associated with the disappearance of wild flooding. Since one of the primary purposes of the dam is to control floods, once the dam is established, the natural floods are expected to cease (Hafslund 1980). Natural seasonal inundation of the floodplain ensures the long-term sustainability of the lake system, which plays a significant role in fisheries. Controlled floods, which would be used for irrigation when required, have been proposed to substitute the wild floods. The wild floods in the present natural conditions are associated with drastic negative consequences when the timing and the size of the floods are not properly determined (euroconsult 1980c). Despite the negative consequences of the wild floods, their positive consequences have far outreaching roles in sustaining the agriculture and the floodplain fisheries. Because the major purpose of the proposed impoundment is to generate hydropower, there exists a potential for great competition between hydropower and the other secondary purposes of the reservoir. Since fishery is carrying less weight in the design purpose of the project, it is unlikely that excessive controlled release for refreshment of the floodplain lakes would be allowed. Other studies show that after completion of the dam, predicted discharges of less that $1000m^3/sec$ will occur in eleven out of every twenty years (Mwalyosi 1982). This, together with the expected riverbed degradation, will significantly affect riverine fish stocks and fisheries in general.

Other anticipated consequences of the proposed river impoundment at Stiegler’s Gorge are related with the saline intrusion from the sea. Under the present natural conditions, the river flow regime varies from a few hundred m^3/s ($<500\ m^3/s$) during the dry season (June-December) to peaks of several thousands of m^3/s ($> 2000\ m^3/s$) during the rainy season. Studies (e.g VHL 1979) show that salt intrusion along the delta distributaries is considered to depend on four factors: 1- Freshwater discharges, 2-tides, 3-depth of river and 4- slope of riverbed. Low freshwater discharge with high tide, Deep River and gentle slope gives the maximum intrusion. The river slope and depth generally do not differ significantly among the different delta branches. However, the amount of fresh water discharges and tidal action among the different branches varies considerably. The estimated flow distribution through the different branches (Table 9) show that most of the discharges of the river during both the low flow (dry season) and wet season (high flow) passes through branch 6 and the lowest flow at all times is found in branch 1. The salinity measurement carried out in different branches demonstrated that the length of salt intrusion along the different branches is related to the above flow distribution pattern (Ngana 1980). Branch No. 1, which has the lowest discharge, yielded the maximum salt intrusion. The length of salt intrusion in Branch 1 during high tide was up to 40 km. The branch with the highest discharge (Branch No. 6) yielded a minimum salt intrusion of about 5-km.

Table 9. Flow distribution (in percent) at the coastline in the main branches during low and high river discharges. Source: VHL (1979).

Branch No	Discharge (100-400)m^3/s	Discharge (1000-4000)m^3/s	Outlet
1	0	10	A
2	15	15	B
3	10	15	C
4	10	10	D
5	10	15	F
6	50	25	
7	5	10	G

It is anticipated that, after impoundment of the river by damming, the frequency of low flow discharges will be significantly lower than at present, and the corresponding salinity intrusion at the delta channels will be significantly increased, with negative impacts on deltaic agriculture and on the health of the delta's mangrove forest.

Acknowledgements

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COASTAL IMPACTS OF DAMMING AND WATER ABSTRACTION IN THE TANA AND ATHI-SABAKI RIVER BASINS OF KENYA

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Abstract

This study was carried in the Kenya's largest river basins which contribute 90 % of the freshwater discharged into the Kenyan sector of the Indian Ocean. While there has been an increase in sediment load of the Athi-Sabaki River, the load in the dammed Tana River has been declining. The state changes that are attributed to the increase in the sediment load of the Sabaki river included siltation, estuary morphological changes (shallowing), changes in the mean flow, extension of mangrove forest, decreased water transparency, macro algal blooms and biodiversity degradation. In case of the Tana River where sediment load has declined due to damming, the state changes were coastal erosion, saltwater intrusion, degradation of biodiversity, decline in floodplain agriculture, changes in mean flow, morphological changes (estuary deepening) and increased turbidity. The impacts of water abstraction on the hydrology of the Athi-Sabaki and Tana rivers was found to be low due to the relatively low levels of exploitation for industrial, domestic, livestock and irrigation purposes. Climate variability, as opposed to water abstraction and damming was found to be responsible for the long-term variability of the flow of the Tana and Athi-Sabaki River systems. While the magnitude of river discharge determines the quantity of sediments transported by the two rivers, land use change in the catchment area, characterized by increased deforestation to open land for agriculture and settlement and the need to satisfy increased wood demand, is responsible for the generally high sediment loads of the two rivers.

Introduction

The AfriCat Project is an initiative of the IGBP-LOICZ funded by the International System for Analysis Research and Training (START). In Kenya, the study focused on Tana and Athi-Sabaki River basins situated in Central and Eastern Kenya (Figure 1 and Table 1). The two rivers' combined discharge is equivalent to more than 90% of the total flow to the Kenya sector of the Indian Ocean.

The main aim of the Kenya component of the LOICZ-START AfriCat project is to establish the trends of change in the hydrology and socio-economic issues in the two river systems as well as the changes in the coastal environment due to abstraction and damming of the two rivers. It is also intended that the impacts of climate change would be established through examination of rainfall and river discharge trends over the last 25-50 years. The project also examined the shifts in government policies in various sectors, particularly water resources, agriculture, rural and urban development, environment, forestry, energy and coastal zone management.

Within both the two basins, a number of consultancy studies have been conducted in the recent past (ILACO 1971; GOK-TARDA 1976a-b, 1981a-c, 1982a-c, 1983, 1986, 1987, 1992; GOK-JICA 1998a-c). These studies have overwhelmingly relied on the data archived by the Ministry of Water Resources Development and Management and other Government Departments. The hydrological data collected routinely by the Ministry of Water Resources has been utilized for the purpose of planning for the development of hydropower, irrigation, dam designing, water quality assessment, water supply, recreation, estimation of the dead

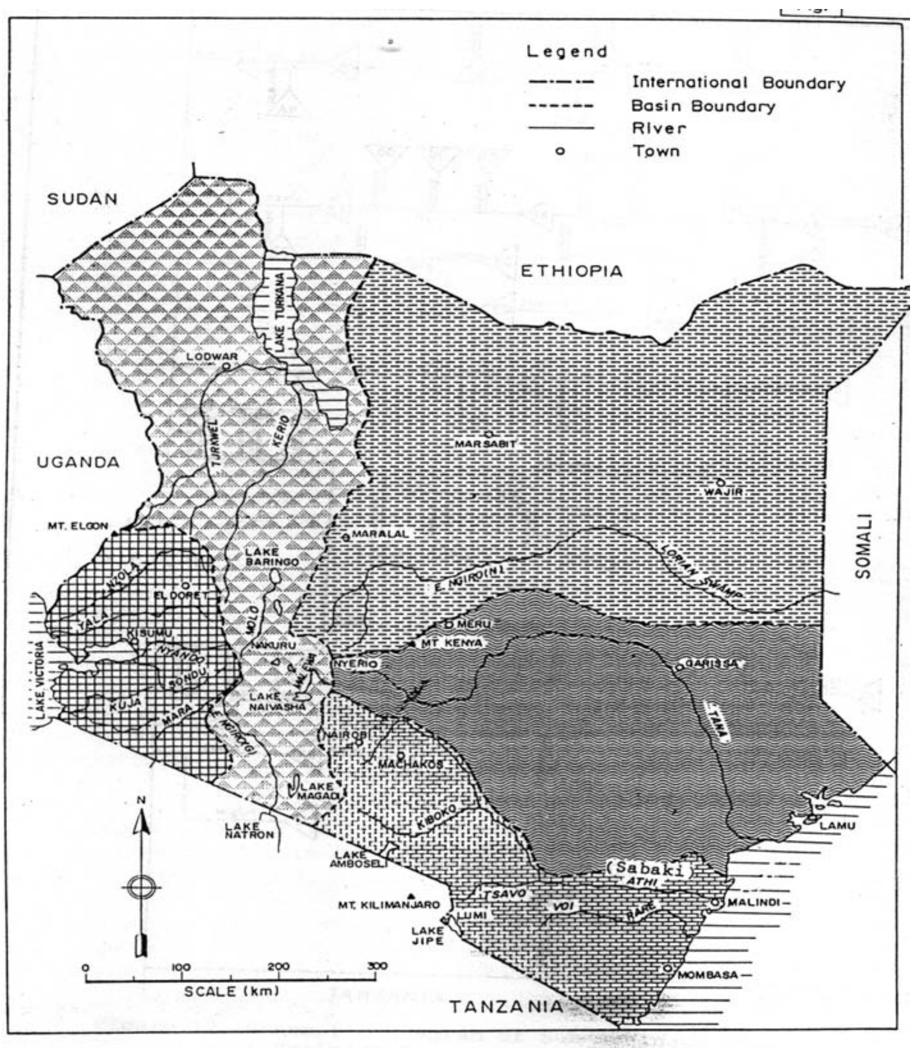

Figure 1. Main drainage areas in Kenya (source: GOK 1992).

storage in reservoirs as well as watershed management (GOK 1991 and 1992). It is however important to note that the quality of these data have been far from what is desired for effective planning for water resources management and development (GOK 1999a, b and 2002).

LOICZ AfriCAT Project used a standardized DPSIR (Driver, Pressure, State, Impact, and Response) framework, developed by the OECD (1993), for the assessment and integration of the results of past studies in the Tana and Athi-Sabaki river basins. This approach permitted a combination of the results from natural and social sciences as well as feedback from and to policy/management options (Arthurton *et al*. 2002).

Description of the Tana and the Athi-Sabaki river basins

Athi-Sabaki River has a basin surface area of 69,930 km^2, thus making it the fourth largest drainage system in Kenya (Ojany and Ogendo 1986; GOK 1974, 1979a). The main catchment areas of the river are found in the Central Kenya highlands, particularly in the Aberdare and Ngong ranges (Figure 1). There are two main tributaries namely Tsavo and Athi Rivers, which joins to form Sabaki River in the lower region of the basin. The waters of the river have not been harnessed for hydropower (GOK 1981a-c).

The Tana River drainage basin has a spatial extent of approximately 132,000 km^2, which is equivalent to about 23% of the total area of the Republic of Kenya (Table 1). In terms of river discharge, it is one of the largest and also one of the most important river runoff conveyors as its annual discharge forms 32% of the total river runoff in Kenya. The river is also the main contributor of freshwater to the Indian Ocean as it supplies 50% of the total river discharge of the Kenyan rivers draining into the Indian Ocean.

The main catchment area is on Mount Kenya (5199m asl) and the Aberdare Ranges in the Central Highlands of Kenya. The snow-covered peaks of Mount Kenya and Seven Forks scheme reservoirs provide a continuous replenishment to the river. As compared to the lower Tana Basin, the Upper Tana Basin has been the focus of a number of studies geared toward understanding soil erosion and sediment transport dynamics (ILACO 1971; Edwards 1979; Dunne and Ongwenyi 1976; Ongwenyi 1983; Schneider 2000).

Table 1: The hydro-climatic features of the main drainage basins in Kenya. Source: National Development Plan (1979-1983). Rainfall-Runoff ratios by author.

	Drainage basin	Surface Area (km^2)	Mean Annual Rainfall (mm)	Mean Annual Runoff (mm)	Rainfall-Runoff ratio (%)
1	Lake Victoria	46,024	1,282	180	14
2	Athi-Tsavo	66,519	593	35	6
3	Rift Valley	124,725	519	30	6
4	Tana River	126,828	566	38	7
5	Ewaso Ngiro	209,230	431	8	2

Assessment of catchment impoundment and water abstraction

Hydro-electric power dams on the Tana River

Table 2 shows the characteristics of existing and potential reservoirs in the Tana Basin. The reservoirs are managed by the Tana and Athi Rivers Development Authority (TARDA), which was created in 1974. Of the dams shown in Table 2, the most important is Masinga reservoir which regulates the flow of the Tana River and therefore makes the hydropower and irrigation possible in the basin (GOK-TARDA 1976a-b).

Power generated from hydro stations forms 78% of the total electricity output in Kenya. Out of this, 65% is produced in the Seven Forks scheme (Masinga, Kamburu, Gitaru, Kindaruma and Kiambere Power Stations). The total installed capacity is 598.5 MW. The five dams have an installed capacity of 458.4 MW.

The demand for hydro electric power in Kenya has risen from very low values in the 1950's (1000 GWh) to the present demand of nearly 4700 GWh, which by 2025 is expected to rise to nearly 6000 GWh. Within the Upper Tana Basin, several sites were identified for construction of at least five more dams for hydropower generations. These include Mutonga, Grand Falls, Karura, Adamson's Falls, Korah and Usueni (GOK 1979; TARDA-GOK 1982).

Table 2: Characteristics of existing and potential reservoirs in the Tana Basin. Sources: TARDA-GOK 1982 a - c: GOK-JICA 1998 a - c.

Reservoir	Gross volume (10^6 m^3)	Surface Area (km^2)	Catchment area (km^2)	Mean river discharge (m^3s^{-1})	Year of completion
Masinga	1,560	113	7,335	97.2	1981
Kamburu	147	15	9,520	149.5	1975
Gitaru	20	3.1	9,520	120.9	1978
Kindaruma	16	2.4	9,807	155.9	1968
Kiambere	315	13	11,975	121.8	1988
Karura	74	8			Planned
Mutonga	1,580	46			Planned
Grand Falls	3,600	119			Planned
Usueni	330	26			Planned
Adamson's Falls	1,730	102			Planned
Kora Hills	3,800	190			Planned

Water demand, abstraction and land use change in the Tana and the Athi-Sabaki basins

Rural and urban water demand and population growth

Water availability *per capita* in Kenya has continued to decline despite enormous growth in population (Mogaka *et al*. 2002). The water availability declined from 1800 $m^3.yr^{-1}$ *per capita* in the 1960s when the population was 10 x 10^6 to the present rate of less than 600 $m^3.y^{-1}$ *per capita* (Figures 2 and 3).

The demand of water for domestic, irrigation and industrial uses has also continued to rise in response to the increase in population (Figures 4 and 5) (GOK 1974, 1979a, 1991, 1992). Data for total water demand for major urban and rural areas in the Tana and Athi River basins was obtained from the National Water Master Plans (GOK 1979, 1992). The analysis of data showed that the total water demand in the two basins rose from 500,000 m^3day^{-1} in 1950s to the present demand, which is estimated to be 1.3 x 10^6 m^3day^{-1} (Figure 4). The anticipated

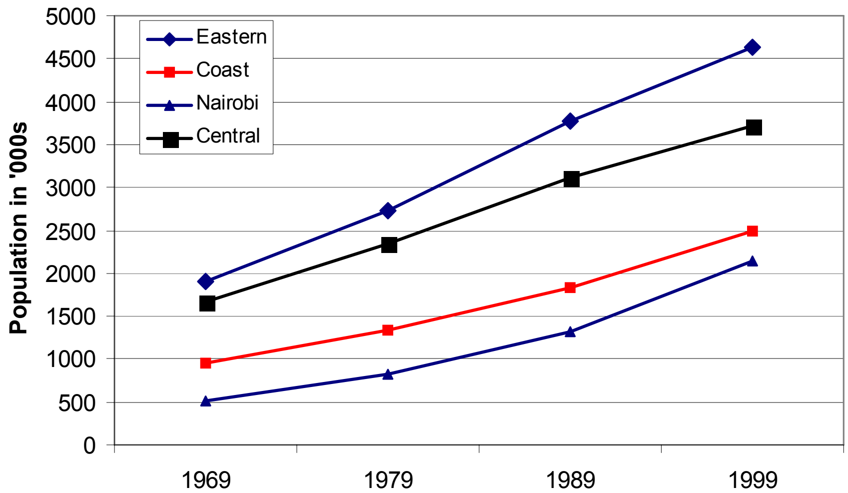

Figure 2. Population distribution by administrative Provinces found in the Tana and Athi-Sabaki river basins.

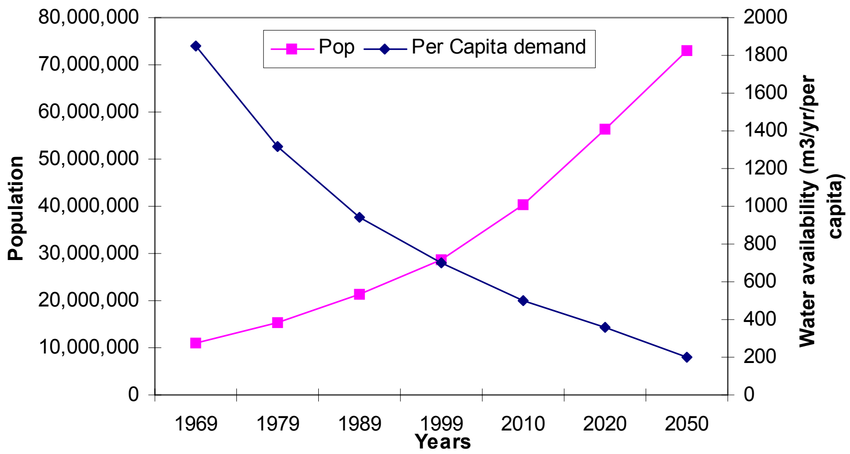

Figure 3. Population growth and water availability in Kenya (Source: Mogaka *et al.* 2002 with extrapolations to the years 2020-2050 by this study).

year 2000 total water supply in the Tana basin was 0.73 x 10^6 $m^3.day^{-1}$ serving a population of 8.9 x 10^6 people (GOK-TARDA 1976 a - b). Despite the above increases in water demand in the two basins, there has been only a moderate expansion of the water supply schemes since 1950's. Thus, the actual water supply in most parts of the basin is less than 60% of the total water demand, which means the actual abstraction from the two rivers is relatively low.

Irrigation schemes and water demand

Several irrigation schemes were commissioned in the Tana Basin in the early 1960s and early 1980s. The irrigation agriculture covers an area of 54,676 ha (GOK 1992). This area encompasses 30,148 ha of private development and 24,528 of Government operated schemes. According to existing estimates, the basins have a potential of 132,000 ha for irrigation. The total irrigation water demand was estimated to be 60 x 10^6 $m^3.month^{-1}$ before the collapse of the schemes. In the last 14 years, there has not been a significant abstraction of water for irrigation in the Bura, Hola and Tana Delta schemes and operations of the Mwea-Tebere scheme have dwindled substantially in the recent past. The total water demand in the Tana River basin is estimated to be 268 x 10^6 $m^3.yr^{-1}$ which is roughly 6% of the total annual flow. However, if all the irrigation schemes in the Tana basin were operating at their optimum

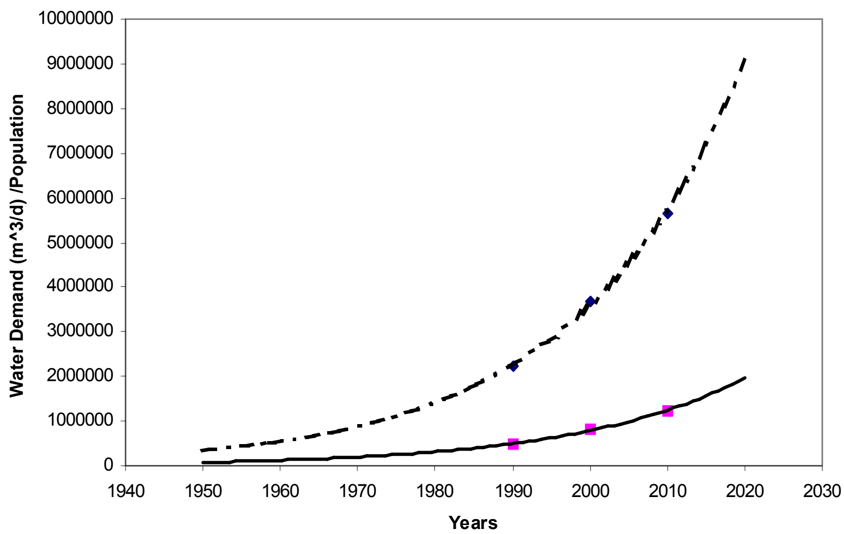

Figure 4. Population growth (solid line) and water demand (dashed line) in the Tana and Athi-Sabaki river basins. Extrapolations to the years 2020 are by this study.

levels, the total water abstraction from the Tana River would have been equivalent to about 20% of the total annual discharge. The current level of non-irrigation water abstraction from the river represents only a small portion of the total annual flow and impact on the hydrology of the river is certainly small.

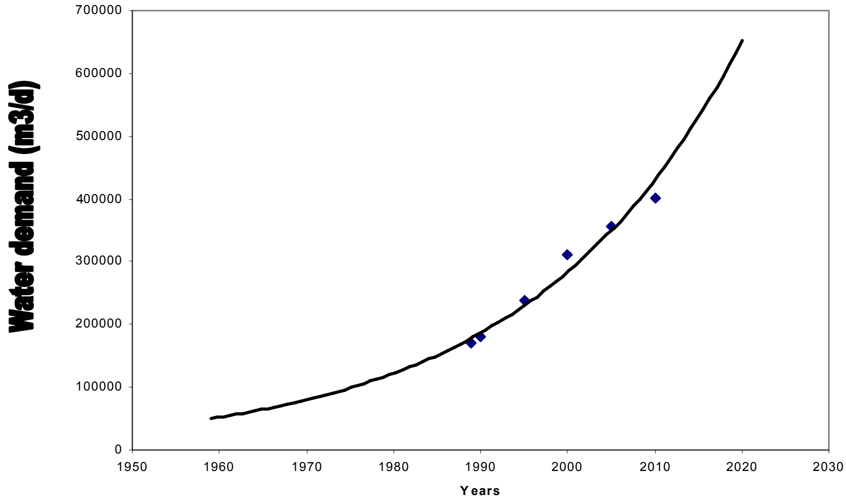

Figure 5. Industrial water demand in the Tana and Athi-Sabaki river basins. Extrapolations to the years 2020 are by this study

Changes in land use in the catchment areas

In the last 50-80 years, tremendous changes have occurred on land use and the level of exploitation of natural resources in both the Tana and Athi-Sabaki river basins. These changes have occurred in the size of forestland that has been converted to farmland for the cultivation of tea, coffee, maize and also for settlement (GOK 1979, 2003). In the 1920s, the total land area under coffee and tea were 10,000 and 5,000 ha, respectively, compared to the present ones which are 500,000 and 150,000 ha, respectively (McMaster 1969; Odingo 1971; Othieno 1989; GOK 1979, 1984, 1994) (Figures 6 and 7). Most of the area under coffee and tea were

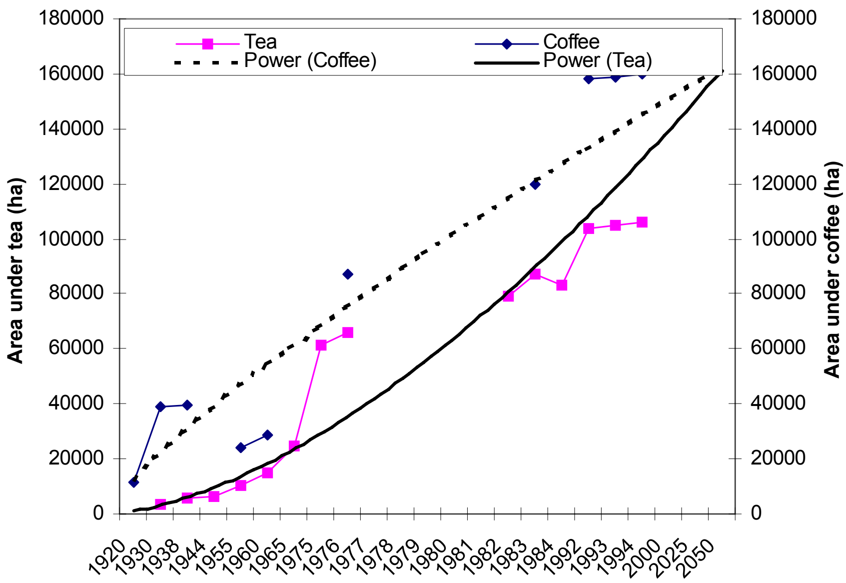

Figure 6. Land area under tea and coffee in the Tana and Athi River basins. Extrapolations to the years 2025-2050 are by this study.

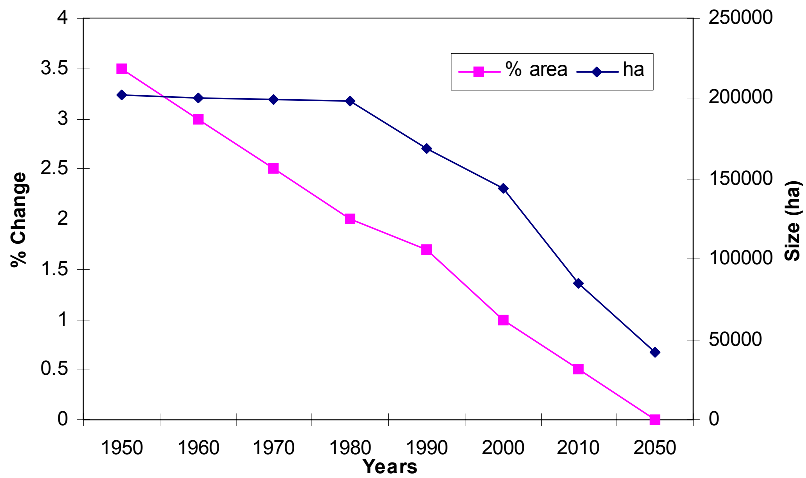

Figure 7. Changes in the total area under forest cover in Kenya. Extrapolations to the years 2010-2050 are by this study.

forestland located in the high rainfall highlands of Central Kenya. Over the last 80 years, the total land area under tea and coffee cultivation has increased by 98% and 67%, respectively (Figure 6).

With the increase in the total land area under coffee and tea plantations, the total area under forest cover in Kenya declined from 3.5% in the 1950s to the present level of about 1%, which represents a destruction of nearly 60,000 ha (600 km^2) of forests in the last 50 years (see also Odingo 1971; GOK 1979, 1984; Annandale 2002). This study based on the extrapolation using the previous deforestation rates, estimates that by 2050, the total land area under forest will be less than 0.5% of the total land area (Figure 7).

Some forests will be completely destroyed in the next 10-15 years if no urgent protective measures are taken. Good example is in case of Endau and Ngong Hills forests whose forest cover will be completely cleared by 2010 (cf. Ochanda 1983). Apart from land conversion for agriculture, forests have been destroyed to meet the increased demand for wood. The wood demand in the 1950's was 1.3 x 10^6 $m^3.yr^{-1}$ as compared to the present demand of nearly 27 x 10^6 $m^3.yr^{-1}$. This will rise to 30 x 10^6 $m^3.yr^{-1}$ by 2030 (GOK 1994).

Destruction of forests in the catchment areas of the Tana and Athi-Sabaki river basins promotes soil erosion (see also Edwards 1979). Surface runoff generated on cleared and cultivated areas washes away loose top soil to the river channels. Furthermore, high population density has increased the rural network of murram roads and footpaths, which, in addition to overgrazed open fields, became important sources of sediments that enter into the Tana and Athi-Sabaki rivers. Cultivation in most cases is done without applying effective soil erosion protection measures.

Climatic variability changes in the river flow patterns

Tana and Athi river basins are already experiencing significant variability in climatic conditions. The two basins are classified as Zone III (Odingo *et al.* 2002) which has a high risk for excess rainfall for both long (March-April-May) and short rainy (October-November-December) seasons. The same region has a high potential of rainfall deficit (Figures 8a-c).

Changes in rainfall and river discharges in the Athi basin

The examination of data from Dagoretti rainfall station revealed significant changes in the patterns of rainfall (Figure 8c). The frequency of occurrence of both flood and drought conditions have increased in the headwaters of the Athi River.

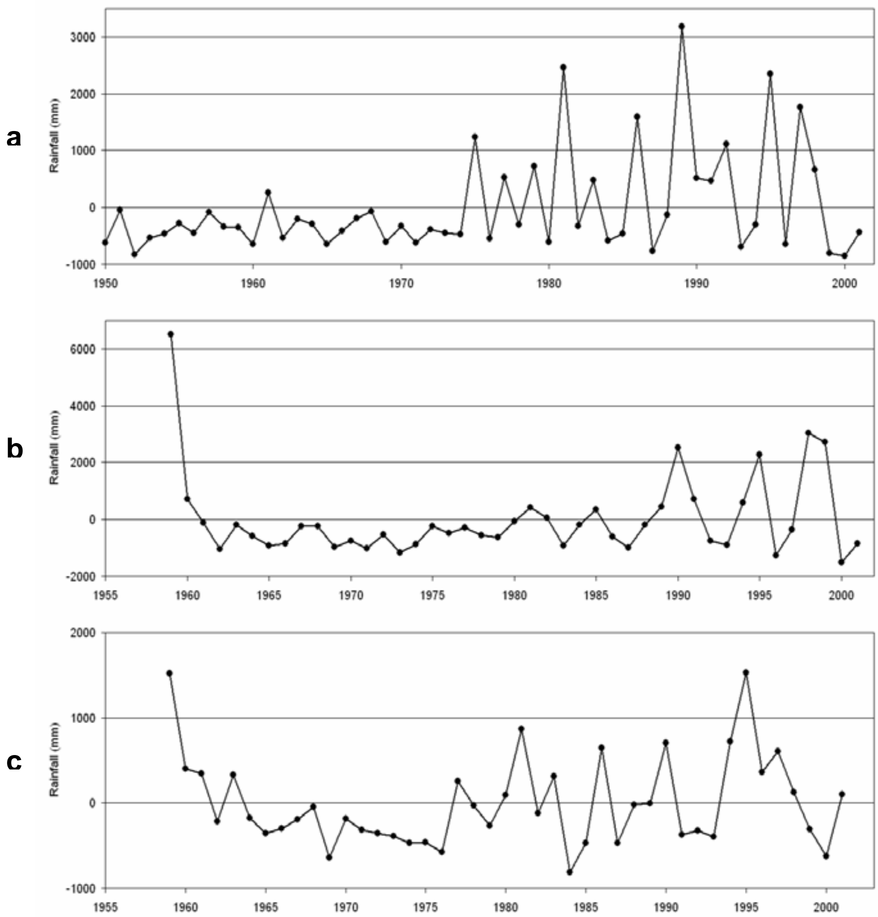

Figure 8. Deviation of annual total rainfall from the long-term mean (a) at Nyeri; (b) at Sagana; (c) at Dagoretti.

Good relationship also exists between rainfall variability and the variability of the main Athi river discharge (Figure 9). The mean flow of Tsavo River showed an increasing trend from 4 m^3s^{-1} in 1950's to 8 m^3s^{-1} in 1979. Recent field investigations showed that the present mean flow of Tsavo River is of the order 10 m^3s^{-1}. Since the Tsavo River receives springs flows fed by melting glaciers on Mt. Kilimanjaro, increased mean flow of the river could be attributed to the increased melting of glaciers on the Mt. Kilimanjaro. Within the main Athi River at Wamunyu, data indicated that there is an increase in mean river discharge. The mean flow rose from 20 m^3s^{-1} in 1960 to 80 m^3s^{-1} in 1977. The most recent river discharge data derived from the 2001-2004 period revealed that the mean flow of the Athi-Sabaki River is 73 m^3s^{-1} and during normal flow conditions, the flow varies from 7 to 650 m^3s^{-1} (Kitheka *et al.* 2003a-b). The 1976-2004 period represents a period of extreme variability in both rainfall and river discharge in the Athi-Sabaki River. This means the frequency of occurrence of low and high river discharges has increased.

Changes in rainfall and river discharge in the Tana basin

Rainfall data for Sagana and Nyeri rainfall stations, which represents the headwaters of the Tana River revealed significant changes in rainfall conditions (Figures 8a-b). Data for Nyeri station revealed that significant shift occurred in 1975-76 period. Extreme conditions have become more frequent, implying that the risk for flooding and drought is high (cf. Odingo *et al.* 2002).

The mean river discharge of the Tana has increased in response to increasing rainfall in the catchment areas found in Central Kenya. This increase is from 50 m^3s^{-1} in 1950's to the present value of 230 m^3s^{-1} (Kitheka *et al*. 2003b). The mean river discharge of the Tana at Garissa also showed an increasing trend from 75-270 m^3s^{-1} (Figures 10a-b). The 2001-2004 discharge data of the Tana River at Garsen showed the discharge to range from 60 to 730 $m^3 s^{-1}$ and the mean flow is 230 m^3s^{-1}.

Changes in sediment loads in the Tana and Athi river basins

The sediment load of the Athi-Sabaki River has increased tremendously from 50,000 $tons.yr^{-1}$ in 1950s (Figure 11a). Measurements carried out in the 2000-2003 period during normal flow conditions found the sediment load to be 5.7 x 10^6 $tons.yr^{-1}$ (Kitheka *et al*, 2003b). However, during extreme flow conditions associated with *El Nino* as in the period between 1997 and 1999, sediment load was 13.2 x 10^6 $tons.yr^{-1}$ (Munyao 2001). The 1997-1999 sediment load is relatively much higher than the 1960-1961 *El Nino* related rate of 8.5 x 10^6 $tons.yr^{-1}$ (Delft Hydraulics 1970). Within the Tana River, sediment load has declined due to damming in the Upper Tana basin (Figure 11b). The rate of sediment discharge has dropped from 1950s rate of 12 x 10^6 $tons.yr^{-1}$ to the present value of 6.8 x 10^6 $tons.yr^{-1}$ (Kitheka *et al*. 2003b). It is expected that there will be a further decline to less than 4 x 10^6 $tons.yr^{-1}$ if large dams are constructed at Grand Falls, Mutonga, Adamson Falls, Kora Falls and Usueni (GOK 1994).

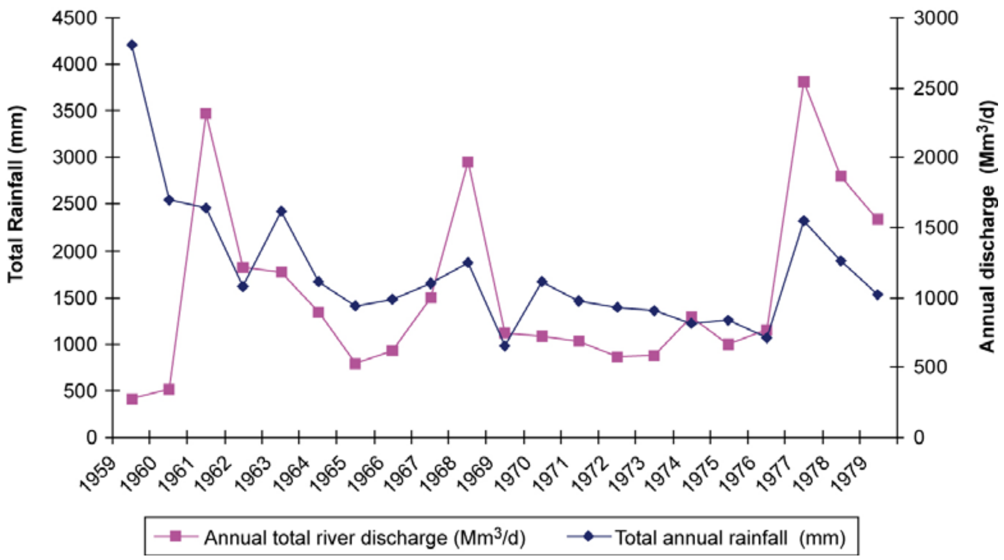

Figure 9. Athi-Sabaki mean river discharge and rainfall in Central Kenya.

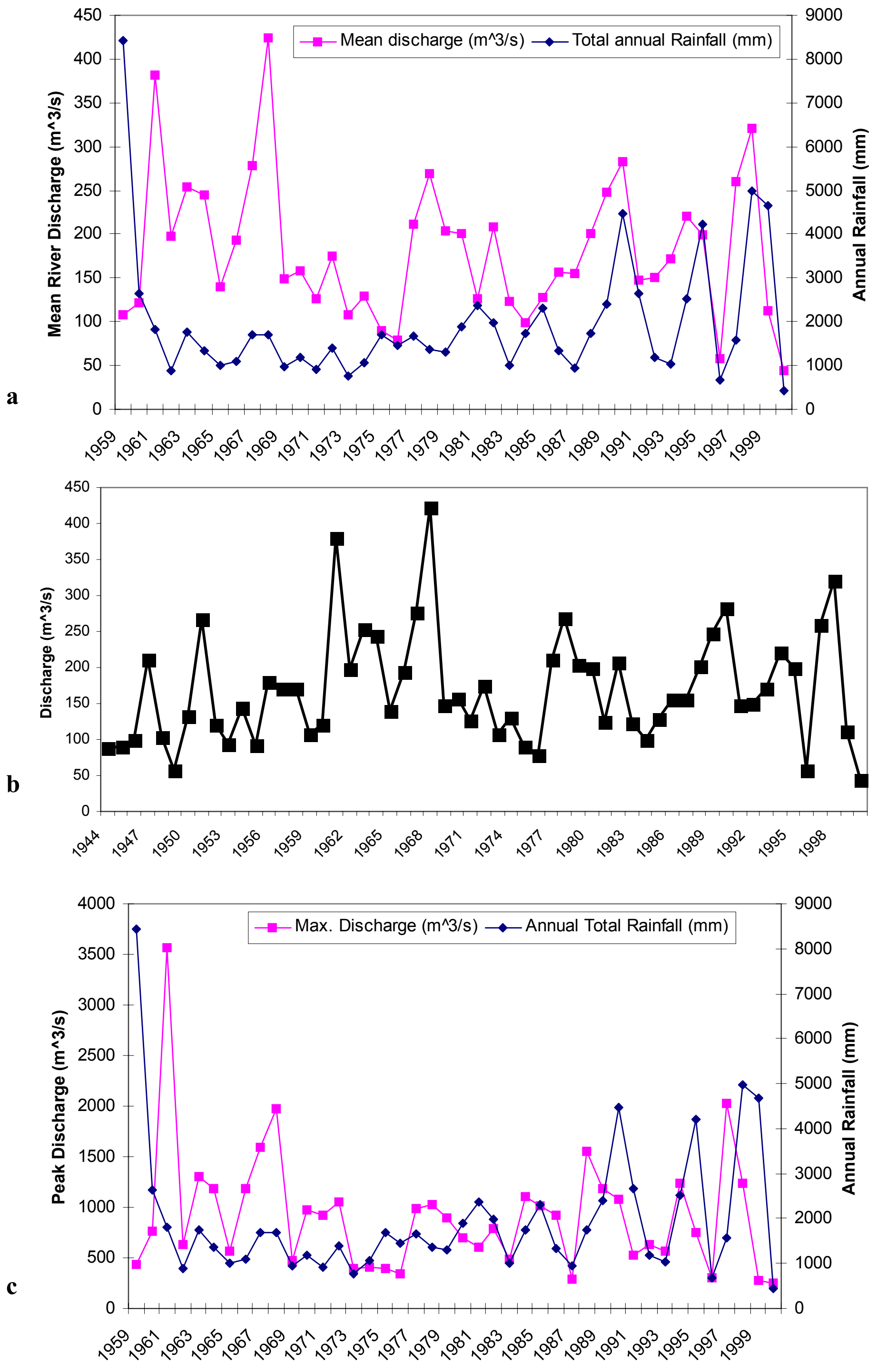

Figure 10. (a) Mean flow of the Tana River at Garissa and rainfall in Central Kenya; (b) Patterns of the Tana River discharge 1941-2001; (c). Peak river discharges in the Tana River at Garissa.

Data relating sediment loads to river discharge were obtained for Kiambere, Mutonga, Garsen and Grand Falls stations. The results showed that the variability in river discharge due to variability in rainfall subsequently causes significant variability in sediment load as shown in Figures 12a-b. Although a large quantity is retained in the reservoirs, the most important factor that regulates the sediment load is the variability in river discharge, which in turn is controlled by variability of rainfall in the catchment areas. Thus, climatic variability is an important driver of change in the two river basins.

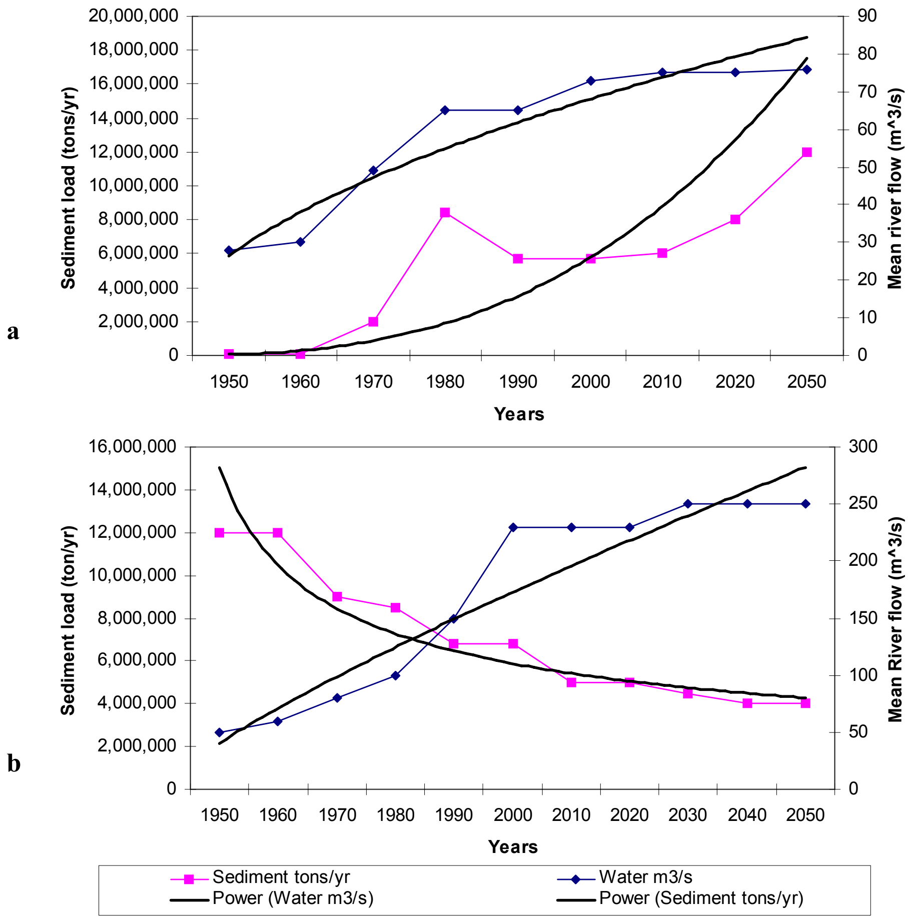

Figure 11. (a) Changes in mean annual sediment load and Athi-Sabaki river discharge; (b) Changes in annual sediment load and mean river discharge of the Tana River. Extrapolations to the years 2010-2050 are by this study.

Socio-economic drivers of damming and water abstraction

The changes in land use, sediment loads and river discharges are being propelled by a number of underlying drivers of change. In this regard, nine underlying drivers have been identified namely government policies, international trading practices and patterns, IMF/WB Structural Adjustment Programme, population growth, widespread poverty, governance and/or institutional failures, lack of accurate long-term data and information for decision-making, land tenure system and weak ownership rights, and economic motives.

Changes in river basin sediment and water discharge

Reduction of sediment load in the Tana River

The construction of seven forks scheme dams reduced the sediment load of the Tana River by about 56%. This has caused erosion of beaches at Kipini and Ungwana Bay (Kitheka *et a*l, 2003a). Although the current rate of sediment transport estimated to be 6.8 x 10^6 tons.yr^{-1} is still high, it seems to be below the threshold value for coastal erosion initiation. The pre-dam construction sediment load for the Tana has been estimated to be 12 x 10^6 tons.yr^{-1} (Ongwenyi 1983, 1985). In the Athi -Sabaki River sediment load range from 2 x 10^6 to 13.2 x 10^6 tons.yr^{-1} (Delft Hydraulics 1970; Munyao 2001; Kitheka *et al*. 2003a). The sediment load for both rivers shows significant inter-annual variability in response to rainfall fluctuations.

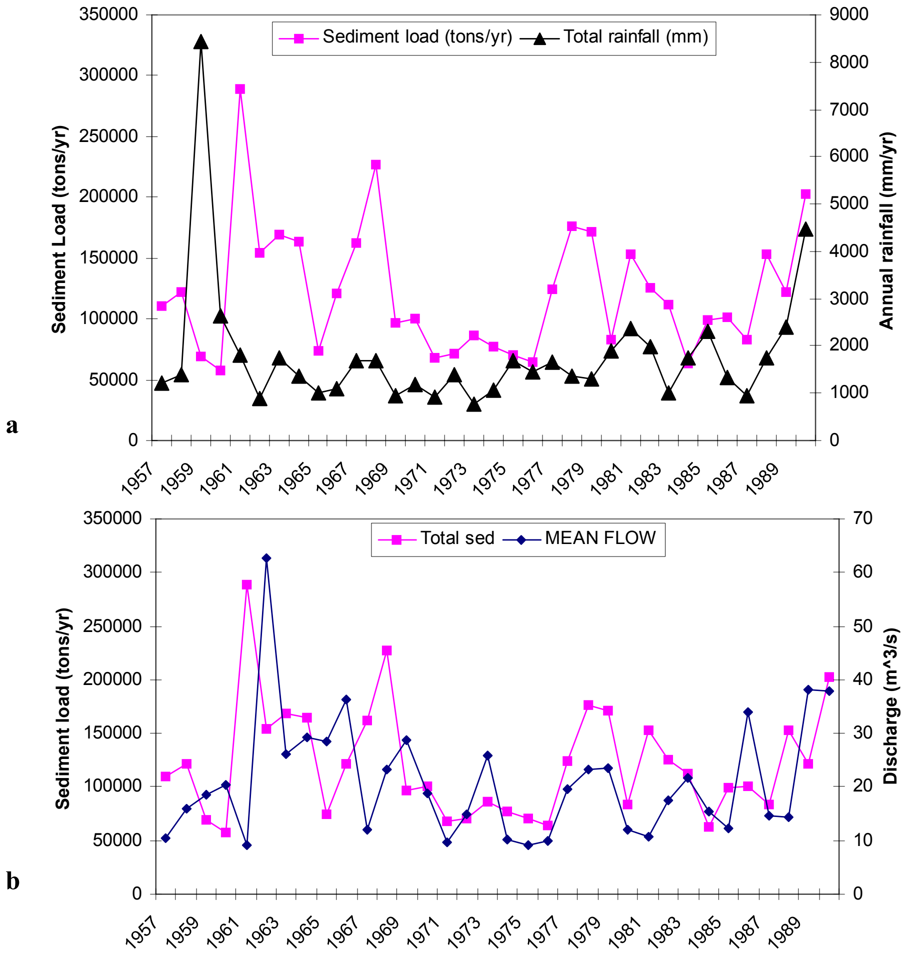

Figure 12. (a) Tana River sediment load variability at Kiambere in response to rainfall in Central Kenya; (b) Tana River sediment load and discharge variability at Kiambere in response to rainfall in central Kenya.

On long-term basis, there is a high possibility that the sediment load in the Tana River will reduce to below critical level, particularly if additional dams are constructed in the Upper Tana Basin (GOK 1979; GOK-JICA 1998a-c). At the moment it is difficult to establish precisely the critical level sediment load because of lack of data on bed load transport (usually assumed to be 10% of the suspended sediment load). But, it is certain that there has been a major reduction in bed load transport to the Tana delta.

Dams constructed in the Upper Tana Basin have also played a significant role in the regulation of flow of the Tana River. The construction of Masinga dam in particular lead to a drastic change in the flooding pattern of the river. The frequency of occurrence of 100-year floods in the Lower Tana Basin has reduced. However, because of the small size of the Upper Tana reservoirs, their effect on the frequency of occurrence of 1000-year floods is small since they fill up rapidly during rainy season. The flooding of the Tana River has beneficial effects since the lower Tana Communities depend on the flooding of the river for cultivation on the flood plains as well as the nourishment of dry season pastures for livestock kept by the pastoral communities (see GOK-TARDA 1982a-c).

Increased sediment discharge in the Athi River

Athi-Galana-Sabaki river sediment discharges into the Indian Ocean have increased from 50,000 tons.yr^{-1} in the 1950s to 8.4 x 10^6 tons.yr^{-1} in 1992 (Annandale 2002). During the 1997-1999 *El Nino* period, sediment load rose to 13.2 x 10^6 tons.yr^{-1} (Munyao 2001). The 2001-2003 data, which represent normal flow conditions, show that the current sediment discharge is 5.7 x 10^6 tons.yr^{-1} (Kitheka *et al*. 2003a).

The high sediment load of the Athi-Sabaki River puts a lot of strain on the infrastructure development, particularly those associated with water supply. The current high sediment loads means the proposed dams will have a short lifespan in the Athi-Sabaki river basin if their design capacities do not take into account the current high rates of sedimentation.

The impacts of high sediment loads are discernible at the mouths of both Tana and the Athi-Sabaki rivers. The red color of the two rivers is a manifestation of the high concentration of suspended sediments that emanates from the heavily cultivated lands in Central and Eastern Kenya. The removal of sediment from water in order to facilitate the supply of clean water to urban and rural areas is an expensive business in case of highly turbid waters (Annandale 2002). Water pumps and canals are usually clogged up with silt making it difficult to pump water and divert it for use in irrigation schemes. Sediments also silt up irrigation canals.

Assessment of coastal state changes and impacts

Reduced sediment load and increased water discharge in the Tana system

The reduction in sediment load and increased flow of the Tana River has caused important state changes at the coast. These include coastal erosion, declined water transparency and clarity, increased river freshwater supply, estuary deepening, decline in mangrove wetland cover and aquatic weeds-floating macrophytes, seawater intrusion, contamination of water supplies and reduced crop production and coastal biodiversity degradation and alteration of critical habitats.

Increased sediment load and water discharge in the Sabaki system

The increased sediment load in the Sabaki River is responsible for several state changes which include heavy siltation, beach accretion, increased turbidity, changing estuary morphology, increased river freshwater supply, mangrove wetland expansion, sand dunes migration, proliferation of algal blooms, water abstraction, biodiversity degradation and critical habitat alterations.

Conclusions

The most important impact of damming of the Tana River has been on sediment transport and river discharge. The trapping of sediments in the reservoirs has reduced the sediment load in the lower Tana basin from 12 x 10^6 tons.yr^{-1} in 1950s to the current rates of 6.8 x 10^6 tons.yr^{-1}. This represents a 56% decline in sediment load. The impact of damming on the Tana River flow has however been moderate since the discharge from the reservoirs is more-or-less equivalent to the normal flow of the river. This is partly due to the fact that the upper Tana reservoirs fill rapidly during the rainy season. The mean flows have however increased from 80 to 230 m^3s^{-1}, partly due to the regulation of the Tana river and also due to increase in rainfall variability in the upper Tana basin. In the Athi-Sabaki river basin, the mean flows have increased from 20 to 73 m^3s^{-1} due to increased rainfall in the catchment areas. However, the sediment load of the Athi-Sabaki River has increased tremendously from 50,000 tons.yr^{-1} in 1950s to the current rates, which range from 5.7 x 10^6 to 13.2 x 10^6 tons.yr^{-1}. This increase has been attributed to catchment degradation as well as to an increase in the capacity of the river to transport sediments to the coast.

The past and current rates of water abstraction in the Tana and Athi river basins are relatively low as they represent about 6% of the total annual flow. The low scale expansion of the area under irrigation in the lower Tana Basin has also kept water abstraction levels down. As a result, no major changes in the flow of the two rivers have resulted due to abstraction of river water. Major changes in the two rivers are mainly due to land use and climate change. Land use change, a product of population growth and expansion, has created the need for more land and as a result huge expanses of forestland have been cleared for timber and also to open land for cultivation and settlement.

The state changes at the coast include coastal erosion, siltation, turbidity, algal blooms, degradation of biodiversity, seawater intrusion and changes in freshwater supply.

Thus future research effort needs to be directed towards establishing the vulnerability of the two river basins to global climate and land use change. It is expected that changes in the climatic conditions will significantly modify the land use and hydrological conditions in the two river basins and future impacts along the Kenya coast will need to be established.

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