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PROFILE

Downstream and Coastal Impacts of Damming and Water Abstraction in Africa

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Abstract Anthropogenic factors associated with damming and water abstraction, and the resultant environmental pressures, are reviewed in six African river catchments using records and forecasts of climatic, demographic, and land-use change. Changes in the states of the flow regime through catchment drainage systems to the coastal sea are considered in conjunction with climate change and other human-induced pressures. The impacts of these changes on downstream and coastal environments and their communities are described in past, present, and future perspectives. Linkages between the issues and the pressures of damming and water abstraction are appraised and scientific, policy, and management responses proposed aimed at remedying existing and perceived future negative impacts. The study proposes that there is a need to integrate catchment and coastal management to account for the whole water flow regime together with its human dimensions. Management priorities relating to the operation of existing damming and abstraction schemes and planning of future schemes include the following: consideration of ways in which water discharges could be adjusted to provide improvements in downstream and coastal environmental and socioeconomic conditions; addressing the problem of sediment trapping impacting on the sustainability of dam reservoirs; and assessment of downstream and coastal impacts of future schemes in the light of climate change forecasts.

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Introduction

The impoundment and abstraction of freshwater in river systems for the purposes of power generation and agricultural irrigation has provided huge economic benefits at the global scale over the last 50 years. However, the environmental and social costs of large dams have been poorly accounted for in economic terms so that the wider long-term cost/benefit

Table 1 State changes in water and sediment discharges at the coast in the river systems studied over the last 25 years

Country	River catchments	Damming objective (s)	Annual water discharge	Mean water flow	Incidence of peak water flow	Annual sediment discharge
Morocco	Moulouya	Irrigation Power	Major reduction	Major reduction	Major reduction	Major reduction
	Sebou	Irrigation Power	Major reduction	Major reduction	Major reduction	Major reduction
Senegal	Senegal	Irrigation Power Food control	Major reduction	Major reduction	Major reduction	Minor reduction
Kenya	Tana	Power mainly	Minor reduction	Minor increase	Medium reduction	Medium reduction
	Athi-Sabaki	Undammed	No significant change	Medium increase	Medium increase	Major increase
Tanzania	Rufiji	Power (Gt.Ruaha trib.)	Minor/medium reduction	Medium reduction	Medium increase	Medium increse

[a]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. One of the catchments—the Senegal—is a transboundary system draining four countries

analysis to determine the true profitability of these schemes remains elusive (World Commission on Dams 2000). For instance, the construction of large dams has significantly reduced the threat of devastation from extreme flood events; however, they often alter seasonal flooding that is critical to the maintenance of floodplain agriculture, fisheries, pasture, and forests.

The regional Land-Ocean Interactions in the Coastal Zone (LOICZ) Basins core project (http://w3k.gkss.de/loiczbasins/Approach.htm) has explored linkages between principal human activities in river catchments and issues affecting downstream and coastal environments and communities. The AfriBasins study (Arthurton and others 2002) identified particular concerns over the coastal impacts of damming and water abstraction in the African region that were subsequently further explored (Arthurton and others 2006) as case studies covering six catchments in four countries; Morocco, Senegal, Kenya, and Tanzania (Table 1, Figure 1). In each of the catchments studied, riverine and coastal biodiversities, as well as livelihoods of their associated populations, have traditionally depended on freshwater inundations resulting from seasonal floods.

Data for each catchment is incomplete but, by considering the catchments collectively, trends emerge that allow comment on the wider implications of damming on river basin–coastal interactions. Although the main emphasis was on the impacts of damming and water abstraction, the case studies also considered the contributions that other socioeconomic and climate-related changes make to downstream and coastal changes and their environmental and socio-economic impacts. The results of the individual case studies are published, together with an overview, in LOICZ R & S Report No. 29 (Arthurton and others 2006) and synthesized in this article.

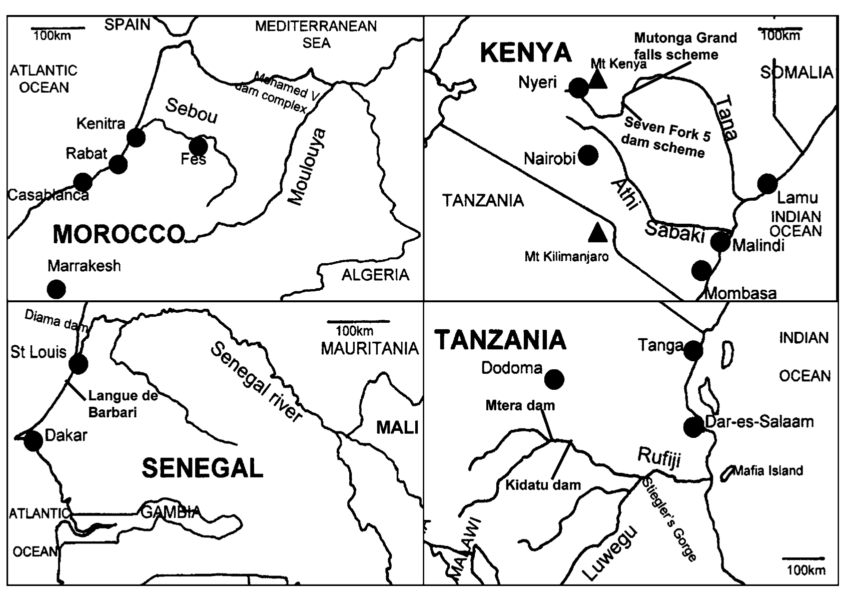

Fig. 1 Locations of the catchments studied

Catchment Descriptions

The Moulouya basin is the largest in Morocco, the river rising in the Atlas Mountains and flowing into the Mediterranean Sea. The lower reaches flow through a fertile floodplain with a highly developed agriculture to an estuary of rich biodiversity. The Sebou River, together with its tributaries, the Ouerrha and the Inaouene, drains the Middle Atlas, Rif, and Prerif Mountains and flows to the Atlantic Ocean through a wide coastal floodplain (the Rharb) that is Morocco's most important agricultural area.

The Senegal basin is a transboundary system. The Senegal River rises in the highlands of Guinea, and flows through Mali and then between Mauritania and Senegal to the Atlantic Ocean through a delta bounded to seaward by a southward-extending sand spit, the Langue de Barbarie. A large population practices riparian agriculture, grazing and fishing, for which seasonal flooding has been traditionally important.

The Tana River, the largest in Kenya, drains the highlands of Mount Kenya and, in its lower reaches, crosses a wide, arid coastal plain before discharging into the Indian Ocean through an extensive delta, fringed to seaward by sand dunes. The delta and its extensive floodplain support a large community of farmers, fishers, and pastoralists as well as a rich biodiversity. Seasonal flooding of the Tana's wetlands has traditionally formed a vital element in the maintenance of these resources.

The Rufiji River, the largest in Tanzania, is fed by three main tributaries: the Great Ruaha, Kilombero, and Luwegu Rivers, which together drain the central part of the country. The Rufiji discharges to the Indian Ocean through an extensive delta that hosts eastern Africa's largest mangrove forest, part of an extensive Ramsar site including the island of Mafia and its associated marine park, with intertidal flats, seagrass beds, and sandbars all ecologically interlinked with the flow of the Rufiji River. The Rufiji flood plain and delta supports a large community dependent on agriculture and fisheries as well as the harvesting of forest products. Seasonal flooding makes an important contribution to the maintenance of the wetland resources including its biodiversity.

Socioeconomic Drivers

Dams are built to manage flood waters and harness water for hydropower, potable water, industry, and agricultural irrigation (World Commission on Dams 2000). In common with the rest of the world, since 1950 population pressures and economic growth in Africa have resulted in a matching increase in the number and size of dams built making a major contribution to power supply and agricultural irrigation. Dams are promoted as an important means of meeting existing and future needs for water and energy services as well as a long-term strategic investment to deliver multiple benefits that include regional economic and industrial development. Besides socio-economic benefits, damming has also produced some serious negative impacts fragmenting river systems and displacing communities. Other impacts include debt burden, destruction of important ecosystems and fishery resources, and the inequitable distribution of costs and benefits.

This study focuses on observed and anticipated downstream and coastal impacts of damming for six African catchments. The principal drivers of dam building for these catchments are shown in Table 1. The LOICZ-Basins approach utilizes the DPSIR (Driver-Pressure-State-Impact-Response) analytical and response framework (OECD 1993, Ledoux and others 2004) (Figure 2) that can be used to explore and organize available information from multiple sector and discipline sources. The DPSIR framework (Figure 2) is based on a concept of causality: human activities (*Drivers*) exert *Pressures* on the environment and change its quality and quantity of natural resources (*State*). State changes *Impact* society that *Responds* through environmental, economic, and sectoral policies. The framework is iterative so that it can consider change over time as scientific understanding of environmental problems increases, and as societal values evolve.

This article considers (1) environmental *pressures* of dam building in relation to other pressures such as land-use change and climate change, leading to (2) *state changes* in the functions and processes of ecosystems and (3) *impacts* on human welfare that require (4) policy *responses* to design management options to modify and/or mitigate the originating drivers and pressures of change.

Pressures Affecting Downstream and Coastal Environments

Damming and Water Abstraction

Impoundment of water in five of the six catchments studied, principally for power generation and irrigation, has enabled urban, industrial, and agricultural growth with considerable socioeconomic benefits at national, though not necessarily catchment, scales.

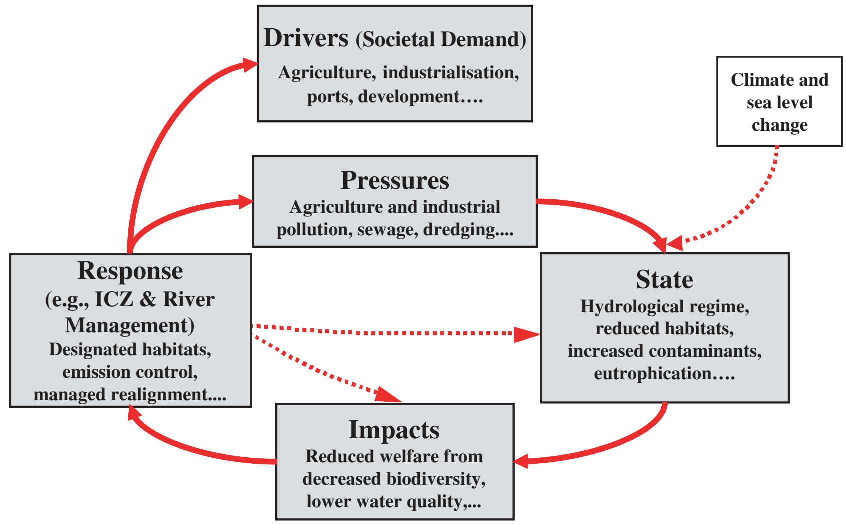

Fig. 2 The DPSIR analytical and response framework (after OECD 1993)

In Kenya, power generated from the Seven Forks series of five dams constructed in the upper Tana basin between 1968 and 1988 forms the bulk of the total national electricity output. On the Great Ruaha River tributary of the Rufiji in Tanzania, there are two reservoirs (Mtera and Kidatu) that have a combined hydropower generation capacity of 284 Mw, and the Kihansi reservoir on the Kilombero tributary has a capacity of 180 Mw (RUBADA 2004). In Morocco, damming in the Moulouya and Sebou basins has allowed a major expansion in industrial and agricultural development (Snoussi and others 2002). However, in Senegal the benefits of the Manantali and Diama dams on the transboundary Senegal River are controversial. These dams were planned to irrigate 375,000 ha of former floodplain, facilitate navigation, and generate 800 Gwh/yr, but only power generation seems likely to be viable in the long term (Hamerlynck and others 2000).

In most of the catchments, the dams control floodwaters so that damage and loss of life and livelihood caused by major flooding episodes are greatly reduced. In the Sebou basin in Morocco, the Al Wahda dam can reduce the flood volumes at the Rharb plain by more than 95%, avoiding an economic loss estimated at close to US$27 million/yr (Ministère de l'Agriculture 1994). The Grand Falls dam on the Tana River, Kenya is designed to allow managed floods to maintain inundation of the downstream floodplain (Acreman 1996). The Diama dam in Senegal is an exception because its barrage is raised to allow the discharge of floods from around July until November and thus provides no protection against flooding in the coastal town of St. Louis 27 km downstream.

Demands for power and irrigation water are set to continue increasing, resulting in new schemes being commissioned or planned. Within Kenya's upper Tana basin, sites have been identified for the construction of six additional dams for hydropower generation (Table 2). The proposed Mutonga–Grand Falls scheme lies downstream of the five existing Seven Forks dams and would be the last stage in the control of the Tana's waters, with no appreciable downstream addition to the river's flow except during extreme events (IUCN 2003). In Tanzania, sites for a further eight dams in the Rufiji catchment have been proposed, including one at Stiegler's Gorge, some 230 km upstream from the coast. Besides a target generating capacity of 2100 Mw, the plans allow for a major reduction in the frequency of major floods, the development of irrigated agriculture in the lower basin, and water supply to Dar es

Table 2 Characteristics of existing the Seven Fork scheme dams and planned reservoirs in the Tana basin, Kenya

Reservoir	Year of completion	Gross volume (Mm^3)	Surface area (km^2)	Catchment area (km^2)	Mean river discharge (m^3/s)
Masigna	1981	1,560	113	7335	97.2
Kamburu	1975	147	15	9520	149.5
Gitaru	1978	20	3.1	9520	120.9
Kindaruma	1968	16	2.4	9807	155.9
Kiambere	1988	315	13	11975	121.8
Karura	Planned	74	8		
Mutonga	Planned	1580	46		
Masinga-Grand Falls	Planned	3600	119		
Usueni	Planned	330	26		
Adamson's Falls	Planned	1730	102		
Kora Hills	Planned	3800	190		

Source: GOK-TARDA (1982a, b, c)

Table 3 Trapping rate and lifespan calculated for the reservois in Morocco (Snoussi and others 2002)

Rivers	Dam	Year of Completion	Surface area of catchement(km^2)	sediment flux (10^6t/yr)	Rate of trapping (%)	Lifespan (years)
	Allal Fassi	1990	5400	2.6	85	42
	Al Wahda	1996	6190	16	96	374
Sebou	Idriss 1st	1973	3680	2.6	99	540
	El Kansera	1935	4542	1.9	94	195
Moulouya	Mohamed V	1967	49920	12	93	59

Salaam (RUBADA 2004). In the Moulouya basin, at least four new dams are planned to limit flood discharge from the Mohamed V dam and satisfy long-term demands for drinking and industrial water and irrigation (Conseil Supérieur de l'Eau 1990) (Table 3).

In addition to water impoundment by damming, there has been a significant increase in recent years in the abstraction of water for irrigation. In the Rufiji catchment, the scope, impacts, and management of such practices in the Usangu basin above the Mtera and Kidatu dams on the Great Ruaha tributary are a subject of current study (Franks and others 2004).

Land-use Change

Although damming and water abstraction in catchments make a major contribution to downstream and coastal environmental pressures with related socioeconomic issues, there are other contributors both at catchment and local coastal levels that need to be understood in order to isolate the specific effects of damming and abstraction. Pressures due to changes in land-use are especially important and have also intensified over the last 50 years driven by a range of human activities at local to global scales. For instance, in Kenya (J. Ochiewo, personal communication) and Morocco (Snoussi and others 2002), poverty and a range of governance issues, national development policies, and external trading agreements are leading to deforestation and cultivation of marginal lands that exacerbate soil erosion and lead to increased rates of water and sediment fluxes. An important economic consequence of increased sediment fluxes is a reduction in the effective volumes of water storage because of sediment trapping with a concomitant reduction in the lifespan of dam reservoirs.

Climate Change

Changes in patterns of precipitation and evaporation are important factors affecting damming and freshwater discharge and are the net effects of natural variability in the earth's climatic system and changes induced by human disruption or alteration of that system. All the catchments studied lie within areas where climate change induced increases in temperatures and changes in rainfall are forecast according to global warming scenarios (IPCC 2001). Projections for Moroccan catchments to 2020 (Secretariat d'Etat chargé de l'Environnement 2001) foresee a decrease of about 4% of the annual volume of precipitation and 15% of surface waters and an increase in the frequency of floods and drought. There is evidence of increased rainfall in the Upper Rufiji from analyses of long-term rainfall data in conjunction with projected climatic scenarios (Mwandosya and others 1998). For Kenyan catchments, extreme conditions are likely to become more frequent, implying increased risks of flooding and drought (Odingo and others 2002). In Senegal, the southerly migration of the 400-mm isohyet (a line joining points of equal precipitation on a map) by nearly 100 km in the north of the country between 1931 and 1990 is evidence of drought conditions becoming increasingly prevalent in the Senegal river catchment.

Downstream and Coastal Pressures

Attributing downstream and coastal state changes to damming and abstraction in catchments requires an understanding of the nature and scale of additional pressures acting locally in downstream and coastal environments. These local pressures include human activities and marine-related pressures, including sea-level rise. In Tanzania, a major issue is the unsustainable use of coastal living resources in the Rufiji lower basin and delta, including overharvesting of woodland and mangrove resources for fuel wood, charcoal production and construction poles, and the clearance of mangrove in favor of agriculture, and which also impact biodiversity that those resources support. Such local, human-generated pressures may be the dominant cause of state changes in these downstream and coastal environments. In considering marine-related pressures, none of the case studies has identified specific evidence of sea-level change relative to coastal land levels. However, in the case of the Senegal estuary, variations in the rates of marine wave-induced longshore sediment transport appear to play a key role in the morphodynamics of the Langue de Barbarie sand spit.

State Changes

Damming and water abstraction cause major changes in the state of water and sediment fluxes in the case-study catchments, but change also results from pressures of land-use change and climate change and from local downstream and coastal pressures (e.g., undammed Athi-Sabaki). Riverine inputs to the coastal zone—nutrients and sediment as well as fresh water—are critical to many coastal ecosystems. A summary of the present state changes within the catchments studied is given in Table 1.

Changes due to Damming and Water Abstraction

Although there are developmental benefits from damming and water abstraction at national and sub-regional scales, the pressures of these activities also cause significant long-term changes in the natural flows of water and sediment within catchments that may have negative downstream and coastal impacts. Changes include not only major reductions in the quantities of water and sediment transported to the coast and coastal sea as a result of impoundment, but also changes in temporal patterns of delivery of those fluxes. Reductions in the incidence of peak water flows are usual. In the case of the Tana in Kenya, there is an increased mean rate of flow because of controlled discharge. Although prior to damming, peak flows have constituted a threat of damaging floods, the delivery of pulses of freshwater at key times of year have been an important element maintaining floodplain agriculture, deltaic mangrove ecosystems, and shrimp or prawn production in estuaries, as illustrated by the Rufiji system in Tanzania.

Damming in the Moroccan basins illustrates the scale of state changes. In the Moulouya, although very variable, the total annual average volume of water carried to the Mediterranean, from which water is diverted for irrigation, was close to 1 billion cubic meters, which has been reduced by 89% after construction of the Mohamed V dam. The corresponding fluxes of suspended sediment show a reduction of 94%, which is illustrated by the retention of sediments by the dam whereby 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

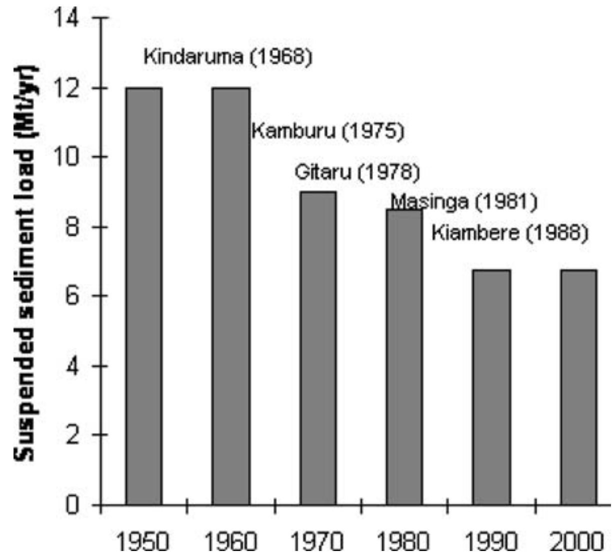

Fig. 3 Changes in annual suspended sediment load of the Tana River, in relation to the commissioning of dams in the upper Tana basin.After Kitheka and others (2003)

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. In Kenya, the construction in 1989 of the Masinga (furthest downstream) dam in the upper Tana basin led to a major change in the pattern of river flooding with a reduced frequency of major floods in the lower basin. Small flood events are now absorbed effectively, although high floods, such as those associated with El-Nino events, are not caused by the limited capacity of reservoirs. The sediment load has also declined from a predamming recorded rate of 12 Mt/yr to 6.8 Mt/yr (Figure 3). The reduction in annual water discharge from the Tana because of abstraction for irrigation in the lower basin is less marked than in the Moroccan rivers, but a significant part of this state change is caused by transfer of water from the upper Tana basin to the Athi-Sabaki system for water supply to Nairobi.

The commissioning of the Diama (at the head of the estuary) and Manantali (upper basin) dams on the transboundary Senegal River has significantly changed the regime of fluctuating levels and flows. The Diama dam initially reduced by 32% the flow of the Senegal River in the lower basin that is now mitigated by controlled release from the Manantali dam upstream to a 20% reduction. A raise in the low water level of the river from the construction of the dams has translated to a rise in the water table in the lower basin by an average of 200–500 mm (Thiebaux and others 1992). The seasonal emplacement of the Diama dam has led to a profound change in the state of tidal dynamics, where the effect of the tide was felt far into the lower basin before the construction of the dam that now forms the tidal limit throughout the dry season inhibiting the intrusion of seawater. The construction of longitudinal embankments that laterally constrain the Diama reservoir has led to significant hydrological changes in the adjoining former floodplains, now converted for irrigated agriculture, while downstream estuarine land has become hypersaline, turning the Diawling National Park into a saline desert (Hamerlynck and others 1999).

Changes due to Climate and Land-use Changes, Including Deforestation

Contributions to state changes in water fluxes due to climate change are difficult to isolate and quantify, particularly in dammed systems. Increases in temperature are likely to reduce fluxes by increasing rates of evaporation from both land and reservoir surfaces, although runoff from land surfaces is likely to reflect patterns of precipitation (e.g., extreme events) and surface retention potential due to vegetation cover. Although lower rainfall and higher temperatures in dammed systems might reduce the volume of water stored, their contributions to downstream and coastal state change may be masked by the regimes of dam discharge and water abstraction within the catchment. In the Moroccan catchments, increased extreme climatic events are reported to increase soil wash and sediment mobilization, exacerbating the serious problem of sediment trapping in reservoirs and reducing their volume, efficiency, and lifespan (Snoussi and others 2002).

Contributions that changes in land use make to changes in water and sediment fluxes reflect a range of socioeconomic drivers including population growth. The undammed Athi-Sabaki system provides evidence of increases in water runoff and major increases in sediment load due in large part to deforestation and changes in agricultural practice, although accompanied by increased rainfall. An increased frequency of flooding of the Rufiji appears to be linked to deforestation for agriculture in the upper catchment (Bantje 1979), although this is countered to some extent by the increasing multiuse demand for water in the upper catchment, notably the Great Ruaha tributary (Franks and others 2004).

Although there is a general perception that forest clearance and the spread of cultivation are major contributors to increases in the rate of water runoff, the mobilization of sediment in catchments, and sediment loads being discharged, it may prove difficult to distinguish the contribution of such changes from those caused by increased rainfall. In Morocco, land-use change is a major contributor to increased sediment flux, which is exacerbated by an increasing frequency and severity of extreme rainfall events (Snoussi and others 2002). Research is needed to clarify the roles of land-use and climate change in changes to fluxes in dammed and undammed catchments alike.

Land-use change itself appears to contribute to local climate changes. Two of the main physical effects of land-use change are to change the albedo (reflectivity) of the earth's surface and the Leaf Area Index (LAI) representing the amount of vegetation contributing to plant transpiration. Regional climate modeling 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, personal communication). Also, changes in albedo on the order of 20% (within the bounds of natural variability) could lead to rises in temperature of 3–4°C and a drying of the continental interior. Although no evidence of these effects is apparent in the case studies here, as land-use change accelerates, its effect on local climates and the hydrological cycle may become significant.

In summary, the principal state changes in the catchments studied are as follows:

- In systems where the impounded water mainly serves power generation (e.g., the Tana in Kenya), there has been only a minor reduction in water discharge at the coast, although with major reductions in sediment discharge and incidence of peak flows. These trends may continue if the proposed new Mutonga–Grand Falls dam is constructed, although plans are being considered to introduce short-term, high-release flows that will simulate the natural, bi-annual flooding events (Acreman 2003).
- In systems where irrigation as well as power has been a priority (e.g., the Moulouya and the Sebou in Morocco and the Senegal River), both sediment and water discharges have shown major reductions, as well as mean water flows and incidence of peak flows that are set to continue, particularly as new dams are commissioned. In the Rufiji system, damming and abstraction have made relatively minor contributions to impacts at the coast. For the Senegal system, the Governments of Mali, Senegal, and Mauritania have signed a Water Charter that includes the release of the annual flood from the Manantali dam when sufficient water is available—normally 9 years out of 10 (Acreman 2003).
- The undammed system of the Athi-Sabaki has shown a medium increase in the incidence of peak

flows and a major increase in sediment discharge, both apparent consequences of climate and, particularly, land-use change in the upper catchment. These trends are set to continue until effective catchment management is implemented.

Impacts in Downstream and Coastal Areas Related to Catchment, and Other Pressures

The case studies reviewed downstream and coastal impacts and issues for the studied catchment to coastal sea fluxes 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 trends of these impacts. This review was carried out separately by two groups of people, namely, scientists who had collected/collated the data and representatives of major funding bodies and policymakers. The latter group included 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 geomorphological issues were generalized by country, as compared with the more detailed science-based assessments. The results of this twin-track ranking process are shown in Table 4, which also includes one noncoastal impact: sediment trapping in dam reservoirs.

For some of the key issues, particularly downstream flooding, saltwater intrusion, and sediment trapping, there is close agreement between the perspectives of scientists and policymakers. Policymakers did not rank the issues of changes in water discharge and water supply and put less emphasis on sediment discharge than did scientists illustrating that, in this African situation, there are significant perception gaps between scientists and policy-oriented advisers on a number of key issues. The outputs from Table 4 suggest that scientists and policymakers perceive the needs and issues relating to downstream effects of damming to be different and, in particular, their appreciation of cause and effect linkages, with scientists focussing on processes whereas policymakers focus more upon management contexts (i.e., knowledge *versus* implementation). It would also appear that policymakers, although recognizing the need to understand future scenarios, have a poor appreciation of trends commensurate with probable changes arising from damming and other factors.

A key part of the scientific review process was an assessment of the validity of perceived causal linkages that connect the downstream and coastal impacts and issues to specific pressures and their drivers in the catchments and that are important to determine a relevant remedial strategy. Consideration of information derived from the undammed Athi-Sabaki system was an important element of this assessment, as was knowledge of climate and land-use pressures in the catchments and socioeconomic and marine pressures acting directly (locally) on the coastal zone.

The impacts of changes due to the pressures of damming and water abstraction are of particular significance, considering that all of the dams in the catchments studied have been constructed and commissioned within the last 60 years. Within this short time-span, major reductions in the availability and discharge of freshwater at the coast have had immediate effects. In the case of the Tana, where it is estimated that in excess of 1 million people depend on the river's flooding regime for their livelihoods (IUCN 2003), there has been a severe negative impact on agriculture and fisheries of the lower basin and delta, and prawn fisheries of the adjoining Ungwana Bay, dependent on seasonal pulses of freshwater from the Tana, have also been degraded. Secondary effects (e.g., salinization of estuarine soils and intrusion of seawater into estuarine groundwater tables affecting agricultural productivity and the health of mangrove forests in estuaries) have been manifest within a few years, for example, below the Diama dam on the Senegal river (Diawara 1997).

The impacts of reduced sediment transport have been slower to be manifest. These include the progressive impoverishment of downstream floodplains through reduced flood siltation, and the adjustment of river beds to diminished bedloads and coastal erosion caused by reduced sediment discharge, for example, at the mouths of the Moulouya and Tana. Changes in the flooding regime of the lower Senegal basin after the commissioning of the Manantali and Diama dams have led to negative impacts, including a major decline in fish catches in the delta, salinization and soil loss in the floodplains, invasion of reservoirs by reeds and water weeds, and the proliferation of diseases affecting both human and livestock health (Hamerlynck and others 2000).

The current trends of change in all of the dammed catchments suggest that the physical adjustments to the water fluxes are incomplete and that the downstream, deltaic, and coastal sea environments will continue to change as a result of damming. Little is known of the likely consequences of the existing damming and water abstraction over the long term or the ways in which catchment systems may respond to further damming, as is planned for the Moroccan, Tana, and Rufiji systems. In the case of the Rufiji, the construction of the proposed dam at Stiegler's Gorge, while reducing the

Table 4 Synthesis of downstream and costal issues

<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 colspan="2"></td><td></td><td colspan="2"></td><td></td></tr>
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<tr><td>2. Changes in sediment discharge</td><td>Policy and decision makers</td><td colspan="2">0</td><td>0</td><td colspan="2">1</td><td>2</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>
<tr><td></td><td>AfriCat scientists</td><td>0</td><td>0</td><td>3 ⇑</td><td>2</td><td>1</td><td>3 ⇑</td></tr>
<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>
<tr><td></td><td>AfriCat scientists</td><td>1 ⇑</td><td>2 ⇑</td><td>3 ⇑</td><td>2</td><td>1</td><td>2 ⇑</td></tr>
<tr><td>5. Costal 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>
<tr><td>Coastal accretion</td><td></td><td>0</td><td>0</td><td>2</td><td>1</td><td>3</td><td>0 ⇑</td></tr>
<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>
<tr><td>Estuary shallowing</td><td></td><td>3 ⇒</td><td>2 ⇒</td><td>2</td><td>1</td><td>2</td><td>1 ⇑</td></tr>
<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>
<tr><td>Habitat</td><td>Policy and decision makers</td><td colspan="2">1</td><td>1</td><td colspan="2">1</td><td>1</td></tr>
<tr><td>Fisheries</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>Agriculture</td><td></td><td>3 ⇑</td><td>3 ⇑</td><td>3 ⇑</td><td>2</td><td>1</td><td>2</td></tr>
<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>
<tr><td>Water supply</td><td></td><td>3 ⇑</td><td>3 ⇑</td><td>3 ⇑</td><td>2</td><td>3</td><td>2 ⇑</td></tr>
<tr><td>7. Loss of biodiversity</td><td>Policy and decision makers</td><td colspan="2"></td><td></td><td colspan="2"></td><td></td></tr>
<tr><td></td><td>AfriCat scientists</td><td>2 ⇑</td><td>3 ⇑</td><td>2 ⇑</td><td>2</td><td>2</td><td>2</td></tr>
<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>
<tr><td></td><td>AfriCat scientists</td><td>3 ⇑</td><td>3 ⇑</td><td>1 ⇒</td><td>3</td><td>n/a</td><td>n/a</td></tr>
<tr><td>9. Adaption strategies</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Capacity</td><td>Policy and decision makers</td><td colspan="2">2</td><td>1</td><td colspan="2">1</td><td>1</td></tr>
<tr><td>Management</td><td>AfriCat scientists</td><td colspan="2">2</td><td>2</td><td colspan="2">1</td><td>1</td></tr>
</table>

[a] Rankings (3=high; 0=low; n/a=not applicable) indicating the perceived importance of issues according to AfriCat scientists and representatives of policy and decision makers. Arrows indicate trends (increasing ⇑ or stable (⇒) where identified and/or feasible. Blank cells indicate that no assessment was made. * indicates river without significant existing dams

impact of periodic damaging floods, is likely to have a negative impact on the downstream, deltaic, and offshore ecosystems and the communities that they support by reducing the regenerative benefits that seasonal flooding brings—introducing sediment and nutrients and, in the delta, reducing salinity—unless environmental flows are introduced.

Responses

The scientific linkages between the catchment pressures, the flux states and the downstream and coastal impacts and issues that have been established by employing the DPSIR approach provide the basis of the recommendations for policy and management. The recommendations for responses that are appropriate to the management of the pressures and their impacts are summarized by country and issue in Table 5. This table includes comments as appropriate on the anticipated benefits accruing from such actions.

As in most coastal countries, catchment and coastal management responsibilities are divided among many different organizations, often focused to specific sectoral goals that lack effective linkage between environmental and developmental objectives. The case

Table 5 Recommendations for response actions and their presumed benefits for downstream and costal issues in the AfriCat countries

Issue	Response actions and (in italics) their presumed benefits			
	Morocco	Senegal	Kenya	Tanzania
Water discharge	Implementation of intergated water management plan to statisfy the seasonal needs of agricultural, drinking, and industrial water	Releases from the dam to maintain freshwater flows to the estuarine zone*.	Implementation of water conservation strategies and planned releases from the dams to achieve environmental flows*. Pla for possible increased rainfall variability.	Maintain the seasonal flooding regime and plan for posssible increasd rainfall*.
	Decreasing of water conflicts between users of the costal areas.	*Recharge of the coastal water table with freshwater and restoration of mangrove eco-systems.*	*Security of downstream freshwater supply; related improvements in agriculture and biodiversity.*	*Maintain the productivity of floodplan and delatic agriculture; also of lake and prawn fisheries.*
Sediment discharge	Limit the effect of the marine sedimentation within the estuary by dredging.	Limit the effect of the marine sedimentation within the estuary by dredging.	Implementation reforestation programmes in the upper tana and Athi-Sabaki catchments*.	Implement reforestation and soil conservation in upper catchment.
	Improvement of estuarine navigation Fixation of sand dunes	*Possibility of river navigation*	*Decreased soil erosin and improved agriculture in the catchment areas.*	*Reduced sediment accretion on the delta front.*
	Combat coastal erosion induces by the river sediment abstraction		Implement soil conservation measures*.	Maintain suspended sediment discharge.
			Reduced freshwater turbidity and coastal sediment discharge.	*Positive impact on Prawn fisheries and floodplain agriculture.*
Downstream flooding	Control of the water releases from dams.	Creation of diversion zones and canalization of the estuary.	Implementation of environmental flows in discharges from the upper Tana dams*.	Consisder alternative site (on the Luwega tributary) to that proposed at Stiegler's Gorge.
	Security of freshwater supply for downstream/coastal communities.	*Reduction of flood risk in the town of St. Louis.*	*Improved agriculture through partial reinstatement of seasonal flooding in the lower tana basin.*	*Serious floods reduced but maintaining beneficial seasonal flooding downstream.*
Salinisation of soils	Drainage and leaching of soils with high salinity.	Increased dry-season freshwater–discharge from the Diama dam.		
	Limited and dependant on the availability of rainfall.	*Enhanced fresh ground-water flux, through the delta area, improving the agricultural potential.*		
Saline intrusion	Construction of dams (Barrage de–Garde) at the limit of marine intrusion.		Dry-season release from dams to flush estuaries*.	Need to maintain freshwater flow through the lower basin/delta.
	Limitation of the salinisation of coastal aquifers.		*May be incompatible with hydro-power generation and water supply plans.*	*Promotion of healthy mangrove forest.*
			Construction of barrages in the Tana delta.	
			Reduced intrusion but costs likely to outweigh benefits.	

Table 5 Continued

Issue	Response actions and (in italics) their presumed benefits			
	Morocco	Senegal	Kenya	Tanzania
Coastal morpho-logical changes	Dredging of channels (Sebou).	Monitor littoral sediment transport, assessing impacts of climate change. Monitor impacts of, engineered changes to Senegal River mouth.	Implementation of sediment load reduction measures in the Athi-Sabaki system*.	Restriction and regulation of mangrove clearance.
	Improvement of navigation but would have to be done frequently (costly).	*Improved management and forecasting of shoreline change.*	*Reduced degree of shoreline change and improved tourism amenity at Malindi and reduced siltation of Malindi harbor.*	*Reduced vulnerability to shoreline erosion.*
Socioeconomic issues	Promote awareness among farmers to combat soil erosion, water pollution (fertilizers) and water loss (irrigation)*.	Improved planning and regulation of urban development at St,Louis.		Reappraise ‘‘villagization’’ policy in the lower Rufiji*. Reduce harvesting of woodland resources in Rufiji floodplain and delta*.
	Improvement of quality of life.	*Reduced impact on urban areas of River flooding.*		*Improve sustainability of agriculture and forest products.*
Biodiversity loss—coastal ecological changes	Medwetcoast Project for the conservation of the coastal wetlands of the Moulouya. Planning environmental flows downstream of the dams.	Adoption of measures to facilitate fish migration between the Senegal estuary and river basin.	Creation of Tana Delta. Conservation Area and re-forestation of degraded mangrove wetlands.	See Adaptation strategies (below).
	Rehabilitation of the ecological values and biodiversity.	*Arresting a decline in the state of estuarine fisheries.*	*Improved biodiversity and sustainability of livelihood systems.* Maintain dry-season discharge*. *Sustainability of marine fisheries.* Implementation of soil conservation in Athi-Sabaki*. *Reduced threat to sensitive marine ecosystem.*	
Sediment trapping	Reforestation of important areas in the Sebou and Moulouya basins.		Implement soil conservation measures including reforestation of upper Tana and Athi-Sabaki catchments and construction of sediment traps and small sacrificial dams*.	
	Decreased runoff and soil erosion.		*Increased lifespan of dams.*	
	Dredging of Mechra Homadi reservoir (Moulouya).		Dredging of reservoirs.	
	Increased lifespan of dams but a costly option.		*Increased lifespan of dams but a & costly option.*	

Table 5 Continued

Issue	Response actions and (in italics) their presumed benefits			
	Morocco	Senegal	Kenya	Tanzania
Adaptation Strategies Integrated management	Creation of the Basin Agencies which coordinate different sectors dealing with natural resource within basins*.	Rationalization of scope of OMVS management in association with SOGEM and SOGED*.	Creation of a Regional integrated river basin-coastal management authority*.	Reform the ''Villagization'' policy of 1969*.
	Improvement of communication and cooperation between the policy makers.	*Improved integration of water management in the Senegal River basin and its coastal zone.*	*Improved coordination of catchment and coastal management authorities.*	*Arresting the negative environmental and socioeconomic Impacts of the policy.*
		Planning adaptive measures for continuing climate change, including provision for the effects of sea-level rise.	Strengthening Tana and Athi Rivers Development Authority (TARDA) and Catchment Boards*. Improved implementation of soil and water conservation programmes and of the the National Environment Coordination Act (1999).	Reform policy related to the utilization of woodland resources in lower floodplain and delta through, e.g. promotion of fuel switching opportunities, tree planting, improving efficiency of fuel wood and charcoal utilization*.
		Improved ability to cope with increasing drought conditions, coastal erosion and marine induced flooding.	*Reduced degradation of land and water resources in catchments.*	*Improving the sustainability and biodiversity of woodland and delta forest resources.*
			Implement or reinstate hydrological monitoring.	
			Improved hydrological data for planning and policy making.	

[a] OMVS is an international body charged with the management of the Senegal river basin. SOGEM (Société de Gestion de Manantali) and SOGED Société d'explotation des eaux de Diama) are private bodies charged with operational management and water licensing
* Indicates priority response

studies here illustrate an imperative for the integration of catchment and coastal management by agencies that take into account the whole water flow regime and its human dimensions—those *affecting* the flow regime within the catchment as well as those *being affected by* the flow regime in downstream and coastal environments. The agencies would have the dual roles of dealing with the *inputs* to the system and coping with the *outputs*.

Development authorities with responsibilities specifically for damming and irrigation water supply, as well as other key stakeholder groups, should be represented within those agencies, which would provide the essential interface with government policymakers. In the case of the transboundary Senegal River, an international management body covering the four catchment countries—the Organisation pour la Mise en Valeur du Fleuve Senegal (OMVS)—already exists, though its remit is currently restricted to the river basin and excludes the coastal zone.

The recommended responses imply a need for capacity building at the institutional level, in the science—both in terms of human capacity and the resources needed for comprehensive monitoring—and in communication, including the improvement of public awareness. There is great scope for the effective application of information technology, whether at local, national, regional, or global levels so that knowledge on the key parameters for management can be shared or exchanged.

A shortage of trained scientists and administrators is a feature of all the countries involved in this study. There is an urgent need to redress this shortcoming if the aims expressed in this article 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 basis of the physical and socioeconomic information and modeling required for catchment management. There is a strong 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 countries to forecast the impacts of climate and demographic changes is another priority.

The responses shown in Table 5. include a wide range of recommended actions, mostly at the catchment level of management. Those specifically concerning damming and water abstraction include

- promoting environmental water discharges to provide improvements in downstream and coastal conditions, while still providing protection against damaging floods: a Strategic Priority of the World Commission on Dams (WCD 2000).
- assessing the downstream and coastal impacts of planned new schemes in catchments that are already dammed, as well as those presently undammed, particularly in the light of climate change forecasts.
- addressing the problem of sediment trapping impacting on the sustainability of dam reservoirs and downstream deposition, together with the rigorous application of soil conservation measures through improvements in land-use in catchments. Facilitating sediment transport bypass around dams.

Beyond the context of damming and abstraction, the studies have highlighted the urgent need to tackle the root causes of land degradation and soil erosion, and the overharvesting of estuarine and coastal living resources.

Summary of Main Findings

Damming and Water Abstraction

Analysis of the AfriCat case studies presented here has confirmed that during the 60-year time span of dam commissioning, there have been some major reductions, linked to damming, in the downstream and coastal availability and discharge of freshwater. Secondary effects of these reductions include soil salinization and saline intrusion. Reduced sediment transport is leading to the progressive impoverishment of downstream floodplains, rechanneling of river beds, and changes in coastal geomorphology. Together these impacts are impacting adversely on downstream and coastal biodiversity and the populations supported by the riverine and coastal wetland ecosystems. Little is known of the likely consequences of the existing damming and water abstraction regime over the long term, or of the ways in which catchment-to-coast systems may respond to further damming and abstraction in the context of climate change.

Other Contributory Pressures

Although damming and water abstraction in catchments are major contributors to downstream and coastal issues, climate and land-use changes are also having a major influence on water and sediment fluxes affecting downstream and coastal environments. Increased sediment mobility in catchments due to climate change and land-use change is exacerbating the serious problem of sediment trapping in reservoirs.

Responses

The case studies recognize an imperative for the integration of catchment and coastal management by agencies that take into account the whole water flow regime and its human dimensions—those *affecting* the flow regime within the catchment as well as those *being affected by* the flow regime in downstream and coastal environments. Areas that merit urgent attention are the following:

- Elaboration of management models through scientific research is necessary to cope with extreme climatic events, satisfy the demands of the population and agriculture, and maintain the ecological functions of the coastal wetlands.
- The promotion of environmental water discharges from dams and sediment bypass facilities around dams to provide improvements in downstream and coastal conditions, while still providing protection against damaging floods, is a priority.
- Enhanced observational monitoring networks should form the basis of the physical and socioeconomic information and modeling required for catchment management. Greater capacity in all countries to forecast the impacts of climate and demographic changes is another priority.

A key objective in all catchments is the reduction of soil wasting and sediment mobility. Further research is needed in particular to clarify the role of land-use change in the changes to catchment fluxes.

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