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Decision Support Systems for Large Dam Planning and Operation in Africa

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Contents

Acronyms and Abbreviations

CPWF	CGIAR Challenge Program on Water and Food
DSS	decision support system
DP	Dynamic Programming
DDP	Dams and Development Project of the United Nations Environment Programme
DWAF	Department of Water Affairs and Forestry, South Africa
EIA	Environmental Impact Assessment
ICOLD	International Commission on Large Dams
IHA	International Hydropower Association
IWRM	Integrated Water Resources Management
LP	Linear Programming
MCA	Multi-Criteria Analysis
NEPAD	New Partnership for Africa's Development
NLP	Non-Linear Programming
WCD	World Commission on Dams
WHO	World Health Organization
WWF	World Wide Fund for Nature (*formerly* World Wildlife Fund)

Summary

In recent years, great emphasis has been placed on the need to improve the management of the environmental and social impacts of large dams. This is particularly important in Africa where there is a drive to build more and yet many people continue to rely on those natural resources which are impacted by dams for their livelihoods. The environmental and consequent social impacts of large dams are often complex and extremely difficult to predict. Dam planners and operators often have to consider a huge number of factors and conflicting objectives, which makes decision-making problematic. In such situations, decision support systems (DSS) have an important role to play. Over the years, many different DSSs have been developed for dam planning and operation. This report presents a review of the different types of DSS and their application in water resource management. Although some information and examples have been obtained from elsewhere, the main focus is Africa. The report is not intended as a comprehensive compendium on DSS application in dam planning and operation. Rather, it provides an overview and framework for understanding issues pertaining to decision-making in relation to large dams in Africa.

INTRODUCTION

Background

Effective water resources development and management is widely recognized as crucial for sustainable economic growth and poverty reduction in many developing countries. Large dams, defined as those greater than 15 meters(m) in height from base to crest, or storage capacity exceeding 3 million cubic meters for heights between 5 and 15 m (ICOLD 2003), often play a key role in water management[1]. Intended purposes of large dams usually include providing water for irrigation, water supply to cities, improving navigation, generating hydroelectric power and flood control. Few dams serve all of these purposes but some multi-purpose dams serve more than one.

The contribution of large hydraulic infrastructure, particularly dams, to development, remains controversial. This controversy stems from the fact that, too often in the past, the construction of dams has brought fewer benefits than envisaged and has resulted in significant social and environmental costs (WCD 2000). Historically, large dam projects have often failed to pay sufficient attention to environmental impacts and those (invariably poor) people adversely affected by the construction and operation of the dam and associated water management system. Those who had to be resettled and those whose livelihoods are affected by changes in river flow regimes have tended to pay the price of dam construction. Even where the negative impacts were appreciated *a priori*, often those making decisions (rarely impacted personally) deemed the “sacrifices” to be acceptable in light of the benefits that would accrue (Beekman 2002).

In relation to reservoir volume, Africa contains some of the world’s largest dams (e.g., Owen Falls (Uganda), Kariba (Zimbabwe) and Aswan High (Egypt) containing 270, 180 and 162 billion cubic meters of storage, respectively). Furthermore, two countries (South Africa and Zimbabwe) are in the top 20 countries for number of dams (Table 1). However, most of these dams were constructed before the 1970s and currently Africa has by far the lowest per capita water storage of any continent (WCD 2000).

Largely as a result of the concerns about negative social and environmental impacts, investment in large dams declined substantially throughout the 1990s and into the early part of the 21st century (WCD 2000). More recently there has been a re-evaluation of the role of large dams and, although the controversy remains, it is likely that investment in large dams in Africa will increase in the immediate future. The current position of the World Bank is that major water resource projects provide the basis for broad regional development, with “significant direct and indirect benefits for poor people” and that current knowledge means that negative social and environmental consequences can be successfully averted or sufficiently mitigated (World Bank 2004). As a result, the Bank is re-engaging in the development of water infrastructure and, in its current water sector strategy, has targeted a 50 percent increase in lending for water resource projects (World Bank 2004). Other institutions, including the African Development Bank, the Commission for Africa and the New Partnership for Africa’s Development (NEPAD) have called for increased investment in the water sector (NEPAD 2003; Commission for Africa 2005). At the African Ministerial Conference on Hydropower and Sustainable Development, held in Johannesburg in March 2006, there was general agreement on the need to accelerate the implementation of dam-building projects throughout Africa. The leaders of the G8 summit in Gleneagles (2005), through the launch of the Infrastructure Consortium for Africa, committed a significant amount of aid assistance to infrastructure development. In addition, the European Union pledged to increase the volume of aid to developing countries, with a significant part going towards infrastructure development projects, and with a special emphasis on Africa. China is also investing significantly in infrastructure throughout Africa, including in large dams (IRN 2006).

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[1] In recent years, dam technology has advanced sufficiently to enable the construction of mega dams (i.e., exceeding 150 m in height) (ICOLD 2003).

Table 1. Number of dams in the top 20 countries with the highest number of dams.

	Country	ICOLD World Register of Dams 2003	Percentage of total dams (%)
1	United States	9,265	28.0
2	China	4,688+	14.2
3	India	4,636	14.0
4	Spain	1,267	3.8
5	South Korea	1,205	3.6
6	Japan	1,121	3.4
7	South Africa	915	2.8
8	Canada	793	2.4
9	Brazil	635	1.9
10	Turkey	625	1.9
11	France	597	1.8
12	Italy	549	1.7
13	Mexico	536	1.6
14	United Kingdom	517	1.6
15	Australia	507	1.5
16	Norway	335	1.0
17	Germany	306	0.9
18	Albania	306	0.9
19	Zimbabwe	253	0.8
20	Romania	246	0.7
	Others	3,803	11.5
	Total	33,105	100.0

Source: ICOLD 2003
Notes: + Other sources estimate the total number of dams in China, to exceed 22,000

Many large dams are currently being planned or are already under construction on the continent (Table 2). Given this background, the key challenge is to determine how dams are best able to contribute to attempts by African countries to obtain reliable and sustainable sources of water, food and energy security, whilst simultaneously avoiding and mitigating harmful impacts as far as possible.

Decision Support Systems for Dam Planning and Management

In its report, the World Commission on Dams (WCD) called for a more equitable distribution of the benefits to be gained from large dams and proposed the inclusion of all identified stakeholders in the planning and management of water resources stored in reservoirs (WCD 2000). To achieve this, dam managers must take into account water uses upstream and downstream of the dam and must give consideration to political, organizational, social and environmental factors, as well as economic and biophysical factors (McCartney and Acreman 2001). However, in any specific situation, the relationships among these different elements are extremely complex and often not well understood. This makes informed decision-making very difficult.

Table 2. Examples of large dams planned or being built in Africa.

Name	Country	River	Primary purpose	Anticipated completion
Capanda	Angola	Kwanza	Hydropower (520 MW)	2006
Dyodyonga	Benin/Niger	Mekrou	Hydropower (26 MW)	Undetermined
Adjarala	Benin/Togo	Mono	Hydropower (96 MW)	Undetermined
Lom Pangar	Cameroon	Lom (tributary of Sanaga)	Hydropower (56 MW)	2008
Memve Ele	Cameroon	Ntem	Hydropower (202 MW)	Undetermined
Nachtigal	Cameroon	Sanga	Hydropower (300 MW)	Undetermined
Grand Inga	Democratic Republic of Congo	Congo	Hydropower (3,500 MW)	Undetermined
Tekeze	Ethiopia	Tekeze (tributary of the Nile	Hydropower (300 MW)	2009
Karadobi	Ethiopia	Abay (Blue Nile)	Hydropower (1,600 MW)	Undetermined
Baro 1 & 2	Ethiopia	Baro – Akobo	Hydropower (916 MW)	Undetermined
Koga	Ethiopia	Gilgel Abay	Irrigation	2007
Tendho	Ethiopia	Awash	Irrigation	2007
Kesem	Ethiopia	Awash	Irrigation	2007
Sambangalou	Gambia	Gambia	Hydropower (45 MW)	Undetermined
Bui	Ghana	Black Volta	Hydropower (157 MW - 310 MW)	Undetermined
Hemang	Ghana	Pra	Hydropower (93 MW)	Undetermined
Sondu-Miriu	Kenya	Sondu	Hydropower (60 MW)	Undetermined
Ewaso Ngiro	Kenya	Mara	Hydropower	Undetermined
Mutonga/Grand Falls	Kenya	Tana	Hydropower, irrigation and water supply	Undetermined
Mashi	Lesotho	Senqu	Inter-basin transfer to South Africa	Undetermined
Metalong	Lesotho	Phuthiastsana	Water supply	Undetermined
Talo	Mali	Bani	Irrigation	Undetermined
Mphanda Nkuwa	Mozambique	Zambezi	Hydropower (1,300 MW)	Undetermined
Epupa	Namibia	Kunene	Hydropower	Undetermined
Popa Falls	Namibia	Okavango	Hydropower (30 MW)	Undetermined
Kandadji	Niger	Niger	Hydropower	Undetermined
Mambila	Nigeria	Benue	Hydropower (3,900 MW)	Undetermined
Zungeru	Nigeria	Kaduna	Hydropower (950 MW)	Undetermined
Imboulou	Republic of Congo	Lefini	Hydropower (120 MW)	2009
Sounda Gorge	Republic of Congo	Kouilou	Hydropower (1,000 MW)	Undetermined
Boegoeberg	South Africa/Namibia	Orange	Irrigation	Undetermined
De Hoop	South Africa	Steelpoort	Mine supply, irrigation and environmental flows	2008
Skuifraam	South Africa	Berg	Water supply	Undetermined
Thukela	South Africa	Thukela	Inter-basin transfer (to Vaal River)	Undetermined

(Continued)

Table 2 (Continued). Examples of large dams planned or being built in Africa.

Merowe	Sudan	Nile	Hydropower (2,500 MW) and irrigation	2007-2008
Kajbar	Sudan	Nile	Hydropower (300 MW)	Undetermined
Rusumo Falls	Tanzania/Rwanda	Kagera	Hydropower (60 MW)	Undetermined
Rumakali	Tanzania	Rumakali	Hydropower (222 MW)	2024
Ruhudji	Tanzania		Hydropower (36 MW)	2012
Bujagali	Uganda	White Nile	Hydropower (200 MW)	Undetermined
Kamdini	Uganda	White Nile	Hydropower	Undetermined
Murchison	Uganda	White Nile	Hydropower	Undetermined
Batoka Gorge	Zambia	Zambezi	Hydropower (1,600 MW)	Undetermined
Gwayi Shangani	Zimbabwe	Zambezi	Water Supply	Undetermined
Tokwe-Mukorsi	Zimbabwe	Tokwe	Irrigation	Undetermined
Bubi-Lupane	Zimbabwe	Bubi	Hydropower?	Undetermined
Kajbar	Sudan	Nile	Hydropower (300 MW)	Undetermined
Rusumo Falls	Tanzania/Rwanda	Kagera	Hydropower (60 MW)	Undetermined
Rumakali	Tanzania	Rumakali	Hydropower (222 MW)	2024
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Murchison	Uganda	White Nile	Hydropower	Undetermined
Batoka Gorge	Zambia	Zambezi	Hydropower (1,600 MW)	Undetermined
Gwayi Shangani	Zimbabwe	Zambezi	Water Supply	Undetermined
Tokwe-Mukorsi	Zimbabwe	Tokwe	Irrigation	Undetermined
Bubi-Lupane	Zimbabwe	Bubi	Hydropower?	Undetermined

Sources: IRN 2006 plus others
Note: MW = megawatt

Over the last 30 to 40 years, major advances have been made in the development and use of a wide range of tools to assist in the planning and management of complex water resource systems (Jamieson 1996). DSSs are intended to provide water resource managers with assistance in making rational decisions based, as far as possible, on an objective assessment of issues.

There is no common definition of a DSS. Some definitions, and perhaps the most widely accepted, refer specifically to computer tools. For example: *DSS are computer based tools having interactive, graphical and modeling characteristics to address specific problems and assist individuals in their study and search for a solution to their management problems* (Loucks and da Costa 1991). Similarly, Reitsma et al. (1996) define DSS as: *Computer-based systems that integrate the following three components into a single software implementation: (i) State information – data which represents the water resource system's state at any point in time; (ii) Dynamic and process information – first principles governing the resources behavior over time iii) Plan evaluation tools – utility software for transforming raw system data into information relevant for decision-making.*

Others argue that a DSS need not be computer-based and anything that assists the decision-making process (including such things as guidelines and frameworks) are forms of DSS. For the purpose of this report, a broad perspective was taken and DSSs were considered to be any tools (computer software or otherwise) that assist the process of decision-making in relation to the planning and operation of dams and the allocation of water between different sectors (McCartney et al. 2005).

Structure of the Report

The report presents a review of current dam planning and operation practices and a brief evaluation of some of the more prominent DSSs used in water resource management. It is based on literature review and the outcomes of an international conference on dams and DSSs held in Ethiopia in January 2006 (CPWF 2006). Although data and examples have been obtained from all around the world, the primary focus is on the use of DSSs in Africa.

The report is divided into six sections. Following this introduction, section: *Environmental and social factors that need to be accounted for in dam planning and operation* describes the issues around dam planning and operation and the range of factors that need to be considered in dam management. Section: *Existing practices for dam planning and operation* is a review of existing practices of dam planning and operation. Section: *Review of DSS* is a review of modern DSSs and their actual, as well as potential, use for dam planning and operation. Section: *Review of DSS development and application to IWRM in Africa* is a review of DSSs used specifically in Africa. Section: *Concluding Remarks* is a brief summary and conclusion.

ENVIRONMENTAL AND SOCIAL FACTORS THAT NEED TO BE ACCOUNTED FOR IN DAM PLANNING AND OPERATION

In its report, the World Commission on Dams concluded that, although large dams have brought development benefits, the poor, vulnerable groups and future generations are most likely to bear a disproportionate share of social and environmental costs of large dam projects without gaining a commensurate share of the economic benefits (WCD 2000; Box 1).

Box 1. Findings of the World Commission on Dams.

The World Commission on Dams was established to assess the development effectiveness of large dams. In its final report it concluded:

- Dams have made an important and significant contribution to human development and the benefits derived from them have been considerable.
- In too many cases an unacceptable and often unnecessary price has been paid to secure those benefits, especially in social and environmental terms, by people displaced, by communities downstream, by taxpayers and by the natural environment.
- Lack of equity in the distribution of benefits has called into question the value of many dams in meeting water and energy development needs when compared with the alternatives.
- By bringing to the table all those whose rights are involved and who bear the risks associated with different options for water and energy resources development, the conditions for a positive resolution of competing interests and conflicts are created.
- Negotiating outcomes will greatly improve the development effectiveness of water and energy projects by eliminating unfavorable projects at an early stage and by offering as a choice only those options that represent the best ones to meet the needs in question.

To address environmental, social and decision-making concerns the WCD proposed a “new framework for decision-making”, in the form of five core values, seven strategic priorities, 29 policy principles and 26 guidelines (WCD 2000). Although the core values and strategic priorities were widely endorsed, there was a mixed reaction to the policy principles and the guidelines. The main concerns of the dam industry and some governments, related to the practical implications of implementing the policy principles and the guidelines. The Dams and Development Project (DDP), which is a follow-up to the WCD, has sought to improve decision-making of dams and their alternatives, particularly through the proper consideration of social and environmental issues (UNEP 2006).

(*Source:* WCD 2000)

Environmental Impacts

For most of the world's existing stock of large dams, environmental requirements have played little part in their design and the specification of operating rules. Most dams have been constructed with the emphasis on maximizing the economic returns from the use of water, with little or no understanding of the long-term consequences of alterations to flow volumes, flow patterns and timing, and water quality. However, over the last 30 to 40 years, there has been an increasing awareness that dams modify, in both obvious and subtle ways, as well as at places far removed from the source of impact and often with long time lags, the conditions to which aquatic ecosystems have adapted. Flow regulation can, and frequently has, caused serious degradation of natural ecosystems (Poff et al. 1997; Rosenberg et al. 2000; Bunn and Arthington 2002; Richter et al. 2003).

Through impoundment, dams modify hydrology, water quality and temperature, and sediment regimes, which affect primary productivity and morphology, which in turn cause changes at higher trophic levels (Petts 1984; Poff et al. 1997). In some places these changes have resulted in the loss of natural resources and processes that contributed to the livelihoods and well-being of people (Postel and Richter 2003; Millennium Ecosystem Assessment 2005).

The impacts of dams vary substantially from one geographical location to another and are dependent on the exact design and the way a dam is operated, as well as the ecological character of the riverine ecosystem and the socioeconomic context. Every dam has specific characteristics and, consequently, the scale and nature of environmental changes are highly site-specific and often very difficult to predict accurately (McCartney et al. 2000).

Social Impacts

River and wetland ecosystems provide many services that contribute to peoples' well-being and poverty alleviation. Amongst others, these include provision of food and fiber, water, building materials and medicinal plants that help meet basic human needs (Millennium Ecosystem Assessment 2005; Falkenmark et al. 2006). The degradation of river and other wetland ecosystems, as a consequence of dam construction and hydrological alteration/river regulation, can have profound economic and social implications. Often the harmful effects of ecosystem service degradation are borne disproportionately by the poor, and are in many cases the principal drivers of poverty and social conflict (WWF 2005). In the past, failure to take into account the cost of these consequences has resulted in much human suffering and the benefits of many dams being overstated (WCD 2000).

Ill-planned re-settlement of people from the area flooded by the reservoir has usually caused the most significant adverse social impacts (Cernea 2004). The WCD report estimates dam-triggered displacements worldwide as between 40 and 80 million people (WCD 2000). The fundamentally negative consequence and effect of forced displacement is the impoverishment of those displaced, the vast majority of whom have been poor even before their forced displacement. Tens of millions of poor people have received insufficient or no compensation, and ended up worse off (Cernea 2004). For example, the Tonga people displaced by the construction of the Kariba Dam on the Zambezi River in the 1950s are still seeking adequate compensation for loss of livelihoods (Soils Incorporated Ltd and Chalo Environmental and Sustainable Development Consultants 2000; Tremmel 1994).

Although often given even less consideration than the impacts on displaced people, there are also many documented cases of dam operation adversely affecting the livelihoods and health of people, living not just in the immediate vicinity of the dam, but also sometimes many hundreds of kilometers downstream (Table 3).

Table 3. Examples from Africa of adverse livelihood impacts attributed to dams.

Location	Impacts
Kafue Flats, Zambia	Changes in the flow regime of the Kafue River downstream of the Itezhi-Tezhi Dam have resulted in (Acreman et al. 2000): - loss of traditional flood recession garden/cultivation systems - decreases in grazing resources as a result of changes to vegetation on the floodplain and increased dry season inundation - a change in fish species and increase in catch effort due to larger areas of dry season open water - a decrease in households supported by fishing from 2,600 to 1,150 between1977 and 1\984
Senegal Delta, Senegal	Changes in the flow regime caused by construction of the Diama Dam on the Senegal River Delta have resulted in (Duvail and Hamerlynck 2003): - collapse of livelihoods dependent on fisheries - loss of livestock grazing through reduced flood dependent pasture - loss of vegetation previously used extensively for mat-making
Tana River, Kenya	Changes in flow regime downstream of dams on the Tana River have resulted in (JICA1997): - decline in riverine pasture - increasing pressure on common pool resources shared by farmers and pastoralists - acceptance and increased reliance of local people on state authority, which is rendering tribal and inheritance-based customary systems of regulated access to floodplain farm and grazing resources increasingly redundant
Atbara River, Sudan	Drought and changes in flow regime downstream of dams on the Atbara River in Sudan have resulted in (Abdel Ati 1992): - dereliction of traditional irrigation methods and increased sharecropping arrangements between farmers and diesel pump owners - decline in households involved in agriculture from 92 to 81% between 1964 and1989 - disappearance of fishing and wood collection as livelihood strategies - greatly increased out-migration as result of the reduction in cultivable land
Hadejia-Jama'are Rivers, Nigeria	Reduction of flooding in the Hadejia-Nguru wetlands due to upstream dam construction, has resulted in (Barbier et al. 1993): - reduction in agriculture (e.g., rice) - loss of grazing resources (mainly cattle of the Fulani people), decrease in non-timber forest products, fuel wood and fishing for local populations - reduction in the economic value of production in the wetlands
Volta River, Ghana	Construction of the Akosombo Dam in Ghana resulted in (Gyau-Boakye 2001): - increased incidence of many waterborne diseases including schistosomiasis, malaria and onchocerciasis, in lakeside villages and those downstream of the dam - increased salinity in water supply for some towns, downstream of the dam - decline in economic activities as a result of loss of agricultural land - breakdown in traditional social order, in part because of the loss of ancient sacred places - erosion of coastal shoreline
Zambezi Delta, Mozambique	Flow regulation by Cahora Bassa and other dams on the Zambezi has resulted in (Manez and Scodanibbio 2004; Hathaway 2006): - A 60% decline in the commercial nearshore prawn catch because of reduced floods - Degradation of mangrove swamps and erosion of river banks - Salinization of soils in the Zambezi Delta - Decline in the water table in the delta
Logone Floodplain, Cameroon	Construction of the Maga Dam in Cameroon resulted in (Mouafo et al. 2002): - growing disputes between various interest groups, over access to water - collapse of fisheries due to loss of floodplain habitat - degradation of soils and pasture due to lack of silt inputs to the floodplain - 40% decrease in population of the floodplain as people have moved away

Changes to flow regimes in arid areas can have particularly adverse impacts, leading to the loss or degradation of many essential services provided by rivers and wetlands (Millennium Ecosystem Assessment 2005). The impacts of degraded rivers and wetlands on human well-being are often not recognized, but can be very significant. For example, reductions in fisheries, flood recession agriculture and/or the provision of construction materials can have significant consequences for peoples' well-being (Adams 2000; Falkenmark et al. 2006).

Health impacts are one of the most critical of the social impacts caused by a dam. The creation of a reservoir and, in some cases, associated networks of water management (not only irrigation) channels and drainage ditches create new habitats for certain insects (e.g., mosquitoes, snails and worms), which spread human and animal diseases (e.g., malaria, bilharzia, onchocerciasis). Consequently dams and canals have had implications for the health of people (Jobin 1999; Keiser et al. 2005). The contribution of the World Health Organization to the WCD (WHO 1999) concluded that:

- many of the adverse health outcomes associated with dams and associated infrastructure can be prevented or mitigated if a broad and holistic view of [dam] project construction and operation is taken; and
- health considerations should always be included alongside economic, environmental and social issues in decision-making on dams.

Contemporary Requirements for Dam Planning and Operation

In the past, planning of dams and their operation focused primarily on meeting future demand (i.e., for water, power or irrigation) through identification of least-cost options. Cost-benefit analysis emerged between the 1950s and 1970s as the dominant economic tool for supporting decision-making on dam projects (Beekman 2002). If the expected benefits of a dam were deemed to outweigh the predicted costs, the project went ahead. Very often environmental and social aspects were largely ignored and little thought was given to how dam operation might be modified to mitigate, to the extent possible, negative environmental and social impacts. It was extremely rare for any sort of post-construction monitoring to be included to enable adaptive management of the system. The relatively narrow nature of the technical and economic analyses undertaken did not necessarily mean that decision-makers that chose dams as a development option were unaware of the social and environmental costs. However, the sacrifices were rarely made explicit and were often deemed to be "acceptable" in light of the perceived benefits that would accrue (Beekman 2002).

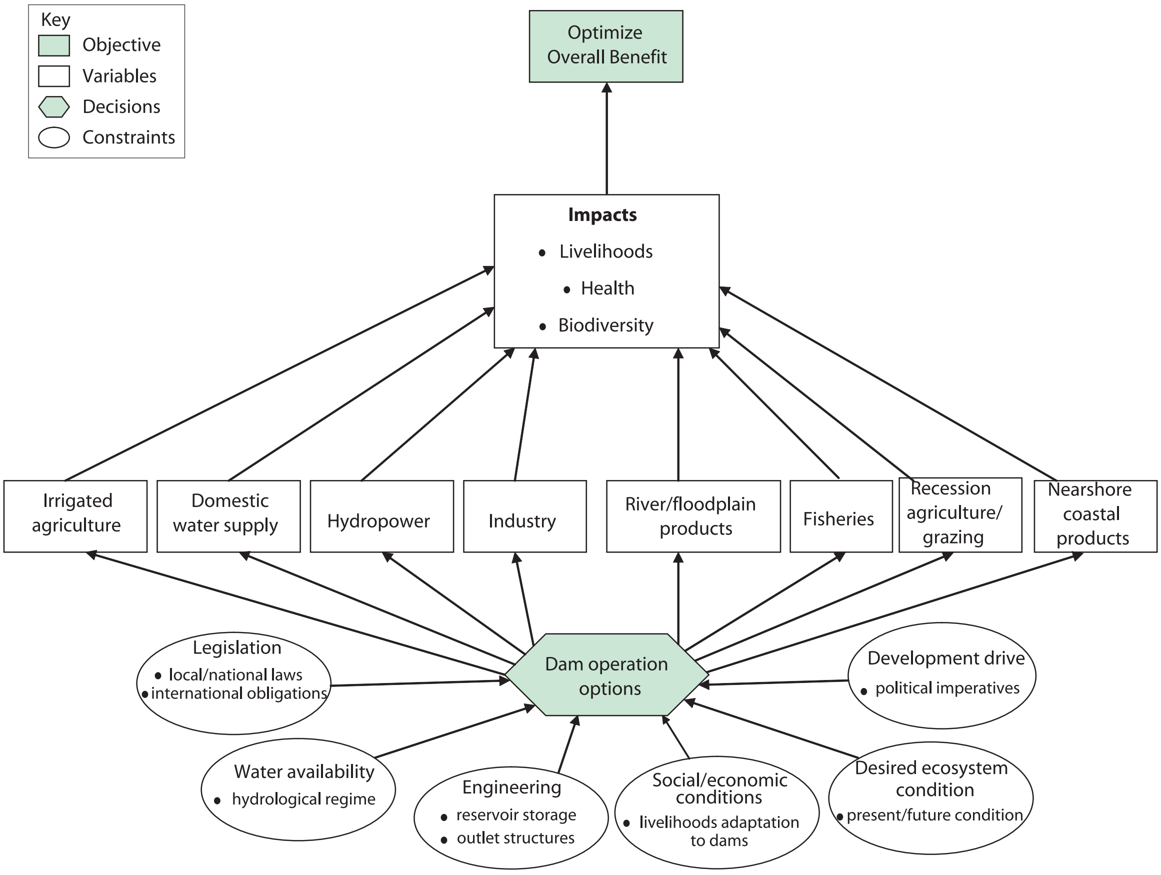
In recent years, Integrated Water Resources Management (IWRM) has come to the fore as a management paradigm for water (Global Water Partnership 2000), and there is increased recognition of the need to improve water management to maximize benefits and minimize negative environmental and social (including health) impacts. This has led to a fundamental re-evaluation of decision-making processes for the planning and operation of dams. It is no longer deemed acceptable to simply maximize the economic profits from a dam, though some nations continue to focus primarily on this aspect. To ensure sustainability, it must be seen that consideration is given to environmental impacts as well as issues of equity and the rights of people who may be adversely affected.

Optimization of dam releases must allow for water uses upstream and downstream of the dam, including water supply, agriculture, fisheries and power generation requirements, as well as the requirements of communities dependent on the natural resources of downstream ecosystems and of the river and its aquatic habitats (Figure 1). For many downstream communities, maintenance of the integrity and resilience of the river and floodplain ecosystems as well as, in some instances, coastal estuaries, is often vital for their livelihoods and well-being.

To take account of the full range of environmental and socioeconomic factors affected by a dam's construction, and subsequently its operation, requires consideration of a number of complex and interrelated subjects, and poses intricate technical and political problems (McCartney and Acreman 2001). For most large dams, at any given time, there may be a huge number of possible release options. The need to consider multiple, and often conflicting, objectives for a large number of stakeholders, and across a broad spectrum of scales, means that thousands of decision variables and constraints may need to be considered.

Decision-making can be further complicated where there are a number of dams in a catchment, either on the same river, or on different tributaries. In such situations decisions pertaining to any given dam are often made without consideration of the operation of the other dams in the catchment (Bergkamp et al. 2000). Nonetheless, in any given catchment, it is likely that benefits can be maximized and negative impacts minimized if the dams are operated in an integrated manner. However, this greatly increases the complexity of the 'system' to be managed and requires consideration of even more variables.

Figure 1. The complex web of interlinked issues and trade-offs that must be taken into account in the planning and operation of a large dam.



EXISTING PRACTICES FOR DAM PLANNING AND OPERATION

For many years, determining the best possible reservoir storage capacities and operating regimes has been a major focus of the water agencies responsible for the planning, design and operation of dams. In the past, and still fairly commonly today, many operators relied on expert judgement and unwritten rules for dam operation (Mwaka, B. pers. comm. 2006). Sometimes it is possible to formalize these rules within a DSS, but this is not always the case.

Policy Frameworks and Guidelines that Influence Dam Construction and Operation

Many countries, as well as diverse international organizations, including both the dam industry (e.g., the International Commission on Large Dams (ICOLD) and the International Hydropower Association (IHA)) and financial institutions (e.g., the World Bank and the African Development Bank), have established or made recommendations on policy frameworks and/or guidelines that influence dam planning and operation (Boxes 2 and 3). In many countries, dam planning and operation are influenced by a complex suite of legislation, strategies and regulations (Appendix 1). In theory, these mechanisms facilitate the efficient implementation and operation of dams. Increasingly, they also address environmental and social implications of the development of water and energy resources.

Box 2. World Bank safeguard policies.

The World Bank has various policies and guidelines relating to the environmental and social impacts of development projects, including projects that involve dam construction. These are published in the World Bank's Operational Manual (*http://wbln0018.worldbank.org/Institutional/Manuals/OpManual.nsf*). This contains both Operational Policies (OPs) that are mandatory policy and Bank Procedures (BPs) that must be followed. The Bank requires the application of environmental assessments to provide information about the ways development activities may directly or indirectly affect ecosystems and people. The Bank requires that the environmental assessments carried out for the projects it supports reflect the views of persons affected by the project – including the poor, indigenous people, and disadvantaged groups. The Bank *"will not support projects which involve the significant conversion or degradation of critical natural habitats unless there are no other feasible alternatives to the project and its siting and the overall benefits from the project substantially outweigh its environmental costs"* (World Bank 2005). The current Bank policies and guidelines that are of most relevance to large dams include:

- World Bank Operational Policy 4.04 (Natural Resources)
- World Bank Operational Policy 4.01 (Environmental Assessment)
- World Bank Procedure 4.01 (Environmental Procedures)
- World Bank Operational Policy 4.07 (Water Resources Management)
- World Bank Operational Directive 4.30 (Involuntary Re-settlement)

Box 3. International Hydropower Association guidelines for optimizing environmental and local outcomes.

Guidelines on optimizing environmental outcomes

1. Water quality – design and operate systems that minimize, as much as possible, the negative impacts within the system and downstream; examples include multi-level off-takes, air injection facilities, aerating turbines and destratification capability.
2. Sedimentation – development proposals need to be considered within the context of existing catchment activities, especially those contributing sediment inflow to the storage.
3. Downstream hydrology – operating rules should not only consider the requirements for power supply, but also be formulated where necessary and practicable, to reduce downstream impacts on aquatic species and human activities.
4. Hydropower developments modify existing terrestrial and aquatic habitats, and when significant changes cannot be avoided, mechanisms to protect remaining habitats at the local and regional scale should be considered in a compensatory manner.
5. Fish – the passage of fish is an issue that must be considered during the design and planning stage of proposed developments and adequate consideration should be given to appropriate mechanisms for their transfer (e.g., fish ladders, mechanical elevators, guidance devices and translocation programs).
6. Health – issues relating to the transmission of disease, human health risks associated with flow regulation downstream and the consumption of contaminated food sources (e.g., raised mercury levels in fish) need to be considered.
7. Construction activities – need to be carried out to minimize impacts on the terrestrial and aquatic environment.
8. Environmental Management Systems – it is recommended that all hydropower schemes implement an independently audited environmental management system, which allows for effective management of the range of environmental issues associated with the ongoing operation of the scheme.

Guidelines on local outcomes

1. Provide affected communities with improved living conditions.
2. Improve public health conditions for impacted communities.
3. Ensure equitable distribution of the benefits of the project, particularly to affected and vulnerable communities, through processes such as revenue sharing, training programs and educational outreach.
4. Ensure that the local knowledge of communities and stakeholders is utilized in project-planning.
5. Support additional community infrastructure associated with the project, particularly water and electricity connection, where positive benefits to the community will result.

(*Source:* IHA 2004)

In Africa, many countries are attempting to improve water resources management because of emerging problems resulting from increasing demand for water and the necessity of protecting water resources and the environment to ensure sustainability. For example, the National Water Act (1998) in South Africa is progressive legislation that makes explicit reference of the need to manage water in an integrated way and to maintain basic human needs and environmental flows (Box 4). In Tanzania, the new National Water Policy (2002) provides a framework for integrated management of water resources, adopting the river basin as the principal unit for management and regulation (Mutayoba 2002). The policy, underpinned by principles of sustainability and equity, embraces concepts such as full cost recovery, water rights and fees and stakeholder participation in water resources management (van Koppen et al. 2004). Similar legislation has been adopted, or is proposed, in many other African countries.

Box 4. South Africa's National Water Act and the Reserve.

The National Water Act (No. 36) (DWAF 1998), which provides the legal framework for management of water resources in South Africa, is extremely progressive in explicitly dealing with issues of the environment, equity and sustainability. The Act asserts that, in conjunction with using water resources to promote social and economic development, it is essential to protect the environment to ensure that the water needs of present and future generations can be met. This is partly achieved by leaving enough water (i.e., a *reserve)* in a river to maintain its ecological functioning. To this end, the Reserve is the only water *right* specified in the National Water Act. As such it has priority over all other water uses and strictly must be met before water resources can be allocated to other uses. The Reserve comprises two parts:

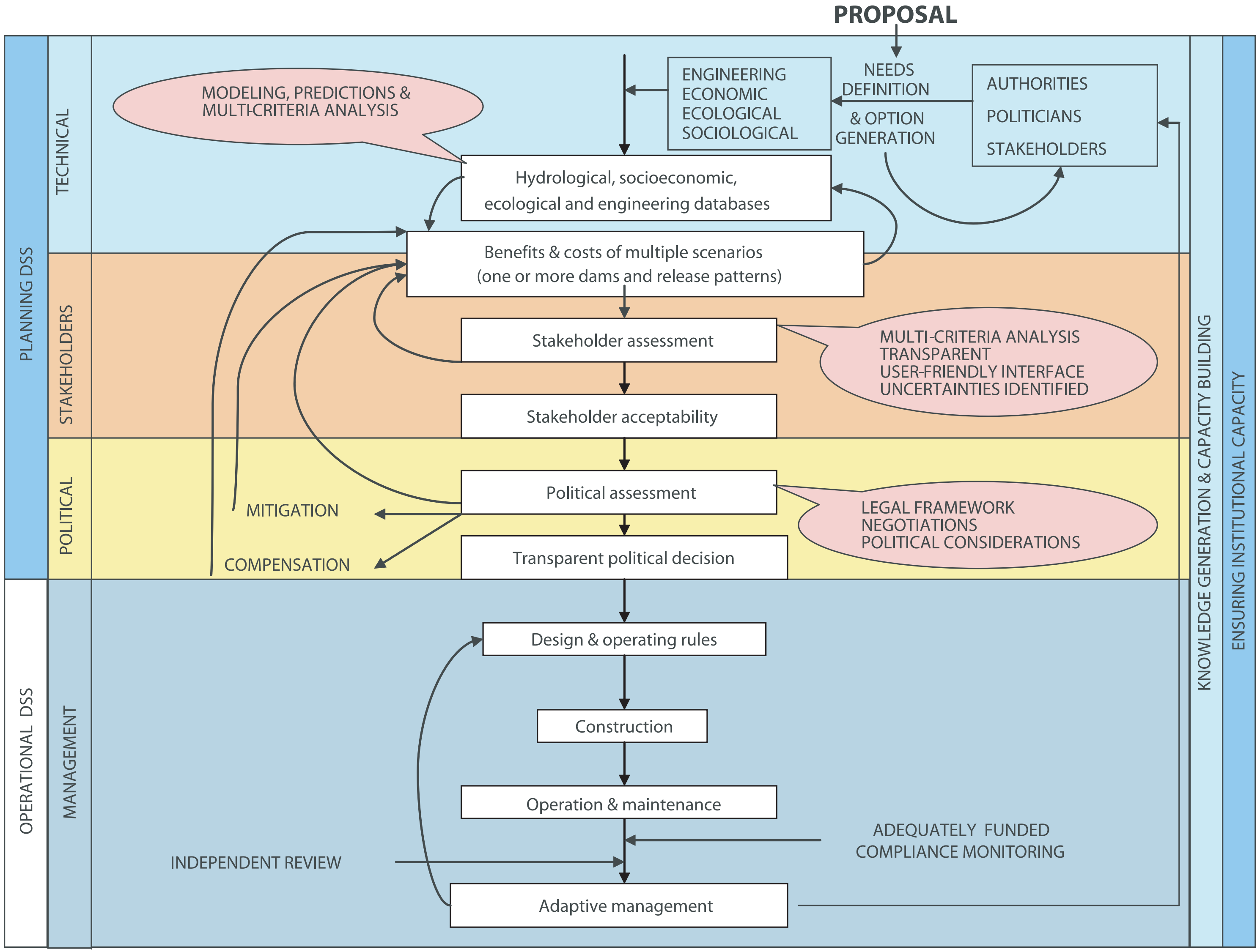
- the basic human needs reserve (i.e., water for drinking and other domestic uses)
- the ecological reserve (i.e., water to protect aquatic ecosystems)

One of the major challenges of the New Water Act is how to assess how much water can be taken from a river before its ability to meet social, ecological and economic needs is reduced. In South Africa standard procedures for Reserve determination have been developed. These are largely based around an approach, called the Building Block Methodology, which was developed by South African scientists, in conjunction with practitioners, over several years (King et al. 2000). Once established, dams should be operated to ensure that reserve flows are maintained at key locations in a river. Various DSSs have been developed to assist in this implementation step, as well as for monitoring and adaptive management.

Decision-making in the Project Cycle

Obviously, the types of decisions that need to be made throughout the planning and operation of dams vary. Figure 2 presents a conceptual framework for decision-making throughout the project cycle of a large dam. This is a slightly modified version of one developed by a working group at the International Conference on Dams and Decision Support Systems (CPWF 2006). Broadly, two types of decision are associated with dam planning and management. The first are those connected to strategic planning, including, before it is constructed, whether or not a dam should be built and, if so, optimum storage volumes and the guiding principles for operation. The second are those associated with day-to-day operation (i.e., management) of the dam to satisfy a range of often competing requirements. The two types of decision (i.e., for planning and for operation) are shown in the left column. The framework conceptualizes the decision-making process stepping through four major sets of activities: technical, stakeholder, political and management (second column on left). None of these four sets of activities is exclusive to the particular group which is used to designate it, but each is seen as the dominant 'actor' at that particular stage in the project cycle. At each stage, the decision-makers and their information requirements vary. For example, decisions

Figure 2. *Conceptual framework for decision-making in dam planning and operation (CPWF 2006).*



on whether or not a dam should be built usually reside with politicians whilst decisions on day-to-day operation (requiring very different information) will be taken by the dam operator or manager.

The decision-making process is initiated by a water-resource proposal (top right). This might be the construction of a new dam on a river (i.e., development) or changes to the operating rules of an existing dam to improve operation and reverse negative environmental and social impacts (i.e., rehabilitation). Responding to the proposal, the relevant authorities and all stakeholders (including all affected communities, both upstream and downstream, and those parties representing ecosystems) should be identified and their specific interests, issues and concerns regarding the proposal ascertained. Through a process of discussion with stakeholders all alternative plausible options, including the 'no change' or the 'no development' option, should be identified for consideration in the decision-making process[2]. Thus, a range of stakeholder concerns, in conjunction with the potential alternative options, guide the ensuing technical activities, which should be designed to provide information on the full range of costs and benefits of each option. In accordance with the recommendations of the WCD, the ecological and social aspects of the various options should be attributed equal weight to the engineering and economic aspects. All technical activities at this stage should be designed to provide the best possible understanding of the current status of the system and of all stakeholders, as well as projections of the likely impacts of all the scenarios. All the gathered information should be stored in a comprehensive database. At this stage, all scenarios should be treated equally and, as far as possible, the full spectrum of costs as well as benefits linked to each (i.e., including the goods and services being provided by the ecosystem) should be evaluated. It is often difficult to make accurate projections of impacts. Use can be made of relatively complex projection techniques (e.g., the analysis of trends, modeling and multi-criteria analysis), but it should be recognized that complex techniques are not an end in themselves and the emphasis should be placed on experience, logic and common sense.

Once the scenarios are completed, they should be presented to all stakeholder groups in a way that is transparent, and readily communicates all possible impacts and is explicit about uncertainties. Clearly, the way information is presented is crucial to ensuring the understanding of different stakeholder groups. Alternative scenarios, that may be proposed by stakeholders, including suggestions for mitigating likely negative impacts, should be given full consideration and evaluated in the same way as other scenarios, with all findings reported back to stakeholders. Clearly, as outlined here, this consultative process may be protracted. Although it should be time-bound (it cannot go on indefinitely), sufficient time must be given to do it properly. Ultimately, it may be impossible to reach consensus on a preferred option, but it is imperative that each stakeholder group feels that it has been listened to, with due consideration to its views. At the end of the process the relative degree of acceptability (or unacceptability) of each scenario for each stakeholder group should be determined.

The information pertaining to different options then moves to the political arena, where a political assessment should be completed. In support of the political process, a range of data should be available for each scenario. This should include quantitative and qualitative information on: (i) the engineering aspects; (ii) the predicted changes in the river ecosystem; (iii) the predicted social impacts; (iv) the economic impacts, for beneficiaries, as well as the mitigation and compensation costs for those likely to be adversely affected; and (v) the input from stakeholders on levels of acceptability. Each scenario should be assessed in terms of the country's legal framework and current political realities, and may involve negotiations with interested parties, perhaps leading to the requirement for additional or 'compromise' scenarios for consideration.

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[2] The DDP designates this stage in the decision-making process "comprehensive options assessment".

The final outcome should be a transparent, well-motivated political decision, detailing which option has been decided upon and why.

At this stage, activities move into the management arena, and implementation. The option that has been politically negotiated and chosen should guide the final design (and in the case of a new dam, construction) of the proposed development or rehabilitation project. Detailed consideration needs to be given to, as far as possible, avoiding and mitigating adverse impacts. For a new dam, this should include consideration of design features (e.g., dam alignment, exact dam height) as well as operating rules that meet all project objectives but also minimize negative impacts.

Once the dam is operational, adequate, appropriately-funded monitoring should be conducted to ensure both: (i) compliance with operation and mitigation measures prescribed in the planning process, and (ii) evaluation of measures to ensure that they are achieving the objectives intended - a process of adaptive management. Monitoring should include both biophysical aspects of the scheme (e.g., to ascertain that flows released downstream are as intended and are effective in maintaining desired features of the river ecosystem) as well as socioeconomic aspects (e.g., to ascertain that intended benefits are being delivered). Monitoring is of extreme importance for mitigation and compensation programmes because costs estimated on earlier predictions need to be verified, and the effectiveness of compensation and benefit-sharing mechanisms ascertained. To this end, all monitoring programmes need to be well designed to ensure that they provide information required for management decision-making. They should be well-structured, parsimonious (focusing on a few well-selected variables), and the results and methods should be subject to independent evaluation and auditing.

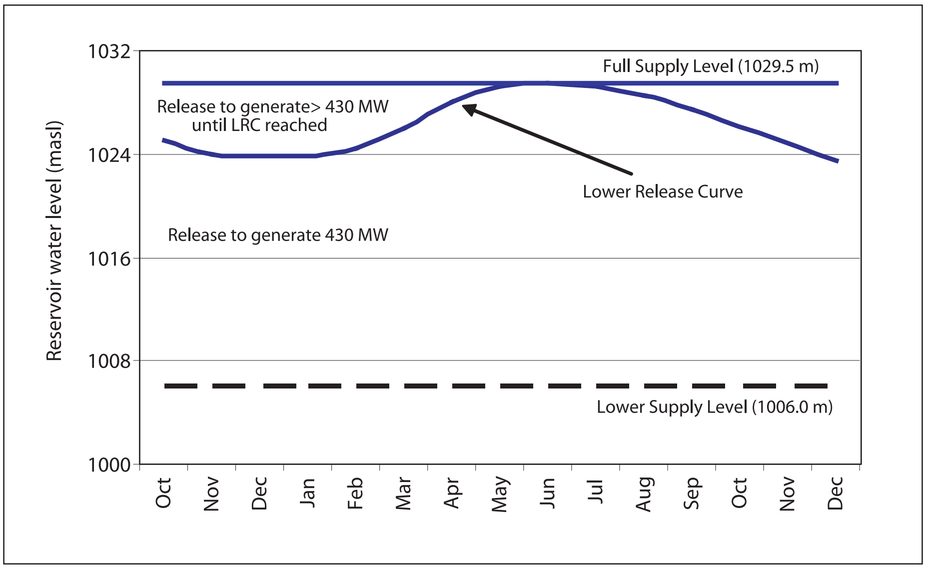
The final part of the process is adaptive management based on the monitoring results. If monitoring is to be an effective part of an implementation plan, management structures need to be able to manage heterogeneity, test the efficacy of their practices and react to monitoring results that reveal change is occurring. Adaptive management is difficult for large government (or other) organizations, as these tend to be prescriptive with rigid rules. A culture needs to be developed that facilitates response to findings from monitoring programmes and assimilation of feedback received from different stakeholders, otherwise recommendations may be made to no effect. Throughout the process, knowledge generation and capacity building should be occurring, as should the development of institutional capacity to react (columns on right of figure).

Operating Rules

Reservoir operating policies are frequently defined by *rule curves* that specify either reservoir (target) storage volumes (levels) or desired (target) releases based on the time of year and the existing storage volume in the reservoir (Box 5). Reservoirs can have multiple rule curves made up of wet season refill curves and dry season drawdown curves. The rule curves that regulate the releases and drawdown of a reservoir are typically often referred to as control rules.

Box 5. Example of control rules for operation of the Itezhi-Tezhi Dam, Zambia.

A computer model, HEC-3, was used to develop a rule curve for the Itezhi-Tezhi Reservoir (SLHP 1990). The aim of the curve is to reduce spillage and hence increase energy generation. The curve was refined slightly in the later Shawinigan Engineering (1993) study. The rule, which is defined by a set of end-of-month target levels or storages, is a statistical one, based on the properties of the flow sequence used, and can be applied independently of flow factors. It is, therefore, of particular use when long-term planning is undertaken in the absence of reliable knowledge of the flows to come, especially wet season floods. It can be considered as a conservative approach to efficient generation, i.e., one that minimizes the risk of reservoir failure to meet the firm demand, while also reducing spillage (Shawinigan Engineering 1993). Releases are made with the objective of attaining the target level at the end of each month. When levels drop below the lower release curve (LRC), releases are reduced to ensure power production of 430 megawatts (MW), but no more.



In recent years the World Wide Fund for Nature (WWF) has been working in collaboration with the Zambia Electricity Supply Corporation and the Ministry of Energy and Water Development to broaden the focus of water resource management and develop operating rules that also take into consideration a number of downstream environmental and social concerns (Schelle and Pittock 2005).

REVIEW OF DSS

Numerous researchers have developed computer-based DSSs for the management and operation of reservoirs and river systems (e.g., Simonovic and Savic 1989; Jolma 1994; DeGagne et al. 1996; Koutsoyiannis et al. 2002). Currently, the vast majority of reservoir system planning and operation is undertaken using simulation and optimization models (e.g., de Monsabert et al. 1983; Lund and Guzman 1999). To date, these have focused primarily on the physical aspects of the system (Reitsma 1996). They are frequently based on simple engineering principles for dam operation, such as keeping reservoirs full for water supply or empty for flood control. As such, they provide a great deal of flexibility in the specification of system operations under various flow, storage and demand conditions. Many rules are based on largely empirical or experimental success, determined either from actual operational performance, performance in simulation studies or optimization results. These experimentally-supported rules are common for large multi-purpose projects.

Both simulation and optimization techniques (see below) require that the management 'problem', whether it be a long-term planning or an operational issue, is formulated explicitly in a mathematical algorithm. While many issues related to dam planning and operation can be expressed in this way, and so are termed "*well structured*", many others cannot. So called '*semi-structured*' or '*unstructured*' problems occur when there are a lack of data or knowledge, non-quantifiable variables or very complex, perhaps unknowable, interactions. For dams, a lack of understanding of the complexity of environmental impacts, and also of the links between biophysical changes and socioeconomic impacts, means that many management problems are, at best, only semi-structured. To add to the difficulties, different stakeholders with different values will often perceive reality/problems in different ways. In some cases they will not even agree on the issue, so that problem formulation can be more a social process than a technical one. In such situations, judgement and intuition are crucial in decision-making. In recent years a number of DSS tools have been developed to bolster the decision-making process for unstructured or semi-structured decision-situations. These include new types of computer-based systems, such as multi-criteria analysis and Bayesian networks, but also completely different approaches such as role playing and board games that can be used to involve different stakeholders in the decision-making process.

A brief review of different types of DSS that have been, or could be, applied to dam planning and operation is presented below.

Simulation Techniques

Simulation modeling replicates the physical behavior of a system on a computer. In effect it is an abstraction of reality. The key characteristics of the system (i.e., the main system processes and variability) are reproduced by a mathematical or algebraic description. Simulation is different from mathematical programming techniques (see below) which find an "optimum decision" for system operation meeting all system constraints while maximizing or minimizing some objective (Yeh 1985). In contrast, simulation models provide the response of the system to specified inputs under given conditions or constraints. Hence, simulation models enable a decision-maker to test alternative scenarios (e.g., different operating rules) and examine the consequences before actually implementing them.

Simulation models for the operation of reservoirs have been applied for many years (e.g., Emery and Meek 1960; Hall and Dracup 1970; Biswas 1976; Stansbury et al. 1991; Huang and Yang 1999; Ito et al. 2001; Thorne et al. 2003). Many models are customized for a particular system. However, more recently, the trend has been to develop general simulation models that can be applied to any basin or reservoir system. For example, HEC-ResSim has been designed and developed by the Hydrologic Engineering Center of the U. S. Army Corps of Engineers specifically to perform Reservoir System Simulation. It is designed to perform reservoir operation modeling at one or more reservoirs for a variety of operational goals and constraints, including release requirements and constraints, hydropower requirements and downstream needs and constraints (HEC 2003).

Optimization Techniques

Although simulation models can accurately represent system operations and are useful in examining long-term reliability of operating systems, they are not well suited to determining the 'best' or optimum strategies when flexibility exists in coordinated system operations. Instead, prescriptive optimization models are often used to systematically derive optimal solutions, or families of solutions, under specified objectives and constraints. The application of optimization techniques in reservoir studies has a long history (e.g., Yakowitz 1982; Yeh 1985; Wurbs et al. 1985; Wurbs 1993; Labadie 1997) and a diverse array of optimization methods for dam operation has been formulated. In all the mathematical optimization techniques, the problem of reservoir operation is formulated as a problem the objective of which is to maximize or minimize a set of benefits over time, subject to a set of constraints. Such constraints include explicit upper and lower bounds on storage (for recreation, providing flood control space and assuring minimum levels for dead storage and power plant operation) and/or limits on releases (to maintain desired downstream flows, in the past often expressed as minima, for water quality control, fish and wildlife maintenance as well as protection from downstream flooding). The most commonly used techniques are Linear Programming (Mannos 1955), Dynamic Programming (Lee and Waziruddin 1970) and Non-Linear Programming (Young 1967). In recent years, these techniques have been combined with new approaches such as "optimal control theory" (Wasimi and Kitanidis 1983), "fuzzy logic" (Fontane et al. 1997) and "artificial neural networks" (Funahashi 1989).

Linear Programming (LP) is a commonly used approach in water resources management. It is concerned with solving a special type of problem; one in which all relations among the variables are linear, both in constraints and the objective function to be optimized. Application of LP to reservoir operations has varied from simple straightforward allocation of resources to complex situations of operation and management. In the past, limitations of computing power meant that optimization was achieved by decomposing reservoir systems in time and space (e.g., Meier and Beightler 1967). These early models were predominantly deterministic, that is, they did not take into account the stochastic nature of inflows but rather were based on long-term average seasonal or monthly flows. However, they have gradually been improved. For example, Loucks (1968) developed a stochastic LP technique for a single reservoir subject to random, serially correlated, flows. Subsequently, much more complicated stochastic models have been developed to reflect more realistically stream flow stochasticity, evaporation losses and more complex systems involving multiple reservoirs (e.g., Dahe and Srivastava 2002; Tu et al. 2003). Under certain assumptions, non-linear problems can be linearized and LP equations solved by iteration or approximation procedures. The program MODSIM is a generic program based around LP approaches that has been developed specifically for modeling water resources systems and reservoir operation (Labadie et al. 2000).

Dynamic Programming (DP), a method for optimizing a multistage process, has been extensively used in the optimization of reservoir operations. Since release decisions are made sequentially, at different time-steps, it exploits the sequential decision structure of reservoir systems to determine optimal solutions to problems. The success and popularity of the technique is attributed to its capability to support non-linear and stochastic features which characterize water resource systems and the added advantage of effectively decomposing highly complex problems with a large number of variables into a series of subproblems, which are solved recursively at each time-step (Yeh 1985). Over the years, numerous variations of DP have been applied to a range of dam operation issues, including systems of multiple reservoirs, conjunctive use of surface water and groundwater and optimizing hydro plant efficiency in multi-turbine systems (Arunkumar and Yeh 1973; Klemes 1977; Giles and Wunderlich 1981; Georgakakos et al. 1997). One problem that remains is the large amount of computation time required, even with modern computers, to determine optimal solutions in complex systems with large numbers of variables (Sadecki 2003).

In contrast to LP and DP, relatively little is published on the use of Non-Linear Programming (NLP) techniques for reservoir system operation. This is possibly because the mathematics involved is a lot more complex, and the optimization process is slow and takes up more computer storage and time than the other methods (Yeh 1985). However, the value of NLP techniques is their more general mathematical formulation which means that effective algorithms for large-scale, multi-objective optimization can be developed (Yeh 1985). There are a number of NLP algorithms, all of which require that the objective functions and constraints are mathematically differentiable. To date, most applications of NLP have been in the field of hydropower optimization in systems comprising several large-scale reservoirs (e.g., Grygier and Stedinger 1985; Arnold et al. 1994; and Barros et al. 2003).

The basis for optimal control theory is the simulation of dynamic systems using quadratic equations that can be solved analytically. For example, Wasimi and Kitanidis (1983) modeled a multi-reservoir system with linear differential equations, but used a quadratic objective function to ensure that the reservoir storages met pre-specified conditions. Similar approaches have been developed that enable the benefits of one objective to be maximized whilst simultaneously satisfying other objectives to pre-specified levels (Georgakakos and Marks 1987; Georgakakos 1989).

Fuzzy logic (Zadeh 1965) is an approach that has been developed to handle lack of precision and uncertainty in model inputs and even objectives. In some respects it is similar to estimating probability in stochastic models. It can be used for problems that are difficult to describe due to subjectivity or vagueness. Fuzzy logic has been used in a number of water resource applications, generally as a refinement to conventional optimization techniques (e.g., Kindler 1992). The approach has been used to simulate reservoir operation (e.g., Russell and Campbell 1996; Shrestha et al. 1996). Panigrahi and Mujumdar (2000) demonstrated the utility of fuzzy logic for reservoir operation through application to the Malaprabha Reservoir, in the Krishna Basin in India.

Artificial neural networks are non-linear, multi-dimensional interpolating functions that have been inspired by studies of animal brains and nervous systems. Over the last decade the approach has attracted wide attention and is found in a growing number of applications, including water resources planning. One characteristic of the approach is that the systems can effectively “learn” or be “trained” in complex relationships (Saad et al. 1994). The ability of an artificial neural network to optimize general operating rules for a multi-purpose, multi-reservoir system has been demonstrated through application to an interlinked system comprising eight reservoirs on three rivers, situated on the borders of Tamil Nadu and Kerala in South India (i.e., the Parambikulam-Aliyar Project) (Chandramouli and Raman 2001). A combined neural network and fuzzy logic approach has been used for the development of a DSS to optimize dam operation for a reservoir used for water supply and flood control in Japan (Hasebe and Nagayama 2002).

Multi-Criteria Analysis

In recent years, a large number of Multi-Criteria Analysis (MCA) techniques and approaches have been developed (Keeney and Raiffa 1976; Saaty 1980; Vincke 1992). The techniques are designed to cope with both qualitative and quantitative data, enabling decisions to be made on the basis of well-informed scientific principles, combined with expert judgement. All MCA techniques make options and their contributions to specified outcomes explicit. They differ in how they combine data, but they allow the decision-maker to take account of a wide variety of factors when reaching a decision. They may also allow alternative ethical and value systems to be taken into account. MCA techniques can be used to identify a single preferred option, to rank options, to short-list options for detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities. Formal MCA techniques provide an explicit weighting system for different criteria on which the decision is based (DCLG 2000).

All MCA techniques are based on a performance matrix which relates the performance of different options against specified criteria. Individual performance assessments can be either numerical or qualitative (e.g., based on a color code). Generally, the more the information in the performance matrix can be converted into numerical values, the more reliable and transparent the decision making. Techniques commonly apply numerical analysis to score and weight criteria in order to give an overall assessment of each option being considered. Different MCA techniques are distinguished from one another in terms of the way that they process information in the performance matrix.

A key feature of MCA is the emphasis on the judgement of the decision-maker, in establishing objectives and criteria, estimating relative importance weights and, to some extent, assessing/ evaluating and judging the contribution of each option to performance criteria. Without doubt this can be highly subjective. However, MCA can bring a degree of structure, analysis and openness to complex decisions that may lie beyond the scope of simulation and optimization techniques (DCLG 2000). The advantages over informal judgement unsupported by analysis, are that: the choices of objectives and criteria that any decision maker makes are open to analysis and change if they are felt to be inappropriate; scores and weights are explicit and can be developed according to established techniques; and it can provide a concrete basis for discussion (DCLG 2000).

Clearly for MCA to be a useful tool, it is important that the basic problem be structured correctly. This is likely to be achieved through consultations with all of those involved, and is a dynamic process which may change with time. The identification of the criteria, the suggestions of alternatives available, and the evaluation approach to be used, all need clarification before the problem can be solved. The problem itself can be structured as a model, and the most widely used approaches place the criteria in a hierarchical format. Typical of this method are the Simple Additive Weighted method (Hwang and Yoon 1981), the Analytical Hierarchy Approach (Saaty 1990), and the Multi-Attribute Value Function approach (Keeny and Raiffa 1976), where criteria are either organized into a hierarchy, or else selected into a small set of important criteria with which the options are compared. Olson (1995) and Yoon and Hwang (1995) provide useful surveys of MCA techniques.

Multi-Criteria Analysis approaches are increasingly being used to contribute to decision-making in natural resources and watershed management (Lamy et al. 2002; Giupponi and Rosato 2002) as well as for water allocation (Harboe 1992; Avogadro et al. 1997). Such an approach has also been recommended for incorporating human values, public goals and preferences into ecosystem management (Pavlikakis and Tsihrintzis 2003). Clearly, in relation to dams, MCA techniques are best suited for the planning, rather than the operational, phase of the project cycle. They have been used to evaluate resource objectives and in trade-off analysis for flow alternatives presented in the environmental impact statement for Glen Canyon Dam on the Colorado River (Flug et al. 2000). Srdjevic et al. (2004) have proposed the use of MCA approaches to "objectively" determine system performance of multiple reservoirs under different operating scenarios (i.e., combining simulation and MCA techniques).

Bayesian Networks

Bayesian networks (sometimes called belief networks or casual probabilistic networks) provide a method for representing relationships between variables even if the relationships involve uncertainty, unpredictability or imprecision (Cain 2001). Based on Bayesian probability calculus, the approach provides links between variables that can be established deterministically or probabilistically using available data or, if more appropriate, expert opinion. The approach assumes that causal associations describe decision problems and that choice among alternative decision actions involves causal relations (Nadkarni and Shenoy 2001). By adding decision variables (i.e., variables that can be controlled) and utility variables (i.e., variables that are to be optimized) to the relationships of a belief network, it is possible to form a decision-making tool, based around a "cause and effect" diagram.

Bayesian networks may be useful in situations such as managing dam releases because, as in the case of MCA techniques, they enable the integration of physical and socioeconomic variables within a single modeling framework. They also allow inclusion of expert knowledge on the same basis as more objectively derived data. Hence, the approach enables the creation of a model that may contain mathematical relationships as well as subjective elements corresponding to the experience of people who are an integral part of the system. Although mathematical in nature, Bayesian networks are superficially simple and the essentially graphical nature of the approach can facilitate formal discussion of the system structure with people from a wide variety of backgrounds. This can encourage interdisciplinary discussion and stakeholder participation (Batchelor and Cain 1998).

Bayesian networks have been used in a variety of scientific fields (Jensen 1996) but only recently applied to the field of environmental and natural resources management (Stassopoulou et al. 1998; Cain et al. 1999; Cain 2001; Said 2006). As with MCA techniques, they would appear to be most appropriate for dam planning rather than operation, but as far as is known, to date, they have not been used for this purpose.

Summary

Clearly, modern computer systems have facilitated the development of a vast range of approaches and tools that have been, or can be, used to assist dam planners and operators in their decision-making. Over the years, these systems have become increasingly sophisticated and complex. Many attempts have been made to take into account the stochastic nature of hydrologic variables, uncertainty in system understanding (i.e., in relation to natural processes as well as uses and demands) and the need for trade-offs among different objectives. In recent years, methods that combine approaches have been attempted. For example, embedding optimization routines within simulation models (Nalbantis and Koutsoyiannis 1997; Ndiritu 2006) and combining MCA approaches with DP and fuzzy logic (Fontane et al. 1997).

However, even from a relatively early stage, concern was expressed about the utilization of system analysis and the proper use of models for decision-making (Liebman 1976). Concerns focus on the lack of communication between model developers and users, lack of documentation and support services, and the lack of the involvement of a subjective and value-dominated human element (Loucks et al. 1985; Rogers and Fiering 1986; Loucks 1995). As a consequence of the emphasis almost exclusively on the development of more sophisticated, complex and bigger models, they often end up not being fully accepted by planners and managers (Savic and Simonovic 1991). Furthermore, although in the past water resources planning and management was left primarily to technical professionals, this is no longer the case.

The need to satisfy societal requirements has expanded beyond the objective of simply water supply and, increasingly, a diversity of concerned parties and organizations' (only a fraction of whom may be represented by technical professionals) demand input into the decision-making process (e.g., Kapoor 2001; Tetra Tech 2004). To facilitate the involvement of a broad spectrum of stakeholders requires different approaches and new types of DSS. Multi-Criteria Analyses and

Bayesian networks are attempts to increase the input of different types of information and human experience into DSS. In addition, non-computer tools (e.g., role playing games) that provide a sense of social inclusion by facilitating the involvement of communities in decision-making processes are recognized as a form of DSS by some practitioners (Lankford and Watson 2006).

The need to move beyond determining immediate physical targets (e.g., volumes of water for irrigation or units of power) to consider far reaching impacts on livelihoods is now broadly recognized, but nonetheless is not widely applied. For example, to date, very few, if any, DSSs have explicitly incorporated public health issues into IWRM. Nonetheless, the link between dams and health impacts is well established (Jobin 1999; Ersado 2005; Lautze et al. 2007) and the idea of modifying dam operations to mitigate negative impacts has been considered and tried in a few places. For example, modification of dam operating rules to remove mosquito breeding habitat from reservoir shorelines (i.e., by fluctuating water levels) has been successfully undertaken by the Tennessee Valley Authority since the 1950s (TVA 1947).

In a review of computer-based DSSs used for water resource planning, Prasad (2004) concluded that *"….while much progress has been made in relation to assessing hydrological and ecological effects of different water management alternatives, attempts to address socioeconomic effects have been insufficient. Despite an increased understanding about the connectedness between water resources management and socioeconomic development objectives, the existing conceptual frameworks and methodologies of decision analyses in the field of water resources engineering and management largely exhibit such a gap*." He emphasized the need for greater use of socioeconomic indicators to: (i) clarify socioeconomic goals and objectives; (ii) assist in the evaluation of trade-offs arising from different operating systems; and (iii) facilitate stakeholder involvement in decision-making through negotiation.

REVIEW OF DSS DEVELOPMENT AND APPLICATION TO IWRM IN AFRICA

As described above many different types of DSS have been developed to assist decision-makers in dam planning and operation; many have been applied to IWRM in Africa. This section is not intended to be comprehensive, but rather briefly describes how some of the DSSs have been used in Africa.

Examples of DSS Applied to IWRM in Africa

Computer-based DSS for water resource management and, specifically for dam planning and operation, have been used extensively in Africa (Table 4). In nearly all the major basins of the continent, the need for improved water management is recognized as a priority and DSSs have been proposed as tools to assist with water allocation and/or in the planning and operation of large dams. For example, in the Volta Basin, an integrated database and DSS have been developed as part of the GLOWA Volta Project, with the specific aim of contributing to policy dialogue on water use (GLOWA Volta 2006). In the Zambezi Basin, the Zambezi Action Plan is being implemented by the eight riparian states, with the specific objective of creating an enabling environment for sound and coordinated management of the basin water resources. Although there is no specific reference to an overarching DSS, as is planned for the Nile (see below), it is clear that some components of the plan (e.g., assessing major energy sources and potential use, energy conservation measures and the feasibility of linking major hydropower plants) will necessarily be facilitated by the use of DSSs.

In the Nile Basin, a range of DSSs have been developed to assess and weigh the benefits and impacts of water development and management strategies (Table 4). These include a planning model for the whole of the Nile Basin (i.e., the Nile Basin Decision Support Tool (DST)), which was developed under the auspices of the Food and Agriculture Organization of the United Nations (FAO) and includes a river and reservoir simulation and management module. This module comprises five components: (a) river network configuration; (b) river hydrology; (c) existing and planned hydropower facilities; (d) water use; and (e) reservoir operating rules. River and reservoir routing models simulate the movement of water through river reaches, quantifying transmission losses and time lags. Reservoir and lake outflows through hydropower facilities and spillways are modeled with sufficient detail for use in managing operations. An optimizing routine enables dam operating rules to be developed that takes into account the complexity and uncertainty of the system. The module can be used to simulate the impacts of alternative water resource development options (Georgakakos 2006).

Table 4. Examples of computer-based DSS used for water resource planning in Africa.

DSS	Description
Lake Victoria Decision Support Tool (LVDST)	Database, utility tools (i.e., to process and prepare data) and control models have been combined to support long-range planning and short-range operation of the Lake Victoria reservoirs and hydropower units. Allows short-term hydropower production to be optimized within constraints imposed by long-range planning decisions (Georgakakos 2006).
The High Aswan DSS	Specifically for the High Aswan Dam, this DSS provides decision support for the Egyptian Ministry of Water and Irrigation. It comprises various decision/ optimization models relating to reservoir releases for irrigation, energy generation and flood protection (Georgakakos 2006).
NileSim	Simulation model of the water resources of the entire Nile Basin. Developed primarily as a learning tool to explain complex river behaviour and management to non-technical people. Enables scenarios to examine the effects of policy options and changes caused by manipulating dams and regulating river use (Levy and Baecher 2006).
River Basin Simulation Model (RIBASIM)	This water balance simulation model enables evaluation of measures related to infrastructure, operational and demand management. It generates water distribution patterns and provides a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs. It has been used to simulate water flows in the whole of the Nile Basin as part of the Lake Nasser Flood and Drought Control project that aimed to evaluate risk and mitigation measures for different flood and drought control scenarios (Delft Hydraulics 2006).
Ruaha Basin Decision Aid (RUBDA)	A water resource simulation model developed to assess the impact of development scenarios in the Great Ruaha River Catchment in Tanzania. Designed with the involvement of key stakeholders in the basin and intended to help assess, among other things, the hydrological and socioeconomic impacts of different allocation decisions (Cour et al. 2005).
Water Resources Planning Model (WRPM)	Developed in South Africa, this simulation model is used for assessing water allocation within catchments. The model simulates surface water and groundwater as well as inter-basin transfers. The impact of dams on catch ment water yield is accounted for. The model is designed to be used by a range of users with different requirements and can be configured to provide output of different information (Schultz et al. 2000; Mwaka 2006).

(Continued)

Table 4 (Continued). Examples of computer-based DSS used for water resource planning in Africa.

Agro-hydrological modelling system (ACRU)	Developed in South Africa, this is a multi-purpose simulation model that has been used to simulate land use/management influences on water resources, sediment yield and selected water quality constituents, dam water budgets and operating rules, irrigation water demand and supply, and crop yields. It includes modules for dam operating rules which have been applied in South Africa (Butler 2001; Schulze and Smithers 2004; Smithers 2006).
GLOWA Volta DSS for the Basin	A scientific information system developed as part of the GLOWA Volta Volta Project to integrate knowledge and provide decision support for the planning, management and use of water resources in the Volta Basin. The nucleus of the DSS is a water optimization model, which represents the decision rules and constraints of water users, the physical water resources system as well as production functions and technology sets (GLOWA Volta 2006).
DSS for Komati Water Resources Planning	The Komati Basin Water Authority (KOBWA) manages water resource development in the Komati River Basin which is shared by South Africa, Mozambique and Swaziland. KOBWA uses a suite of three DSSs to plan and manage dams in the catchment. These are DSSs for water allocation (yield), water curtailment *(*rationing*)* and river hydraulic application (Dlamini 2006).
Decision Support Systems for Senegal River Delta	The hydrodynamic model, MIKE 11, has been used in conjunction with a the digital elevation model, to assess hydraulic functioning of different release regimes on the Senegal River Delta and the consequent implications for the ecology and hence livelihoods of local people (Duvail and Hamerlynck 2003).
The Nile Decision Support Tool (Nile DST)	Developed as part of the FAO Nile Basin Water Resources Project to objectively assess the benefits and trade-offs associated with various water development and sharing strategies. Comprises six main components: databases, river simulation and management, agricultural planning, hydrologic modeling, remote sensing and user-model interface (Georgakakos 2003, 2006).
Kafue DSS	A hydrodynamic model (KAFRIBA-Kafue River Basin) has been developed to improve the operation of dams located upstream and downstream of the Kafue Flats (wetland system) on the Kafue River, Zambia. Used in conjunction with improved forecasting of flows into the upstream reservoir, the DSS enables the dam operator (Zambia Electricity Supply Corporation) to make decisions on releases in a systematic way that balances hydropower requirements with other water uses and protection of the ecology (and hence livelihood benefits) of the Kafue Flats (DHV Consultants 2004).
Global Water Availability Assessment (GWAVA) model	This model provides a global/regional or catchment scale approach to modeling hydrology and assessing water resource availability. It provides assessments of water availability on a spatial basis (GIS), in terms of indices of water supply versus water demand. It enables impacts of climate and population change to be investigated and can also be used to look at land-use change impacts and development of hydropower schemes. It has been used to simulate regional water resources across eastern and southern Africa as well as, more specifically, in Swaziland and the Okavango Delta (Tate et al. 2002).
Water Evaluation and Planning (WEAP) model	A simulation model developed to evaluate planning and management issues associated with water resource development. WEAP can be applied to both municipal and agricultural systems and can address a wide range of issues including: sectoral demand analyses, water conservation, water rights and allocation priorities, stream flow simulation, reservoir operation, ecosystem requirements and project cost-benefit analyses (Stockholm Environment Institute 2005). The model has been applied to assess scenarios of water resource development in the Olifants Catchment in South Africa (Arranz and McCartney 2007), and for the Pangani Catchment in Tanzania (King pers. comm. 2006).

(Continued)

Table 4 (Continued). Examples of computer-based DSS used for water resource planning in Africa.

TALSIM 2.0	Reservoir simulation model, developed by the Technical University of Darmstadt, Germany. This model has been used to simulate operation of the Kidatu and Mtera dams on the Great Ruaha River, Tanzania (Yawson et al. 2003).
DamIFR	Developed and applied in South Africa to derive dam operating rules that satisfy environmental flow requirements. The model is intended to compliment traditional reservoir yield models. It can be used to simulate several linked reservoirs and computes what proportion of daily environmental flow requirements to release during periods of low reservoir storage when there is competition from other users (Hughes and Ziervogel 1998).
Desktop Reserve Model	Developed in South Africa, this is a hydrological model for estimating environmental flow requirements in situations where a rapid appraisal is required and data availability is limited (Hughes and Hannart 2003). The model is built on the concepts of the Building Block Methodology (King et al. 2000) and provides estimates of both low and high flow requirements. It has been used extensively in South Africa to provide initial estimates of the Ecological Reserve (Box 4).
Downstream Response to Imposed Flow Transformation (DRIFT)	Used in the Lesotho Highlands Dam Project, to assess the impact of different present and future flow release regimes on the river ecology and, via relationships determined between ecology and social benefits, and the livelihoods of riverine communities (King et al. 2003). DRIFT has also been used in abbreviated form in Zimbabwe (Tharme 2003).

Interestingly, although the Nile Basin DST exists, the Nile Basin Initiative is planning to develop a new DSS as part of the Water Resources Planning and Management Project of the Shared Vision Initiative (NBI 2006). The objective of this DSS is to fulfil requirements identified through a needs assessment for national water policy.

In the past in Africa, as elsewhere in the world, the focus of dam operation and planning was primarily on optimizing releases for one particular sector. However, increasingly, consideration is being given to the wider socioeconomic implications. For example, in Ethiopia, HEC-5, a precursor to the HEC-ResSim simulation model (see above) has been used to improve operating rules for the Koka Dam located on the Awash River. The model enabled the operating rules to be updated and improved, allowing for reservoir sedimentation and the increase in downstream irrigation since the dam was built (Seleshi 2006). In Zambia, operating rules for the Itezhi-Tezhi Reservoir on the Kafue River, initially developed to maximize hydropower, have been modified to incorporate broader aims and objectives (Box 5). In Lesotho, the DRIFT methodology, which takes into account social factors in determining environmental flow requirements (Brown and King 2000) was applied and used to assist the development of operating regimes for the dams constructed as part of the Lesotho Highlands Water Project (Watson 2006). This project highlighted the need to include an environmental flow assessment early on in the planning process (i.e., at the stage of the EIA), as well as the need to be able to present information that can be understood by decision-makers and for an appropriate policy and legislative framework (Brown and Watson 2006; Watson 2006).

In Uganda and Egypt, DSSs have been developed specifically for planning dam operation, at the outlet of Lake Victoria (i.e., the LVDST) and from the High Aswan Dam (i.e., HAD DSS), respectively. Both DSSs include optimizing routines and allow trade-offs between different sectors, including power, flood control and environmental flows to be considered. The LVDST comprises long-, mid-, and short-term components that enable short-term hydropower gains to be optimized, but within constraints imposed by long-term planning decisions (e.g., relating to lake level targets and acceptable downstream impacts) (Georgakakos 2006). The HAD DSS is similar in structure and functionality to the LVDST and enables trade-offs between irrigation, energy production and flood protection for different release regimes to be assessed (Georgakakos 2006).

Stakeholder Participation in Decision-making

The recognition that decisions are more sustainable if stakeholders are actively involved in the decision-making process has increasingly led to DSSs being designed with their participation and involvement. Many government policies, at least, acknowledge the need for participation (Appendix 1) and some experience has been gained in Africa. In Senegal, the water requirements of different stakeholders utilizing different natural resources were identified, and this informed modeling efforts to determine dam release regimes on the Senegal River (Box 6). In South Africa, attempts to involve stakeholders in planning flood releases from the Pongolapoort Dam have been only partially successful (Box 7).

Box 6. Participatory process for decision-making for Diama Dam, Senegal.

Construction of the Diama Dam on the Senegal River led to the collapse of the local economy which was dependent on seasonal flooding (Table 3). Local livelihoods were strongly dependent on natural productivity, including fisheries, livestock grazing and the production of artisanal mats. In 1994, a participatory process was initiated with local communities to develop a joint management system for the floodplain. After the initial Participatory Rural Appraisal, by a multi-disciplinary team, in-depth interviews were held with resource users in order to understand traditional resource governance systems (including tenure), to sound out their resource use strategies and to record their, sometimes conflicting, water requirements. On the basis of these needs, different flood scenarios were developed and their potential benefits analyzed, using hydrodynamic modeling and GIS integrated with empirical relationships linking flood characteristics to the spatial distribution of pasture, quantities of mat-making reeds and fish catch. Feedback from the analyses was discussed collectively and a compromise scenario proposed, constrained by other dam operating requirements. Subsequently, flooding regimes have been modified gradually, based on feedback from resource users. It was concluded that the data collection and research required for the modeling interacted favorably with the participatory process of the development of the management plan. The need for standards for the ‘optimal’ flood required the formalization of local knowledge and extensive interviews on resource use strategies with the stakeholders. This informed technical staff of the perceptions and needs of the stakeholders. Prudent initial flood releases also permitted familiarization with the artificial system for both the stakeholders and the managers, through ‘learning by doing’.

(*Source:* Duvail and Hamerlynck 2003)

In the Great Ruaha River in Tanzania, attempts have been made to involve stakeholders directly in the development of a computer simulation model for water resource planning (Box 8). Simultaneously, an innovative, non-computerized, tool was developed in an attempt to involve local communities in the decision-making process (Box 9). It is believed that such processes help to increase the acceptability and hence sustainability of decisions made (Lankford and Watson 2006).

Box 7. Experience in participatory planning of releases from the Pongolapoort Dam, South Africa**.**

A participatory approach has been developed to identify and decide upon options for managed flood releases from the Pongolapoort Dam. The releases attempt to balance requirements for four primary needs: (i) to maintain environmental processes on the downstream floodplain, both for livelihood support and for wildlife in a National Park; (ii) to support agriculture and minimize the flood damage to crops; (iii) to support the irrigation agriculture that has developed on the floodplain and on the surrounding uplands; and (iv) to meet the concerns of Mozambique, into which the river flows.

Viable options are determined by the Department of Water Affairs and Forestry (DWAF) which provides advice on the spatial extent and duration of inundation of different releases. Fifteen water committees, each one representing a different tribal region, have been established. Each committee comprises five members representing fisherfolk, agriculturalists, livestock keepers, domestic water users and the community health services. In the past the committees were supported by local development initiatives and NGOs who championed the process and provided logistical support (i.e., transport, etc.) to enable the committees to meet. The committees provided a conduit for information transfer between the DWAF and the communities, and also a forum for negotiation both within and between different community groups. In addition, they negotiated with other stakeholders on the different release options.

Initially, the water committees were very effective in reconciling differences and reaching a consensus. Furthermore, the committees were perceived by the communities to be successful in negotiating with other stakeholders. However, since the mid-1990s the effectiveness of the committees has declined and in recent years the participatory process has, to a large extent, broken down.

The failure of the water committees has been attributed to a number of factors, but is principally due to the lack of planning of natural resource use and development on the floodplain. In particular, during the 1990s, the Department of Agriculture made no attempt to divert commercial farming off the floodplain. As a result, cotton farming spread and, by the mid-1990s, the floodplain cotton farmers represented a strong political force. In 1997, they threatened to initiate legal proceedings against the DWAF if flood releases were made at a time inappropriate for their cotton crop. In the face of such belligerence, the DWAF was forced to acquiesce and no managed flood release was made despite the needs of other stakeholders. In subsequent years, the planning process has become increasingly complex as new stakeholders, including those upstream of the dam, have wanted to become involved. At the present time, the DWAF continues to attempt to involve all interested and affected groups, but developing a consensus is increasingly difficult.

(*Source:* McCartney et al. 2003)

Box 8. RUBDA – an example of DSS development with stakeholder participation.

The Ruaha Basin Decision Aid (RUBDA) is a DSS developed for the management of water resources in the Great Ruaha River Catchment in Tanzania. Its aim is to support users, such as the Basin Water Office and District Councils in making water allocation decisions. It provides a means of determining the likely hydrological and socioeconomic consequences of different allocation scenarios. It was recognized early on in the project that if it was to be used by those for whom it was intended, the DSS would need to live up to their expectations and objectives. Consequently, considerable effort went into determining user information needs and requirements, through numerous interviews, workshops and seminars. Early versions of the DSS were presented to stakeholders and their feedback was used to modify it to make it more user-friendly and flexible enough to meet a range of different expectations.

(*Source*: Cour et al. 2005)

Box 9. The River Basin Game – a tool to facilitate stakeholder participation in decision-making.

The River Basin Game is a dialogue tool for decision-makers and water users that was being tested in Tanzania and South Africa in workshops involving both high-level decision-makers and community representatives. It comprises a physical representation of the catchment in the form of a large wooden board. The river flows between the upper and downstream catchment and has on it several intakes into irrigation systems of varying sizes. Glass marbles that 'flow' down the channel represent the water. Participants make decisions about water abstraction and allocation between different irrigation schemes and can see the impact of wet and dry years. The game has been found to promote mutual understanding of different people's levels of access to water and allows participants to actively react to different scenarios. Experience shows that, by the end of the game, participants have a good understanding of system dynamics and common property pitfalls. The game also enables them to identify which water management issues are most critical and what solutions might be considered. The game is *socially inclusive* in that it enables a range of stakeholders to contribute ideas for water management solutions and make suggestions about institutional arrangements.

(*Source:* Lankford et al. 2004)

Constraints to DSS Development and Use in Africa

In Africa, where the need for economic development is urgent, but many people continue to rely on natural resources and agriculture to sustain their livelihoods, the necessity of assessing all the implications of dams, both positive and negative, is paramount. Given the complexity of water resource systems, DSSs that help decision-makers to answer specific questions related to the planning and operation of dams have a crucial role to play. However, constraints to the successful application of DSSs throughout much of Africa arise for technical reasons and because of limitations in human, financial and institutional capacity.

Limited understanding of the complex environmental and social interactions caused by river regulation is, as elsewhere in the world, a major constraint to dam planning and management (McCartney et al. 2000). To address this requires, first, increased research into both the environmental and social impacts of dams and, second, that specific evaluation of uncertainty and risk should, as far as possible, be key components of DSSs. It is also important to recognize that simple transfer of technology and/or knowledge from elsewhere is often inappropriate.

The lack of data, even fundamental biophysical data (e.g., on river hydrology) and socioeconomic data, is often a key limitation to the successful application of DSSs. Even today, despite the recognition of the importance of well-managed water resources, the acquisition of basic hydrometric data is rarely given high priority by government institutions (Houghton-Carr and Fry 2006). Often data are not of sufficiently high spatial or temporal resolution to assist planning and decision-making at a local level. Even where they exist, the administrative challenges of accessibility to data, including lack of familiarity of government officials with requests for information, deficient protocols for requesting data and lack of common data standards that promote data sharing, all hinder data use (The National Academies 2002). In some instances, particularly transboundary basins (e.g., the Nile), issues of national security also lead to restrictions on data sharing. There is need for much greater efforts in data collection, which should commence early in the project cycle and continue throughout. There is also the need for better coordination among different data collection agencies and improved data sharing.

The lack of qualified professionals to develop, manage and use DSSs is also often a limitation to their application in African countries. Technical capacity in the fields required (e.g., water resources, agriculture, hydrology, ecology, public health, conflict resolution, socioeconomics, etc.) and, particularly in the integration of different disciplines, is frequently insufficient. This undermines the effectiveness of DSSs, people and institutions and constitutes a major challenge to IWRM throughout much of the continent (Georgakakos 2006). While development funding for large schemes has often been made available, the schemes have largely been based on expertise hired from outside, with little of the experience and expertise remaining within the region at the end of a project (Hughes n.d.). To address this challenge requires comprehensive professional training and capacity building programs. Sufficient training, retention of qualified personnel, continuing education and long-term capacity building must all be part of a general educational strategy. There is particular need for cross disciplinary programs that can provide future engineers and scientists with holistic understanding of IWRM processes (Georgakakos 2006).

CONCLUDING REMARKS

The role of large dams in African development remains controversial. Many argue that the water regulated and stored by large dams is an absolute requirement to meet the development objectives of water supply, agriculture, industry, energy generation and other sectors (Lempiere 2005; Grey and Sadoff 2006). Others disagree and suggest that in many places alternatives to dams are better suited for Africa (e.g., Falkenmark and Rockström 2005; McCully 2006). However, it is likely that many dams will be built in the near future, particularly for hydropower (see Table 2). Consequently, there is a great need to improve dam planning and operation in order to avoid the mistakes, and resultant human suffering, of the past. Greater awareness of environmental concerns and social responsibilities significantly increases the complexity of dam planning and operation and makes decision-making increasingly complicated. In such situations, if designed and used appropriately, DSSs can make a considerable contribution to decision-making throughout the project-cycle of a dam or in relation to dam networks.

The extent to which DSSs contribute to better and more sustainable decision-making depends on many things, including the way in which decisions would have been made in their absence. Numerous approaches to DSS for dam planning and operation have been developed over the years. Which DSS, or even type of DSS, is most appropriate in any given situation depends on a range of factors, including what types of decision are being made and for whom the output is required. Clearly DSSs are only beneficial when they provide data and information that are recognized as useful and valued by the decision-maker(s). DSSs that do not do this will not be used; they must be useful in the real world.

Many of the challenges of IWRM come to the fore in the planning and management of large dams. Although there are constraints in the use of DSSs in Africa, their value has been proved in many cases. For dams, it is often necessary to go beyond the objective analysis of options and their merits and to consider more subjective issues such as equity. In such situations, decision-making is not simply a matter of identifying and selecting the best or most acceptable alternative in the face of conflicting objectives, rather, it is a process that needs to be managed. DSSs can assist in this process by helping to structure decision-making issues, supporting analysis and making clear the consequences (including trade-offs) of possible choices.

Ideally, DSSs used in dam planning and operation, contribute to decision-making processes that:

- facilitate examination of the wider social and ecological context of a particular dam;
- assist in conflict mitigation, enabling compromises to be found;
- enable integration of more and diverse sources of information from different scientific disciplines, but also include non-scientific inputs including local community knowledge;
- sharpen the focus on stakeholder involvement in decision-making so that all stakeholders participate from early on in the process; and
- facilitate negotiation-based approaches to decision-making that hopefully lead to increased cooperation and consensus building between different stakeholders.

It is surmised that contemporary DSSs such as Bayesian networks and MCA approaches that attempt to go beyond short-term goals and facilitate consideration of long-term implications can make a significant contribution to these objectives.

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Appendix 1. Examples of Policy and Regulatory Frameworks for Large Dam Construction and Operation in Selected Countries.

South Africa: The Department of Water Affairs and Forestry (DWAF) is responsible for the operation of dams. In some cases, operational control is devolved to agencies such as municipalities, water boards and irrigation boards, but operations are monitored by the DWAF. Dams are built and operated in accordance with a policy framework that comprises: (i) the Southern African Development Community Protocol on shared water courses, which stipulates the need for equitable allocation of water between nations; (ii) the National Water Act (1998), which stipulates the need for an environmental reserve; (iii) the National Environment Management Act (1998), which requires environmental authorization for any development projects that may impact negatively on the environment; and (iv) the National Heritage Resources Act (1999). The country has the intention to build more large dams; pre-feasibility and feasibility studies are currently being conducted.

Uganda: The majority of large dams in Uganda are for hydropower and are operated by the national power company. The Ministry of Water, Lands and Environment issues water permits, which stipulate how dams should be operated. Dams built on the Nile are operated in accordance with a policy framework that includes: (i) the Nile Basin Initiative, which seeks to improve and coordinate the policies of the riparian countries with regard to the equitable development of water resources within the basin; (ii) the protocol for sustainable development of Lake Victoria Basin (2003); (iii) the Owen Falls agreement (1953), a water sharing agreement signed by Uganda (at the time governed by Great Britain) and Egypt; and (iv) The National Environment Act of 1995, which is the enabling legislation for EIA in the country. For dams funded by the World Bank, the Bank's safeguard policies are implemented. In the face of growing energy shortages, the government policy is to build more large dams, particularly along the Victoria Nile.

Ethiopia: The Ministry of Water Resources (MoWR) is responsible for the planning and design of large dams. The majority of them are for hydropower and are operated by the national power company, Ethiopia Electricity Power Company (EEPCO). Operations are monitored by the MoWR. The government's Water Resources Policy highlights the need for water supply for people and livestock. The Environmental Protection Authority (EPA) of Ethiopia, established by government proclamation in 1995, is the main administrative body for EIA in Ethiopia. The enabling legislation for EIA in the country is the EIA proclamation of 2002. EIA procedures and framework guidelines were finalized in 2000. A draft National Water Resources Strategy, written in 2005, calls for major investments in water resources infrastructure and management capacity to ensure water security in the country. The Government's Irrigation Development Program (IDP) calls for an additional 274,000 hectares to come under irrigation within its 15-year plan period of 2002-2016 (i.e., a 135 percent increase over current levels).

China: A body of water laws and related policies, rules, regulations and decrees at national level and their provincial implementing regulations, exists to manage water resources in China. The Water Law (1988) is the overarching legislation and covers integrated planning and management of inter-provincial river basins. Other relevant laws that influence dam construction and operation include: (i) Laws for Water and Soil Conservation (1991); (ii) the Law for Flood Control (1997), which requires a unified and integrated planning approach with comprehensive river basin plans prepared by the river basin commissions; (iii) The Law for Water Pollution Control (1994); and (iv) The Environmental Protection Law (1989). The Regulation for Land Acquisition and Resettlement for the Construction of Large and Medium Size Water Conservancy Projects (1991) stipulates compensation and resettlement subsidies for displaced communities. The Ministry of Water Resources (MWR) is responsible for implementing the Water Law and overseeing implementation by provinces and local governments. The State Environmental Protection Administration (SEPA) established at ministry level in 1998 is responsible for formulating national environmental rules and standards and oversees their implementation. Dams are owned and operated by provinces, prefectures or irrigation districts. For large dams of national importance (e.g., the Three Gorges Dam), semi-autonomous agencies are established to be owner/operators. The MWR and River Basin Commissions usually set operating rules. China is one of the most active dam building countries in the world and dams continue to enjoy considerable institutional support. Current practices and institutional reforms emphasize the need for large-scale public works to address drought and flood management problems and to meet expanding energy requirements.

India: The planning, approval, financing, construction, operation and maintenance of large dam projects take place within the constitutional and legal framework of the country, and in particular, within the provisions relating to water. This includes: National Water Policy (NWP)(1987) and National Commission's Report on Integrated Water Resources Development Plan (1999), both of which emphasize the need for large-scale storage to support economic and social development in the country. The NWP makes reference to several important facets of water-related projects including: planning for a hydrological unit such as a basin or a sub-basin; drinking water to be a primary consideration; study of impacts on human settlements to be an essential component of project planning; the preservation of the environment to be a primary consideration; the need for an integrated, multi-disciplinary approach to project planning; water allocation to be done with due regard to equity and social justice. Some State Governments have formulated their own Water Policies (e.g., the Orissa Water Policy 1994, the Tamil Nadu Water Policy 1994). These are based on the NWP. In addition, the provisions of the Tribal Self-Rule Act 1996, which provides for consultation with tribal communities, are a necessary part of project planning and design. Since 1985, the Ministry of Environment and Forests (MoEF) has been responsible for carrying out environmental impact assessments and granting both environment and forest 'clearances'. In 1985, the MoEF issued guidelines for the environmental impact assessment of river valley projects. These guidelines deal mainly with upstream impacts. Within the Central Water Commission, an Environmental Monitoring Committee was constituted in 1990. This committee oversees the implementation of environmental safeguards stipulated by the MoEF. Dams are operated by both the Central Government (under the auspices of the National Thermal Power Corporation (NTPC) and the National Hydroelectric Power Corporation (NHPC)) and the States. Operation of the dams is regulated by a set of rules formulated by the State Government in accordance with the category of the Dam-Irrigation/Hydropower Generation. These rules, known as 'Rules of Regulation', generally, address: period or duration the reservoir will remain open for irrigation; mode of impounding river flows in the reservoir during normal and monsoon seasons; minimum storage to be maintained to safeguard the riparian interests, to protect the fish life in the reservoir, etc.; rules for operating the spillway gates to attenuate flood flows and to dispose of floods safely. India plans to build many more dams in the near future. Currently, approximately 75 Billion Cubic Meters (BCM) of storage is at various stages of construction and another 132 BCM is being considered. If implemented, the proposed River Linking Project (Kalla 2004) will massively increase storage in the country.

Nepal: Water resources in the country are governed by national policies and strategies including: (i) Water Resources Act (1992); (ii) Environmental Protection Act (1997); (iii) Soil and Watershed Conservation Act (1982). (iv) Water Resources Strategy (2002); (v) Nepal National Water Supply Sector Policy (1998); (vi) Irrigation Policy (2003); and (vii) Hydropower Policy (2001). The National Environment Impact Assessment guidelines (1993) provide a framework for EIA. Most dams in the country are hydropower dams, operated by the Nepal Electricity Authority, but with oversight from the Ministry of Water Resources. Projects requiring an EIA include: generation projects with a capacity of more than 5 MW; medium and large-scale irrigation projects; and resettlement programs. The Ministry of Population and Environment is responsible for overseeing EIAs. Public participation for gaining public acceptance is an accepted strategy. Nepal plans to build more dams. Currently there are 10 dams, mostly multi-purpose, that are at different stages of study.

Vietnam: Vietnam Electricity builds and operates many of the dams in Vietnam. Ministry of Natural Resources and Environment is responsible for environmental authorization of projects and enforcement of the Law on Environmental Protection (1993). Dams are being planned and constructed. (e.g., Tuyen Quang dam and Son La dam).

Turkey: The General Directorate of State Hydraulic Works (DSI) is the national agency responsible for planning and managing Turkey's water resources. EIAs are required for dams with reservoirs greater than 15 square kilometres (km^2) and/or volumes greater than 100 Mm^3. The operation and maintenance department of DSI is responsible for all large dam operation. Turkey continues to build large dams. In 2003, 54 large dams were under construction, primarily for irrigation and flood control purposes.

Norway: The Norwegian Water Resources and Energy Directorate (NVE) is the national agency responsible for enforcing the legal and regulatory framework that has developed over a long period of time (ca., 100 years) for securing appropriate operating rules and compliance with technical requirements. A government licensing process has been established. The process includes comprehensive environmental and social impact assessments that involve stakeholders. Licences include explicit conditions stipulating operating rules. Benefit sharing with local communities affected by the presence of a dam is a key requirement. Large dams continue to be built in Norway (Wold et al. 2006).

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