Hydropower Dams and Fluvial Morphological Impacts – An African Perspective

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Abstract

This paper provides background information on historical and future projected hydropower growth in Africa. Two high priority regional hydropower developments in Africa as identified by NEPAD are discussed. The impacts of hydropower dams on the fluvial morphology of the downstream river are reviewed, with specific reference to the role of low flows, intra-annual floods and inter-annual floods, and the sediment regime and ecosystem functioning. A Southern African case study: Cahora Bassa Dam on the Zambezi River, and its impact on flood attenuation, the river and the delta are evaluated.

Mitigation measures to limit the impacts of hydropower development on the ecology and fluvial morphology are reviewed, considering impacts upstream and downstream of the dam. An empirical reservoir classification system is also presented which will aid in the decision on which mode of operation should be selected for a reservoir.

1. Introduction

Large hydroelectric dams are amongst the most controversial of all types of development projects. Critics of large hydroelectric projects point to a wide range of negative environmental and related social impacts, from the destruction of unique biodiversity to the displacement of vulnerable human populations. Defenders of large dams note that they are often the economically least-cost source of electric power available, especially to large urban centers; they are a renewable electricity source; and most other power generation technologies also imply significant adverse environmental impacts. Due to reservoir sedimentation many of these projects are however not sustainable in the long term, and often the environmental costs incurred in the river downstream of the dam are not quantified adequately.

Worldwide, many countries rely upon hydropower for a substantial portion of their electricity. In developing countries, rapid urbanization and continued population growth will ensure increased demand for electric power for decades to come, even with the most successful of demand management and energy efficiency measures. Electricity remains a key ingredient for improving the lives of millions of poor people throughout the developing world. The historic and predicted world hydropower development is shown in Figure 1.1 and it is clear that developments in Africa have been lagging behind the rest of the world.
It is estimated that only 4 to 5% of Africa’s energy demands are met through hydropower in spite of proven large potential. Small-scale hydropower potential particularly for rural energy supply is hardly exploited. Future prospects in Africa include integrated planning and development of multipurpose schemes that take into account power generation, irrigation, fishery, recreation and transport together with ecological considerations.

Dams cause flood attenuation and sediment trapping. Flood attenuation has a major impact on flow variability downstream and rivers tend to narrow if major tributaries do not help to restore the flow and sediment balance downstream. Reservoir sedimentation occurs worldwide at an estimated rate of 0.3% year, giving an expected average reservoir life of about 300 years. This loss in storage capacity relates to an annual replacement cost of USD 13 billion (Palmieri, 2003). The historical growth in storage capacity up to 2000 and sedimentation is shown in Figure 1.2.

Water is the basis of life, and its proper management and conservation is essential for all socio-economic developments. It has been recognized that, due to its crosscutting nature, sustainable use...
of available water resources is critical to meeting the goal of eradicating poverty in Africa. Providing access to basic water supply and sanitation to a large number of Africa’s population, contributing to food security through use of water for agriculture, and also developing the substantial untapped and renewable hydropower potential of the continent, are some of the key areas which need to be addressed if the war against poverty is to be won. Two short term large hydropower developments based on New Partnership for African Development (NEPAD) priorities are discussed in the next section.

2. Proposed hydropower developments in Africa

2.1 The Mozambique Mepanda Uncua (MU) Hydropower Project

A 1300 MW hydropower project will be developed north of Maputo, on the Zambezi River downstream of the Cahora Bassa hydropower plant, both for domestic demand and export to the South African Power Pool’s (SAPP). The project is scheduled for completion in 2010, and the investment cost is estimated at US$1.6 billion. Of this only US$ 15 million is allocated for environmental management.

The main market for electricity from the project will be in the Republic of South Africa (RSA). The higher energy demand experienced during 2001 in this country has resulted in a decrease in the system operating reserve margin from 22% in 2000 to 18% in 2001. In 2001, Eskom's peak demand on the integrated power system reached 30599 MW. When adding other countries, SAPP estimated annual maximum demand is expected to reach 47400 MW by 2010. According to most recent estimates, existing capacity in the sub-region will be fully utilised by about 2007-2008.

The project is technically feasible and economically viable with “minimum environmental impact” based on the NEPAD (2002) report. People displacement will be low: 1.08 person/MW, but the downstream impacts could in fact be dramatic due to flood attenuation.

2.2 The DRC Grand Inga Integrator Study

The River Congo with an estimated total length of 4400km and draining a basin of 3.60 million km² is the largest in Africa and contains 30% of Africa’s total water resources. The river, with a discharge of approximately 1269 km³ per year at its outlet, is shared by DRC, Central African Republic, Congo, Angola, Cameroon, Burundi, Rwanda, Tanzania and Zambia. Irrigation and hydropower potentials are abundant, with great possibilities for co-operation in joint development. Existing irrigation development is less than 1% of the potentials.

The Grand Inga Integrator Study (NEPAD, 2002) was intended to investigate the possibility of developing the hydropower potential at Grand Inga and transmitting the power to the continent’s sub-regions (east, west, north, south and central). The study will also look into distributing the power through the North African interconnection to Europe and the Middle East. Once the sub-regional power interconnection is complete, Grand Inga would serve as an integrator of the sub-regional interconnections.

The Republic of Congo (DRC) has extensive hydropower resources. When considering the average potential hydropower output of 774 TWh per annum, the DRC stands third behind China and Russia, which can produce 1320 TWh and 1096 TWh per annum respectively. The USA and Canada follow the DRC with potential production figures of 701 TWh and 530 TWh per annum respectively. When expressed as firm power capacity, the DRC potential is equivalent to 100 000 MW of which approximately 40% is located at Grand Inga.
The potential of Grand Inga is about 40% of the present installed generation capacities in Africa. The proposed study is intended to investigate how, in the long-term, the Grand Inga hydropower potential could be developed to (a) integrate the power system interconnections of the sub-regions (central, east, west, north and south), and (b) strengthen the power exchange between the continent and Europe to enhance the north-south partnership.

3. **Impacts of hydropower dams on the river fluvial morphology and ecosystem**

3.1 **The parts of a river ecosystem**

All parts of a river ecosystem are inter-connected. Disturbance to one part will create a greater or lesser response over much of the system. For instance, a large in-channel dam can stop migration of fish to spawning grounds in the headwaters, impact a marine fishery at the other end of the system, and eradicate the floods needed to maintain floodplain vegetation in the middle reaches that is used for subsistence. Clearing bank vegetation can lead to bank collapse, increased sediment loads in the river, clogged fish gills and blanketing of spawning grounds, as well as reduced life of downstream reservoirs. Management of rivers and their flows should thus involve consideration of all likely responses of the river to a planned disturbance.

3.2 **The parts of a flow regime**

The flow regime is the pattern and timing of high and low flows in a river. Each river’s flow regime is different, depending on the characteristics of its catchment and the local climate, although regional trends do emerge. River ecologists recognise that different parts of the flow regime play different roles in maintaining a river (Table 3.1) (King, 2002).

<table>
<thead>
<tr>
<th>Flow component</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low flows</td>
<td>The low flows are the daily flows that occur outside of high-flow peaks. They define the basic seasonality of the river: its dry and wet seasons, and degree of perenniality. The different magnitudes of low-flow in the dry and wet seasons create more or less wetted habitat and different hydraulic and water-quality conditions, which directly influence the balance of species at any time of the year.</td>
</tr>
<tr>
<td>Small floods</td>
<td>Small floods are usually of great ecological importance in semi-arid areas in the dry season. They stimulate spawning in fish, flush out poor-quality water, mobilise smaller sediments and contribute to flow variability. They re-set a wide spectrum of conditions in the river, triggering and synchronising activities as varied as upstream migrations of fish and germination of riparian seedlings.</td>
</tr>
<tr>
<td>Large floods</td>
<td>Large floods trigger many of the same responses as do the small ones, but additionally provide scouring flows that influence the form of the channel. They mobilise coarse sediments, and deposit silt, nutrients, eggs and seeds on floodplains. They inundate backwaters and secondary channels, and trigger bursts of growth in many species. They re-charge soil moisture levels in the banks, inundate floodplains, and scour estuaries thereby maintaining links with the sea.</td>
</tr>
<tr>
<td>Flow variability</td>
<td>Fluctuating discharges constantly change conditions through each day and season, creating mosaics of areas inundated and exposed for different lengths of time. The resulting physical heterogeneity determines the local distribution of species: higher physical diversity enhances biodiversity.</td>
</tr>
</tbody>
</table>
Manipulations of the flow regime will affect the river ecosystem, and we have the choice of ignoring this in water-resource developments and awaiting (or being surprised by) unwelcome changes as the river responds, or trying to predict the potential changes and managing them. Until about fifteen years ago most, if not all, countries were doing the former. The following section describes how this has led to dams changing rivers.

3.3 The impacts of dams on river ecosystems

Dams are designed to manipulate the flows of rivers. In doing so, they impact indirectly on the downstream river ecosystem by potentially affecting every part of the flow, sediment, thermal and water-quality regimes. They may also impact the ecosystem directly by, for instance, blocking fish passage. Each of these aspects is discussed briefly below.

3.3.1 Low flows

Dams may store low flows during the wet season, for release downstream in the dry season. In doing so, the seasonal pattern of low flows may be partially or wholly reversed, eradicating conditions needed for life cycles to reach completion. Aquatic plants that need to push flowers above the water surface in the dry season for pollination, may be unable to and so gradually species disappear. Aquatic insects that are programmed to emerge during months when flow is usually quiet, to fly, mate and lay eggs in the river, may be forced to emerge in fast turbulent water, and so die. If they can adapt to emerge in months when flows are slower, they may meet unsuitable air temperatures or find no food, and so still die.

In some rivers, dry-season low flows are periodically completely eradicated by damming or direct abstraction. Such reaches will lose their fish, and other river life will be drastically reduced in diversity and numbers because most cannot cope with periods of drying out, even for a few hours. In ephemeral rivers, dams or other abstractions may halt the movement of groundwater along the channel, killing ancient riparian trees. This has happened in the Luvuvhu River, Kruger National Park (which should be a perennial river), and could happen to the linear oases of trees along the rivers flowing east to west across Namibia that support the large desert mammals and local indigenous peoples (King, 2002).

The ecosystem components do not exist in isolation, but are interdependent. Insects provide food for fish; leaves falling from native trees provide the right food at the right time for the insects; plants stabilise banks, controlling sediment inputs into rivers, and so protecting spawning and feeding grounds, gills and eggs. As flow impacts any of these components, the effects are felt throughout.

3.3.2 Intra-annual floods

Small and medium floods may be completely stored in reservoirs. These floods are thought or known to: sort riverbed sediments, maintaining physical (and therefore biological) diversity move sediments along the river, maintaining bars and riffles (low flows cannot do this, and very high flows may bring more sediments into the river than they remove) help maintain and control the spread of marginal vegetation such as reed beds, trigger fish spawning provide depth of water for fish migrations along the river, enhance water quality during the dry months.

Sometimes such floods spill over the dam wall once the reservoir is full. This may not happen until late in the wet season, and so be of limited use for ecosystem maintenance. Fish triggered by spills to spawn late in the season, for instance, will produce juveniles that may not be sufficiently...
developed to survive the coming adverse season. This can happen naturally, but when it is managed to happen year after year, the fish species so affected will decline and could disappear. Small and medium floods could be released from the dam to encourage early spawning, but with recognition that any reduction in the numbers of floods (e.g. used to be 15 per year, now two per year released from the dam) translates into a higher risk of the fish numbers declining. This is because the fish have fewer chances to spawn, and there are fewer batches of young to survive sporadic adverse conditions such as cold spells, toxic spills or bulldozing of the riverbed.

3.3.3 Inter-annual floods

The large floods that occur less often than yearly are thought or known to:

- maintain riparian belts of trees that can be metres to hundreds of metres wide on either bank;
- scour channels, maintaining their capacity to carry flood water;
- scour riverbeds, cleansing substrates and flushing fines that clog spawning and feeding grounds;
- eradicate patches of in-channel and bank vegetation, enhancing diversity as new growth appears.

One major importance of larger floods is through the geomorphological changes they bring, which may not be directly ‘welcomed’ by the aquatic plants and animals. Fish, for instance, have to seek refuge from them. They are essential as re-setting agents for the river, however, scouring slimy films from rocks, renewing habitats and eradicating old and diseased individuals. Other important functions of large floods are their flooding of floodplains and scouring of estuaries including maintaining an open mouth. Both of these are areas of high productivity and diversity, highly important to people and wildlife.

It is often claimed that dams cannot harness the larger floods, which will spill over. They may well reduce their size, however, so that ones of a magnitude that occurred on average every two years could occur as a spill of that magnitude only once in five to ten years. Some consequences of floods becoming rarer can be inferred from earlier sections of this paper.

3.3.4 Sediment regime and the ecosystem

Dams trap sediments passing down the river, as well as altering flows. Because of this, the channel may show signs of degradation (loss of sediments), or aggradation (accumulation of sediments), depending on whether the remaining floods can move the remaining incoming sediments. In both circumstances the ecosystem changes, because different plants and animals live on or in different kinds of substrates. Most trees, for instance, cannot survive on banks degraded down to bedrock, whilst increasing amounts of sand encourage growth of reed beds. The highest diversity of aquatic insects is on well-scoured cobbles, and this is the favoured feeding area of many valued fish species such as trout. A shift of the riverbed to sand will reduce both diversity and abundance of the food species, as most cannot survive in sand. Those that can live in sand cannot be seen by, and therefore fed on by, the fish.

In developing regions such as southern Africa, millions of people are subsistence users of rivers. They may be using river resources for food, medicines, nutritional supplements, firewood, construction materials, potable and washing water, crafts, and grazing for animals. Shifts in the river ecosystem directly affect these poorest of poor people, often deeply threatening their health, ability to work, and spiritual well-being. Until recently, it was assumed that the major impact of dams on rural people was through displacement of those living in the planned reservoir basin. It is now known that the number of people affected downstream of a dam by the changing health of the river can be orders of magnitude greater than the number directly displaced by the project (WCD, 2000).
3.4 Case Study: Cahora Bassa Dam

3.4.1 Background

The Zambezi River is the fourth largest floodplain river in Africa and the largest system flowing into the Indian Ocean. Rising in Angola it has a catchment area of 1,570,000 km², drains the Southern borders of the DRC and traverses Botswana, Zambia, Zimbabwe, Tanzania, Malawi and Mozambique. The river comprises three segments: Upper (1,078 km) from its source to the Victoria Falls, Middle (853 km) between the Victoria Falls and Cahora Bassa Gorge, and Lower (593 km) from Cahora Bassa to the sea. Figure 3.1 shows a map of the lower Zambezi.

![Figure 3.1 Schematic representation of the Lower Zambezi River](image)

In the uplifted mountainous areas below Cahora Bassa, the channel is confined to a 500m wide narrow valley with relatively high gradients. Boulder and bedrock outcrops and high stream energies dominate the instream environment of the gorge zones. Downstream of these zones the valley-floor-trough broadens to several kilometres. Because gradients are still relatively high and boundaries sediments are highly mobile, a braided sand-bed river dominates. The zone is further characterised by extremely high sediment fluxes.

Jackson (1986) describes the Zambezi as a ‘sandbank’ river with pronounced flood (Jan-April) and dry season (June-October) flows. The average floods ranges between 8,000 and 14,000 m³/s. In this section we focus on the effects of the Cahora Bassa dam on the lower river.

Between December 1973 and October 1974 the Lower Zambezi was surveyed seven times at thirteen sites from the Zimbabwe border to the coast at Chinde in order to assess the potential effects of Cahora Bassa on the already regulated Lower Zambezi.

Recommendations that were made after the surveys included:

a) Reservoir filling over a minimum of 2 years.

b) Minimum compensation flow of 450 m³/s during filling with releases to match seasonal cycles.

c) Filling from March 1975, to avoid loss of the flood.
Predictions about future ecological changes that would occur should the recommendations be ignored were also made:

a) A rapid decline in coastal fisheries and shrimp industry, and artisanal river Fisheries: the first two due to loss of silt and associated nutrients, the last to reduction of wetland flooding, loss of recruitment and exposure to main-channel predators.

b) Loss of mangroves and coastal erosion through flood reduction and silt loss (coastal erosion was evident during aerial surveys conducted on January 16, 1974; these were attributed to the effects of Kariba Dam (storage capacity 180 600 million m^3) over 16 years).

c) Up to 70% reduction in sediment transport during floods, coupled to lack of scour and upstream penetration of the estuarine salt wedge.

d) Changes in riparian and wetland vegetation structure consistent with classically regulated rivers and concomitant decline of large mammal and bird populations on the Marromeu Wetlands.

e) Spread of human disease vectors due to increased habitat (pools, lack of flushing).

f) Invasion of wetlands by alien aquatic plants.

3.4.2 Flow curtailment in the lower Zambezi Valley

Lake Cahora Bassa with total storage capacity of 63 000 million m^3 commenced filling on December 5, 1974. It was rapidly filled in a single flood season (1974-1975) without compensation flows (60 m^3/s reached the river as leakage). By March 1975, an emergency flood release discharged 1.27 billion m^3 over 5 days to prevent overtopping the still incomplete wall. A discharge of 14 753 m^3/s was achieved with a combination of eight sluice gates and emergency spillways and inflows exceeded 20 000 m^3/s.

Figure 3.2 shows a graph of recorded flood flows downstream of Cahora Bassa Dam.

Figure 3.2 Observed historical flood peaks downstream of Cahora Bassa Dam site

The largest floods released from the dam occurred in 1978 at 14900 m^3/s, and in 2001 at 9000 m^3/s. After the 1978 flood new operating rules were adopted to attenuate the flood in Cahora Bassa as much as possible, and it was possible to attenuate the 1997 inflow into the reservoir of 12000 m^3/s, to an outflow of 2000 m^3/s. In 2001 the flood attenuation was however much less from an inflow peak of 13800 m^3/s to an outflow of 9000 m^3/s (35 % reduction). There have been no unregulated spills from the dam since its closure. Interestingly, owing to a variety of factors including...
Mocambique’s 18-year-long civil war, the turbines have never produced full capacity and during June 1996, only 15 MW (installed capacity 2075 MW) were being produced while releases from the dam were constant at 758 m³/s.

Aerial surveys, conducted during June 1996, indicated dramatic changes in the morphology of the river-floodplain system downstream of the dam. Morphological responses to flow regulation and the subsequent reductions in sediment loads and flows varied in the different river-floodplain zones. For example, due to enhanced flow capacities in the gorges, the majority of the river channel bars had eroded. The loss of these temporary sediment storage areas resulted in a ‘canal’ like system with marked reduction of in-channel habitat. In the anabanch zone, marked reductions in the magnitude and frequency of floodplain inundation have caused dominance of one main channel, whereas previously there were several active channels. Many secondary channels have become isolated from the main channel through silting of entrance points. Figure 3.3 shows a satellite image of the current (2000) river morphology 300 km downstream of the dam.

![Figure 3.3 Satellite image showing dominance of one main channel near Caia (2001).](image)

It is clear that many of the predictions of the original study team were correct. Particularly in the Marromeu Complex, where upstream sectors had experienced widespread encroachment by woody savanna onto the herbaceous floodplain. Meander trains and oxbows were choked, while invasion by the alien plants, *Azolla* and *Eichhornia* at least was clear. Bird and mammal life was virtually non-existent compared to the 1970’s – the once enormous populations of Cape buffalo, Syncerus cater (over 70 000 head) had virtually disappeared. However, although altered flooding and sediment depletion could be cited for the loss of wildlife, enhanced human access, the civil war, and poaching are more likely causes.

Connectivity of wetlands to the main channel had been disrupted with severe consequences for local artisanal fisheries and avifauna, and only one of the main channels of the Zambezi had relatively newly recruited and healthy mangrove.

Aerial surveys had indicated a 40% loss of mangrove while coastal erosion was obvious. Hoguane (1997) reported that prawn catch rates have declined by 60% between 1978 and 1995, which is directly correlated to falling runoff to the offshore Sofala Bank from the Zambezi. The delta has decreased in size from a width of 600 km to only 150 km since construction of Cahora Bassa Dam.
The consistancy of flow imposed by Cahora Bassa Dam can be summarised as little short of catastrophic.

4. Minimising the impacts of hydropower development on the ecosystem and fluvial morphology

4.1 Adverse environmental impacts of hydropower development

The range of adverse environmental and related social impacts that can result from hydroelectric dams is remarkably diverse. While some impacts occur only during construction, the most important impacts usually are due to the long-term existence and operation of the dam and reservoir. Other significant impacts can result from complementary civil works such as access roads, power transmission lines, and quarries and borrow pits. In terms of fluvial morphology the impacts are both upstream (reservoir sedimentation) and downstream river changes which could be down to the ocean.

Mitigation measures can effectively prevent, minimize, or compensate for most adverse impacts, but only if they are properly implemented. Moreover, for some types of negative impacts, at some project sites, the available mitigation measures – even when properly implemented – are inherently unsatisfactory.

The impacts of hydropower dams on the environment and fluvial morphology could be minimized by good site selection and operation. The following section provides a brief description of impacts and mitigation options.

4.2 Flooding of natural habitats

Some reservoirs permanently flood extensive natural habitats, with local and even global extinctions of animal and plant species. A mitigation option is to establish one or more compensatory protected areas that are managed under the project.

4.3 Loss of terrestrial wildlife

The loss of terrestrial wildlife to drowning during reservoir filling is an inherent consequence of the flooding of terrestrial natural habitats. Mitigation options include wildlife rescue efforts. They might be useful for public relation purposes, but they rarely succeed in restoring wild populations (Ledec and Quintero, 2004).

4.4 Involuntary displacement

Involuntary displacement of people is often the main adverse social impact of hydroelectric projects. It can also have important environmental implications, such as with the conversion of natural habitats to accommodate resettled rural populations.

The main mitigation measure for physically displaced populations is resettlement, including new housing, replacement lands, and other assistance, as needed. Figure 4.1 shows the relationship between reservoir area and the number of people displaced for different regions of the world. The world average is 60 ha/MW flooded in a reservoir. The median value of people/MW displaced based on World Bank data is 16 (Ledec and Quintero, 2004). All the African dams considered have a high area/MW ratio (Figure 4.2) and many people have been displaced, which is due to the variable climatic conditions which require a relatively large storage capacity and densely populated areas.
4.5 Loss of cultural property

Cultural property, including archaeological, historical, paleontological, and religious sites and objects, can be inundated by reservoirs or destroyed by quarries, borrow pits, roads, or other works. Structures and objects of cultural interest should undergo salvage after community consultation, when feasible, through scientific inventory, physical relocation, and documentation and storage in museums or other facilities.

Figure 4.1 The relationship between reservoir area and number of people displaced

Projects with a small reservoir surface area (relative to power generation) tend to be most desirable from both an environmental and social standpoint, in part because they minimise natural habitat losses as well as resettlement needs.

Figure 4.2 The relationship between reservoir area and power generation
4.6 Deterioration of water quality

The damming of rivers can cause serious water quality deterioration, due to the reduced oxygenation and dilution of pollutants by relatively stagnant reservoirs (compared to fast-flowing rivers), flooding of biomass (especially forests) and resulting underwater decay, and/or reservoir stratification (where deeper lake waters lack oxygen). Mitigation Options. Water pollution control measures (such as sewage treatment plants or enforcement of industrial regulations) may be needed to improve reservoir water quality.

4.7 Downriver fluvial morphological

Major downriver hydrological changes can destroy riparian ecosystems dependant on periodic natural flooding, exacerbate water pollution during low-flow periods, and increase saltwater intrusion near river mouths. Reduced sediment and nutrient loads can increase river-edge and coastal erosion and damage the biological and economic productivity of rivers and estuaries. Induced degradation of rivers below dams can kill fish and other fauna and flora, and damage agriculture and water supplies.

These adverse impacts can be minimized through careful management of water releases and in this regard variability is very important. Objectives to consider in optimizing water releases from the turbines and spillways include adequate downriver water supply for riparian ecosystems, reservoir and downriver fish survival, reservoir and downriver water quality, aquatic weed and disease vector control, irrigation and other human uses of water, downriver flood protection, recreation, and of course power generation. From an ecological standpoint, the ideal water release pattern would closely mimic the natural flooding regime.

4.7.1 The Cahora Bassa Dam case study

Variability is a key component of healthy riverine ecosystems. In the Cahora Bassa case, flow regulation has radically reduced the spatial and temporal dynamics of the river. Whilst one may not be able to rehabilitate the entire river to its original ‘pre-regulated state’, the condition of several key ecological functions would be improved with prescribed flood events. Releases of water from the dam to ensure significant floodplain inundation would ensure the reinstatement of some ecological functioning.

Ideal flood and low flows, seasonal patterns of sediment transport desired, water quality states, and minimum requirements for fish-spawning cues can be generated for a particular river or river zone in relation to an identified water project using system- and site-specific knowledge, and the best available expert opinion. In Africa most rivers have not been developed as extensively as elsewhere in the world and the responsibility is therefore even higher to limit the impacts of new developments as much as possible and this can only be done with state-of-the-art mathematical models (1D and 2D) to simulate longterm fluvial processes, with local expert knowledge. Managed flood releases for river channel maintenance should be designed to maintain the pre-dam sediment load-discharge relationship along the river at different baseline sites.

In a rule-of–thumb approach, Wilson (1997) calculated that some 49km$^3$ out of a total reservoir storage capacity of 63 km$^3$ (this seems a high ratio), are available annually from lake Cahora Bassa without loss of power production. Further, with correct intra-annual variability, a drop in present dry season flows from the reservoir by 3 km$^3$/month could stimulate prawn production by some $30 million /year.
Such flow variations would have to be coupled to an exhaustive social programme, for the newly formed islands and stabilised margins of the lower river now have large human populations.

4.8 Water-related diseases

Some infectious diseases can spread around hydroelectric reservoirs, particularly in warm climates and densely populated areas. Some diseases are borne by water-dependant disease vectors, others are spread by contaminated water, which frequently becomes worse in stagnant reservoirs than it was in fast-flowing rivers. In Africa bilharzia, malaria and cholera kill millions of people every year. Public health measures should include preventative measures, monitoring of vectors and disease outbreaks, vector control, and clinical treatment of disease cases, as needed.

4.9 Fish and other aquatic life

Hydroelectric projects often have major effects on fish and other aquatic life. Reservoirs positively affect certain fish species (and fisheries) by increasing the area of available aquatic habitat. However, the net impacts are often negative, especially in the downstream river. Management of water releases are required for the survival of certain species in and below the reservoir.

4.10 Floating aquatic vegetation

Floating aquatic vegetation can rapidly proliferate in eutrophic reservoirs, causing problems such as (a) degraded habitat for most fish and other aquatic species, (b) improved breeding grounds for mosquitoes and other nuisance species and disease vectors, (c) impeded navigation and swimming, (d) clogged electromechanical equipment at dams, and (e) increased water loss from some reservoirs. Pollution control and pre-impoundment selective forest clearing will make reservoirs less conductive to aquatic growth. Physical removal or containment of floating aquatic weeds is effective but imposes a high and recurrent expense for large reservoirs. Biological control is an effective instigation measure.

4.11 Greenhouse gasses

Greenhouse gasses are released into the atmosphere from reservoirs that flood forests and other biomass, either slowly or rapidly. Greenhouse gasses are widely considered the main cause of human-induced global climate change. Gas release from reservoirs can be reduced by salvage of commercial timber and fuelwood.

4.12 Impacts of complementary civil works.

Complementary civil works can induce major land use changes – particularly in the case of access roads, power transmission lines, quarries and borrow pits and associated development plans, but the effects are usually localized. The siting of these works should be in the environmentally and socially least damaging areas.

4.13 Reservoir Sedimentation

Over time, live storage and power generation are reduced by reservoir sedimentation, such that much of some projects’ hydroelectric energy might not be renewable over the long term, since most dams are only designed for a 50 to 100 year live storage life.
4.13.1 Measures to limit the sediment yield

a) Soil-water conservation in the catchment

Whereas it would be wonderful if large scale catchment management policies could serve to limit reservoir sedimentation and to practise soil conservation at the same time, success in this regard has been very limited. Some of the decreases in sediment loads which have been observed are due to depletion of erodible top soils rather than successes with soil conservation measures. It is also very difficult to get governments to apply strong soil conservation measures as these are generally expensive and unpopular.

It should be remembered that soil erosion is a natural phenomenon. In South Africa erosion gullies were observed as long back as 1830 under near natural conditions.

Soil and water conservation programmes were implemented in large catchments from the 1950s. These included farming practises, control of overgrazing, and the control of gully erosion. The latter engineering measures were introduced to control erosion but it is doubtful whether it was successful in limiting the long-term sediment yield. The clear water spilling from check dams scoured sediments downstream and degraded the riverbed. Once the small reservoirs became filled with sediment to the spillway elevation, bypassing with new gully erosion often occurred. Generally it is now believed that check dams are not cost-effective in semi-arid conditions to limit sediment yields (Basson and Rooseboom, 1997). Apart from the problems mentioned above, the fine sediment loads transported during the dominant flood which is typically the 1:10 year flood in semi-arid conditions, need long distances to become deposited in slow flowing conditions, which can only be attained with extremely large and costly structures.

Terraces on steep slopes have been implemented in Europe, North Africa and China, but are not always successful. In semi-arid regions terracing can however permanently damage the catchment.

The implementation of soil-water conservation programmes is important to limit erosion. The effectiveness of these programmes to reduce the long-term sediment yield in large catchments is however doubtful. This is because there is a poor understanding of the interrelationship between soil erosion and sediment yield in large catchments (> 2500 km²). Except in very small catchments (farm scale), catchment management should therefore not be relied on as the only means of limiting reservoir sedimentation.

The most reliable approaches for quantifying erosion rates are considered to be (in order of increasing complexity): (i) sediment yield maps, (ii) sediment load-discharge relationships, and (iii) process based mathematical models. These methods can be used to identify high sediment yield areas in a catchment where the soil-water programme should be focused.

b) Vegetation screens

Vegetation screens upstream of a reservoir were at one stage regarded as one of the most effective ways to reduce sediment inflow to a reservoir. Vegetation control is however not practical in arid conditions and leads to high evapo-transpiration.

c) Sediment diversion (warping)

The diversion of sediment-laden flows upstream of reservoirs for warping and irrigation is practised on a large scale in China where floods transport high concentrations of very fine sediment rich in nutrients for crops, thereby creating new fertile farm land and at the same time reducing reservoir sedimentation.
d) Sediment bypassing
Where the topography allows it a bypass canal or tunnel can be constructed to transport high sediment loads past a reservoir. Nagle Dam in South Africa was constructed in 1950 with a bypass and the main reservoir has remained relatively free of sediment.

e) Off-channel storage reservoir
On rivers with high sediment loads diversions to off-channel reservoirs located on tributaries can be used. Transfer to the off-channel dam is typically achieved through a low head river pumping station via a sand trap, and pumping can be stopped during periods of high sediment transport in the river. Canals or tunnels with water diversion under gravity are also used.

4.13.2 Methods to pass sediment loads through a reservoir
a) Sluicing
Successful sluicing depends on the availability of excess water and relatively large bottom outlets at the dam. For successful flushing the reservoir capacity-mean annual runoff ratio should be quite small, say less than 0.2 year (<0.03 year in semi-arid regions). Free outflow conditions are preferable, but not a requirement as with flushing, and only partial water level drawdown is required as long as the sediment transport capacity through the reservoir is high during a flood.

b) Density current venting
Density currents, also known as turbidity currents, form under very specific boundary conditions and require a high percentage of fine suspended sediment and a relatively steep reservoir bed slope for their creation. After plunging of the sediment laden stream, all the coarse particles are deposited and the fines can be carried over long distances towards the dam.

Theory is available to predict the formation and sediment transport of density currents (Basson and Rooseboom, 1997), and should be applied at all reservoirs to predict possible density current formation under the various operational conditions. Turbidity sensors should also be installed at several elevations upstream of the dam wall for management of density currents by releasing high sediment concentrations through low level outlets.

4.13.3 Measures to remove deposited sediment from the reservoir
a) Flushing
Flushing can be a very effective way to remove accumulated sediment deposits from a reservoir. As with sluicing, excess water is required with large low-level outlets capable of passing say the 1:5 year flood under free outflow conditions. Retrogressive erosion makes flushing a highly effective method to remove large quantities of sediment. Effective flushing requires excess water, suitably large low level outlets, a steep, narrow reservoir basin, and judicious operation.

b) Excavation
Dredging to recover lost storage capacity has been carried out only on a limited scale worldwide mainly because of the high costs and the environmental problems associated with disposal of the dredged sediments. Sediment removal by dredging to recover lost storage capacity should be seen as a last resort as the removal of sediment deposits is extremely expensive and disposal creates new social and environmental problems.
4.13.4 Sedimentation compensation measures

a) Dam raising

Dam raising in many cases provides an economical solution to regain storage capacity lost due to sedimentation. The raising options which are typically considered are fixed uncontrolled spillways, crest radial gates, automatic crest gates or fusegates. Uncontrolled spillways are however preferred from a dam safety perspective, especially in Africa.

b) New dams

Dam sites should be selected in regions with relatively low sediment yields. The upper reaches usually have a relatively high runoff, while the sediment loads are small. This is however not always possible due to the location of the power demand centres and the availability of dam sites. In the past long and wide reservoir basins were usually selected to create maximum storage capacity, but under certain conditions where sediment flushing during floods is possible, a narrow reservoir would be more suitable in providing a sustainable solution.

c) Design for sedimentation

A storage operated (minimisation of spillage) reservoir is typically sized to accommodate the expected 50-year sediment volume allowing for trap efficiency. This volume is considered as dead storage in the yield analysis, which means that only after 50 years of operation will sedimentation start to impact on the water yield. In practice sedimentation first occurs in the live storage zone with more than 80 percent of sedimentation taking place in this zone. The dams are however designed to withdraw water from the dead storage zones allowed for sedimentation.

d) Augmentation from adjacent catchments

Regulation of runoff and sedimentation control requirements in a reservoir are often in conflict. Transfer of water from adjacent catchments can provide a solution to sedimentation control in an existing reservoir if the scheme is economically feasible and if the donor catchment can provide sufficient excess runoff.

4.14 Sedimentation management based on reservoir life versus retention time

When the storage capacity-mean annual runoff (MAR) ratios of reservoirs in the world are plotted against the capacity-sediment yield ratio, the data plot as shown in Figure 4.1. Most reservoirs have a capacity-MAR ratio of between 0.2 to 3, and a lifespan of 50 to 2000 years when considering reservoir sedimentation.

When the capacity-MAR ratio is less than 0.03 especially in semi-arid regions, sediment sluicing or flushing should be carried out during floods and through large bottom outlets, preferably with free outflow conditions. Flushing is a sustainable operation and a long-term equilibrium storage capacity can be reached. Seasonal flushing for say 2 months per year could be used in regions where the hydrology is less variable with capacity-MAR ratios up to 0.2, especially where the sediment yield is high. Seasonal flushing can also be practised at these relatively high capacity-MAR ratios when water demands and high sediment loads in the river are out of phase.

When capacity-MAR ratios are however larger than 0.2, not enough excess water is available for flushing and the typical operational model is storage operation. Density current venting can be practised at these reservoirs, as well as dredging to recover lost storage capacity.
The operating rules for a reservoir need not be inflexible, but can change with different stages of storage loss. Storage operation may be continued in reservoirs with large capacities relative to the sediment loads, while sluicing/flushing operation can be introduced once the loss of storage capacity reaches a certain stage. These transition zones can be found between the zones represented in Figure 4.1.

![Figure 4.1 Empirical reservoir classification system in terms of storage, runoff and sediment yield](image)

**5. Conclusions**

The impacts of hydropower dams on the fluvial morphology can be summarised as follows:

- sediment trapping in the reservoir which often makes projects unsustainable in the long term.
- flood attenuation and elevated baseflows in the downstream river, could change the river morphology and ecosystem completely.
- sedimentation and relatively clear water releases leads to bed degradation near the dam, but the flood attenuation caused by the dam could be dominant, leading to bed aggradation downstream of tributaries bringing in high sediment loads.

Proposed measures to limit the above impacts are:

- dam site selection upstream of relatively large tributary and in a relatively low sediment yield catchment.
- operation to mimic natural river flow patterns, with managed flood releases if required.
- regional planning and development across international borders to select the most suitable low impact sites.
6. References


Ledec, and Quintero, JD. (2004); Environmental criteria for choosing new hydroelectric project sites. ICOLD Symposium, Korea.

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