ASSOCIATED PROGRAMME
ON FLOOD MANAGEMENT

INTEGRATED FLOOD MANAGEMENT TOOLS SERIES

RESERVOIR OPERATIONS AND MANAGED FLOWS

ISSUE 5
DECEMBER 2015

Global Water
Partnership

World
Meteorological
Organization
Weather • Climate • Water

The **Associated Programme on Flood Management** (APFM) is a joint initiative of the World Meteorological Organization (WMO) and the Global Water Partnership (GWP).

It promotes the concept of Integrated Flood Management (IFM) as a new approach to flood management. The programme is financially supported by the Federal Office for the Environment of Switzerland (FOEN), the French Ministry of Foreign Affairs and International Development, the National Water Commission of Mexico (CONAGUA) and the U.S. Agency for International Development (USAID).

www.floodmanagement.info

The **World Meteorological Organization** is a specialized agency of the United Nations. It is the UN system’s authoritative voice on the state and behaviour of the Earth’s atmosphere, its interaction with the oceans, the climate it produces and the resulting distribution of water resources.

It co-ordinates the meteorological and hydrological services of 191 countries and territories.

www.wmo.int

The **Global Water Partnership** is an international network whose vision is for a water secure world. The GWP mission is to advance governance and management of water resources for sustainable and equitable development. The GWP network is open to all organizations which recognize the principles of integrated water resources management endorsed by the network.

www.gwp.org

Integrated Flood Management Tools Series No.5 version 2.1

Cover photo: Palagnedra dam, Centovalli, Switzerland © and courtesy of Ludovic Delavière / Getty
Layout, design and iconography : www.lamenagerie.net

To the reader

This publication is part of the *"Flood Management Tools Series"* being compiled by the Associated Programme on Flood Management. The *"Reservoir Operations and Managed Flows"* Tool is based on available literature, and draws findings from relevant works wherever possible.

This Tool addresses the needs of practitioners and allows them to easily access relevant guidance materials. The Tool is considered as a resource guide/material for practitioners and not an academic paper. References used are mostly available on the Internet and hyperlinks are provided in the *References* section.

This Tool is a *"living document"* and will be updated based on sharing of experiences with its readers. The Associated Programme on Flood Management encourages flood managers and related experts engaged in reservoir operations around the globe to participate in the enrichment of the Tool. For this purpose, **comments and other inputs are cordially invited**. Authorship and contributions would be appropriately acknowledged. Please kindly submit your inputs to the following email address: apfm@wmo.int under Subject: *"Reservoir Operations and Managed Flows"*.

Acknowledgements

Acknowledgement is due to the members of the Climate and Water Department in WMO and the members of the Technical Support Unit of the APFM for their competent technical guidance and frank discussions on the issues and for bringing various perspectives into focus. The kind contributions of Water Resources Environment Technology Center (WEC), Japan, for enriching the contents are gratefully acknowledged.

Special thanks to Mr Makoto Hyodo, IDEA Consultants Inc., Japan, for providing this second revised version of the Tool.

CONTENTS

FIGURES, TABLES & BOXES

1 INTRODUCTION

1 Reservoirs play an important role in flood management. They store floodwater and reduce flood risks by attenuating the flood peaks and intensity of flooding in the downstream reaches. Within the context of Integrated Water Resources Management **(IWRM)**, water storage by reservoirs is an important means of meeting the needs of various activities when the natural supply is less than the demand. In both respects, reservoirs have been providing substantial benefits to human societies and their economic activities.

2 Reservoirs result in alteration of the natural flow regime, depending on the given purpose of storage of the water and the way the rule curves for their operation are established. Retention of water in the reservoir may affect its temperature, nutrient content and the quantity of the sediment it transports. The way a reservoir is operated may alter the frequency, timing and duration of the flood events downstream of the reservoir.

3 Reservoir operations for mitigating floods flatten out the peak flows and disconnect the floodplains from the river channel. The ecosystems or the natural processes, both within the channel and the floodplains dependent on the existing natural regime flows, may be adversely impacted by such changes (WMO, 2006(a)). Natural flow regimes, including the high and low flows, shape the physical character of the river channel, including pools and riffles. At the same time, they determine how much habitat space is available for aquatic organisms; maintain suitable water temperature and quality; and enable fish to move to feeding or spawning areas. These impacts can manifest themselves in the form of changes in terrestrial and aquatic habitats in the ecosystem, as well as social and economic activities.

4 An environment-sensitive reservoir operation, duly considering the ecological needs and releasing adaptive managed flows, can help reduce these adverse impacts without significantly compromising the fulfilment of the economic purpose of the reservoir. The adaptive managed flows in both cases, i.e. high flows and low flows, can help mitigate adverse impacts on natural ecological and morphological processes in the river channel, downstream floodplains, wetland ecosystems and their dependent livelihoods.

5 The present practice of reservoir operations, based on rule curves which are predominantly guided by direct economic benefits ignoring the ecosystem requirements, needs to be reviewed. It may be noted that sometimes, with some minor structural modifications, the existing reservoirs can adapt to the managed flows. It is recognized, however, that maintaining (in the case of new dams) or re-establishing (in the case of existing dams) the natural river condition by managed flow may not always be possible and may require a conflict-management mechanism to adopt the approach. It is, therefore, essential to develop a decision-making framework capable of handling the conflicting demands and adopting an integrated approach. An effective organizational learning and cross-organizational interaction process is important within the context of both sustainable development and human security.

6 This Tool aims to provide guidance for reservoir operations and managed flows that optimize the benefits from ecosystems in the floodplains, as well as social and economic activities. It provides guidance on the issues that need to be addressed in designing and operating reservoirs to meet the requirements of various users and uses, along with the ecological needs. Wherever possible, references to more specific sources of information – predominantly online sources – are given.

7 The central concern of this paper is to describe the various aspects of reservoir operations and to show how flows can be managed in order to minimize their adverse impacts. The Tool therefore aims at:

- Understanding changes in flow and sediment regimes caused by reservoirs;
- Identifying the issues that need to be included for deciding the managed flows;
- Introducing options to tackle these issues by modifying reservoir operations;
- Planning the managed flows;
- Providing a framework for environment-sensitive reservoir operations.

8 The Tool is primarily addressed to flood managers and other reservoir operators/owners while, at the same time, providing useful information for policymakers, environmental groups, non-governmental organizations and communities. It must be realized, however, that environment-sensitive reservoir operation is a multidisciplinary pursuit and therefore requires close collaboration with environment specialists on the one hand and stakeholders' participation on the other to mediate conflicting interests.

9 This paper should not be seen as a technical manual for reservoir operation and provision of managed flows but rather as an initiator and starting point for environment-sensitive reservoir operations.

2 INTEGRATED FLOOD MANAGEMENT AND RESERVOIR OPERATIONS

2.1 Integrated flood management

10 Floodplains have been preferred areas for human settlement since records began because of the advantages that they offer in support of a range of socioeconomic activities, for which the normal floods provide a variety of services. Many people depend for their livelihoods on the services provided by the river and its corridor ecosystem. The floodplains are occasionally flooded by events of exceptional magnitude, however, adversely impacting economic activities and resulting in loss of life and property.

11 Under natural conditions, rivers migrate continuously across their floodplain belt and change the topography. Flow and sediment regimes, interacting with riverbed and bank materials and riverine vegetation, create and destroy fluvial features, thereby providing habitats for diverse biotic communities. Flooding not only allows aquatic organisms to move in or out of the main channel, but also causes morphological change, creates new habitats, deposits silt and fertile organic material, sustains wetlands, renews floodplain ponds and temporarily stores water on the floodplains. Ecological and morphological connectivity across longitudinal (upstream catchments and downstream corridor reaches), lateral (between the river and its floodplain) and vertical dimensions (surface with subsurface zones) need to be maintained with adequate quality and seasonal variability of flow regimes.

12 Flooding of the floodplains attenuates flood peaks downstream. The inundated floodplains can retain the moisture for a long time and thereby provide an opportunity for rainfed agriculture. At the same time, it replenishes groundwater, which forms an essential source of water for drinking and irrigation. The wetlands on the floodplains are also replenished and provide different ecosystem services.

13 The goal of Integrated Flood Management **(IFM)** is to maximize, in a sustainable manner, the net benefits from floodplains, manage flood risks and minimize loss of human life from flooding. IFM achieves this objective through a mix of various structural and non-structural interventions and by addressing the three components of flood risks, namely: hazard magnitudes, exposure and vulnerability. The vulnerability of communities is largely influenced by livelihood opportunities. Ecosystem services provide an essential source of livelihood for the people, particularly the poor, who live on floodplains (WMO, 2012).

14 In order to conserve these ecosystem services to a maximum extent possible, IFM adopts a threefold approach of avoiding, reducing, and mitigating adverse environmental impacts without compromising its flood-management objectives. It adopts an environmentally sensitive flood-management decision-making framework based on the following elements:

- Scientific understanding and analysis;
- Environmental assessment;
- Environmentally sensitive economic analysis;
- Stakeholders' involvement;
- Adaptive management approach;
- Monitoring; and
- An enabling mechanism.

15 Reservoir operations for flood moderation, as one flood-management option, play an important role in protecting people and their socioeconomic activities in floodplains from flooding. Reservoir operations, however, have the potential to alter flow regimes, fix river shape or separate river channels from the floodplains under new flow and sediment regimes. The need for sustainable development has highlighted the importance of addressing the negative consequences of such flood-control and protection measures on natural flow regimes that have the potential to threaten human security, including life, livelihoods and food and health security (WMO, 2006a).

2.2 Managed flows

16 Reservoirs should provide for flow release to meet their specific purposes, as well as to fulfil the downstream ecosystem's needs and the livelihood objectives, identified through scientific and participatory processes. These flows are also referred to as "ecological flows", which do not simply represent a quantity of water released downstream of a reservoir: they have to serve certain objectives which need to be understood and defined. Several approaches are available for assessing the ecological needs of the river systems downstream of a reservoir.

17 These approaches are based on managed-flow requirements, ranging from "in-stream flows", which refer to within-bank flows, to "managed flood releases" designed to overflow and supply floodplains and deltas. The managed-flow approach (Dyson et al., 2008) includes both of these, stressing the need to meet clear downstream social and ecosystem objectives, rather than simply releasing a quantity of water. The managed flow attempts to maintain the variability

of natural flow and sediment regimes as close as possible to a situation where no reservoir is present.

18 It is important to understand the objectives of providing managed flows in the rivers downstream of reservoirs. This has to be appropriately addressed at the design and operation stages in an attempt to attain a dynamic equilibrium under new flow and sediment regimes. This helps in maintaining ecological health. Nevertheless, it must be realized that natural flows existing before the construction of the reservoirs cannot be achieved unless all the interventions to abstract or regulate water in the entire basin are decommissioned.

19 The main objective of managed flows, therefore, is to reverse, at least partially, the unsustainable development of water resources and to minimize the adverse impacts of future development activities, while reducing flood risks and supporting livelihoods by reducing vulnerability. Although no single method can determine the managed flows, based on a certain IFM approach and given an environment-friendly framework, attempts can be made to identify and achieve the desired objectives. Within IFM and IWRM the objective of managed flow should be:

20 While society has realized the importance of maintaining the ecological services provided by nature, the stress on natural resources is increasing with increased population and aspirations for prosperity and well-being under the given economic model. Human interventions can therefore only increase with time. Given the overall objective, the specific outcomes of managed flows have to be clearly defined, keeping in view the following:

- It is not feasible to attain the original/natural flows;
- The developments in most of the cases cannot be undone;
- The managed flow should start by addressing the most critical adverse impacts;
- The new flow regimes to which the flora and fauna have adapted should be respected;
- Decisions are taken under a large band of uncertainty in knowledge, as well as understanding.

3 IMPACTS OF RESERVOIRS

21 It is important to understand the various purposes of reservoirs, how they impact the river flows and how these changes in river flows, in turn, affect the ecology and economic activities.

3.1 Reservoir purposes and moderation of flow

22 In almost all cases, a reservoir is constructed to perform multi-purpose functions with water storage as the main function for different sectoral needs of society, such as water supply for drinking, industrial use, navigation or irrigation and hydropower generation. In all cases, the reservoir serves the important function of moderating the flows. It is useful to understand the special characteristics of reservoirs with the following purposes.

3.1.1 Flood moderation

23 Flood moderation reservoirs store all or a portion of the floodwater in the reservoir, particularly during peak floods, and then releases the water slowly. Space within a reservoir is generally reserved to store impending floods. Small-to-medium floods generated from the catchment are fully captured by the reservoirs but extreme flood events are only partially attenuated and their transformation downstream is delayed. The extent of attenuation depends on the available storage capacity vis-à-vis the magnitude of the flood event (WMO, 2006(a)).

24 The purpose of the reservoirs for flood management may be required only for a few days or weeks in any particular year in order to:

- Store floodwater to reduce discharge downstream;
- Keep space empty for the storage of impending floodwater (storage space in the reservoir is required);
- Maintain appropriate operation in accordance with flow discharge into the reservoir.

25 In order to provide maximum attenuation of the peak floods, it is imperative that maximum possible storage space is available when the floods approach the reservoir. This can be achieved by drawing the reservoir level down to the minimum possible. The need to store water for other socioeconomic purposes, however, presents contradictory demands. Long-range inflow forecasting forms an important tool to provide decision support in such cases.

3.1.2 Water supply

26 Water-supply reservoirs store water during times of high flow in order to supply water downstream during times of low flow for uses such as agricultural production (irrigation), dilution of pond/river contamination, human and industrial use, etc. It is desirable to keep the storage capacity as full as possible. Their special characteristics are that they:

- Store water during the rainy season and utilize it during the dry season;
- Keep water level high in order to store the maximum amount of water.

3.1.3 Hydropower generation

27 Hydropower is a major renewable energy resource that can play an increasingly important role in enabling communities around the world to meet sustainability objectives in respect of long-term, low-cost and eco-friendly energy. As a high-quality, reliable and flexible energy source it has a pivotal role in integrated energy systems. This flexibility, through energy storage in reservoirs, is increasingly being seen as a means of expanding the effective contribution of other less reliable and more dilute renewable energy sources, such as wind and solar energy.

28 In most industrialized countries, hydropower is being used to meet peak-time demands. As such, their operation, if exclusively for hydropower, are intermittent and at pre-determined times. This characteristic of releases from such reservoirs can be used to advantage through certain modifications. Wherever the needs and the topography permit, these releases are further used either for maintaining the navigable depths or diverted for irrigation purposes. The multiple-use benefits of hydropower, particularly in relation to the availability, reliability and quality of freshwater supplies, can also contribute to a fundamental sustainability goal – the alleviation of poverty (Dyson et al., 2008).

29 Concerning climate-change issues, hydropower energy is not only among the energy sources producing low levels of carbon-dioxide emissions from their fuel cycle, but is also a renewable resource.

3.2 Impacts of reservoirs on the flow and sediment regimes

30 The impacts of reservoir operations on the ecology and, in turn, the adverse deprived ecological services, can be understood only once the way they are impacted is understood. This section attempts to put them briefly in perspective, addressing changes in water quantity and quality, sediment volume transported and the physical composition of the sediment, which are likely to cause substantial impacts of reservoirs on the river corridor ecosystems. Natural flows are a result of random meteorological inputs, in terms of precipitation, the variability of which are attenuated by the hydrological response of the catchments. This natural variability is greatly

altered by the storage but can be restored to a certain extent through studied operational practices at minimal or no cost.

3.2.1 Water quantity

31 Reservoir operations for flood moderation will flatten out the peak flows. Reduction of flood peaks reduces the frequency, extent and duration of floodplain inundation. As a result of changes in water quantity, river shape will be fixed or river channels will be separated from the floodplains. Reduction of channel-forming discharge and truncated sediment transport often alters channel and floodplain morphology (Acreman et al., 2000). These changes in water quantity induce:

- Reduced variability of flow;
- Reduced magnitude, duration and frequency of flooding.

32 To envisage the concept of channel-forming discharge, imagine placing a hose discharging at a constant rate in a freshly mown garden. A small channel will eventually form and reach equilibrium geometry. At a larger scale, consider a newly constructed floodwater-retarding reservoir that slowly releases stored floodwater at a constant flow rate. This flow becomes the new channel-forming discharge and will alter the morphology of the channel until it reaches equilibrium (FISRWG, 1998). If this uniform rate of discharge is changed to another constant rate, however, the channel will attain a new equilibrium. On the other hand, the variable discharge results in another equilibrium, which is stable in the long term but varies from year to year in that long-term stability condition range. Such equilibrium is a function of a number of elements of water quantity **(Figure 1)**:

- Volume;
- Depth;
- Velocity; and
- Turbulence.

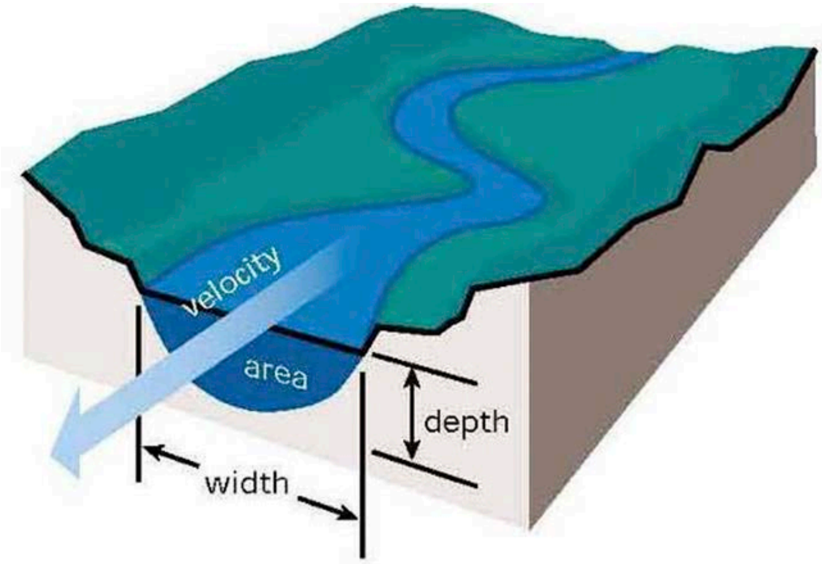


Figure 1 — Water discharge (FISRWG, 1998)

3.2.2 Water quality

33 Storage of water in reservoirs alters the water quality. In general, oxygen transfer in natural waters depends on the following:

- Internal mixing and turbulence due to velocity gradients and fluctuation;
- Surface films;
- Water-column depth:
- Water temperature.

34 Absence of turbulence and mixing and a quiescent stagnant surface or films on the surface, reduce re-aeration. Inside reservoirs where the velocities are extremely low, even stagnant at some places, and depths of water column extremely large as compared to normal flow depths, anaerobic (methane-producing) processes and algal populations tend to dominate (for instance, environmental consequences four years after completion of a dam are provided in the report of the International Union for Conservation of Nature **(IUCN)**, on the Senegal river basin (IUCN, n.d.(a)). This is particularly intensive if there is an excess of nutrients (organic matter, nitrogen and phosphorus) in the water and sediment. Eutrophication, resulting in excessive algal growth and deoxygenation of the water, may occur in such reservoirs. The process is supported by the lack of mixing and oxygen transfer in standing water. In warmer climates, reservoirs with increased eutrophication can suffer from toxic algal blooms, the excessive growth of aquatic plants, such as water hyacinth, and the production of methane (WMO, 2006(a)).

35 Water-column depth. Where agricultural pesticides, toxic industrial pollution, heavy metals from upstream mining operations etc., have accumulated in the reservoir, their release downstream can impact the biological activities of the river, threatening human water use or ecological values (Dyson et al., 2008).

36 Water temperature. Large storage reservoirs tend to stratify, so that the water in the upper layers acquires temperatures in consonance with the air temperatures, while the bottom layers are much cooler. Water released from such reservoirs through outlets provided near the bottom can result in water downstream that has significantly cooler temperatures compared to the seasonal natural flow, which may not always be conducive to native fish and other aquatic life. The impact can be stronger on aquatic invertebrates. Relatively constant flows can create constant temperatures, which affect those species that are dependent on temperature variations for reproduction or maturation. When streams are excessively dewatered, because of no downstream releases, the unnaturally low flows with smaller depth of flow can warm more easily, thus holding less dissolved oxygen. In winter, on the other hand, such streams can become too cold and sometimes freeze (FISRWG, 1998).

37 Water temperature is a crucial factor in the river stream for a number of reasons:

- Dissolved oxygen solubility decreases with increasing water temperature, so the stress imposed by oxygen-demanding waste increases with higher temperatures;
- Many biochemical and physiological processes in cold-blooded aquatic organisms are governed by water temperature; increased temperatures can increase metabolic and reproductive rates throughout the food chain;

- Many aquatic species can tolerate only a limited range of temperatures; any change in the range of temperatures within a stream can have profound effects on their composition; and
- Many abiotic chemical processes, such as reaeration rate, adsorption of organic chemicals to particulate matter and volatilization rates, are strongly linked to the water temperature.

38 Temperature increases can lead to increased stress from toxic compounds, for which the dissolved fraction is usually the most bioactive fraction.

3.2.3 Sediment volume transported

39 The creation of reservoirs changes the hydraulic and sediment transport characteristics of the river, causing increased potential sedimentation within the storage and depriving the area downstream of the sediment material. Excessive sedimentation and consequent loss of water-storage capacity, which may reduce the long-term viability of development, is an important sustainability issue in many reservoirs. Such a situation may result from excessive surface erosion of the catchment area, often due to deforestation or underestimation of the sediment yield from the catchment at the design stages. Reduction in the sediment load to the river downstream can change geomorphic processes, e.g. erosion and river form modification (Dyson et al., 2008).

40 The total sediment load in a stream at any given time and location is divided into two parts: wash load and bed-material load. The primary source of wash load (which is very fine in size) is the watershed, including sheet and rill erosion, gully erosion, and upstream stream-bank erosion. The source of bed material (the coarser of the two loads) is primarily the streambed itself, but includes other sources in the watershed. The entire bed-material load is trapped in the reservoir, while the wash load, composed of the finest sediment particles in transport held in suspension by turbulence, is partially settled, depending on the residence time of water in the reservoir. Wash-load concentration is normally a function of supply, i.e. the stream can carry as much wash load as the watershed and banks can deliver (FISRWG, 1998).

41 The bed-material load is normally deposited at the mouth of the reservoir, creating a small delta, which moves downstream into the reservoir with time. This sediment load essentially occupies what is conventionally known as live storage. Generally, the fine wash load, taking a long time to settle, is deposited all along the reservoir, particularly near the outlets. The wash load essentially occupies the dead storage all along the bed, consolidating over time. In the early life of the reservoir, the deposited wash load is at a level much below the level of the outlets. The deposited wash load is therefore seldom rejuvenated and brought into the flow. During large floods, however, almost all the wash load passes over the spillway on to the downstream area.

42 Retention of the bed-material load in the reservoir results in a shortage of the sediment in the river-flow discharge as compared to its sediment-carrying capacity. As a result, the reaches immediately downstream of a reservoir are subjected to large-scale erosion of the riverbed and banks. Such flow conditions result in the formation of a deep, single channel, thereby cutting off the others with much reduced heterogeneity of flow conditions.

3.2.4 Physical composition of the sediment

43 **Scouring and armouring of the riverbed:** In addition to changes to sediment dynamics as a result of hydrological changes from dam operation, the presence of dams prevents downstream movement of sediment. This in turn results in greater deposition of sediment upstream of dams, due to lower flow velocities, physical blockage of the river and increased erosion downstream as a result of reduced sediment load from upstream. Reduced sediment delivery downstream can have serious consequences for channel geomorphology (UNEP-DDP, 2000). If the dam is allowed to release water from its reservoir, small floods, as are seen in nature, lead to scouring and armouring of the riverbed. The higher energy of the sudden floods picks up and removes finer sediments such as silt, sand and gravel. The riverbed below the dam therefore resembles a pavement of cobbles and loses its value as a habitat for plants, macro-invertebrates and fish (Kondolf, 2000).

44 **Impact on fish spawning:** The size of available streambed gravel can limit the success of spawning by fish, e.g. salmonids (Groot and Margolis, 1991). The armoured bed material may be too coarse for spawning fish to move, a problem particularly common where dams eliminate supplies of smaller, mobile gravel (Parfitt and Buer, 1980). Excessive levels of interstitial fine sediment may clog spawning gravel, effects that have been documented downstream of land uses increasing sediment yields, such as timber harvest and road construction (Cederholm and Salo, 1979; Everest et al., 1980; Meehan, 1991). It is therefore important to assess and maintain the most appropriate physical composition of the sediment for the ecosystem.

3.3 Impacts on social and economic activities and environmental conditions

3.3.1 Fisheries

45 A dam built in the upper reaches of a river could have substantial impact on the availability of fish downstream (Dyson et al., 2008). The alluvial reaches of a river present a variety of aquatic environments used for spawning by a wide range of fish species. If a river reach is subjected to constant flows, it may not be able to provide a variety of habitats appropriate for the survival of certain species. Many habitats are lost in the lateral channels and in the floodplain, resulting in a sharp decrease in local and, finally, regional, biodiversity (WMO, 2006(a); IUCN, n.d.(a)).

46 Artificial low flows may lead to fish kills and depletion of populations of species sensitive to higher water temperatures and lower oxygen conditions (Postel and Richter, 2003). Inadequate low flows may result in overcrowding of fish populations in poor-quality water, with no option to move to other feeding areas. Absence of high flows may also result in fish not being able to access floodplains for spawning and feeding: for instance, fish movement in response to flow regime is provided in the IUCN report on the lower Mekong River basin (IUCN, n.d.(b)).

3.3.2 Water utilization

47 Rights over access to, and use of, water for various purposes such as agriculture, dilution of river contamination, supply of water to cities for domestic uses, industry, etc. and the related

water rights would need to be accommodated or adjusted in systems where water is already over-allocated. This is likely to involve the inevitable questions of whether, how and by whom compensation might be payable when water rights are changed and will require decisions as to who might "hold" the river water "in trust". A flexible and adaptive style of management is needed (Dyson et al., 2008).

3.3.3 Groundwater recharge

48 Lack of floodplain inundation reduces infiltration and consequent groundwater recharge, thereby severely affecting the groundwater resources and their associated ecological and economic benefits. This also has adverse impacts on the baseflow-groundwater interactions and degrades riverine habitats (WMO, 2006(a)). Lowering of the groundwater table could have a direct impact on species of floodplain flora and fauna which are dependent on shallow groundwater.

3.3.4 Preserving ecosystems

49 Dams and reservoirs have the potential to alter flow regimes, fix river shape or separate river channels from the floodplains. They tend to impede natural ecological and morphological processes and oversimplify the river corridor, resulting in a spatially homogeneous ecosystem, which is not able to provide varied habitat features for a diverse range of species. It is, therefore, important to maintain the structure and function of fluvial ecosystems because most of the ecosystem services provided by river corridors depend on these and they are lost when rivers are simplified (WMO, 2006(a); IUCN, n.d.(a)).

3.3.5 Protection of river-management facilities

50 Degradation of the riverbed and erosion of banks downstream of a reservoir may result in exposing the foundation of existing infrastructure such as bridges.

51 The rotting of wooden river-management facilities (foundation of embankment and pile works, etc.) may accelerate as a result of the low water level due to the decrease in discharge in such reaches. It is desirable to prevent these adverse impacts by changing the design practices of new installations and modifying the existing ones, including changes in the materials of river-management facilities (MLIT, n.d.).

3.3.6 Recreational activities

52 Rivers, coastal areas and banks of other water bodies are preferred areas for human settlements as proximity with water provides, among other resources, a high degree of visual satisfaction and opportunities for recreation. On the rivers where sightseeing boats are operated, the reduction in river discharge may result in non-feasibility of their operation. Recreation value can be enhanced if connecting channels are deep enough for small boats or canoes. Considerations similar to those presented in **Section 3.3.8** will be required (MLIT, n.d.).

53 Further, in the alluvial floodplains, the reduction in such discharges may shift the main channels of the river away from the city banks, thereby resulting in lost opportunities. Such a situation could be tackled through appropriate river-engineering interventions, due care being given to the ecological impacts of such interventions.

3.3.7 Flushing of pollutants and sediments

54 Floods can have a flushing effect on stagnant waters, removing pollutants such as human waste, unblocking drains or flushing away mosquito larvae (Acreman et al., 2000). This is particularly important in the downstream reaches of cities in semi-arid areas, particularly in developing countries, where not all urban wastewater is treated before it is released to the river.

55 As incidents of high discharges decrease, the possibility of dilution of such polluted reaches, as well as movement of the sediment, particularly in the estuary at the coastal zone, may be blocked. Since it is not always possible to increase the normal discharge, the installation of a guide levee and other facilities should be examined (MLIT, n.d.).

3.3.8 Navigation

56 The reservoirs built exclusively for power generation have, in general, a positive impact on the navigability of the downstream reaches due to almost constant releases. In reservoirs where the water is withdrawn from the river channel to be used for irrigation or public water supply, however, the downstream releases (if any) may not be sufficient to continue the operation of boats. The situation is worsened if non-release of flows downstream results in the drying-up of certain reaches, thereby completely severing the waterways which might otherwise be used by smaller boats. It is considered that there is a limit to the volume of water that can be released for such purposes for ensuring sufficient draught for various types of boats (MLIT, n.d.).

3.3.9 Prevention of salt intrusion

57 Fluvial processes also greatly influence estuarine and deltaic processes since rivers provide the main sources of freshwater, sediments and nutrients. Morphological changes in river deltas result from the interaction of fluvial and marine forces in the vicinity of the river mouth.

58 In estuarine reaches, the salt-rich seawater moves up the river during high tide and is pushed back by the high flows in the river from time to time. This creates a condition of stable equilibrium of fresh- and saltwater in the estuarine areas, thereby creating a habitat rich in biodiversity. In the absence of normal freshwater supply from the river, this equilibrium may be disturbed. When saltwater ascends the river, salt concentration in irrigation water and groundwater rises, resulting in severe adverse effects on the sources of public water supply and agriculture. The loss of high flows may result in the river mouth closing and the fish being unable to enter the estuary, which they use as a nursery area (Dyson et al., 2008). To cope with such situations, it is necessary to examine the possibility of installing salt levees and improving intake facilities (MLIT, n.d.).

3.3.10 Other impacts

59 As symbols of purity, renewal, timelessness and healing, rivers have shaped human spirituality as few other natural features. To this day, millions of Hindus in India immerse themselves in the waters of the Ganges in cleansing rituals that are central to their spiritual life (Postel and Richter, 2003). It is, therefore, important to acknowledge native customs and beliefs, respect indigenous needs and make use of local knowledge to read and heed nature (WMO, 2006b).

Table 1 — Requirement of the elements of flow and sediment regimes

	Water quantity	Water quality	Water temperature	Sediment transport
Fisheries	•	•	•	•
Water utilization	•	•	•	
Groundwater recharge	•			•
Preserving ecosystem	•	•	•	•
Protection of river management facilities	•			•
Recreational facilities	•	•	•	•
Flushing of pollutants and sediments	•			•
Navigation	•			
Prevention of salt intrusion	•			•
Other	•	•	•	

4 FACTORS TO BE CONSIDERED FOR MANAGED FLOWS

60 The life forms in each river and the ecological roles they play have evolved over thousands of years in synchrony with the river's naturally variable pattern of flow and sediment regimes, its highs and lows, its floods and dry spells. Protecting freshwater biodiversity and ecosystem services therefore requires establishing an allocation of water for supporting the ecosystem. Eco-allocation will vary, depending upon whether society chooses to maintain a river in excellent ecological health or to allow some deterioration in its health in order to satisfy human needs for water and energy. In the case of existing reservoirs, where all the water has been allocated for different users, it requires re-establishing such an allocation.

61 That boundary implies a limit on how much water and sediment can be extracted from the river, as well as on the degree to which its natural pattern of flows and sediment can be altered considering the:

- Technical feasibility;
- Cost-benefit analysis and cost allocations;
- Water allocations; and
- Flood risks.

4.1 Technical feasibility

4.1.1 Managed flows

62 Generally, water can be passed through a reservoir to the river downstream either through the outlets for diversion or through power turbines or over the spillway, in case of large floods. The outlet releases water at a controlled rate, determined by downstream needs for public water supply, agriculture or the environment, requirements for flood regulation, storage

considerations or legal requirements for minimum flows. In the case of a hydropower reservoir, water is released primarily through the turbines and there may be no separate, low-level outlet. In the case of an irrigation or water-supply reservoir, there may be a direct release of water into a canal or pipeline and thus no low-level outlet into the river downstream.

63 The capacity and location of the outlets are determined by the use to which the water is put and whether the sediment-laden water is acceptable for diversion or release into the turbines. Often, the outlets are not located in the body of the main dam and the released water does not join the river directly downstream but rather joins after a certain distance. The surplus water resulting from flood inflows that cannot be contained within the reservoir and cannot be released through a low-level outlet are released through the spillway. A further function of the low-level outlet is to enable the reservoir level to be drawn down in a controlled manner should this be required for dam safety reasons.

64 In order to achieve the objectives of managed flows, the alteration of the established release practices based on rule curves with minimal impacts on existing uses can be achieved through structural or non-structural measures or a combination of the two:

- Non-structural measures:
  - Adopting water-saving policies and practices,
  - Revised rule curves and operation practices;
- Structural measures:
  - Structural alterations in the existing dams;
  - Structural retrofitting; or
- A combination of the two or more.

65 The new requirements of managed flows can be met if the water available for various uses could be more efficiently used through demand management in order to meet the economic requirements with less supply. It is therefore important to study the possibility of such savings at various levels through appropriate changes in policies, practices and financial incentives.

66 Technical options for managed flows are given in **Figure 2** and **Table 2**. A multi-depth selective water-intake facility is effective, since the intake of water can be operated from arbitrary layers. This effectively avoids cold and turbid water being released in the reservoirs, which negatively affects the downstream ecosystem. Bypass channels are also effective in minimizing the impacts of dams on the downstream ecosystem, through which inflow water upstream of a reservoir is transported into the downstream site. Other options for managing quality of water in reservoirs, such as air bubbles, graduated fences and a sub-dam for trapping nutrition coming into a reservoir, are also technically operational.

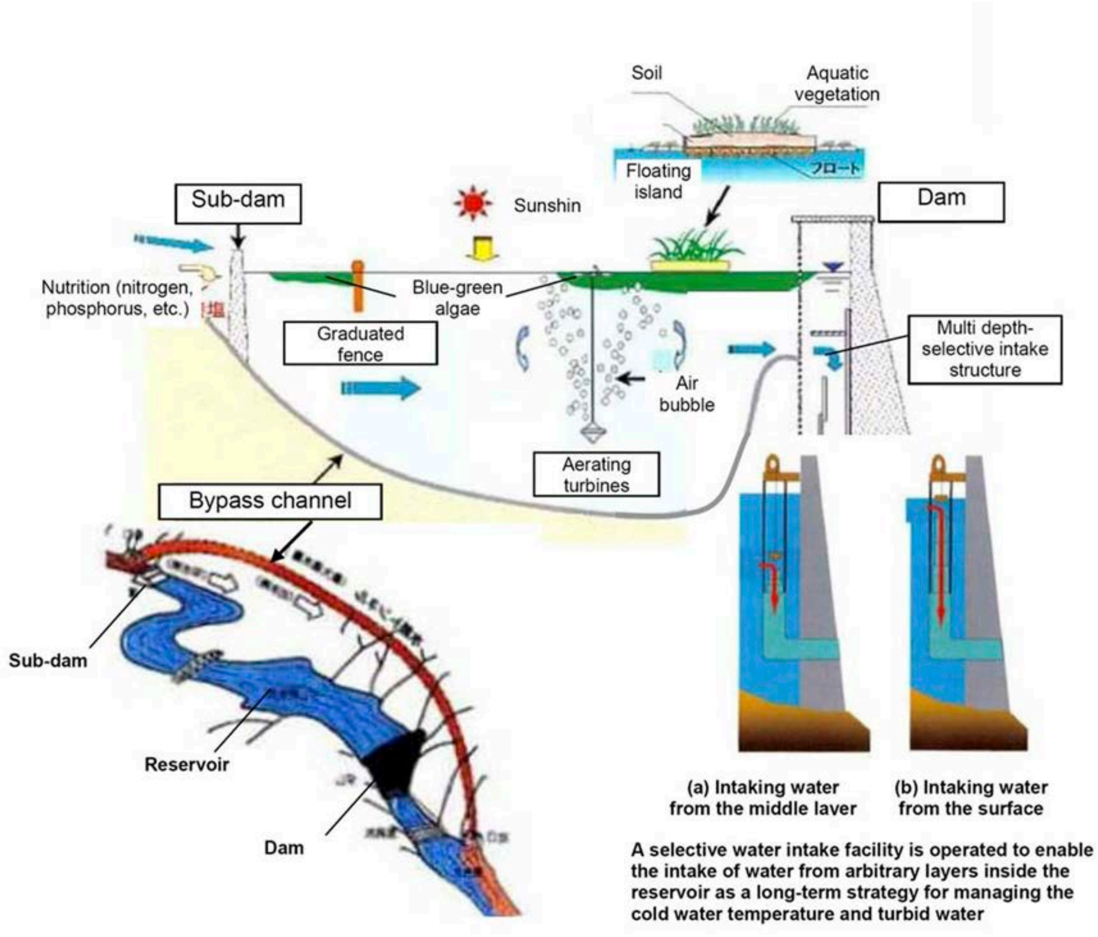


Figure 2 — Technical options for managed flows

67 By gaining time in the operation of the reservoir, reservoir releases can be managed in a more environmentally friendly manner. This can be achieved through advanced hydrological forecasts and climate predictions. Such forecasts and predictions give the reservoir operator greater flexibility to manage flows that mimic the natural flows to a certain extent.

68 It should be pointed out, however, that these technical options are highly site-specific and need thorough investigations similar to those carried out for establishing the feasibility of a new reservoir. Their adoption also depends on the technical capacities in remote areas where such facilities are located. In certain developing countries, it may not be possible to carry out highly technical modifications on such a small scale. In any case, the modifications should not jeopardize the safety of existing structures.

69 In the case of new reservoirs, various options to achieve the goals of managed flows have to be studied and are sometimes easier than making changes to existing dams.

4.1.2 Sediment management

70 Common engineering practices have been implemented in design and operation that, unintentionally, lead to filling of reservoirs with sediment. Such unsustainable approaches lead to sedimentation and project abandonment, which will leave fundamental issues for future generations. There is a need to develop ingenious solutions for integrated sediment and water

management in order to maintain the available water resources and the healthy ecosystem in a sustainable manner. A strategy for sediment management towards sustainable reservoirs is to evaluate and select a suitable management option based on sufficient data collected on deposited sediment (Kantoush and Sumi, 2010). Further, it is important to establish technical options for assessing sediment regimes and improving existing dams, some of which are flushing sediment load from the reservoir, replenishment of sediment load in the downstream, sediment bypass, etc.

71 **Figure 3** shows an example of a flood-control dam, which flushes sediment load from a reservoir through reservoir operations. During high flows, a dam gate is opened to release only floodwater but not sediment material, which is captured in the reservoir. When inflow floodwater is reduced, an outlet for sediment is opened. Then water and sediment stored in a reservoir during flooding are flushed and transported downstream, thus maintaining longitudinal connectivity of streamflows and sediment transport.

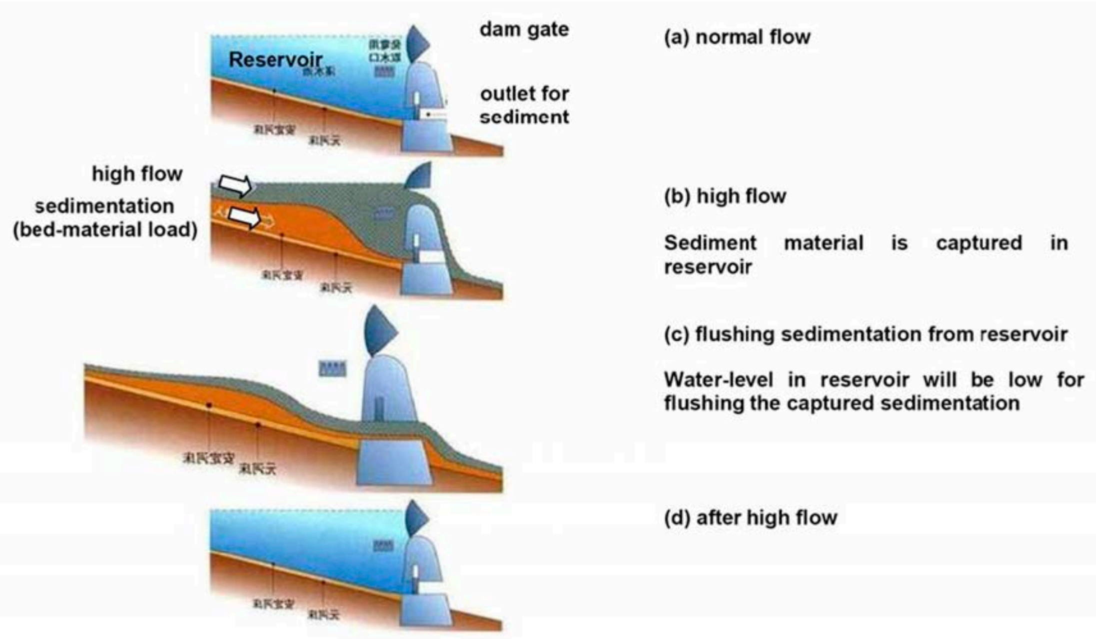


Figure 3 — Technical options for sediment management

72 Besides the qualitative analysis of the physical and chemical composition of sediment for ecosystem conservation purposes (e.g. spawning habitat for fish species), discussed in **Section 3.2.4**, it is important, in order to assess sediment regimes, to perform throughout the whole river basin a quantitative analysis of the changes in total transported sediment volume. This quantitative analysis enables the evaluation of the impacts of dams on the environment, addressing not only flow regimes but also the associated sediment regimes.

73 **Figure 4** illustrates a river basin in Japan, showing a comparison of the total sediment volume transported throughout the river basin before and after the construction of a new dam. *CA* refers to catchment area, from where sediment is originally produced and transported, *R* refers to reaches of the main river (where sediment may be further produced or deposited) and *A* to affluents (bringing extra sediment to the main river). Numbers in red indicate the sediment (in thousands of cubic metres per year) transported at a point of a river basin (selected for sediment-measurement purposes). The brown sections correspond to the volume of the

sediment transported and black numbers (+ or -) indicate the change of sediment transported in the corresponding river reach. A decrease in the transported sediment in a reach means that some sediment is deposited in the river channel of this reach. On the other hand, the increased value of transported sediment in a reach shows that the river channel is eroded there, losing sediment. When the sediment volume is the same at the upstream and downstream of a reach, it means there is a dynamic equilibrium of sediment transport, meaning that the total sediment deposition is balanced by the river channel erosion. This assessment can also quantify volumes by each particle size (for methodologies on measurement of sediment transport, see WMO, 2003 and Maidment, 1993).

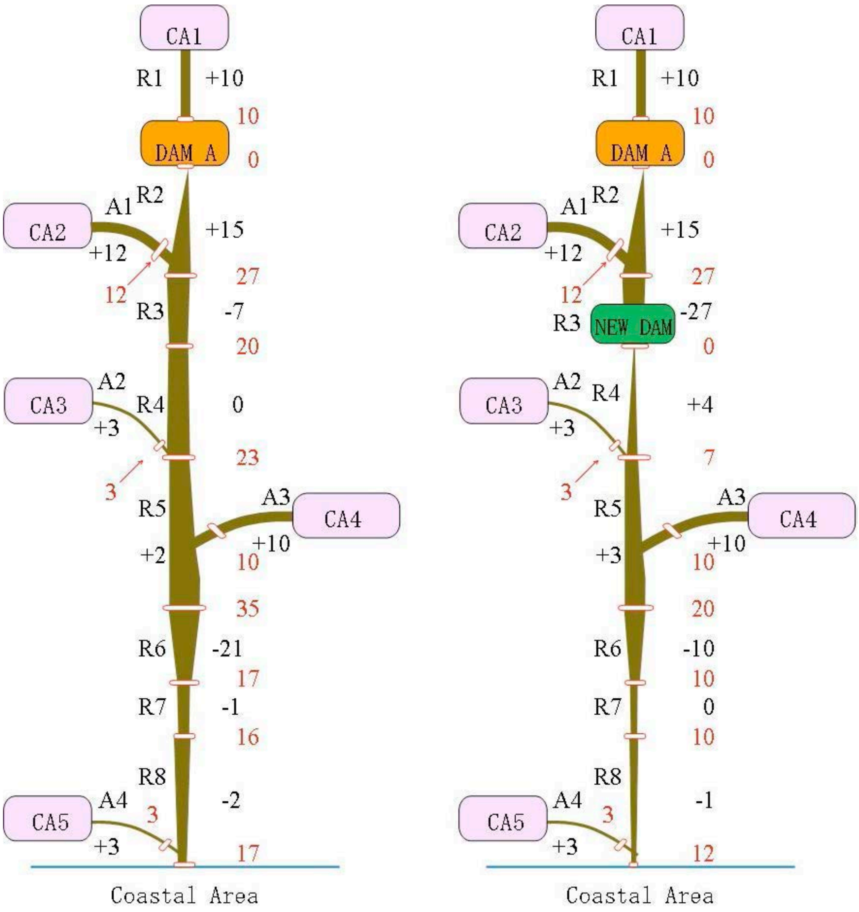


Figure 4 — Total sediment volume transported throughout the river basin

74 It is evident from **Figures 3** and **4** that sediment transport is a complex issue. In the example given in **Figure 4**, the new dam construction, trapping all sediment coming from upstream in the middle reach of a river basin (27 000 m3/year in the figure), does not simply decrease the final sediment transported to the coastal area by the same value, as sediment-transport regimes are also affected. The volume originally transported into the coastal area is slightly reduced by the construction of the new dam, but what is more important is that the original sediment-transport regimes in the different reaches are modified: this implies that fish requiring fresh, movable sediment may be severely affected, as their optimal ecosystem conditions (in terms of sediment) have been “shifted” to a different river reach, if not totally eliminated.

Table 2 — Technical options for managed flows and sediment management

Change due to reservoirs		Downstream impacts	Possible preventive measures
Water quantity	– Reduction of flood peaks – Decrease of turbulent motion – Decrease of sediment transport and organic silt	– Reduced seasonal variability of flow, i.e. increased low flows and decreased high flows – Increased flow fluctuations at hourly and daily timescales – Change in frequency and timing of floods (impacts depend on reservoir capacity and dam design and operation)	– Water saving through demand management supported by policies and practices – To mimic the characteristics of natural flow-regime conditions – Artificial/flushing flooding
Water quality	– Eutrophication (enrichment of water by nutrients, especially compounds of nitrogen and phosphorus, which will accelerate the growth of algae and higher forms of plant life) – Propensity of disease proliferation – Muddy water – Reduced oxygenation – Algal bloom potential (depends on the residence time of water within a reservoir)	– Possible accelerated eutrophication, due to the reservoir incorporating and trapping nutrients – Deeply plunging spillway releases can cause bubble disease in fish because of nitrogen dissolution in the water – Water turbidity is decreased, which can lead to increased primary productivity – Reservoir will export plankton downstream, changing availability of food resources (most impacts on quality depend on the reservoir's retention time)	– Setting equipment for aeration – Multi-level offtakes, air-injection facilities, aerating turbines and destratification capability – Graduated fence – Bypass channel – Floating island

Change due to reservoirs		Downstream impacts	Possible preventive measures
Water temperature	– Temperature stratification in the reservoir (water at the bottom of reservoir is much cooler)	– Release of cold water if taken from the bottom of the reservoir – Constantly cold water released from deep layers of the reservoir reduces the temperature variability of downstream river water	– Multiple and/or depth-selective intake structures for released flows in reaches below dams, as well as water quality
Sediment transport	– Decrease of sediment transport and organic silt	– Changing form of sediment bars, floodplains, and landscape – All sediment but the wash-load fraction is trapped in the reservoir – Reduced sediment downstream leads to possible accelerated bed degradation and river-bank erosion in the reach immediately downstream of a dam – Possible changes in bed-material composition and channel pattern downstream of the dam (e.g. from braided to single-thread) – Encroachment by riparian vegetation, decreasing the channels conveyance capacity – Possible coastal erosion	– Flushing sediment load from reservoir – Replenishing of sediment load in the downstream area – Sediment bypasses, flushing systems or dredging – Appropriate sediment bypassing devices – Graduated fence

4.2 Cost-benefit analysis and cost allocation

75 Most planning and development decisions to build and operate a reservoir are based on an economic assessment of its benefits compared to its costs, although other factors such as environmental impact are increasingly considered. The benefits generated by the reservoir

operations due to the increase in "upstream" water uses may include intensive irrigation, domestic supply or power generation. Traditionally, the assessment of costs was restricted to the capital costs of reservoir construction and the recurrent costs of maintaining canals and pipes. More recent assessments have examined the wider impacts of reservoirs, in particular the potential loss in "downstream" economic benefits that may result from reduced or diverted hydrological flows and restricted inundation of natural floodplains; for instance, a threat to the livelihoods of middle-stream riparian communities from reducing annual flood is provided in the IUCN report on the Senegal River Basin (IUCN, n.d.(a)). Although social and environmental costs and benefits are difficult to quantify, an environmentally sensitive flood-management decision-making process (WMO, 2007) can be of great help. A brief discussion of the methods such as multi-criteria analysis (MCA) that helps put value on social and environmental costs and benefits are provided elsewhere therein.

76 In some cases, this has led to the redefinition of operating rules to allow for managed flow to maintain downstream benefits. To apply cost-benefit analysis – the economic assessment of costs and benefits to determine the gains and losses to society of development options, including environmental costs and benefits – requires projecting different managed-flow scenarios and the benefits and costs associated with each managed-flow scenario.

77 Various scenarios of managed flows need to be specified, including the resulting physical impacts associated with each flow regime in terms of changes in "upstream" water uses (irrigation projects, hydropower, water supply, etc.), any necessary modifications to dam design, structure and operation, and the likely health, livelihood and resource implications of any changes in the "downstream" hydrology and floodplain area. Financial implications of each projected scenario need to be assessed and translated into monetary terms through the application of economic valuation methods. The benefits and costs associated with each flow regime occur over time, but the decision as to which managed flow to adopt must be taken today, meaning that future benefits and costs must be "discounted" into "present values".

78 The resulting discounted benefits and costs for each managed flow must be compared and evaluated, based on MCA. The flow regime with the highest present value net benefits (i.e. benefits less costs) should be preferred, provided that this value also exceeds the present-value net benefits of the dam design without any managed flow.

79 It is highly recommended that the economist conducting the cost-benefit analysis should be involved with the hydrologists, ecologists, socioeconomists and other experts assessing the physical impacts of the various managed flows in order to determine jointly the appropriate benefits and costs that need to be assessed.

80 Compensations for the loss of benefits derived from the reservoir form part of the costs of reform of operation procedures. Cost allocations of meeting the requirements of managed flows need to be distributed among various uses and users of the reservoir facility. This requires the development of procedures which are acceptable to all, as well as effective stakeholders' participation in the process starting from setting the targets of managed flows. It has to be considered that:

- Dam operators may have the right to store certain volumes of water but not to release sufficient to create a flood downstream;

- Land tenure and access may have changed, which may negate the potential benefits of managed flows.

4.3 Water allocation

81 Construction of a multi-purpose reservoir leads to establishing certain rights for water use by different sectors or sections of the society. Establishment of such rights is generally a result of negotiations and discussions and may be based on the principles of equity of development, but this may not always be the case. Only a few cases exist where water was allocated exclusively for meeting the needs of the river environment. While establishing the managed-flow procedures, a certain quantity of stored water has to be allocated to nature. This will require forgoing the established water-use rights by existing users and has the potential to re-open old grievances. There is a need to address these concerns and have mechanisms that are equitable and just in accordance with accepted international and national laws, rules and regulations. For instance, the Senegal River Water Charter signed a legal and regulatory framework stating that river water must be allocated to riparian States, not in terms of volumes of water to be withdrawn but rather in terms of uses as a function of possibilities (IUCN, n.d.(a)). Some of the essentials in establishing such a mechanism require:

- Identifying all stakeholder groups and their aspirations;
- Identifying and strengthening existing institutions that can represent their interests or, in the absence of such institutions, creating new ones;
- Identifying the likely impacts of changes in managed flow on their livelihoods, as evaluated by their aspirations;
- Identifying their vulnerability to different hazards;
- Developing awareness of issues related to reservoirs and floods and disseminating easilyunderstandable information.

82 On rivers that are shared by more than one nation, state or administrative region, such a reallocation exercise becomes increasingly complex, requiring mutual cooperation and understanding and has to be guided by international or national laws/agreements, as the case may be. Existing agreements may have to be revisited to make allocation for the managed flows, however.

4.4 Flood risks

83 When a river and its floodplain are known to be prone to flooding, infrastructure, such as roads, railways and pipelines, is normally designed and constructed to avoid or withstand flooding. Nevertheless, floods higher than the designed floods still cause damage to infrastructure and disrupt activities, particularly where protective measures have been poorly or under-designed. In the floodplain downstream of a reservoir, small- and medium-sized floods may be significantly reduced or virtually eliminated, which often leads to new houses, schools, clinics, factories and roads being constructed on previously flood-prone land. It will thus be important to consider the impact of managed flows on this infrastructure. In some cases, facilities within the “floodway” may be relocated before managed flows can be implemented. However, it may

not always be possible to relocate the facilities and the only alternative may be to construct protective embankments around such flood-prone infrastructure.

84 In most cases, managed flows will have to be smaller than those that would have occurred without the reservoir, since one of the objectives of flood management is to reduce the disruptions to economic activities caused by flooding and, consequently, the well-being of floodplain dwellers. It is thus important to ensure that floodplain inundation is used in the most effective way. Embankments constructed to protect one area will mean that water is diverted to another part of the floodplain. Additional embankments may be constructed with sluice gates to enable particular areas of the floodplain to be inundated to specified depths at particular times, thus fine-tuning the effectiveness of the managed flow. Some issues that need to be considered while looking at the effectiveness of the managed flows are:

- Different floodplain stakeholders (including farmers, fishermen and herders) require managed flow at different times;
- Where the target floodplain is at a significant distance downstream of the reservoir, flows from the intervening catchment and tributaries need to be taken into account in achieving target levels of inundation;
- Indirect impacts of managed flows, such as health issues, may be significant.

85 **Dam safety:** Especially on rivers where dams are constructed, dam-break risk has to be appropriately addressed. Safety requirements of dams have to be applied to the design, construction and operation of all dams. These requirements may be set by professional responsibilities or may be legally enforced. Costs for safety requirements affect the feasibility of projects and it is common to define these requirements with regard to the hazards created by a potential dam-break. At low-hazard dams, the safety requirements are low and the dam owner often carries a higher risk of incurring the costs which may be generated by dam failure (rebuild the dam, carry operational production losses and losses during the reconstruction period). Public-safety expectations are increasing internationally and dam-safety legislation is becoming common, increasing the need for dam-break analysis. Planning for efficiency means that flood hazards have to be evaluated accurately and rescue-action preparedness needs detailed planning (ICOLD, 1998).

5 CASE STUDIES OF MANAGED FLOWS AND SEDIMENT MANAGEMENT

86 This chapter provides case studies on managed flows and sediment management in the world. Three case studies have been collected from existing and published material and are presented below.

Managed flows

- Reservoir operation and managed flows for the Missouri River, USA (Postel and Richter, 2003)
- Low-flow regulations through reservoir operation in the Green River, Kentucky, USA (Postel and Richter, 2003)

Sediment management

- Sediment routing through reservoirs in Japanese rivers (Sumi and Kantoush, 2010)

5.1 Managed flows

5.1.1 Reservoir operation and managed flows for the Missouri River

A | Introduction

87 Like many large rivers in Europe, Australia, the USA and other industrialized countries, the Missouri River **(Figure 5)** has been altered substantially from its natural state. The lower third of the river, a total of 1,212 km, is no longer connected to its floodplain due to deepened and straightened channels, enabling barges to run to and from the port of St. Louis, where the Missouri River joins the Mississippi River. The middle reach, with a length of 1,233 km, is now controlled by six large federal dams. Fort Peck, the most upstream of these, was completed in 1939. Five other dams were completed between 1952 and 1963 under a plan known as Pick-

Sloan, as a joint endeavour of the US Army Corps of Engineers (USACE) and the Bureau of Reclamation. With a combined storage capacity of 90.6 billion cubic meters, these dams and reservoirs constitute the largest reservoir system in North America.

Figure 5 — The Missouri River basin (Postel and Richter, 2003)

B | Impacts of dams and reservoirs on the environment

88 The impacts: Accompanied with levees and other engineering works built on the Missouri, these dams completely altered the natural flow regime of the river and the habitat for much of the life that evolved in its watershed. The natural flow pattern had three key attributes (see **Figure 6**):

- Large floods in March to April caused by snowmelt in the Great Plains;
- Somewhat smaller floods in May to June caused by melting of the Rocky Mountains snowpack along with spring rains; and
- A period of relatively low flows from August to January.

89 Operation of the mainstem dams and reservoirs has flattened the river's flood flows, raised its low flows and greatly reduced its variability in flow for many years **(Figure 6)**.

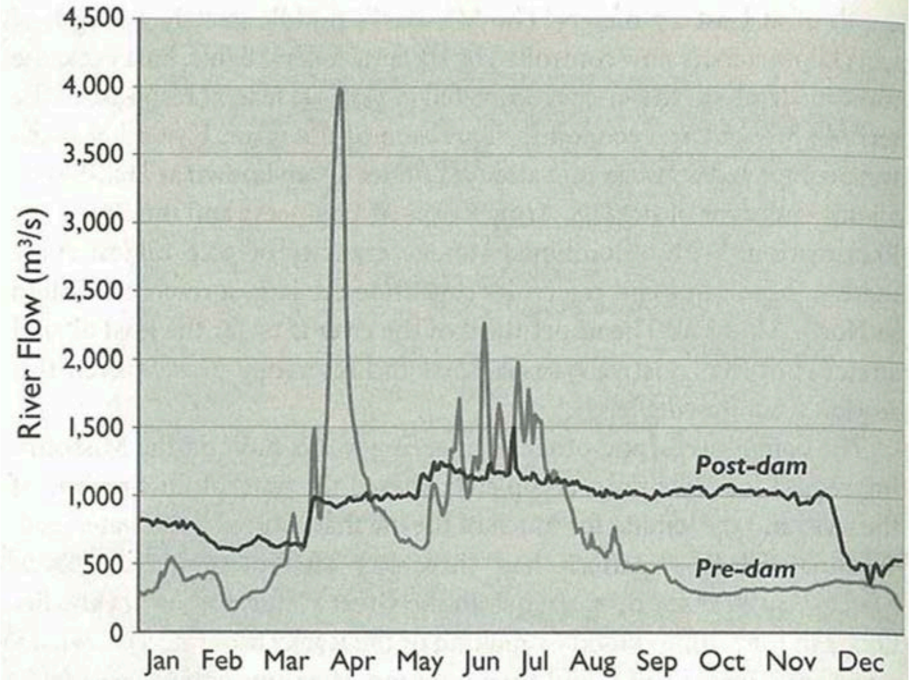


Figure 6 — Altered flows in the Missouri River before and after regulation by dams (Postel and Richter, 2003)

90 **Impacts on the environment:** These modifications have caused major changes in freshwater habitats. As a result, numerous species within the Missouri River ecosystem are now at risk. Federal or state agencies have listed as endangered, threatened or rare a total of 16 species of fish, 14 species of birds, seven species of plants, six species of insects, four species of reptiles, three species of mammals and two species of mussels. Of 67 native fish species living in the Missouri River, 51 are now judged to be rare, uncommon and/or diminishing in number across all or part of their ranges. The Missouri River thus topped the list of most endangered rivers in the USA in both 2001 and 2002.

91 **Causes of ecosystem degradation:** The elimination of the spring flood pulses and the disconnection of the river from its floodplain have been especially harmful to ecological processes. **Table 3** summarizes how alternations caused by the dams impacted the ecosystem and eliminated ecological processes of the Missouri River. As shown in **Table 3**, this highlights the importance of flow and sediment regimes and resulting connectivity of the river and its floodplain in maintaining ecological processes.

92 **Degradation of the Missouri River ecosystem will continue:** The National Research Council (NRC) concluded that degradation of the Missouri River ecosystem will continue unless some portion of the hydrological and geomorphic processes that sustained the pre-regulation of the Missouri River and its floodplain ecosystem are restored – including flow pulses that emulate the natural hydrograph and cut-and-fill alluvial processes associated with river meandering.

Table 3 — Alteration and resulting eliminated key ecological processes

Alteration	Key ecological processes eliminated in the Missouri River	
Reduced large floods in March to April, and reduced smaller floods in May to June	Flow regime	— Yearly floods distributed plant seeds, organic matter and nutrients throughout the river and floodplain, thereby sustaining the system's biological productivity. — Floods replenished floodplain pools and backwaters. — Floods spurred growth and reproduction of cottonwoods, willows and other streamside plants and trees. — Floods served as a cue for fish to spawn and for insects to emerge from the water phase of their lifecycle. — Floods enabled fish and other organisms in the channel to move on to the floodplain to breed, feed and grow and then return to the channel as the floodwaters reduced.
	Sediment regime	— Missouri River systems carried on average some 142 million tons of sediment a year past Sioux city in Iowa before the completion of the Pick-Salon dams, which reduced sediment load by 97% after completion of the dams. — Much sediment was trapped in the reservoirs and transport of what remained was minor, due to reduced high flows. — The sediment transport has helped lateral meandering of the river channel, which was critical to the regeneration of riparian vegetation and to the creation of sandbars, where endangered plovers and terns build their nests.
Increased relatively low flows from August to January	Flow regime	— Low-flow periods exposed sandbars for nesting birds and channel-bank sites for nesting turtles. — Sturgeon and other fish found ideal nursery conditions in the shallow waters along sandbar margins and in braided channels. — In autumn, migrating shorebirds would stop over on exposed mudflats to feed on insects and worms during their long-distance flights from the northern plains to the Gulf of Mexico and South America.

C | Action taken

93 USACE is responsible for regulating the Missouri River. It has the authority to control operation of the mainstream dam to serve its primary planned purposes, such as flood control, irrigation, navigation, hydropower, industrial and domestic water supply, wildlife protection, and recreation.

94 **Restoration of natural high and low flows:** There was a need for recreating to some degree the river's natural high and low flows, as well as allowing a portion of the Missouri River to meander again. These options obviously involve trade-offs among the competing uses of the river. USACE operates the Missouri River dams, according to procedures spelled out in the Master Manual, which was first developed in 1960 and revised by USACE in 2006 (USACE, 2006a).

Moreover, certain activities have been taken to restore some degree of natural flow regimes as explained below.

95 **Adaptive management approach:** NRC in its 2002 report (NRC, 2002) called for a moratorium on the revisions to the Manual until they incorporated a scientifically sound adaptive management approach to improving the Missouri River's condition. It also recommended that, in view of the river's poor condition, actions to begin restoring its health should commence and not be delayed by the moratorium on revising the Manual. NRC felt that the learning-while-doing approach of adaptive management could enable constructive progress to be made towards restoring the river, even while a new operating strategy for the dams and reservoirs was worked out.

96 **Release of higher and warmer spring flows:** In May 2002, USACE had planned to release higher and warmer spring flows from Montana's Fort Peck dam to attempt to provide hydrological and temperature cues for the endangered pallid sturgeon, even though an upper-Midwest drought caused it to delay the test.

97 **Creation of habitat on the floodplain:** The 1986 Water Resources Development Act authorized USACE to create habitat on 7 365 ha of existing federal and state land on the floodplain, as well as to purchase an additional 12 100 ha from willing sellers, of which 9 530 ha have been acquired. Further, a 1999 federal water act authorized acquisition of an additional 48 000 ha over the next 35 years. Currently, this acquisition – costing US$ 750 million – has yet to be achieved.

98 **Flood-prone area for the Big Muddy wildlife refuge:** The US Fish and Wildlife Service (USFWS) has purchased floodplain land as part of the Big Muddy wildlife refuge, where levee breach occurred a dozen times between 1943 and 1986 and irreparable damage in 1993. The acquired land has been used as active floodplain and formed a major secondary channel. In 2000, pallid sturgeon larvae were found there: a clear sign of hope. The Big Muddy refuge now comprises 6 730 ha and the USFWS has proposed expanding it to more than 24 280 ha through purchases from willing sellers.

D | Decision-making processes, tools and information

99 **Challenge to balancing economic and environmental goals:** As mentioned earlier, a process of revising the Master Manual by USACE, providing procedures for dam operation, has been undertaken. This was carried out as a result of important differences of opinion voiced by the wide range of stakeholders, unable to reach a compromised final outcome. The meshing of two goals developed at different times (prior economic goals, enacted in the mid-1940s under the Pick-Sloan scheme; and subsequent environmental goals, identified under the 1969 National Environmental Policy Act, the 1972 Clean Water Act and the 1973 Endangered Species Act) has proved complicated and contentious in Missouri River management. Under such circumstances, efforts have been made to reach a compromise goal.

100 **A moratorium on the manual revisions:** As explained in the previous section of this chapter **(Action taken)**, in a report on prospects for recovery of the Missouri River, NRC called for a moratorium on the revisions to the Manual but recommended that actions to begin restoring its health commence and not be delayed by the moratorium.

101 **Alternative to mimic historical flow patterns:** Before publishing the revised Manual in 2006, USACE developed various alternatives for revising the Master Manual, of which the most likely to restore river health and protect species at risk was the one referred to as GP2021. This alternative mimics the river's historical flow patterns more closely, as well as a late summer low closer to natural historic lows, and was thus favoured by many river scientists and conservation organizations. This alternative was intended to provide a flow trigger to simulate fish spawning, increase sandbar habitat for endangered least terns and piping plovers, increase shallow-water habitat for native fishes and augment recreational benefits.

102 **Adaptive management approach as compromise solution:** From an ecological perspective, some scientists feared that this alternative would be far from perfect and would not mimic the natural flow regime sufficiently to improve ecosystem health and habitat significantly (some opinions are listed below). USACE, however, was not able to accept their opinions from the perspectives of flood management and hydropower generation, since their proposed options could not anticipate significant impacts on flood-control benefits and a small increase in hydropower benefits.

103 Some issues raised from ecological perspectives (in 2003):

- The proposed spring-flow rise would occur later than the natural spring flood and earlier than the natural early-summer floods.
- The proposed spring rise would be only slightly larger than is currently being provided and only a tiny fraction of what would have occurred naturally.
- The late-spring rise would occur naturally in two out of every three years and the once every three years on average proposed by USACE was therefore not enough.
- In terms of economic trade-offs, it would require curtailing navigation during a portion of the low-flow period in summer, since barge traffic could remain at normal levels during the spring and autumn, when most agricultural goods are shipped.

104 Further studies were therefore carried out, including the revision of the Missouri River Master Water Control Manual – Review and Update – Final Environmental Impact Statement (FEIS) (USACE, 2004(a)), USFWS's Biological Opinion and the 2003 Amendment to the 2000 Biological Opinion on the Operation of the Missouri River Mainstem Reservoir System (USFWS, 2003), the operation and maintenance of the Missouri River Bank Stabilization and Navigation Project, and the operation of the Kansas River Reservoir System, as well as comments and correspondence received in response to the public coordination of these documents.

105 As a follow-up, a preferred alternative water-control plan was identified (and made effective from March 2004), generally based on the FEIS and called the Selected Plan (USACE, 2004(b)), which was incorporated into Chapter 7 of the new Missouri River Master Water Control Manual (Master Manual) for the System. A periodic review process of this water-control plan was also identified in order to provide opportunities to make adjustments. In this framework, prior to any modifications to the plan, appropriate public coordination to satisfy environmental, economic and technical issues was also included as a necessary element of the review process.

106 The Selected Plan includes several changes from the previous Master Manual's water-control plan, focusing mainly on:

- Drought conservation measures;

- Unbalancing of the upper three reservoirs;
- Non-navigation flows; and
- An adaptive management process.

107 Of particular interest, the Selected Plan includes an adaptive management process recognizing scientific uncertainty and the potential for future physical changes. As physical changes occur or uncertainties are reduced, the adaptive management element of the Selected Plan allows flexibility in adjusting system regulation.

5.1.2 Low flow regulations through reservoir operation in Kentucky's Green River

A | Introduction

108 In 1906, USACE built a structure called Green River Lock and Dam 6, at a point nearly 300 km upriver from the Green River's confluence with the Ohio River, just downstream of Mammoth Cave **(Figure 7)**. The Mammoth Cave National Park preserves the cave system and a part of the Green River valley and hilly country of south-central Kentucky. This is the world's longest known cave system, with more than 627.5 km explored. Steamboats had been operating on the Ohio since 1811, but Green River Lock and Dam 6 enabled big boats to make their way safely over the mussel-laden shoals of the Green River to reach the cave. The new lock and dam backed up the river's flow and raised water levels in Mammoth Cave by nearly 4 m.

109 The Green River Dam was built in 1969 by USACE 200 km upstream of Green River Lock and Dam 6 for flood control and recreational purposes. Along with 47 other dams, the Green River Dam was authorized by the national Flood Control Act in 1938, but was funded after devastating flooding in 1962.

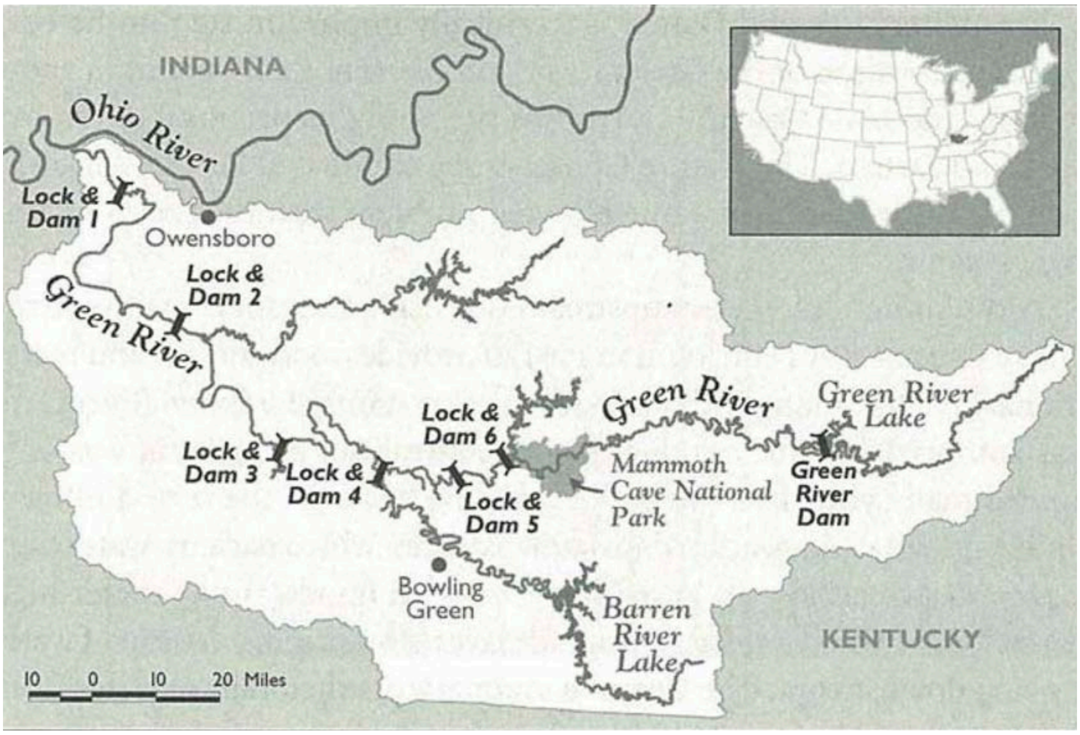


Figure 7 — Green River basin (Postel and Richter, 2003)

110 **Increased water level and passage of the shallow river:** This posed a serious threat to the rich variety of animal colonies in the cave. The Green River itself harbours one of the most diverse collections of fish and freshwater mussels in the USA. More than 150 fish species and more than 70 mussel species have been found. Today, however, more than one-third of the fish species in the Green River are considered rare, threatened or endangered at the state or federal level. A total of 14 mussel species have disappeared from the river in recent decades: a loss attributed to the lock and dam structures.

111 **Altered streamflows in spring and autumn:** These severely affected the river ecosystems downstream of the Green River Dam. Small navigation dams located downstream store water during low-flow periods, but have little impact on flood control. The 43-m high Green River Dam, however, completely plugs the river, storing all incoming water moving downstream. The dam operation then releases water through a concrete pipe 5 m in diameter under the control of USACE. In most months, flows are released downstream in the same volume of water as incoming flows. During portions of the spring and autumn, however, flows were being substantially altered.

112 In spring, the reservoir operation stores water to raise reservoir water levels to maximize the surface areas of lakes for fishing and recreational boating, resulting in reduced flows of the river downstream. In autumn, on the other hand, a considerable volume of water is released downstream in order to have more capacity in the reservoir to prepare for winter flooding, thereby increasing flows downstream (Figure 8). In particular, flow alterations associated with the dam were causing serious problems for mussels and fish, particularly the autumn transitions and increased flows downstream. According to the Nature Conservancy analysis, the prolonged out-of-season flows in autumn were harmful to fish spawning and mussel reproduction. Some mussels and small fish may perhaps be flushed downstream.

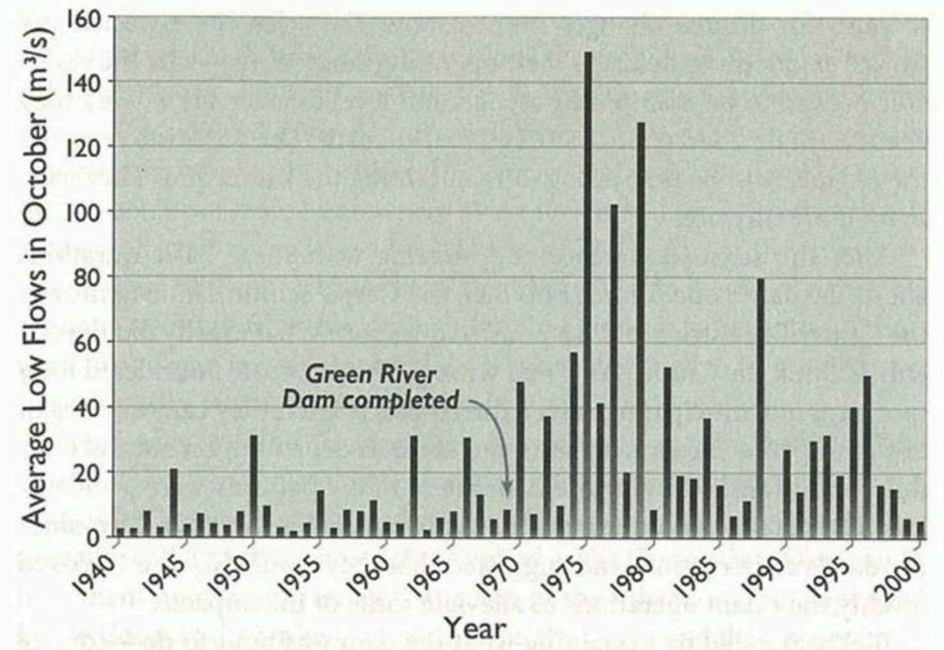


Figure 8 — Altered low flows downstream in the autumn transitions since completion of the Green River Dam (Postel and Richter, 2003)

C | Action taken

113 **Change in dam operations:** The Nature Conservancy and USACE worked together to restore the river ecosystem through dam operations and managed flows. The Nature Conservancy developed a monitoring programme that could tell USACE whether modifying dam operations was making a difference for the river. The Nature Conservancy scientists collected extensive ecological data on the health of the river, providing USACE with an excellent baseline from which to compare ecological changes resulting from the revised dam operations.

114 The Louisville District of USACE prepared various reports necessary to gain approval of a new plan for dam operations within the agency and conducted public meetings to gain input from landowners along the river. In the autumn of 2002, USACE began implementing the new plan, designed to be the first step in an adaptive management programme.

D | Decision-making processes, tools and information

115 Multidisciplinary approach. Based on an analysis conducted by the Nature Conservancy, USACE, together with the Nature Conservancy, sought possible compromise solutions for restoring the river ecosystems by dams and locks. USACE had the opportunity to listen to the opinions of the scientific community, which, at the same time, had a chance to present their doubts and concerns to USACE.

116 Through discussions involving different perspectives (see Table 4, for example), some possible solutions were identified. The winter reservoir level could be raised by a modest amount – about one metre or a little higher. By reducing the difference between summer and winter reservoir levels, elevated water capture in spring and elevated water release in autumn, would not be necessary. By prolonging the transitions between high and low reservoir levels, impacts could be further minimized.

Table 4 — Some different perspectives likely in a multidisciplinary approach

Ecological perspective	Flood control and recreational perspective
— Changes in river flows since the dam construction affect the river's plants and animals, depending on natural river flow regimes. — The current dam operations by USACE should be modified to alleviate some of the impacts, i.e.: - Reducing flow volume downstream resulting in increased reservoir level in autumn transitions; and - Increasing flow volume downstream resulting in reduced reservoir level in spring transitions.	— The dam was built to control floods and provide for recreational uses. Marina owners constructed their facilities in accordance with the expected summer reservoir level: lowering that level would be costly and contentious.

5.2 Sediment management

5.2.1 Sediment routing through reservoirs in Japanese rivers

A | Introduction

117 Japanese rivers usually have short, steep slopes compared to large rivers in Europe and the Americas, causing recurrent flash flooding in heavy storms. The Pacific side of Japan receives heavy rain in June to October, while the Japan Sea side experiences flooding in spring during the snowmelt periods. Steep-slope rivers, associated with heavy storms, result in widespread landslides with extensive stream powers. Dams and reservoirs have usually been constructed with multi-purposes criteria, such as flood control, agricultural productivity, hydropower generation and recreational use. Multi-purpose dams trap sediment and inevitably lead to physical and ecological changes downstream of the reservoirs.

B | Impacts of dams and reservoir on the environment

118 Downstream impacts of dams translate into discontinuity in flow and sediment regimes. Change in sediment regimes brings not only environmental but also socioeconomic impacts – by loss of reservoir capacity, for example. Dams alter flow regimes of downstream rivers, which help ecological processes, including sediment transport and nutrient exchange. These alterations result in fixed sandbars, degradation and intensive riparian tree growth and change in riverbed material due to bed armouring, i.e. the riverbed is formed with coarse sediment particles where fine sediment is removed by stream power.

C | Action taken in the Kurobe River through flushing sediment

119 Sediment flushing. The Dashidaira Dam and Unazuki Dam in the Kurobe River were constructed for flood control and hydropower generation and have been operated to bring sediment deposited in the reservoirs to downstream reaches in a coordinated manner. In July 2006, the Dashidaira Dam flushed out 910 000 m^3 of sediment, including 420 000 m^3 of newly inflowing sediment. The Unazuki Dam has an inflow of 1 380 000 m^3 of sediment. From this inflow, the dam passes through 1 010 000 m^3, i.e. 73%, which mainly consists of fine sediments smaller than 2 mm. The amount of coarse sediments larger than 2 mm passing through the Unazuki Dam is only 20 000 m^3, i.e. 10% of total coarse sediment inputs into the reservoir, while the remaining 90% is currently trapped in the reservoir.

120 Flushing of sediments stored in a reservoir involves reservoir drawdown by opening the bottom outlet to generate and accelerate unsteady flow towards the outlet. This accelerated flow possesses increased stream power and consequently erodes a channel through the deposits and flushing the fine and coarse sediments through the outlet. During this process, progressive and retrogressive erosion patterns can occur in the tail reach and delta reach of the reservoir, respectively.

121 This method has been used for small dams but not for large dams, because it takes time to refill a large reservoir after flushing and so makes it difficult to maintain the dam's power-generating functions. It was easy to introduce this method at these dams, however: the risk

relating to refilling the reservoirs was low because of the large volume of water flow compared to the capacities of the reservoirs and because the impact of sediment flushing on the riverbed downstream was relatively small due to the steepness of the river downstream from the dams and the short distance to the Sea of Japan (30 km from the two dams).

122 The flushed water quality deteriorates when sediment is flushed after being deposited in a reservoir for a long period of time. Therefore, the feature of the dam sediment flushing has been conducted as frequently as possible at times of flood turbidity and dissolved oxygen levels in the river, mouth of the river and the sea area have been monitored while looking at the impact of sediment flushing on the lower river basin.

123 Restored sediment regimes. Downstream of the Kurobe River, the first 6 km from the river mouth are braided channel and from 6 km to 13 km, starting from the river mouth, the river is single bar. The riverbed degradation occurred in the downstream river channel until 1991 but, since the introduction of sediment flushing, has been alleviated and riverbed level is currently rising, especially in the downstream reach. The Unazuki Dam has not impacted riverbed degradation since its completion in 2000 **(Figure 9(a))**. By considering a representative grain size of D60 (mm), the riverbed materials have been becoming coarse, a phenomenon known as armouring, since completion of the Dashidaira Dam **(Figure 9(b))**. Since the introduction of sediment flushing, however, armoured sediment became finer in the downstream reach of these dams owing to the sand content of the sediment.

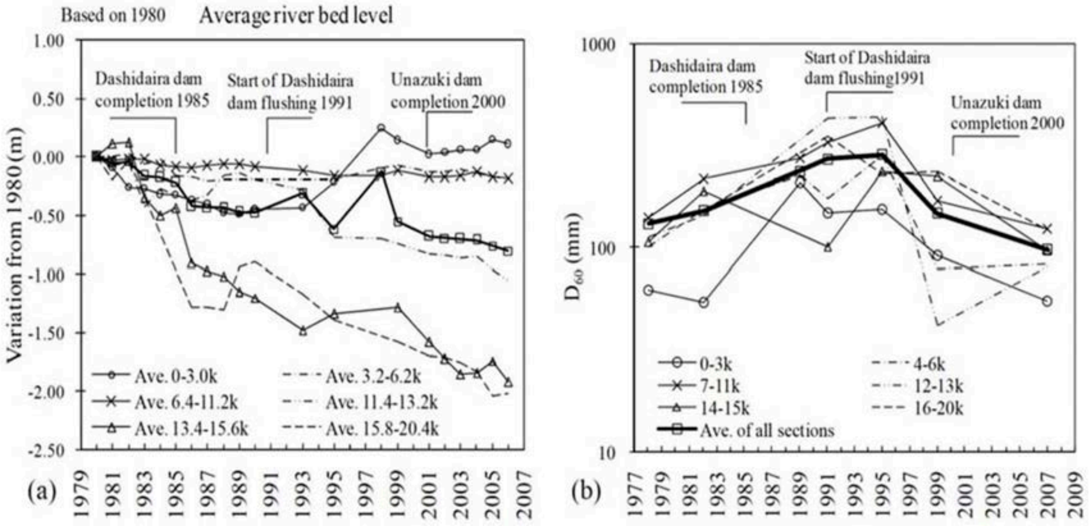


Figure 9 — Relationship between (a) riverbed level; and (b) representative grain size (D60), and annual sediment flushing at different cross-sections (Sumi and Kantoush, 2010)

D | Action taken in the Nunome River through sediment replenishment

124 In Japan, it is common practice to remove accumulated coarse sediment by excavation and dredging and to make effective use of the removed sediment. The sediment replenishment method is a new measure in sediment management, by which trapped coarse sediment is periodically excavated (or dredged, depending on the site conditions) and then transported and placed temporarily on the channel downstream of the dam. The replenishment processes are sufficient to restore the bed-load transport and the associated habitat by coupling reintroduction with floodplain habitat restoration. Along the Nunome River, new depositions over sandbars

and in the river channel are shown in **Figure 10**. A completely new sandbar self-formed 600 m downstream of the dam. Large Japanese rivers are often trained to a large extent, to maintain services such as navigation, hydropower generation and flood defence.

Figure 10 — Nunome Dam and the downstream reaches with morphological changes due to sediment replenishment below the dam and self-forming sandbar on 14 October 2009 (Sumi and Kantoush, 2010)

125 In the case of the Managawa Dam, a sediment restoration trial was also carried out to enhance river refreshment. **Figure 11** shows placed sediment before and after flushing flow below Managawa Dam. The main objective of the flushing flow is to move bed gravel and initiate detaching algae, which are important for providing fresh food sources for Ayu fish species. Peak discharges of 30 m^3/s and 50 m^3/s, with and without sediment restoration, were compared by water level, flow velocity, temperature, turbidity, suspended sediment concentration and movement of riverbed materials. Rate of detached algae on riverbed gravels were also measured both upstream and downstream of the sediment placed point.

Figure 11 — Placed sediment before and after flushing flow

E | Action taken in the Tenryu River through sediment bypass

126 Sediment bypass by directly diverting sediment load downstream of a dam was introduced in the Asahi Dam **(Figure 12)**. The planning and construction of the bypass have also advanced in the Miwa, Matsukawa and Koshibu dams in Japan.

127 This technique involves high costs owing to tunnel construction, but there are several advantages: it is applicable to existing dams; it does not involve drawdown of reservoir level and therefore no storage capacity loss; and it has a relatively small impact on the environment because sediment is not discharged as rapidly as sediment flushing.

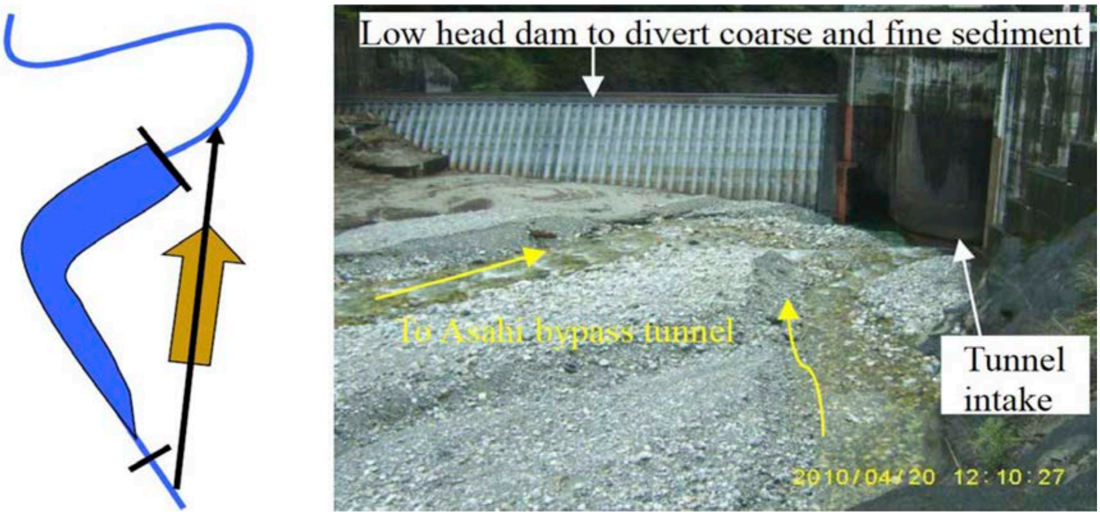


Figure 12 — Coarse sediment load bypass around an Asahi in-stream reservoir using a bypass tunnel (Sumi and Kantoush, 2010)

F | Decision-making processes, tools and information

128 A current key challenge to maintaining ecological processes of rivers derives from determining the adaptive range of river systems to absorb changes represented by flow and sediment regimes. It is important to identify flow and sediment regimes that can fulfil requirements of various functions of hydrology, water quality and quantity, sediment quantity and quality and associated ecosystems.

6 PLANNING FOR MANAGED FLOWS

129 This chapter outlines a transparent process to meet requirements of various users and uses which need to be undertaken to achieve effective managed flow from existing reservoirs to restore and maintain downstream ecosystems and the livelihoods that depend on them.

130 It is not possible, even if desirable, to reproduce the natural flow and sediment regimes downstream of reservoirs. The aim of managed flows is to find a compromise in the allocation of water between managed flows and retaining sufficient water within the reservoir to support economic activities, e.g. flood moderation, water supply and hydropower, for which the reservoirs were originally built or the purposes for which a new reservoir is proposed to be built. It is not likely to create managed flows solely from the reservoir, nor should it be necessary to do so.

131 The managed flows should be carried out at four distinct levels within a project-management cycle:

- Planning and feasibility;
- Design;
- Implementation; and
- Evaluation:

132 The sequence of the 10 steps adapted from Acreman (Acreman et al., 2000) may vary, depending on the circumstances surrounding the particular reservoir or downstream floodplain or delta.

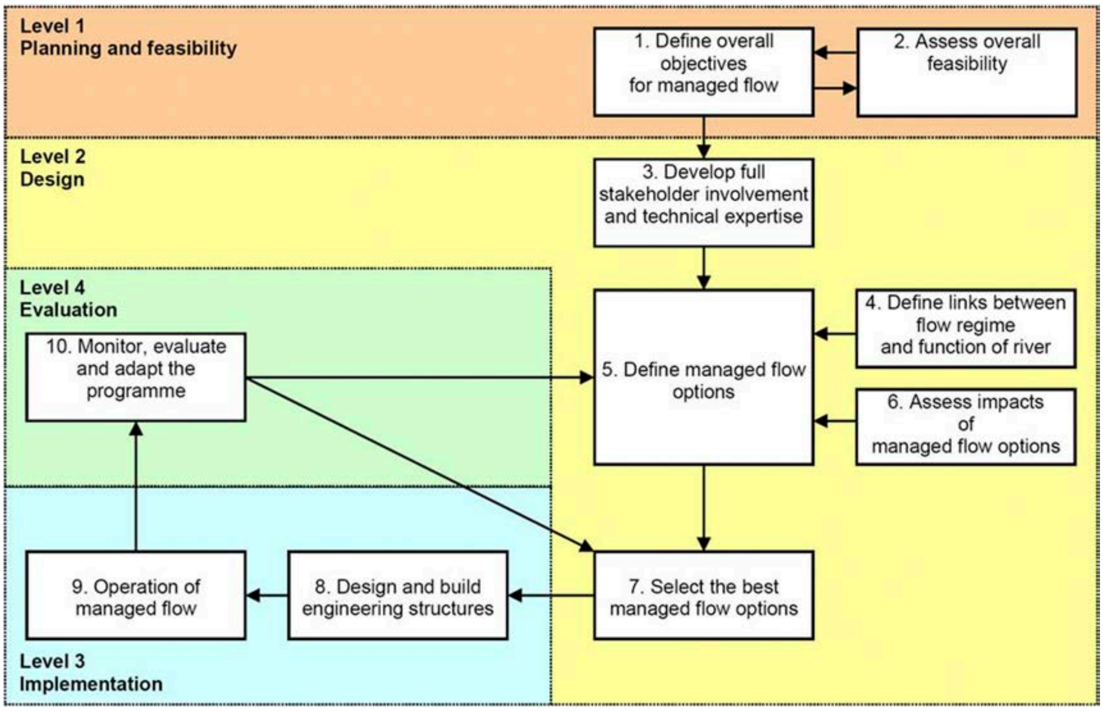


Figure 13 — Managed-flows programme
Adapted from (Acreman et al., 2000)

6.1 Planning and feasibility

133 **Step 1:** Define overall objectives of managed flow

- Clear overall objectives for managed flows must be defined through a scoping study of the flood risks incurred by ecosystem, economy and social structure of the floodplains.
- The aim should be to ensure that managed flows are compatible with the livelihood strategies of the floodplain communities.
- The sectors and sections of society that will benefit from managed flows must be identified, together with any that may suffer.
- Objectives must be compatible with the river-basin management plan and related national/regional policies.

134 **Step 2:** Assess overall feasibility: The technical and financial feasibility of various scenarios and options to attain managed flows must be defined. The following factors are significant:

- The engineering characteristics of reservoirs must be adequate.
- Reservoir storage capacity must be sufficient, the outlet structures (suitable release structures) must be large enough to permit major releases and able to work operationally.
- The environmental characteristics of the reservoir and its catchment must be appropriate.
- The extent to which the dam controls flooding in target ecosystems will depend on flow contributions downstream of the dam.
- Changes to outlet structures that enable greater volumes of water to be released should be considered.

- The costs of installing new release structures in the dam and the opportunity costs of releases must be factored in.

6.2 Design

135 If the preliminary screening, based on technical and financial feasibility, points to significant benefits from managed flows, further steps towards designing the feasible option should be taken.

136 **Step 3:** Develop full stakeholder involvement and technical expertise

- A key element in defining appropriate managed flows is to bring together the expectation of stakeholders, e.g. reservoir operators/owners, local authorities, electricity companies, irrigation farmers, floodplain residents, and those presently benefiting from the various services from the reservoir. This should begin with the identification of various stakeholders.
- Many of the techniques commonly included under the label "participatory rural appraisal" should be applied towards a genuine commitment to participation, with adequate time and resources.
- A range of specialists (ecologists, geomorphologists, sociologists and resource economists) should work together in undertaking field surveys to provide a comprehensive description of the affected river.
- The team develops datasets, models and various analytical tools that can be used in creating scenarios to assist in decision-making.
- Data collection at the early stage is to improve understanding of the physical, chemical, biological and socioeconomic aspects of reservoir and floodplain, in a common data and information-knowledge base and made publicly available.
- Technical skills should be strengthened within organizations through training and awareness-building to understand and use floodplains wisely (for instance, establishment of a "plenary group" is reported in Environmental Assessment for the Inclusion of Technical Criteria for Spring Pulse Releases from Gavins Point Dam) (USACE, 2006(b)).

Box 1 — Level of Public Participation *(UNESCAP/WMO, 2008)*

Principal challenges to water management are 1) the technical challenge of finding solutions to increasingly complicated flood management problems and 2) to communicate effectively with the water.related participants like: up. and down.stream residents; dam owner and non.governmental organizations for environmental impacts; dam owners with different purposes; national and local agencies; decision support between flood management center and reservoir operation center; land users and environmental agency, etc.

Recently flood managers have recognized the limitations of a traditional technical response to the complex issue of expectations and behaviours of the flood management community, as well as the limitations of the current technocratic policy models. Therefore, public-driven decision making model might be an alternative to address the policy intent of involving the community, decision. making process and comparative participations such as technocratic.driven and social.driven policy model **(Table 5)**. According to these requirements, collaborative water management is identified and agreed upon by the water-related organizations.

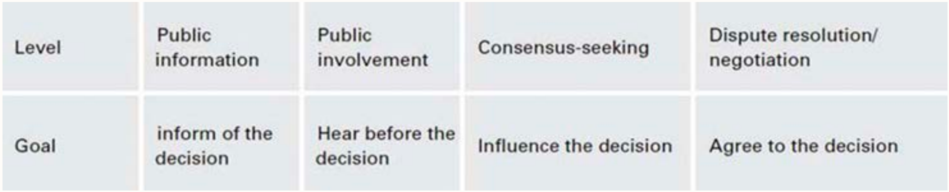
Box 1 — Level of Public Participation *(cont'd)*

Table 5 — Comparative policy

Social policy	Technocratic policy
• Community is integral to decision-making process	• Community is an appendix to decision-making process
• Power and control with citizens	• Power and control with government
• Enables, empower and educates	• Uses technical expertise
• Increases complexity	• Decreases complexity
• - sophistication	- simplification
• Driven by community needs	• Driven by legislative requirements and professional biases
• Multidisciplinary process	• Single discipline experts
• Optimal solution through community partnerships	• Optimal solution is technical

An important task for water-related organizations is: to implement participatory processes in flood management and to design appropriate participation activities and actions at appropriate participation levels. In other words, the decision.making process is a continuum, in which several "intermediate decisions" are often made, and the concept of "public participation" may thus have different meanings, according to the time and place where it occurs. Four simple levels of participation contributing to the design of adapted and efficient participatory processes are shown in **Table 6**.

Table 6 — Levels of participation



Level	Public information	Public involvement	Consensus-seeking	Dispute resolution/ negotiation
Goal	inform of the decision	Hear before the decision	Influence the decision	Agree to the decision

137 **Step 4:** Define links between flow regime and function of river

- The relationship between flow regime and function of river should be defined in terms of frequency, duration, timing and discharge. In particular, the flooding necessary to maintain many parts of the ecosystem required to fulfil the agreed objectives needs to be quantified.
- Present river use, exploitation of river-related natural resources and health of the affected people are quantified and possible flow-related health risks identified.

138 **Step 5:** Define managed-flow options

- A small number of managed flow options should be identified and quantified.
- Assessment should include not only the magnitude, timing, frequency and duration of managed flows from the reservoir to produce a target flood extent on the floodplain, but also the impact on water-reserves retained within the reservoir for other processes (hydrological/hydraulic model of the floodplain, reservoir, main channel and catchment will be required in this assessment).
- The no-flood option should always be included in the analysis. Appropriate flows during the non-flood season must also be addressed. For instance, the environmental flow assessment

in the Mekong River by an expert panel from the four countries in the lower river basin, created different scenarios, of which one will be selected in the management actions. A detailed report is provided in the IUCN report on the lower Mekong River Basin (IUCN, n.d.(b)).

139 **Step 6:** Assess impacts of managed-flow options

- Since the final managed-flow option will inevitably be a compromise between different objectives, it is important to assess the impacts of the various options, both on the floodplain-dependent livelihoods and on reservoir-dependent livelihoods.
- Assessment must include equally the impacts on the reservoir and its dependent activities.

140 **Step 7:** Select the best managed-flow options

- For each option, the monetary and non-monetary costs and benefits and their distribution amongst all stakeholders should be estimated. National/local economic benefits should not be the only criterion on which to make decisions about managed flows.
- A decision should be made on the most appropriate option using a transparent method, which includes consultation with stakeholders (Multi Criteria Analysis is one such decision tool, see WMO, 2007).

6.3 Implementation

141 If, after detailed assessment, one or more of the options of managed flow constitute an appropriate use of water in the reservoir, implementation is undertaken.

142 **Step 8:** Design and build engineering structures

- The dam-outlet structures will need to be designed and constructed or may need to be adapted to allow managed flows to be made and sediment passed.
- Embankments may need to be constructed on the floodplain to protect infrastructure – houses, roads, factories – from flooding or to enhance/control inundation in selected areas.

143 **Step 9:** Operation of managed flow

- Pilot-managed flows of various sizes should be made over a period of a couple of years to test the various models and assumptions made and thus to better determine the response of the ecosystem and local communities.
- Awareness development and capacity-building exercises should be undertaken through demonstration of the impacts of the new flow regime.

6.4 Evaluation

144 **Step 10:** Monitor, evaluate and adapt the programme

- Adequate ecological, socioeconomic monitoring must be designed and established to assess the effectiveness of managed flows in relation to the stated objectives.

- Since the timescales for ecological, morphological and hence social change may be of the order of many decades, monitoring must be continued for long periods of time and adequate funding provided.
- The managed-flow programme should be modified as necessary, which may require use of an alternative option or the definition of new options. For instance, a plan to monitor and evaluate releases is reported in *Environmental Assessment for the Inclusion of Technical Criteria for Spring Pulse Releases from Gavins Point Dam* (USACE, 2006(b)) and adaptive management is reported in *Missouri River Mainstem Reservoir System Master Water Control Manual* (Appendix I) (USACE, 2006(a)).

7 FRAMEWORK FOR ENVIRONMENT-SENSITIVE RESERVOIR OPERATION

7.1 Clear policies

145 It is essential to have a clear national policy on managed flows that is commensurate with national realities, priorities for sustainable development and well-being of the people. Such policies should preferably be incorporated in legal instruments, such as environmental laws.

7.2 Legal and Institutional

146 Integrated flood management in itself – and managed flows in particular – requires collaboration and coordination between various disciplines and agencies within and outside a country. There is the need for an appropriate institutional mechanism for dealing with multi-disciplinary issues. The need for a legal provision for data- and information-sharing, not only with various stakeholders within a country but also among stakeholders in countries sharing such basins, is essential. A detailed discussion is provided in *Legal and Institutional Aspects of Integrated Flood Management,* APFM Technical Document No. 2, Flood Management Policy Series (WMO, 2006(c)).

147 In certain cases, a reallocation of water-use rights may require a fresh look at the national water rights legal system.

7.3 Financial mechanism

148 It is important to apply an environmentally friendly flood-management decision-making framework to assess the economic feasibility of various options since all the benefits of managed flows are unlikely to be assessed in monetary terms. Detailed discussion of such a

framework is provided in *Economic Aspects of Integrated Flood Management,* APFM Technical Document No. 5, Flood Management Policy Series (WMO, 2007).

149 Since a reallocation of water-use rights in favour of managed flows is likely to result in loss of benefits for certain sections of the society, there is the need to develop a financial mechanism either for sharing the cost of "opportunity lost" or compensating those who lose already acquired benefits.

7.4 Data and information base

150 A range of specialists undertake field surveys to provide a comprehensive description of the affected river and the interaction of ecological and social values. It is important to: prioritize various water uses and evaluate the scope; use flow forecasting to optimize reservoir operation with simulation models where feasible; and assess the scope for optimizing the supply of water and energy and other different uses to improve the overall value of the services from the system. It may sometimes be feasible to optimize interactive operation of the reservoir with other reservoirs, diversions or facilities using basin-level decision-support systems.

151 There is a need to define clear responsibilities and procedures for emergency warning and improved preparedness of downstream communities, including emergency preparedness and response. To achieve the above, it is essential that monitoring systems are in place and feed into operational decision-making.

7.5 Stakeholders' participation

152 Involvement of stakeholders in the entire process, starting from developing the objectives up to the monitoring and evaluation process is essential, as many of the benefits derived from the managed flows are non-quantifiable in monetary terms. Decisions have to be taken based on combined societal aspirations and understanding. As the entire process is aimed at making balanced choices, there is a need for mechanisms that resolve conflicts between different sections. A detailed discussion on the subject can be found in *Social and Stakeholder Involvement in Integrated Flood Management*, APFM Technical Document No. 4, Flood Management Policy Series (WMO, 2006(b)).

GLOSSARY

Aeration: *the mixing of air and water, usually by bubbling air through water or by contact of water with air*

Algae: *small (generally microscopic) plants that live either floating in the water or attached to submerged objects*

Dissolved oxygen: *the oxygen dissolved in water is necessary to sustain aquatic life.* It is usually measured in milligrams per litre (mg/l) or parts per million (ppm).

Erosion: *natural processes by which soil or rocks are moved from one location to another.* Typical examples include streambank or shoreline erosion in which soil particles are washed away by the forces of water.

Eutrophication: *the nutrient enrichment and response in productivity of a water body (i.*e. relatively high levels of aquatic plant life); this is a natural ageing process that can be accelerated by nutrients added by humans.

Invertebrates: *animals without backbones; used to refer to all animals except fish, amphibians, reptiles, birds and mammals (vertebrates)*

Managed flow: *a release from reservoirs provided to meet hydropower production, reservoir-level targets, downstream water needs (such as aquatic habitat, water supply and waste assimilation) and other commitments.* Managed flows are those required to be released from a specific reservoir over a specific time period, not the lowest amount of water. Managed flows are those needed at some point in the system to meet specific needs for power, waste assimilation, navigation and other beneficial uses.

Spillway: *a channel or passageway around or over a dam, through which water is released or "spilled" past the dam without going through the turbines.* Spillways at some dams are controlled with gates. At others, water flows over the top of the spillway automatically when the reservoir level reaches a certain elevation. A spillway is a safety valve for a dam; it can be used to discharge rainfall and runoff from major storms, as necessary, to maintain the reservoir below a predetermined maximum level.

Temperature stratification: *the variation of water temperature at different depths in a reservoir; the coldest water is typically the densest and is found at the bottom of the reservoir; the warmest water is at the surface.*

Water intake: *a pipe or more complex structure designed and used to withdraw water from a stream or reservoir.*

REFERENCES

A

Acreman, M.C., F.A.K. Farquharson, M.P. McCartney, C. Sullivan, K. Campbell, N. Hodgson, J. Morton, D. Smith, M. Birley, D. Knott, J. Lazenby, R. Wingfield and E.B. Barbier, 2000: *Managed Flood Releases from Reservoirs: Issues and Guidance. Report to UK Department for International Developmen and the World Commisson on Dams.* Centre for Ecology and Hydrology, Wallingford, United Kingdom
www.nwl.ac.uk/ih/www/research/images/managedreleases.pdf

C

Cederholm, C.J. and E.O. Salo, 1979: *The Effects of Logging – Road Landslide Siltation on the Salmon and Trout Spawning Gravels of Stequaleho Creek and the Clearwater River Basin, Jefferson County, Washington, 1972–1978.* Fisheries Research Institute, University of Washington, FRI-UW-7915, Seattle, Washington, USA.

D

Dyson, M., G. Bergkamp and J. Scanlon (eds), 2008: *Flow – The Essentials of Environmental Flows, second edition.* IUCN, Gland, Switzerland
cmsdata.iucn.org/downloads/e_flow_2003_021_english_versoin.pdf

E

ESCAP (United Nations Economic and Social Commission for Asia and the Pacific) and WMO (World Meteorological Organization), 2008: *Guideline for Reservoir Operation in Relation to Flood Forecasting.* WMO/TD-No. 1471. Published by K-Water, Republic of Korea
typhooncommittee.org/docs/publications/WMO_TD1471_2008.pdf

Everest, F.H., C.E. McLemore and J.F. Ward, 1980: *An Improved Tri-tube Cryogenic Gravel Sampler.* US Forest Service Research Note PNW-350
www.fs.fed.us/pnw/pubs/pnw_rn350.pdf

F

FISRWG (Federal Interagency Stream Restoration Working Group), 1998: *Stream Corridor Restoration: Principles, Processes, and Practices.* 15 Federal agencies of the US government). GPO Item No. 0120-A; SuDocs No. A 57.6/2:EN 3/PT.653
www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/manage/?&cid=stelprdb1043244

G

Groot, C. and L. Margolis, 1991: *Pacific Salmon Life Histories.* University of British Columbia Press, Vancouver, Canada
swrcb2.swrcb.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/exhibits/nmfs/spprt_docs/nmfs_exh4_healey_1991.pdf

I

ICOLD (International Commission on Large Dams), 1998: *Dam-break Flood Analysis: Review and Recommendations.* Bulletin 111.

IUCN (International Union for Conservation of Nature), n.d.(a): *The Senegal River Release of an Artificial Flood to Maintain Traditional Floodplain Production Systems.* Environmental Flow Case Studies from Africa
cmsdata.iucn.org/downloads/senegal.pdf

IUCN, n.d.(b): *The Lower Mekong River: International Collaboration for Sustainable Development.* Environmental Flow Case Studies from Asia-Pacific.
cmsdata.iucn.org/downloads/mekong_1.pdf

K

Kantoush, S.A. and T. Sumi, 2010: *River Morphology and Sediment Management Strategies for Sustainable Reservoir in Japan and European Alps.* Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 53 B.
www.dpri.kyoto-u.ac.jp/nenpo/no53/ronbunB/a53b0p83.pdf

Kondolf, G.M., 2000: *Assessing Salmonid Spawning Gravel Quality.* Transactions of the American Fisheries Society 129:262–281.
www.yubaaccordrmt.com/Studies%20%20Reports/Kondolf%202000%20Assessing%20Gravel%20Quality.pdf

M

Maidment, D.R., 1993: *Handbook of Hydrology.* McGraw-Hill Education, 1424 pp.

Meehan, W.R., 1991: *Influences of Forest and Rangeland Management on Salmonid Fishes and their Habitats.* American Fisheries Society. Special Publication 19, Bethesda, Maryland, USA.

MLIT (Ministry of Land, Infrastructure, Transport and Tourism), n.d.: *Manual for River Works in Japan Planning/Survey/Design of Dams.* River Bureau, MLIT, Japan.

N

NRC (National Research Council), 2002: *The Missouri River Ecosystem: Exploring the Prospects for Recovery.* Water Science and Technology Board, Division on Earth and Life Studies, NRC. National Academies Press, Washington DC
www.nwd-mr.usace.army.mil/mmanual/MRMM_NAS_Study_EXSUMSections1%262.pdf

P

Parfitt, D., 1980: *Upper Sacramento River Spawning Gravel Study.* California Department of Water Resources, Northern Division, Red Bluff, USA
www.sacramentoriver.org/forum/index.php?id=atlases

Postel, S. and B. Richter, 2003: *Rivers for life – Managing Water for People and Nature.* Island Press Washington, USA and London, United Kingdom.

S

Sumi, T. and S.A. Kantoush, 2010: *Integrated Management of Reservoir Sediment Routing by Flushing, Replenishing, and Bypassing Sediments in Japanese River Basins.* 8th International Symposium on Eco-Hydraulics (ISE 2010), COEX, Seoul, Korea, 651–673
ecohyd.dpri.kyoto-u.ac.jp/data/sumi/2010/201012.pdf

U

UNEP-DDP (United Nations Environment Programme – Dams and Development Project), 2000: *Dams and Development: a New Framework for Decision Making.* The World Commission on Dams Report. Earthscan Publications Ltd., London, United Kingdom and Sterling, VA, USA
www.unep.org/dams/WCD/report.asp

USACE (US Army Corps of Engineers), 2004(a): *Missouri River Final Environmental Impact Statement (FEIS), Master Water Control Manual Review and Update.* USACE, Northwestern Division
www.nwd-mr.usace.army.mil/mmanual/feis/Index.htm

USACE, 2004(b): *Selected Plan – a*.k.a. Record of Decision Missouri River Master Water Control Manual Review and Update. USACE, Northwestern Division
www.nwd-mr.usace.army.mil/rcc/reports/pdfs/recordofdecision.pdf

USACE, 2006(a): *Missouri River Mainstem Reservoir System Master Water Control Manual – Missouri River Basin.* Reservoir Control Center, USACE, Northwestern Division – Missouri River Basin, Omaha, Nebraska
www.nwd-mr.usace.army.mil/rcc/reports/mmanual/MasterManual.pdf

USACE, 2006(b): *Environmental Assessment for the Inclusion of Technical Criteria for Spring Pulse Releases from Gavins Point Dam (Missouri River Mainstem Reservoir System Master Water Control Manual).* Missouri River Water Management Division, Northwestern Division
www.nwd-mr.usace.army.mil/rcc/reports/pdfs/MRMainstemSystemSpringPulseEAFINAL.pdf

USFWS (US Fish and Wildlife Service), 2003: *Amendment to the 2000 Biological Opinion on the Operation of the Missouri River Main Stem Reservoir System, Operation and Maintenance of the Missouri River Bank Stabilization and Navigation Project, and Operation of the Kansas River Reservoir System*
*www.*nwd-mr.usace.army.mil/mmanual/FinalBO2003.pdf

W

WMO (World Meteorological Organization), 2003: *Manual on Sediment Management and Measurement.* Operational Hydrology Report (OHR), 47- WMO, No. 948
www.whycos.org/whycos/sites/default/files/public/pdf/948_e.pdf

WMO, 2006(a): *Environmental Aspects of Integrated flood Management.* APFM Technical Document No. 3, Flood Management Policy Series., WMO-No. 1009, Geneva
www.floodmanagement.info/?portfolio=environmental-aspects-of-integrated-flood-management

WMO, 2006(b): *Social and Stakeholder Involvement in Integrated Flood Management.* APFM Technical Document No. 4, Flood Management Policy Series, WMO-No. 1009, Geneva
www.floodmanagement.info/?portfolio=social-aspects-and-stakeholder-involvement-in-integrated-flood-management

WMO, 2006(c): *Legal and Institutional Aspects of Integrated Flood Management.* APFM Technical Document No. 2, Flood Management Policy Series, WMO-No.997, Geneva
www.floodmanagement.info/?portfolio=legal-and-institutional-aspects-of-integrated-flood-management

WMO, 2007: *Economic Aspects of Integrated Flood Management, APFM Technical Document No.* 5, Flood Management Policy Series, WMO-No. 1010, Geneva
www.floodmanagement.info/?portfolio=economic-aspects-of-integrated-flood-management

WMO, 2012: *Conservation and Restoration of Rivers and floodplains, APFM Technical Document No.* 18, Flood Management Tools Series. Geneva
www.floodmanagement.info/ifm_tools.htm

FURTHER READING

D

David, R. and R. Hijri, 2003: *Environmental Flows: Concepts and Methods.* Water Resources and Environment Technical Note C.1, World Bank (Introduces concepts and methods for determining environmental flow requirements for rivers.)
water.worldbank.org/publications/environmental-flows-concepts-and-methods

David, R. and R. Hijri, 2005(a): *Environmental Flows: Case Studies.* Water Resources and Environment Technical Note C.2, World Bank (Reviews some important case histories)
water.worldbank.org/publications/environmental-flows-case-studies

David, R. and R. Hijri, R., 2005(b): *Environmental Flows: Flood flows; Water Resources and Environment Technical Note C.*3, World Bank (Describes the reinstatement of flood release from reservoirs for floodplain inundation.)
water.worldbank.org/publications/environmental-flows-flood-flows

H

Hamerlynck, O. and S. Duvail, 2003: *The Rehabilitation of the Delta of the Senegal River in Mauritania.* IUCN, Gland, Switzerland and Cambridge, United Kingdom, viii + 88 pp.
data.iucn.org/dbtw-wpd/edocs/WTL-029.pdf

I

International Union for Conservation of Nature (IUCN) Viet Nam, 2005: *Environmental Flows: Rapid Environmental Flow Assessment for the Huong River Basin, Central Vietnam.* IUCN Viet Nam, Hanoi, Viet Nam. xx+82 pp
data.iucn.org/dbtw-wpd/edocs/2005-120.pdf

IUCN, various years: *FLOW Case studies*
*www.*iucn.org/about/work/programmes/water/resources/toolkits/flow/

L

Loth, P. (ed.), 2004: *The Return of the Water: Restoring the Waza Logone Floodplain in Cameroon.* IUCN, Gland, Switzerland and Cambridge, United Kigdom, xvi + 156 pp
data.iucn.org/dbtw-wpd/edocs/WTL-030.pdf

T

Tennessee Valley Authority (TVA), 2004: *Programmatic Environmental Impact Statement – Record of Decision.* Reservoir Operations Study, in cooperation with US Army Corps of Engineers and US Fish and Wildlife Service
http://www.tva.gov/environment/reports/ros_eis/

(Unless otherwise noted, all online references were last accessed on 29 June 2015; n.d.: no date)

For more information, please contact:

Associated Programme on Flood Management
c/o Climate and Water Department
World Meteorological Organization

tel	+41 (0) 22 730 83 58
fax	+41 (0) 22 730 80 43 apfm@wmo.int
email	www.floodmanagement.info

World Meteorological Organization
Communications and Public Affairs Office
7 bis, Avenue de la Paix – P.O. Box 2300
CH-1211 Geneva 2 – Switzerland

tel	+41 (0) 22 730 83 14/15
fax	+41 (0) 22 730 80 27
email	cpa@wmo.int www.wmo.int

GWP Global Secretariat
Linnégatan 87D - PO Box 24177
SE-104 51 Stockholm – Sweden

tél	+46 8 1213 86 00
fax	+46 8 1213 86 04
email	gwp@gwp.org www.gwp.org