World Meteorological Organization

RESERVOIR OPERATIONS AND MANAGED FLOWS

A Tool for Integrated Flood Management

ASSOCIATED PROGRAMME ON FLOOD MANAGEMENT

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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 governments of Japan and the Netherlands.

World Meteorological Organization
Weather • Climate • Water

The World Meteorological Organization (WMO) is a specialized agency of the United Nations. It coordinates the activities of the meteorological and hydrological services of 188 countries and territories and such is the centre of knowledge about weather, climate and water.

Global Water Partnership

The Global Water Partnership is an international network open to all organizations involved in water resources management. It was created in 1996 to foster Integrated Water Resources Management (IWRM).

Note for the reader

This publication is part of the "*Flood Management Tools Series*" being compiled by the Associated Programme on Flood Management. The contained Tool for "Reservoir Operations and Managed Flows" 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 environmental assessment around the globe to participate in the enrichment of the Tool. *For the 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 Tool".

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1. INTRODUCTION

1 Reservoirs play an important role in flood management. They store flood water 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 needs of various activities when the natural supply is less than the demand. From both aspects, 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 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 river flood plains from its channel. The ecosystems or the natural processes, both within the channel and the flood plains dependent on the existing natural regime flows may be adversely impacted by such changes [1]. Natural flow regimes, including the high flows, shape the physical character of the river channel, including pools and riffles. At the same time, low flows, 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 form of changes in terrestrial and aquatic habitats in the ecosystem as well as the social and economic activities.

4 The environment sensitive reservoir operations duly considering the ecological needs and releasing adaptive managed flows can help reduce these adverse impacts without significantly compromising to fulfil 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 flood plains, wetland ecosystems and their dependent livelihoods.

5 The present practice of reservoir operations based on the rule curves, which are predominantly guided by the 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. However it is recognised 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 be always 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 integrated approach. An effective organizational learning and cross-organizational interactions 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 flood plains and 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 bring the various aspects of reservoir operations as well as to show possibilities of how flows can be managed successfully to minimize their adverse impacts. The tool therefore aims at:

- Understanding changes in flow and sediment regimes by reservoirs
- Identifying the issues that need to factored for deciding the managed flows

- Introducing options to tackle these issues by modification of reservoir operations
- Planning the managed flows
- Providing a framework for environment sensitive reservoir operations

8 The Tool is primarily addressed to flood managers and the other reservoir operators/owners, at the same time it provides useful information for policy makers, environmental groups, NGOs and communities. However, it must be realised that environment sensitive reservoir operation is a multi-disciplinary pursuit and requires close collaboration with the environment specialists on 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 an initiator and starting point for the environment sensitive reservoir operations.

2. INTEGRATED FLOOD MANAGEMENT (IFM) AND RESERVOIR OPERATIONS

2.1 INTEGRATED FLOOD MANAGEMENT

10 Floodplains are the preferred areas for habitation since time immemorial for their various advantages. They support various kinds of socio-economic activities. The normal floods provide variety of services to support these human activities. Many people depend for their livelihoods on the various services provided by the river and its corridor ecosystem. At the same time the floodplains are occasionally flooded thereby adversely impacting the economic activities and resulting in loss of property and life.

11 Under natural conditions, rivers continuously migrate across their flood plain belt and change the configuration of the landform. Flow and sediment regimes, interacting with river-bed and bank materials and with riverine vegetation, create and destroy fluvial features, thereby providing a variety of habitats for diverse biotic communities. Flooding not only allows aquatic organisms to move out of or into the main channel, but also causes morphological change, creates new habitats, deposits silt and fertile organic material, sustains wetlands, renews flood plain ponds, and temporarily stores water on the flood plains. Ecological and morphological connectivity across longitudinal (upstream catchment and downstream corridor reaches), lateral (between the river and its flood plain), and vertical (surface with subsurface zones) dimensions 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 long duration and thereby provide agricultural opportunity in rain-fed agriculture. At the same time it replenishes groundwater, which forms an essential source of water for drinking and irrigation. The wetlands on the flood plains also get replenished and provide different ecosystem services.

13 The goal of Integrated Flood Management (IFM) is to maximize the net benefits from flood plains, to reduce flood risks, and to minimize loss of human life due to flooding in a sustainable manner. It achieve it through a mix of various structural and non-structural interventions and addressing all the three components of flood risks, viz., hazard magnitudes, exposure as well as the vulnerability of the society exposed to floods. The vulnerability of the communities, among others, is largely influenced by the livelihood opportunities. Ecosystem services provide an essential source of livelihood for the people, particularly poor, living on flood plains.

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

- Scientific understanding and analysis,
- Environmental assessment,
- Environmentally sensitive economic analysis,
- Stakeholders involvement,
- Adaptive management approach,
- Monitoring, and
- Enabling mechanism.

15 Reservoir operations for flood moderation, as one of flood management options, play an important role in protecting people and their socio-economic activities in flood plains from flooding. Reservoir operations, however, have the potential to alter flow regimes, fix river shape or separate river channels from its flood plains 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 and livelihoods, and food and health security [1].

2.2 MANAGED FLOWS

16 Reservoirs should provide for flow release to meet their specific purposes as well as the downstream ecosystem and livelihood objectives identified through scientific and participatory processes. These flows are also referred to as the "ecological flows", which are simply not a quantity of water released downstream of a reservoir. They have to serve certain objective which needs 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 overtop and supply flood plains and deltas. The "Managed flow" [2] includes all of these and stresses the need to meet clear downstream social and ecosystem objectives rather than simply releasing a quantity of water. The managed flows attempt to maintain the natural flow and sediment regimes variability as close as possible.

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. At the same time it has to be realised that natural flows that existed before the construction of the reservoirs would never be possible to be achieved unless all the interventions to abstract or regulate water in the entire basin are decommissioned.

19 Therefore the main objective of managed flows is to reverse, at least partially the unsustainable development of water resources and to minimise the adverse impacts of future development activities, while reducing the flood risks and at the same time supporting the livelihoods to reduce vulnerability. There is no single method that can determine the managed flows. However, based on certain IFM approach and given an environment friendly framework one can try to fix the desired objectives and achieve them. Within IFM and IWRM the objective of managed flow should be:

> *"To mimic the natural flow conditions, as far as possible, in order to minimise the adverse impacts on the livelihoods of people through eco-services."*

20 While the society has realised the importance of maintaining the ecological services provided by nature, the stress on natural resources are increasing with increase in population and the aspirations for achieving the prosperity and well being under the given economic model. As such the human interventions can 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 virgin/natural flows
- The developments in most of the cases cannot be undone
- The managed flow should start addressing the most critical adverse impacts
- The new flow regimes to which the flora and fauna has adapted should be respected
- The decisions are taken under a large band of uncertainty in knowledge as well as understanding

* [ ] indicate the reference listed at the end of the article

3. IMPACTS OF RESERVOIRS

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

3.1 RESERVOIR PURPOSES AND MODERATION OF FLOW

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

3.1.1 Flood moderation

23 Flood moderation reservoirs store all or a portion of the flood waters in the reservoir, particularly during peak floods, and then releases the water slowly. Space within reservoir is generally reserved to store impending floods. Small to medium floods generated from the catchment are fully captured by the reservoirs. However, 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 [1].

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

- store flood water to reduce discharge downstream
- try to keep space empty for storage of coming flood (storage space in the reservoir is required)
- appropriate operation in accordance with flow discharge into reservoir

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

3.1.2 Water supply

26 Water supply reservoirs store the water during time of high flow, in order to supply water to downstream for water utilization, e.g. agricultural production (irrigation), dilute contaminated pond/river, human and industrial use, etc. It is desirable to keep the storage capacity as filled as possible. Their special characteristics are that they:

- store water during rainy season and utilize it during dry season
- keep water level high in order to store water to the maximum

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 terms 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 industrialised countries, hydropower is being used to meet the peak time demands. As, such their operations, 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 permits 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 fresh water supplies, can also contribute to a fundamental sustainability goal - the alleviation of poverty [2].

29 Concerning climate is greenhouse gases, emissions that are thought to be associated with global warming. Hydropower energy is not only among energy sources producing low levels of carbon dioxide emissions from their fuel cycle, but 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 once the way they are impacted is understood. Following section attempts to briefly put them in perspective. The natural flows are a result of random meteorological inputs, in terms of precipitation, the variability of which are attenuated by the hydrologic response of the catchments. This natural variability is greatly altered by the storages but can be restored to certain extent through studied operational practices at no cost or minimal costs.

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 flood plain inundation. As a result of changes in water quantity will fix river shape or separate river channels from its flood plains. Reduction of channel-forming discharge and truncated sediment transport often alters channel and flood plain morphology [3]. These changes in water are:

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

32 To envision the concept of channel-forming discharge, imagine placing a water hose discharging at constant rate in a freshly tilled garden. Eventually, a small channel will 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 channel morphology until the channel reaches equilibrium [4]. However, if this uniform rate of discharge is changed to another constant rate, the channel will attain 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 about that stable condition. Such equilibrium is a function of a number of elements of water quantity:

- Volume
- Depth
- Velocity and
- Turbulence

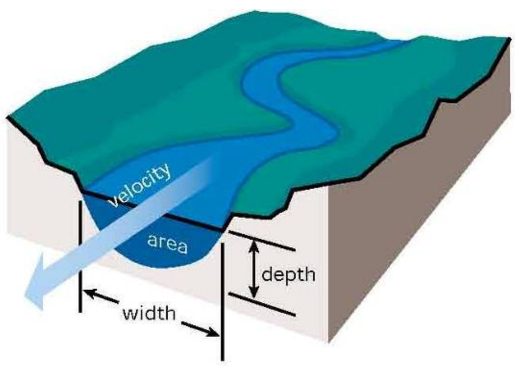

Figure 1: Water discharge

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.
- 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 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 dam are provided in *IUCN report, in Senegal River Basin* [5]). 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 de-oxygenation 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 [1].

35 Where agriculture pesticide, toxic industrial pollutions, heavy metals from upstream mining operations etc, have accumulated in the reservoir, the sediment trapped in such reservoirs, when releases downstream can impact the biological activities of the river would threaten downstream human water use activities or ecological values [2].

3.2.3 Water temperature

36 Large storage reservoirs tend to stratify, so that the water at 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 release of water downstream that has significantly cooler temperatures which may not always be conducive to the 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 [4].

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 temperatures, and increased temperatures can increase metabolic and reproductive rates throughout the food chain;
- many aquatic species can tolerate only a limited range of temperatures, and any change in the range of temperatures within a stream can have profound effects on species composition; and
- many abiotic chemical processes, such as reaeration rate, absorption of organic chemicals to particulate matter, and volatilization rates.

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

3.2.4 Sediment transport

39 The creation of reservoirs change the hydraulic and sediment transport characteristics of the river, causing increased potential sedimentation within the storage and depriving the downstream of the sediment material. Excessive sedimentation and consequent loss of water storage capacity in many reservoirs that may reduce the long-term viability of development is an important sustainability issue for some reservoirs. Such a situation may result from the excessive surface erosion of the catchment area, often due to deforestation, or due to 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 [2].

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 by turbulence in suspension is partially settled depending on the resident 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 [4].

41 The bed-material load is normally deposited at the mouth of the reservoir, creating small delta, which moves downstream into the reservoir with time. This sediment load essentially occupies the conventionally known as the live storage. It is generally the fine wash load which takes long time to settle and is deposited essentially all along the reservoir, particularly near the outlets. The wash load essentially occupies the dead storage all along the bed. Over time the wash load is consolidated. In the early life of the reservoir, the deposited wash load is at the level much below the level of the outlets. The deposited wash load is seldom rejuvenated and brought into flow. However, during the large floods almost all the wash load passes over the spillway on to the downstream.

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 river bed and banks. Such flow conditions result in formation of deep single channel thereby cutting off the others with much reduced heterogeneity of flow conditions.

3.3 IMPACTS ON SOCIAL AND ECONOMIC ACTIVITIES AND ENVIRONMENTAL CONDITION

3.3.1 Fishery

43 A dam built in the upper reaches of a river could have substantial impact on the availability of fishery downstream [2]. The alluvial reaches of a river presents 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 various species. Many habitats are lost in the lateral channels and in the flood plain, resulting in a sharp decrease in local, and finally in regional, biodiversity [1] [5]).

44 Artificial low flows may lead to fish kills and deplete populations of species sensitive to higher water temperatures and lower oxygen conditions [6]. Inadequate low flows may result in overcrowding of fish population in poor-quality water, with no option to move to other feeding areas. Absence of high flows may result in fish not being able to access flood plains for spawning and feeding (for instance, fish movement in response to flow regime is provided in *IUCN report, in the lower Mekong River Basin* [7]).

3.3.2 Water utilization

45 Rights over access to and use of water for various purposes such as agriculture, dilution of contaminated river, supply of city water for domestic and 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 on who might 'hold' the river water 'in trust'. A flexible and adaptive style of management is needed [2].

3.3.3 Groundwater recharge

46 Lack of flood plain 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 base flow-groundwater interactions, and degrades riverine habitats [1]. Lowering of groundwater table could have a direct impact on flood plain flora and fauna where species are dependent on shallow groundwater.

3.3.4 Preserving ecosystem

47 Dams and reservoirs have the potential to alter flow regimes, fix river shape or separate river channels from their flood plains. As such, 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 [1] [5]).

3.3.5 Protection of river management facilities

48 The degradation of river bed and erosion of banks downstream of a reservoir may result in exposing the foundation of existing infrastructure such as bridges.

49 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 decrease in discharge in such reaches. To prevent these adverse impacts changes in the design practices of new installations and modification of the existing ones including changes in the materials of river management facilities is desirable [8].

3.3.6 Recreational activities

50 Rivers, coastal areas and banks of other water bodies are preferred areas for human settlements as proximity with water provides a high degree of visual satisfaction and opportunities for recreation. On the rivers where sightseeing boats are operated, the reduction in the river discharges may result in non-feasibility of their operation. Recreation value can be enhanced if connecting channels are deep enough for small boats or canoes. Consideration similar to the ones indicated in 3.3.8 will be required [8].

51 Further, in the alluvial flood plains the reduction in such discharges may shift the main channels of the river away from the city banks, thereby resulting in opportunity lost. However, such a situation could be tackled through appropriate river engineering interventions, giving due care to the ecological impacts of such interventions.

3.3.7 Flushing of pollutants and sediments

52 Floods can have a flushing effect on stagnant waters, removing pollutants such as human waste, unblocking drains or flushing away mosquito larvae [3]. This is particularly important in the downstream reaches of the cities in semi-arid areas, particularly in developing countries where not all the city waste water is treated before letting it out into the river.

53 As incidents of high discharges decrease, the possibility of dilution of such polluted reaches as well as movement of the sediments, 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 [8].

3.3.8 Navigation

54 The reservoirs, exclusively built for power generation, in general, have a positive impact on the navigability of the downstream reaches due to almost constant releases. However, in reservoirs where the water is withdrawn out of the river channel to be used for irrigation or water supply, the downstream releases, if any may not be sufficient to continue the flow of boats. The situation is worsened if non-release of flows downstream results in 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 draft for various types of boats [8].

3.3.9 Prevention of salt intrusion

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

56 In estuarine reaches the sea water rich in salt 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 water and salt water in the estuarine areas thereby creating a habitat rich in biodiversity. However, in the absence of normal fresh water supply from the river this equilibrium may be disturbed. When salt water 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 they use as a nursery area [2]. To cope with such situations, it is necessary to examine the possibility of installation of salt levees and improving intake facilities [8].

3.3.10 Others

57 As symbols of purity, renewal, timelessness, and healing, rivers have shaped human spirituality like few other natural features. To this day, millions of Hindus in India immerse themselves in the waters of the Ganges in rituals of cleansing that are central to their spiritual life [6]. It is, therefore, important to acknowledge native customs and beliefs; respect indigenous needs; and make use of local knowledge for its ability and willingness to read and heed nature [9].

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

		Water quantity	Water quality	Water temperature	Sediment transport
1	Fishery	√	√	√	√
2	Water utilization	√	√	√	
3	Groundwater recharge	√			√
4	Preserving ecosystem	√	√	√	√
5	Protection of river management facilities	√			√
6	Recreational activities	√	√	√	√
7	Flushing of pollutants and sediments	√			√
8	Navigation	√			
9	Prevention of salt intrusion	√			√
10	Others	√	√	√	

4. FACTORS TO BE CONSIDERED FOR MANAGED FLOWS

58 The life-forms within 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, its highs and lows, its floods and dry spells. Protecting freshwater biodiversity and ecosystem services therefore requires establishing an allocation of water for ecosystem support. 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 case of existing reservoirs where all the water has been allocated for different users it requires re-establishing such an allocation.

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

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

4.1 TECHNICAL FEASIBILITY

60 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 the downstream needs for water supply, agriculture or the environment, by requirements for flood regulation, by storage considerations or by 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 a pipeline and thus may have no low level outlet into the river downstream.

61 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 to be let into the turbines. Many a times the outlets are not located in the body of the main dam and the released water does not join the river directly downstream of the dam but rather joins after certain distance downstream. The spillway releases surplus water resulting from flood inflows that cannot be contained within the reservoir and cannot be released through a low level outlet. 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.

62 In order to achieve the objectives of managed flows the alteration of the established release practices based on rule curves with minimal impacts on the 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

63 The new requirements of managed flows can be met if the available water 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.

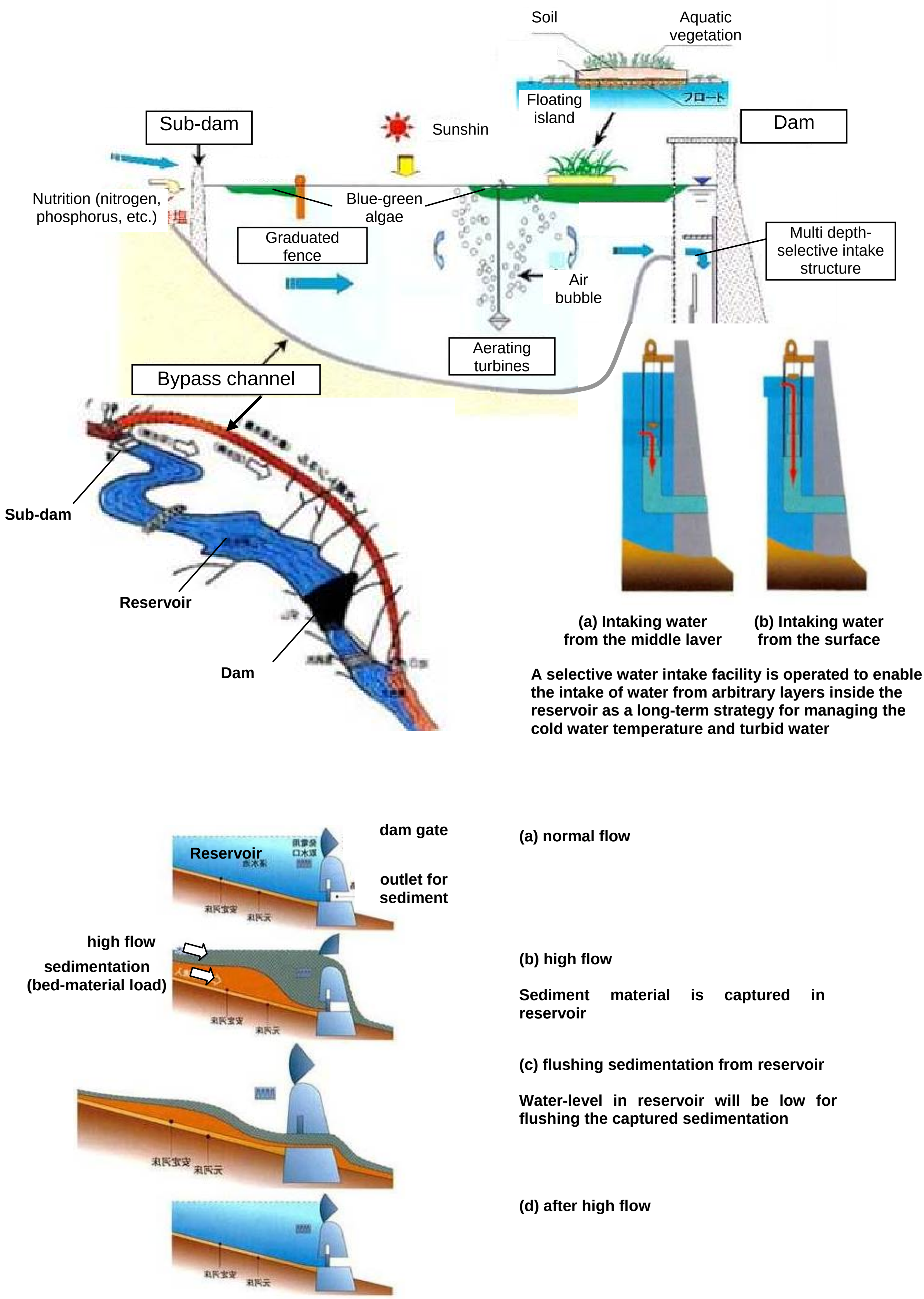

Figure 2: Technical options

64 Similarly by gaining time advantage in operation of the reservoir one can manage the reservoir releases in a more environment friendly manner. This can be achieved through advanced hydrological forecasts and climate prediction. Such forecasts and predictions give a better flexibility to the reservoir operator to manage flows that could mimic the natural flows to certain extent.

65 Some of the feasible technical options are briefly mentioned in Table 2 and some others are illustrated in Figure 2. However, it may be pointed out that these technical options are highly site specific and need thorough investigations akin to the ones carried out for establishing the feasibility of a new reservoir. Their adoption also depends on the technical capacities in the remote areas where such facilities are located. It may be pointed out that in certain developing countries it may not be possible to carry out highly technical modifications at such a small scale. In any case the modifications should not in any case jeopardise the safety of the existing structures.

66 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 the existing dams.

4.2 COST BENEFIT ANALYSIS AND COST ALLOCATION

67 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 flood plains (for instance, a threat to the livelihoods of middle-stream riparian communities from terminating annual food is provided in *IUCN report, in Senegal River Basin* [5]). Although social and environmental costs and benefits are difficult to quantify, an environmentally sensitive flood management decision-making process [10] can be of great help. A brief discussion of the methods such as Multi-criteria analysis (MCA) that helps put value on the social and environmental costs and benefits are provided elsewhere therein [10].

68 In some cases this has led to the re-definition 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.

69 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 (e.g. 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 flood plain area. Financial implications of each projected scenario need to be assessed and translated into monetary terms through the application of economic valuation methods. As the benefits and costs associated with each flow regime occur over time, yet the decision as to which managed flow to adopt must be taken today, this means that future benefits and costs must be 'discounted' into 'present values'.

70 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.

71 It is highly recommended that the economist conducting the Cost Benefit Analysis (CBA) should be involved with the hydrologists, ecologists, socio-economists 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.

72 Compensations for the loss of benefits from the reservoir form part of the costs of reform of operation procedures. Cost allocations of meeting the requirements of managed flows needs to be distributed among various uses and users of the reservoir facility. This requires development of procedures which are acceptable to all and requires effective stakeholder's participation in the process right from setting the targets of managed flows.

- dam operators may have rights 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

73 Construction of a multi-purpose reservoir leads to establishing certain rights for use of water by different sectors or the sections of the society. Establishment of such rights are generally a result of negotiations and discussions and may be based on the principles of equity of development. However, this may not always be the case. Hardly a few cases exist where water was allocated exclusively for meeting the needs of the river environment. While establishing the managed flow procedures certain quantity of stored water has to be allocated to nature. This will require forgoing the established water use rights by the existing users and has the potential to open old grievances afresh. There is need to address these concerns and have mechanisms that are equitable and just in accordance with the accepted international and national laws, rules and regulations (for instance, 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 [5]). 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 easily understandable information

74 On rivers that are shared by more than one nation, state or administrative region such a re-allocation exercise becomes increasingly complex which requires mutual cooperation and understanding and has to be guided by international or national laws/agreements as the case me be. However, the existing agreements may have to be revisited to make allocation for the managed flows.

4.4 FLOOD RISKS

75 When a river and its flood plain are known to be prone to flooding, infrastructure, such as roads, railways, pipelines, are 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 flood plain 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.

76 In most cases, managed flow 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 that are caused by flooding to the economic activities and consequently the well being of flood plain dwellers. It is thus important to ensure that flood plain 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 flood plain. Additional embankments may be constructed with sluice gates to enable particular areas of the flood plain to be inundated to specified depths at particular times, thus fine-tuning the effectiveness of the managed flow. Some of the issues that need to be considered while looking at the effectiveness of the managed flows are as follows.

- different flood plain stakeholders (including farmers, fishermen and herders) require managed flow at different times
- where the target flood plain is a significant distance downstream of the reservoir, flow 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

Table 2: Technical options for managed flow

Change due to reservoirs		Impacts in the downstream	Possible preventive measures
Water quantity	• Reduction of flood peaks • Decrease of turbulent motion • Decrease of sediment transport and the organic silt	• Reduced seasonal variability of flow, i.e. low flows increased and high flow decreased • 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 (depend 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 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 a reservoirs retention time)	• Setting equipment for aeration • Multi-level off-takes, air injection facilities, aerating turbines, and de-stratification capability • Graduated fence • Bypass channel • Floating island,
Water temperature	• Existing of temperature stratification in the reservoir (water at the bottom of reservoir is much cooler)	• Cold water release if the water will be taken from the bottom of 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 the organic silt	• Changing form of sediment bars, flood plains, 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 • Sediment bypasses, flushing systems or dredging • Appropriate sediment bypassing devices • Graduated fence

5. PLANNING FOR MANAGED FLOWS

77 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 their dependent livelihoods.

78 It is not possible, even if desirable, to reproduce the natural flow and sediment regimes in 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 new reservoir is proposed to be built. It is not likely to be to create managed flows solely from reservoir, nor should it be necessary to do so.

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

- Planning and Feasibility
- Design
- Implementation and
- Evaluation

80 The sequence of the 10 steps adapted from Ackerman et al [3] may vary depending on the circumstances surrounding the particular reservoir or downstream flood plain or delta.

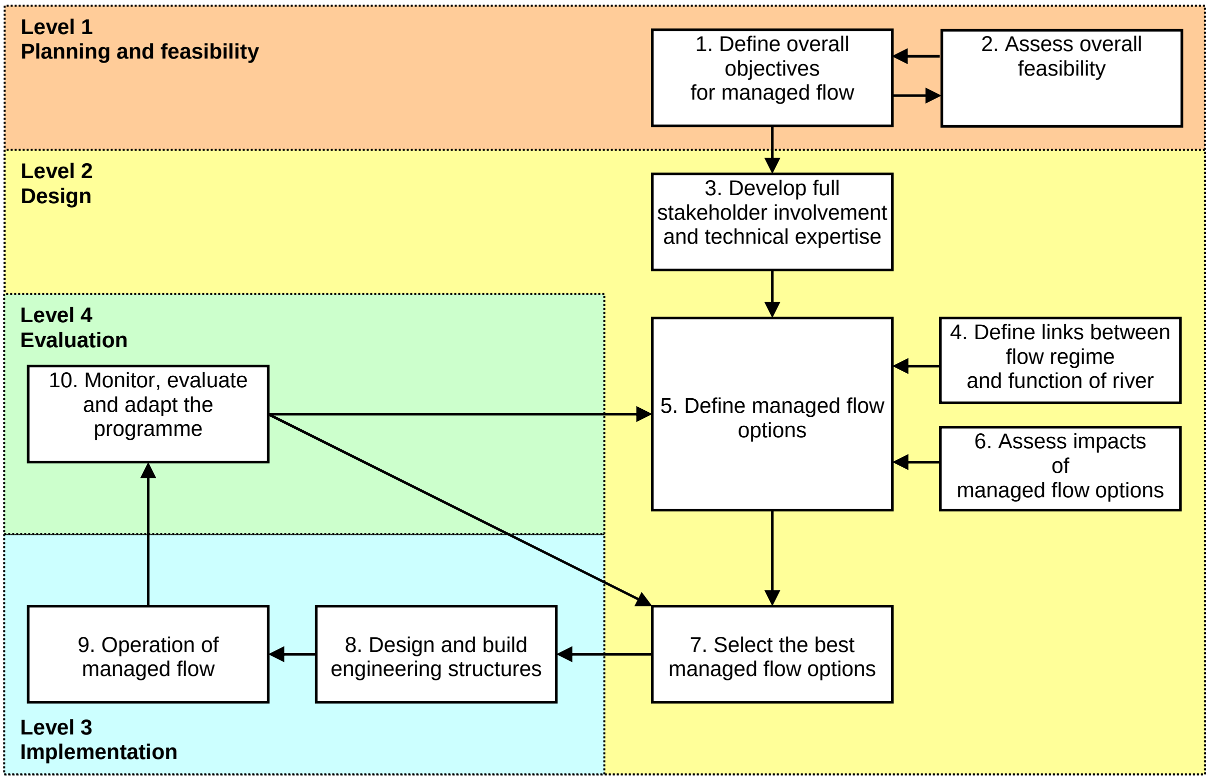

Figure 3: Managed Flows Programme

5.1 PLANNING AND FEASIBILITY

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

81

- Clear overall objectives for managed flows must be defined through a scoping study of the flood risks, ecosystem, economy and social structure of the flood plains.
- The aim should be to ensure that managed flows are compatible with the livelihood strategies of the flood plain communities
- The sectors and section 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

5.1.2 Step 2: **Assess overall feasibility**

82 The technical and financial feasibility of various scenarios and options to attain managed flows must be defined. The following three 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 dam controls flooding in target ecosystems, will depends 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.

5.2 DESIGN

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

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

84

- 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, flood plain residents, and those presently benefiting from the various services from the reservoir. This should begin with identification of various stakeholders.
- Many of techniques commonly included under the label of “Participatory Rural Appraisal” which should be a genuine commitment to participation, with adequate time and resources.
- A range of specialists (ecologist, geomorphologist, sociologist, and resource economist) should work together to undertake field surveys to provide a comprehensive description of the affected river.
- The team develops data sets, models and various analytical tools that can be used in scenario creation to assist decision-making.
- Data collection at the early stage is to improve understanding of the physical, chemical, biological and socio-economic aspects of reservoir and flood plain, 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 flood plain wisely

(for instance, establishment of "Plenary Group" is reported in *Environmental Assessment for the Inclusion of Technical Criteria for Spring Pulse Releases from Gavins Point Dam* [11])

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

85

- 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.
- The present river use, exploitation of river related natural resources, and health of the affected people are quantified, and possible flow-related health risks identified.

5.2.3 Step 5: **Define managed flow options**

86

- 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 flood plain, but also the impact on water-reserves retained within reservoir for other process. (hydrological/hydraulic model of the flood plain, reservoir, main channel and catchment will be required in this assessment)
- The no-flood option should always be included in the analyses. Appropriate flows during the non-flood season must also be addressed.

(for instance, environmental flow assessment in Mekong river, expert panel from the four countries in the lower river basin will create scenarios and one scenario will be selected in the management actions. A detailed report is provided in *IUCN report, in the lower Mekong River Basin* [7])

5.2.4 Step 6: **Assess impacts of managed flow options**

87

- 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 for the flood plain-dependent livelihoods and for reservoir dependent livelihoods.
- Assessment must equally include the impacts on the reservoir and its dependent activities.

5.2.5 Step 7: **Select the best managed flow options**

88

- 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)

5.3 IMPLEMENTATION

89 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.

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

90

- 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 flood plain to protect infrastructure, e.g. houses, roads, factories, from flooding or to enhance/control inundation in selected areas.

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

91

- 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.

5.4 EVALUATION

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

92

- Adequate ecological, socio-economic monitoring must be designed and established to assess the effectiveness of managed flows in relation to the stated objectives.
- Since the time-scales 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 the releases is reported in *Environmental Assessment for the Inclusion of Technical Criteria for Spring Pulse Releases from Gavins Point Dam* [11], and adaptive management is reported in *Missouri River Mainstem Reservoir System Master Water Control Manual* (Appendix I) [12])

6. FRAMEWORK FOR ENVIRONMENT SENSITIVE RESERVOIR OPERATION

6.1 CLEAR POLICIES

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

6.2 LEGAL AND INSTITUTIONAL

94 Integrated flood management in itself and managed flows in particular require collaboration and coordination between various disciplines and agencies within and outside a country. There is 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 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 [13].

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

6.3 FINANCIAL MECHANISM

96 It is important to apply an environmental 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 [10].

97 Since a reallocation of water use rights in favour of managed flows is likely to result in loss of benefits that certain sections of the society, there is need for developing a financial mechanism for either sharing the cost of "opportunity lost" or compensate those who lose already driven benefits.

6.4 DATA AND INFORMATION BASE

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

99 There is 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 to ensure that monitoring systems are in place and feed into operational decision-making.

6.5 STAKEHOLDERS PARTICIPATION

100 Involvement of stakeholders in the entire process starting from developing the objectives and right up to 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 need for mechanisms that resolves conflicts between different sections. A detailed discussion on the subject could be found at *Social and Stakeholder Involvement in Integrated flood Management*, APFM Technical Document No.4, Flood Management Policy Series [9].

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Further reading

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- The rehabilitation of the delta of the Senegal River in Mauritania; Fielding the ecosystem approach (IUCN, 2003)

- Environmental Flows; Rapid Environmental Flow Assessment for the Huong River Basin, Central Vietnam (IUCN, 2004)

- Brochure; Water Resources and Environment Technical Note C.1, Environmental Flows: **Concepts and Methods** (World Bank, 2003)
  (Introduces concepts and methods for determining environmental flow requirements for rivers)

- Brochure; Water Resources and Environment Technical Note C.2, Environmental Flows: **Case Studies** (World Bank, 2003)
  (Reviews some important case histories)

- Brochure; Water Resources and Environment Technical Note C.3, Environmental Flows: **Flood Flows** (World Bank, 2003)
  (Describes the reinstatement of flood release from reservoirs for flood plain inundation)

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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 that 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 stream-bank 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 aging 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 (the 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 gets to 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.