ICOLD BULLETIN ON ENVIRONMENTAL HYDRAULICS

THE INTERACTION OF HYDRAULIC PROCESSES AND RESERVOIRS

MANAGEMENT OF THE IMPACTS THROUGH CONSTRUCTION AND OPERATION

DOWNSTREAM IMPACTS OF LARGE DAMS

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1 INTRODUCTION

1.1 BACKGROUND

Dams are planned, constructed and operated to meet human needs - generation of energy, irrigated agricultural production, flood control, public and industrial supply, supply of drinking water, and various other purposes. Dams impound water in reservoirs during times of high flood that can be used for human requirements during times with inadequate natural flows. Positive impacts of dams are improved flood control, improved welfare resulting from new access to irrigation and drinking water. Without dams there would be insufficient food to feed the world's people and energy would be generated by burning fossil fuels that produce greenhouse gases.

Despite this progress there remain significant concerns about the environmental impacts of dams. The control of floodwater by dams usually reduces flow during natural flood periods. Altering the pattern of downstream flow (i.e. intensity, timing and frequency) may lead downstream of the dam to a change of sediment and nutrients regime. Water temperature and chemistry is altered and consequently may lead to a discontinuity in the river system.

These environmental impacts are complex and far reaching, remote of the dam, and may occur in time with the dam construction or later and may lead to a loss of biodiversity and of productivity of natural resources.

Each dam has his own operation characteristic. Dams are built in a wide array of conditions, from highlands to lowlands, temperate to tropical regions, fast and slow flowing rivers, urban and rural areas, with and without water diversion. The impact of water diversion differ between northern countries where temperate climates and little irrigation occur, in contrast to semi-arid counties which may have extensive out-of-river uses and high evaporation rates. The combination of dam type, operating system, location, height and reservoir characteristic, yields a wide array of environmental conditions that are site specific and extremely variable. This complexity makes it difficult to generalise the impacts of dams on ecosystems, as each specific context is likely to have different types of impacts and to different degrees of intensity.

Table 1-1: Characteristics of Dams and Reservoirs

Name of dam/country	Height (m)	Reservoir capacity (10^6 m^3)	Reservoir area (km^2)
Akosombo / Ghana	111	148,000	8,482
Kariba / Zambia-Zimbabwe	123	180,000	5,400
Three Gorges/China	185	39,300	1,045
Itaipu / Brazil-Paraguay	196	33,475	1,550
Jinping I/ China	305	7,760	82

Dams for flood control moderate peak flow. Hydroelectric dams are designed to create a constant flow through turbines, and therefore tend to have similar effect on flow pattern. However, if the intention is to provide power at peak periods, variations in discharge of considerable magnitude can occur over short timescales, creating artificial freshets or floods downstream. Dams for irrigation cause moderate variations in flow regime on a longer timescale, storing water at seasons of high flow for use at times of low flow. Flows that exceed the storage capacity are usually spilled, allowing some floods to pass downstream, albeit in a routed and hence attenuated form. Dams are often designed to have multiple functions in which case their impacts will have a combination of the above forms. It should be noted that hydraulic structures such as barrages and weirs can have similar impacts to dams, as well as water diversion structures or inter-basin transfer projects.

This bulletin compiles improvements in knowledge and state of the art technology to avoid or mitigate environmental impacts of dams on the natural ecosystem as well as to the people that depend upon them for their livelihood and also addresses the mitigation of environmental impacts on dams and reservoirs.

1.2 UPSTREAM IMPACTS

1.2.1 Water Quality

Water stored in a deep reservoir has a tendency to become thermally stratified. Typically three thermal layers are formed: a well-mixed upper layer (the epilimnion), a cold dense bottom layer (the hypolimnion) and an intermediate layer of maximum temperature gradient (the thermocline). Water in the hypolimnion may be up to 10° C lower than in the epilimnion. In the epilimnion the temperature gradient may be up to 2° C for each meter.

Thermal stratification depends on a range of factors, including climatic characteristics. Reservoirs nearest to the equator are least likely to become stratified. At higher latitudes the governing factor is the input of solar energy. Shallow reservoirs respond rapidly to fluctuations in atmospheric conditions and are less likely to become stratified. Strong winds can effect rapid thermo-cline oscillations. The pattern of inflows, as well as the nature of outflows from the reservoir influences the development of thermal stratification.

Currents generated from large water level fluctuations in reservoirs caused by operating regimes can also sometimes prevent thermal stratification. Many deep reservoirs, particularly at mid and high latitudes become thermally stratified as do natural lakes under similar conditions. The release of cold water into the receiving downstream river can be a significant consequence of stratification.

Water storage in reservoirs induces physical, chemical and biological changes in the stored water and in the under lying soils and rocks, all of which affect water quality. The chemical composition of water within the reservoir can be significantly different from that of the inflows. The size of the dam, its location in the river system, its geographical location with respect to altitude and latitude, the storage detention time of the water and the source of the water all influence the way that storage detention modifies water quality.

Major biologically induced changes occur within thermally stratified reservoirs. In the surface layer, phytoplankton often proliferate and release oxygen thereby maintaining concentrations at near saturation levels for most of the year. In contrast, the lack of mixing and sunlight for photosynthesis in conjunction with oxygen used in decomposition of submerged biomass often (but not always) results in anoxic conditions in the bottom layer.

Nutrients, particularly phosphorous, are released biologically and leached from flooded vegetation and fertilized soil. Although oxygen demand and nutrient levels generally decrease over time as the mass of organic matter decreases, some reservoirs require a period of tens of years to develop stable water-quality regimes. After maturation, reservoirs, like natural lakes, can act as nutrient sinks particularly for nutrients associated with sediments. Eutrophication of reservoirs may occur as a consequence of organic loading and/or nutrients. In many cases these are consequences of anthropogenic influences in the catchment such as the application of fertilisers rather than the actual presence of the reservoir. However there are reservoirs, particularly in tropical climates that have the ability to recycle nutrients from the reservoir sediments through the water column, without any significant addition of new nutrients from the stream flow.

1.2.2 Sedimentation

Rivers transport particles from fine ones in turbid water to coarser ones such as sand, gravel and boulders. The speed and turbulence of currents enable transport of these materials. When river bed gradient or the river flow diminishes, particles tend to drop out. This happens when river flows reach reservoirs.

Large reservoirs store almost the entire sediment load supplied by the drainage basin. The sediment transport into the reservoir depends on the size of the reservoir’s catchment, on the characteristics of the catchment that affect the sediment yield (climate, geology, soils, topography, vegetation and human disturbance) and the ratio of reservoir size to mean annual inflow into the reservoir. Sediment transport shows considerable temporal variation, seasonally and annually. The amount of sediment transported into the reservoir is greatest during floods.

Measures to minimise erosion (sediment load) in the upper watershed include reasonable land use and agricultural practices and reforestation. Upstream trapping by check dams and vegetation screens can be used to hold back sediments. A sound integrated water resources management in a catchment should treat water as an integral part of the ecosystem, a natural resource and a social and economic good.

There are two ways to pass sediments through reservoirs. The sediment-laden flow is passed through reservoirs at a reduced water level during flood seasons. This method is called sluicing and is mainly applicable to fine sediments. Under special conditions density currents may develop and transport suspended sediment underneath a fluid layer of lower density towards the dam. This method is called density current venting. However for some reservoirs where sedimentation is in danger of filling the reservoir, it may be necessary to divert high flows with high sediment concentrations through bypass channels or tunnels.

Mitigation for the accumulation of sediments can be achieved in several ways. The accumulation can be reduced by periodic dredging. This method usually requires low water levels for extended periods of time. Dredging is costly and the disposal of large quantities of sediment often creates problems. In other cases the sediments can be removed through periodic flushing of the reservoir by releasing large volume of water through the low level outlet structures. This method has the advantage of renewing the sediment load to the downstream channel and also flushing the downstream channel with a high flood event.

For many dams, sediment accumulation remains a major concern. Due to the configuration and bathymetry of most reservoirs, sediments frequently accumulate at the head of the reservoir, a long way from the dam wall and the bottom outlet.

1.3 DOWNSTREAM

1.3.1 Flow Regime

The hydrological characteristics of a river, in particular the frequency of floods as well as the magnitude and timing of flood peaks, will change when a reservoir is constructed. The effect of a reservoir on individual flood flows depends on both the storage capacity of the dam relative to the volume of flow and the way the dam is operated. Reservoirs having a large flood-storage capacity in relation to total annual runoff can exert almost complete control upon the annual hydrograph of the river downstream. Even small-capacity detention basins can achieve a high degree of flow regulation through a combination of flood forecasting and management regime.

The hydrological effects of the dam become less significant the greater the distance downstream, i.e. as the proportion of the uncontrolled catchment increases. The frequency of the tributary confluence below the dam and the relative magnitude of the tributary streams, play an important part in determining the length of the river affected by an impoundment. Catchment with significant storage may never recover their natural hydrological characteristics even at the river mouth, especially when dams divert water for agriculture or municipal water supply.

Flow regimes are the key driving variable for downstream aquatic ecosystems. Flood timing, duration and frequency are all critical for the survival of communities of plants and animals living downstream. Small flood events may act as biological trigger for fish and invertebrate migration; major events create and maintain habitats. The natural variability of most river systems sustains complex biological communities that may be different from those adapted to the stable flows and conditions of a regulated river.

A sufficient, continuous, minimum water supply to the downstream reaches of a dam is one main prerequisite to reduce the impact on the ecosystem. The water should be released in a way to mimic the natural hydrological regime in the river. This may be achieved by modifying the operation of a reservoir. These minimum flows are called instream flows or environmental flows. The environmental flow should enable the downstream river ecosystems to retain their natural diversity and productivity. The amount, timing and conditions under which water should be released have to be carefully determined.

1.3.2 Bottom Outlets

Bottom outlets are normally provided at most dams to release water for a variety of purposes. Flow may be passed through bottom outlets to empty reservoirs, to impound or drawdown reservoirs in a controlled way, to satisfy in-stream flow requirements, for sluicing or flushing sediments or for preventing sediments entering intakes. Bottom outlets designed for evacuating sediment have to be placed at low levels in the dam. Suspended load discharges at high concentration as well as coarse particles may pass through outlets at high velocities. Tunnels and gates have to be protected against abrasion, using abrasion resistant materials for protection. Sluicing or flushing requires bottom outlets with large discharge capacities, often several times the mean flow rate of the river.

However by releasing water from low in the reservoir, this can result in undesirable temperature and water quality pollution in the downstream flow regime. These aspects are further examined in Chapter 2.

1.3.3 Degradation and aggradation in downstream river reaches

Changes in the flow and sediment regime initially cause degradation of the river bed downstream from the dam, as the entrained sediment is no longer replaced by material arriving from upstream. Depending on the relative erodibility of the streambed and banks, the degradation may be accompanied either by narrowing or widening of the channel. A result of degradation is a coarsening in the texture of material left in the streambed, in many cases a change from sand to gravel is observed, or scour may proceed to bedrock. On most rivers these effects are constrained to the first few kilometres below the dam.

Further downstream, increased sedimentation (aggradation) may occur because material mobilised below a dam and material entrained from tributaries cannot be moved quickly enough through the channel system by regulated flows. Channel widening is a frequent concomitant of aggradation.

The accumulation of sediments in the river channel downstream from the dam due to the altered flow regime may be mitigated through periodic flushing of the river channel with artificial flow events. Flushing requires outlet structures like sluice gates of sufficient capacity to permit generation of managed floods. These should normally be timed such that the releases can be made when the reservoir storage exceeds 50 % of its capacity.

Damming a river can alter the character of floodplains. In some circumstances the depletion of fine suspended solids reduces the rate of overbank accretion so that new floodplain takes longer to form and soils remain infertile or channel bank erosion results in loss of floodplains.

In the Nile Valley following the closure of the Aswan High Dam in 1969, the lack of sediment in floodwater reduced soil fertility in the Nile Valley downstream of the dam. The reduction in sediment flows has led to the erosion of the shoreline of the delta and saline penetration of coastal aquifers.

Erosion was particularly pronounced at alluvial sites with non-cohesive sandy bank materials and has been attributed to the release of silt free water, the maintenance of unnatural flow levels, sudden flow fluctuations and out-of-season flooding. However, in some cases the reduction in the frequency of flood flows and the provision of stable low flows may encourage vegetation encroachment, which will tend to stabilise new deposits, trap further sediments and reduce floodplain erosion. Hence, depending on specific conditions, dams can either increase or decrease floodplain deposition/erosion.

Managed flood releases can be a strategy to mitigate the detrimental impact downstream of dams. An objective of these managed flood releases is the conservation or restoration of floodplain ecosystems.

1.3.4 Degradation in Coastal Areas

In contrast to the impact on river and floodplain morphology, where aggradation may occur, impounding rivers invariably results in increased degradation of coastal deltas, as a consequence of the reduction in sediment input. For example the construction of the High Aswan Dam has reduced the amount of sediment reaching the delta. As a result much of the delta coastline is eroding at rates up to 5 – 8 meters per year. The consequences of reduced sediment flow may cause long stretches of coastline to be eroded by waves, which are no longer sustained by sediment inputs from rivers.

1.3.5 Water Temperature

Water temperature is an important quality parameter for the assessment of reservoir impacts on downstream aquatic habitats because it influences many important physical, chemical and biological processes. In particular, temperature drives primary productivity. Thermal changes caused by water storage have the most significant effect on instream biota. The level in the reservoir from which the discharge is drawn, e.g. cool deep temperatures or warm surface temperatures may affect temperatures downstream of the dam, which in turn may affect spawning, growth rate and length of the growing season. Cold-water releases from high dams of the Colorado River are still measurable 400 km downstream and this has resulted in a decline in native fish abundance. Even without stratification of the storage, water release from dams may be thermally out of phase with the natural temperature regime of the river.

The quality of water release from stratified reservoirs is determined by the elevation of the outflow structure relative to the different layers within the reservoir. Water release from near the surface of a stratified reservoir will be well-oxygenated, warm and nutrient depleted water. In contrast water released from near the bottom of a stratified reservoir will be cold, oxygen-depleted, nutrient-rich water, which may be high in hydrogen sulphide, iron, and/or manganese. Water depleted in dissolved oxygen is not only a pollution problem in itself, affecting many aquatic organisms (e.g. salmonid fish require high levels of oxygen for their survival). Such water has a reduced assimilation capacity and so a reduced flushing capacity for domestic and industrial effluents. The problem of low dissolved oxygen levels is sometimes mitigated by the turbulences generated when water passes through turbines.

Water passing over steep spillways may become supersaturated in nitrogen and oxygen and this may be fatal to the fish immediately below a dam, particularly those with a swim bladder.

Measures to mitigate the potential effects of nutrient accumulation in an impoundment have focused on reducing the inflow of nutrients to the reservoir and increasing the removal of nutrients from the water. Reduction of inflow of nutrients has been accomplished through the construction of wastewater treatment facilities at communities along the margins of the impoundment as well as in the watershed upstream. Other methods include training of local farmers in the use of fertilizers or seasonal flushing of the reservoir. The effectiveness of this process however is dependent upon the volume of the reservoir relative to the inflow.

1.3.6 Fish Migration

The changes in the aquatic fauna regime can be quite far ranging. One of the most significant indicators of these changes can be the impact on the migratory patterns and relative abundance of fish species. The effects of changed temperature regimes on fish abundance have been referred to in the previous paragraphs.

Fish species have several migratory patterns. Well known are the anadromous fishes like salmon or steelhead trout and catadromous fishes like eels. Adult salmon migrate up the rivers to spawn and the young descend to the ocean where they spend much of their adult life, while the reverse occurs with the catadromous fishes. Preservation of the fisheries resource is extremely important in planning a dam project on these rivers. The blockage of fish movement can be one of the most significant negative impact of dams on fish biodiversity.

The river continuum includes the natural change in river flow, water quality and species that occur along the river length from the source to the coastal zone. A dam breaks this continuum and can stop the movement of species unless appropriate measures are taken. Effective measures to mitigate the blockage to upstream migration of fish include the installation of fish passage facilities to facilitate movement of fish from below the dam to the reservoir and further upstream. The design of fish passage facilities includes fish ladders, fish elevators, trap and haul techniques.

A discussion of these issues is not covered in this Bulletin, the reader should refer to other ICOLD publications such as Bulletin 116, for further information.

2 RESERVOIR WATER QUALITY

2.1 INTRODUCTION

From the beginning of the 20th century, technological progress as well as energy and water demand motivated an increase in the number of dams constructed all over the world in response to enormously increase of water needs and flood control. Although lakes and reservoirs contribute to only 0.35% of the whole volume of fresh water in our planet (Baumgartner and Reichel, 1975), as a response to this enormously increased demand more than half of ICOLD's registered 45 000 large dams have been built in the period of 1962-1997 (ICOLD, 1998). The storage capacity of the total registered large dams is about 6 000 km^3.

The construction of dams, although initially motivated for power generation, creates reservoirs with multipurpose uses and functions which include the availability of water to urban water supply and agriculture, to mitigate devastating floods, navigation, and the support of leisure activities. The new habitats these water bodies create and their scenic value, attract activities that produce waste.

All dams and reservoirs become a part of the environment, which they influence and transform to a degree and within a range that varies from project to project. Frequently seeming to be in opposition, dams and their environment interrelate with a degree of complexity that makes the task of the dam engineer particularly difficult (ICOLD, 1997).

Reservoirs can become the receiving body for urban, agricultural and industrial wastewater. These wastes and the evolution of the water quality in the reservoir, due to the fact that the prevailing processes and characteristics change when water is stored and not flowing, cause changes on the water quality discharged downstream.

In the sixties, along with increased recognition of water quality problems, a large number of relevant technical publications, started to be produced (PETTS 1984). Nevertheless, in contrast with flowing waters, lakes and impoundments were not a priority subject in the early years of water quality modelling. This is because, with notable exceptions such as the Great Lakes of North America, they have not been historically a major focus of urban development.

Research activities on the water quality of reservoirs followed not only the great development of dam construction but also aimed at answering the challenges of sustainable use and the preservation of the newly created ecosystems. The often conflicting uses of reservoirs requires the introduction of management systems and these created the need to have management tools that have the ability to model water quality.

The "Guidance" for the implementation of the European Union Water Framework Directive (WFD) (Directive *establishing a framework for Community action in the field of water policy,* 2000/60/EC of 23 October 2000) advises the classification of reservoirs as "Strongly Modified Water Bodies" on which a "*Good Ecological Potential*" has to be maintained or achieved. The environmental quality objectives for the characteristics of such water bodies will be as similar as possible with the ones that would prevail in similar "natural" water bodies (in terms of, *e. g*. morphology, location) in pristine conditions.

This report presents an overview of the pressures and processes that affect reservoir water quality. A general description of the basic characteristics that have a direct connection with the water quality of such water bodies is also presented, as well as a description of the behaviour of the chemical entities that characterize water quality. Particular attention is paid to the eutrophication phenomenon. A review of the general issues related to water quality modelling of reservoirs, modelling methodology and types of models most commonly used is also presented. Finally, a summary of the process of identification of heavily modified water bodies in the context of EU-WFD is also presented.

2.2 GENERAL CHARACTERISTICS OF RESERVOIRS

2.2.1 Morphology and Hydrodynamics

Water quality characteristics as well as ecological features of reservoirs are strongly interconnected and are a function of their morphology and hydrodynamics as well as of the energy fluxes driven by the climatic factors. They are also a function of the morphology and of the hydrology of the region.

The phenomena that occur in a reservoir are complex and their interpretation and their analysis is a difficult task that must take into consideration the context provided by the morphology and physical processes. An overview of those factors influencing the quality of water in reservoirs is presented below.

As most reservoirs are created by damming a river, they generally tend to be elongated or dendritic. For water quality purposes, the most important morphological features are connected to the ratio of area/volume, that is, with the average depth (H) of the reservoir. This parameter will contribute to the tendency for stable stratification and will determine the relative importance of interface processes such as re-aeration and benthonic nutrient recycling. Some authors (*e. g*. Chappra, 1996) propose the classification of shallow reservoirs (or lakes) those with H<7m and deep water bodies those with H>7 m.

The hydrodynamic regime of a reservoir is one of the most important factors to control its behaviour and water quality. Average retention time, defined as the ratio of mean annual inflow to the net reservoir volume, is a relevant characteristic that allows water quality characteristics to be anticipated. A "run-of-the-river" type of reservoir will have a relatively small retention time, in the order of days or weeks, while a "large" reservoir, with capacity for flow regulation, will have a long residence time with values of the order of years or even decades.

Also relevant in the control of water quality characteristics and behaviour are the physical processes that occur, taking into account the characteristics of the various inflows and withdrawals, as well as the circulation induced by the wind, this with particular relevance in shallow water bodies. Figure 2-1 presents a diagram of the main physical processes present in a reservoir.

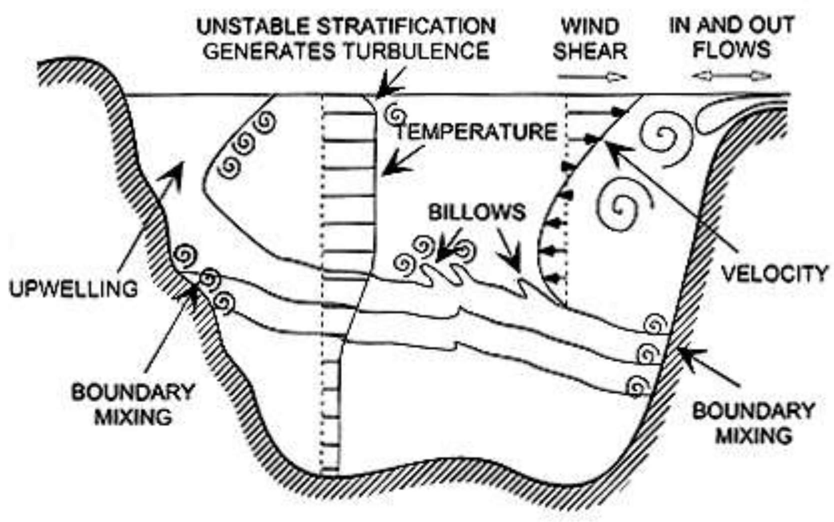

Figure 2-1: Physical processes in reservoirs (Adapted from UNDP- IETC)

2.2.2 Thermal stratification

The thermal energy exchange at the water surface is a relevant factor in the control of water quality in a reservoir, especially if the water column is deep. Other important climatic factors are the wind and the precipitation regime in the catchment, which determines the regime of the runoff to the reservoir and its hydrodynamics (ORLOB, 1983).

Stratification is of major importance for water quality of reservoirs throughout the year. Most reservoirs are well mixed during winter. As spring progresses and the temperature rises, thermal stratification will be established in the near surface of water and progress until mixing is confined to the upper layer. The attainment of persistent stratification leads to the establishment of 3 circulation regimes – the upper (epilimnion) and the lower (hypolimnion), separated by a narrow region of sharp temperature change - the thermocline or metalimnion (Figure 2-2). In late summer and fall the unstable situation returns and strong vertical convection mixing occurs, with a progressive deepening of the thermocline creating the event called the ***autumn/fall turnover***. However in some tropical areas, where there is less temperature variation, these processes may not be as dominant.

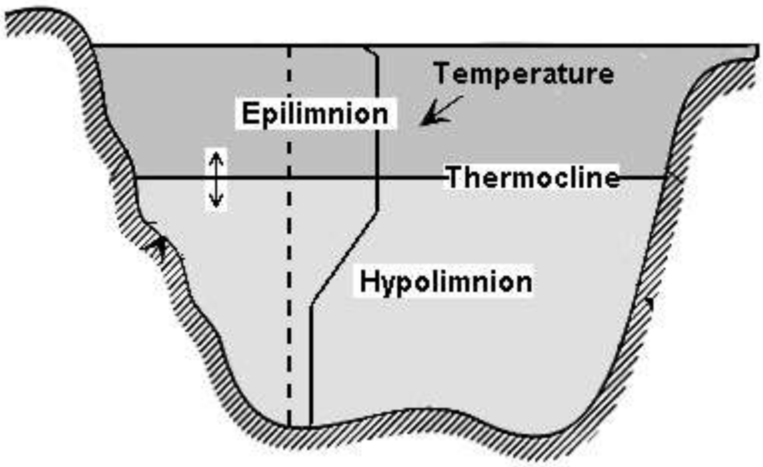

Figure 2-2: Vertical structure of the water column in a stratified reservoir

2.3 POLLUTANTS AND STRESSORS ON RESERVOIRS

As with any other type of water body, water quality of reservoirs is greatly affected by the different pressures that are exerted on it. Pressures are derived from its uses and the most relevant in the present context are polluting loads.

A study presented by the US-EPA (http://www.epa.gov/owow/lakes/quality.html) identified the pollutants and stressors that cause water quality degradation in US lakes and reservoirs. The most common cause of water quality deterioration is associated with excessive nutrient (nitrogen and phosphorous) input, followed by metals. Third in the ranking of pressures is solids input causing siltation. Also important as a cause for water quality degradation is the input of carbonaceous organic matter, in general from sewage, with a high oxygen demand.

The same study identified agriculture as the leading source of pressures; also important are the inputs from urban run-off and storm sewers. General non-point sources and municipal point sources have an equivalent contribution in relative terms. The data base used in the study referred to pertains not only to reservoirs but also includes natural lakes and other impoundments, which suggests that the relative importance of agricultural sources may still be more relevant when only reservoirs are considered as fewer urban settlements are established on their direct drainage basin.

The same study also proposes a qualitative classification of reservoirs using as criteria their capability to support traditional or desired uses, as follows:

- **Good** – Fully supporting all of their uses or fully supporting all uses but threatened for one or more uses
- **Impaired** – Partially or not supporting one or more uses

- **Not attainable** – Not able to support one or more uses.

In the context of the previously mentioned EU - Water Framework Directive, five quality classes must be defined, as explained in the paragraph dedicated to the issues associated with this Directive.

Figure 2-3 contains a representation of the conditions observed in a reservoir impacted with different polluting sources and one with healthy ecosystems. The figure addresses the issue of nutrient enrichment and the effects of inputs of metals that accumulate in sediments and, later, contaminate biota. In some circumstances the aquatic fauna will accumulate xenobiotics in such quantities that their life cycles and their edibility are impaired.

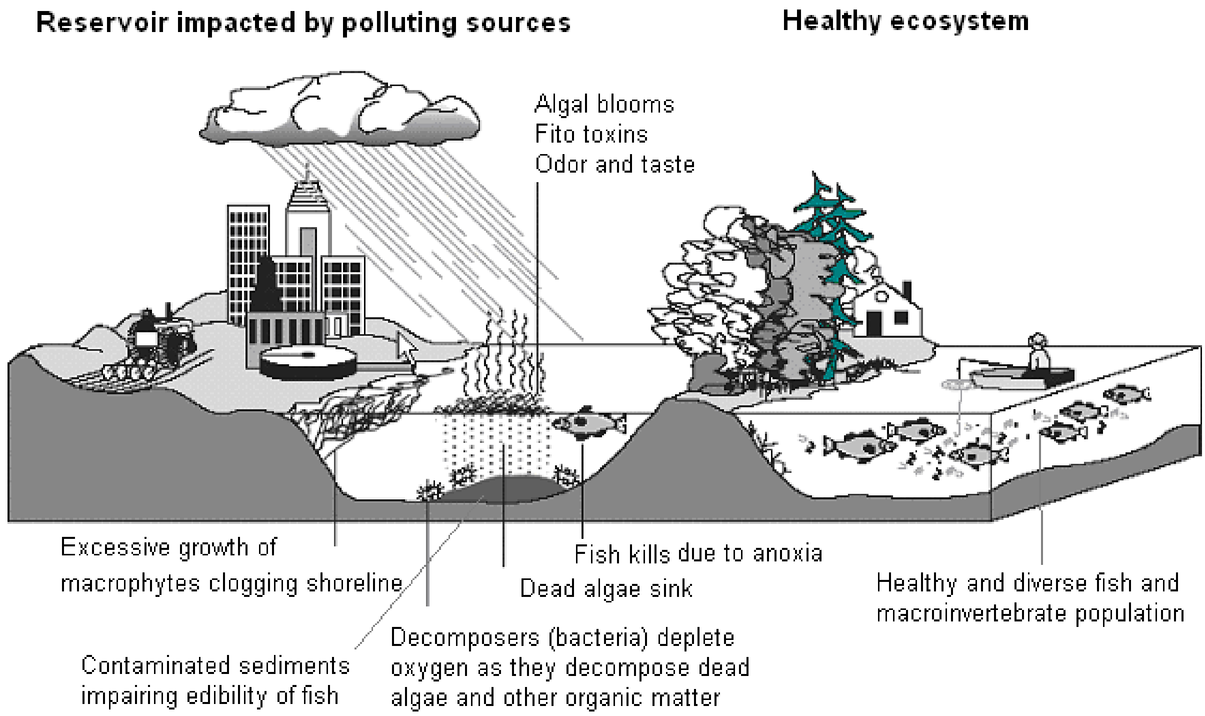

Figure 2-3: Comparison between a healthy ecosystem and one impacted by polluting loads (adapted from http://www.epa.gov/owow/lakes/quality.html)

The eutrophication process, its effects and symptoms, as well as assessment criteria are addressed in detail in the following paragraphs.

When reservoirs are used as potable water sources, the contamination by faecal pathogens is a major issue and is becoming more relevant as urban settlements, in many cases associated with the growing interest of reservoirs as tourist centres and places for water sports, become more common around reservoirs. Urban settlement on the one hand requires high quality water quality and at the same time has the potential to significant degradation of the value of the resource, representing a paradigmatic situation for the need to implement clear user rules and codes of practice framed required to harmonize uses and to preserve the health of the ecosystems.

The contamination by xenobiotics, metals and micro-organic pollutants, although not referred as a very widespread problem, may be of local relevance. As an example of a situation where that type of pollution may be relevant are the reservoirs that have mining zones in their catchment, either in exploitation or abandoned.

2.4 WATER QUALITY PROCESSES - EUTROPHICATION AND OXYGENATION

2.4.1 Introduction

The physical, chemical and biological behaviour of stored surface waters has been the subject of research in the domain of limnology. Stored water may improve water quality but in some cases this water may be more susceptible to deterioration. These aspects have to be taken into account during the design phase of dams and later, when management plans for the reservoir and its catchment are in place.

As nutrient inputs are the most frequent and serious pressures on reservoirs, the resulting eutrophication and the related influence on oxygenation status are the most important water quality processes to take into consideration. They will be treated in some detail in the following paragraphs.

2.4.2 General Concepts

Eutrophication can be defined as the process of enrichment of water with organic matter, caused by an increase of nutrients for plants (as nitrogen and phosphorous), that stimulate primary production (Nixon 1995; Wollenweider *et al*., 1996; Dodds *et al*., 1998).

Lakes and reservoirs can be broadly classed as *ultra-oligotrophic*, *oligotrophic*, *mesotrophic*, *eutrophic* or *hypereutrophic* depending on concentration of nutrients in the body of water and/or based on ecological symptoms of the nutrient loading although strict boundaries for these classes are often difficult to define.

There are commonly three main criteria for the degree of eutrophication:

- total phosphorus concentration;
- mean chlorophyll concentration and
- mean Secchi disk visibility.

In general terms, *oligotrophic* lakes and reservoirs are characterized by low nutrient inputs and primary productivity, high transparency and a diverse biota. In contrast, *eutrophic* waters have high nutrient inputs and primary productivity, low transparency, and high biomass of fewer species with a greater proportion of cyanobacteria.

Although the fundamental characteristics of eutrophication are similar in all water bodies, differences in basin shapes and flow patterns may lead to longitudinal variations in the degree of eutrophication in reservoirs (Figure 2-4). In addition, water supply and power generation requirements often lead to large variations in water level in reservoirs. These changes in level usually expose or inundate littoral regions which may enhance nutrient supply.

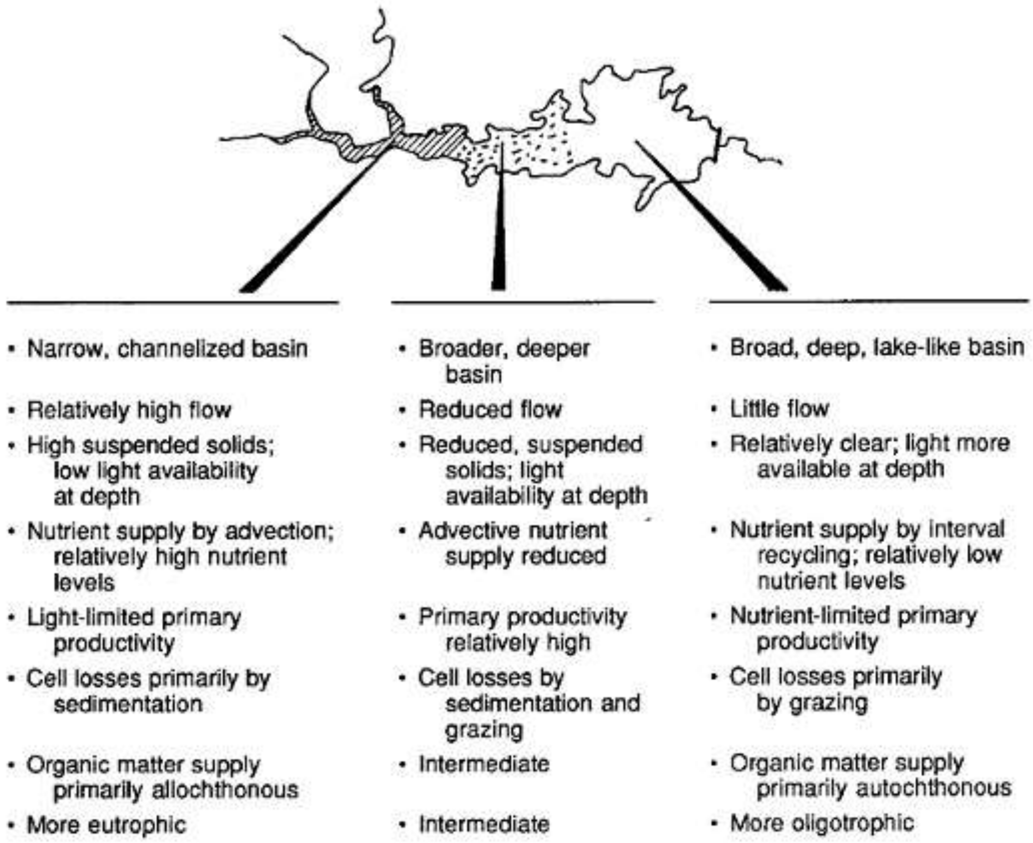

Figure 2-4: Longitudinal zones of environmental factors controlling trophic status in reservoirs (from Ryding and Rast, 1989)

2.4.3 Eutrophication Symptoms and Effects

The process of eutrophication in all water bodies causes a series of effects that are visible by symptoms that often impair some or most of the uses of the water. A brief description of those eutrophication consequences is presented below.

Harmful algal blooms

A common result of eutrophication is the increased growth of algae. *Cyanobacteria* are an especially harmful group, causing the formation of surface scum, severe oxygen depletion and fish mortalities. The ingestion of freshwater toxins (neurotoxins, hepatotoxins, cytotoxins and endotoxins), which are produced almost exclusively by cyanobacteria, may lead to death of cattle and other animals from ingestion of algal toxins. Gastrointestinal disorders in humans can also be associated with the drinking of water that contained blooms of cyanobacteria.

Cyanobacteria and filamentous species of chlorophytes (green algae) can cause odours and clogging of filters in water treatment or industrial facilities. *Dinoflagellates,* the so-called red tides, are another group of concern that is known to develop, which can include toxic strains. One by-product of dense algal blooms is high concentrations of dissolved organic carbon (DOC). When water with high DOC is disinfected by chlorination, potentially carcinogenic and mutagenic trihalomethanes are formed.

2.4.4 Growth of Aquatic Plants

Dense mats of floating aquatic plants, such as water hyacinth (*Eichhornia crassipes*), can cover large areas near-shore and can float into open water. These mats block light from reaching submerged vascular plants and phytoplankton, and often produce large quantities of organic detritus that can lead to anoxia and emission of gases, such as methane and hydrogen sulphide. Accumulations of aquatic macrophytes can restrict access for fishing or recreational uses of lakes and reservoirs and can block irrigation and navigation channels and intakes of hydroelectric power plants.

2.4.5 Anoxia

Another symptom of eutrophication is the depletion of oxygen concentration in the water column. Anoxic conditions are not compatible with the survival of fishes and invertebrates. Moreover, under these conditions, ammonia, iron, manganese and hydrogen sulphide concentrations can rise to levels deleterious to the biota and to hydroelectric power facilities. The anoxic conditions also increase the rate of re-dissolution of phosphate and ammonium what increases the nutrient availability in the water column, creating a positive feed back loop in the eutrophication process.

2.4.6 Species Changes

Shifts in the abundance and species composition of aquatic organisms often occur in association with the alterations of ecosystems caused by eutrophication. Reduction in underwater light levels because of dense algal blooms or floating macrophytes can reduce or eliminate submerged macrophytes. Changes in food quality associated with shifts in algal or aquatic macrophyte composition, and decreases in oxygen concentration often alter the species composition of fishes. For example, less desirable species, such as carp, may become dominant. However, in some situations, such changes may be deemed beneficial.

2.4.7 Hypereutrophy

Hypereutrophic water bodies are in the upper end of eutrophication process. A water body becomes hypertrophic when reductions in nutrient loading are not feasible or will have no effect at reversing the trophic enrichment. Hypereutrophic systems usually receive uncontrollable diffuse and non-point sources of nutrients, originating from overfertilized or naturally rich soils.

Nevertheless, these systems may constitute a valuable and integral part of the landscape, providing sanctuaries for birds and an important aquatic habitat and, if properly managed, can provide valuable and highly productive fisheries.

2.4.8 Enhanced Internal Recycling of Nutrients

When the eutrophication process is well established, internal loading of nutrients from benthonic re-solubilisation may became the dominant source, in addition to external loading of nutrients from both point and diffuse sources. This process is of particular relevance when average depth is small and near-bottom anoxic and nutrient-rich layers of water mix frequently with surface layers. Once a eutrophic or hypereutrophic state is reached, the dependence on external sources of nutrients is diminished and the water body will function as a system with positive feed back, the sediments providing an adequate supply of nutrients, even when the external sources are reduced.

2.4.9 Elevated Nitrate Concentrations

High concentrations of nitrate resulting from nitrate-rich runoff or nitrification of ammonium within a lake can cause public health problems. Methyl-haemoglobinaemia occurrence in infants results from nitrate levels above 10 mg/l in drinking water. By interfering with the oxygen carrying capacity of blood, the high nitrate levels can lead to a life-threatening deficiency of oxygen.

2.4.10 Increased Incidence of Water-related Diseases

In some situations, where a portion of the population producing sewage suffers from infections transmitted directly or indirectly via water, the spread of human diseases can be a very significant impact of sewage entering a water body. While such situations are especially prevalent in tropical countries, avoiding the spread of disease via water is a concern for all countries.

2.4.11 Increased Fish Yields

In some circumstances, the eutrophication process, up to a certain point, can have a positive impact on fisheries as yields of fish tend to increase as primary productivity increases. Greater increases in fish yields occur for smaller increments in primary productivity in oligotrophic or mesotrophic waters than in eutrophic systems. However, when the undesirable effects of eutrophication are present, namely oxygen depletion or significantly altered (as in alkaline or reduced as in acid) pH and elevated ammonia levels, the increases in fish yields as primary production rises will be reduced. In this situation the edible and marketable condition of the fish catch may also be threatened.

2.4.12 Nutrient Recycling

Aquaculture of fishes can be an effective way to obtain a positive benefit from nutrients that cause eutrophication. The fish in an aquaculture system can take up a large portion of the nutrients and transform them in a harvestable, marketable form.

Phytoplankton and floating aquatic macrophytes can be very effective at nutrient uptake and are capable of reducing dissolved inorganic nutrient concentrations to very low levels. Hence, if the plants are subsequently removed from the water, they may function as tertiary municipal wastewater treatment or as sources of organic matter for other uses (e.g. biogas generation or agro-fertilizers).

2.4.13 Assessment of Trophic Status

There is not an established methodology to determine what the trophic state of a water body is. As previously referred, there are commonly three main criteria for the degree of eutrophication:

- total phosphorus concentration,
- mean chlorophyll concentration,
- mean Secchi disk visibility.

Many simple empirical models have been developed to predict the concentration of total phosphorus in a lake as a function of annual phosphours loading. Extensions of such models offer predictions of chlorophyll concentration, Secchi disk visibility, pH or dissolved oxygen levels. The values predicted by these models can have uncertainties from as low as ±30% to as high as ±300%, and usually require modifications for different regions.

The most known and widely applied model is the Vollenweider method (Vollenweider, 1975; Vollenweider 1976; OECD, 1982; Vollenweider *et al*., 1996). This method relates the reservoir (or lake) trophic condition with nutrient loading, on the basis of the relationships presented in Figure 2-5. Originally, the abscissa was H, the average depth of the lake, but later it was recognized that flushing rate of the lake also played a relevant role in the tendency for eutrophication, and the "Vollenweider plot" was transformed with the consideration of the flushing time (τ_w), to q_s, the hydraulic overflow rate (m yr^{-1}).

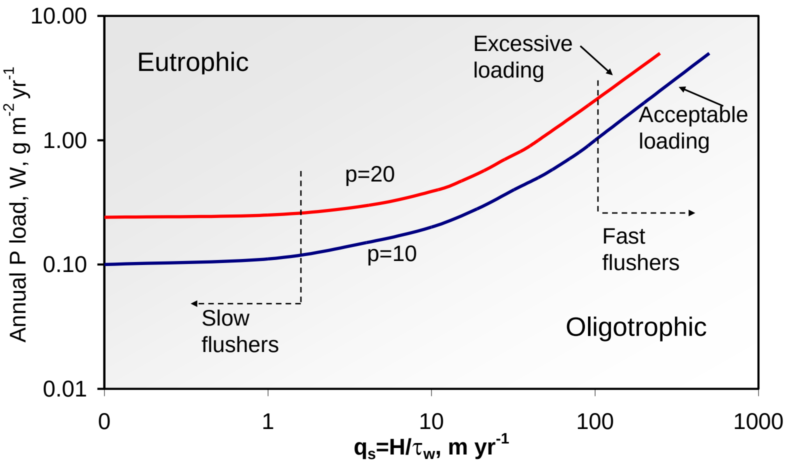

Figure 2-5 : Nutrient loading and trophic condition (redraw from Chapra, 1997; Thoman & Mueller, 1987)

Refinements and adaptations of Vollenweider's approach have improved correlation and added or substituted nitrogen loading for some regions. Further research is required to incorporate responses of aquatic macrophytes into these models.

The trophic state is also dependent on knowing which of the macro nutrients is the limiting factor of primary productivity and this is a function of:

- The ratio of nitrogen to phosphorus in the inputs and in the vertical fluxes of dissolved nutrients in the water column.
- Preferential losses from the euphotic zone by processes, such as denitrification, adsorption of phosphorus to particles and differential settling of particles with different nitrogen to phosphorus ratios.
- The relative magnitude of external supply to internal recycling and redistribution.
- The contribution from nitrogen fixation.

Unfortunately these processes have only been measured in a coordinated manner in very few lakes. Instead, inferences from several indicators of nutrient limitation must be made. The nitrogen to phosphorus ratio in suspended particulate matter is a potentially valuable index of the nutritional status of the phytoplankton, if contamination from terrestrial detritus can be discounted. Healthy algae contain approximately 16 atoms of nitrogen for every atom of phosphorus. Ratios of nitrogen to phosphorus less than 10 often indicate nitrogen deficiency and ratios greater than 20 can indicate phosphorus deficiency. When phosphorous is the limiting nutrient, criteria for the classification of reservoirs is presented in Table 2-1 (Chapra, 1997)

Table 2-1 : Trophic state classification

Variable	Oligotrophic	Mesotrophic	Eutrophic
Total phosphorous (ug l^{-1})	<10	10-20	>20
Chlorophyll *a* (ug l^{-1})	<4	4-10	>10
Secchi disk depth (m)	>4	2-4	<2
Hypolimnium oxygen (%sat.)	>80	10-80	>10

2.5 WATER QUALITY PARAMETERS

2.5.1 Behaviour in Reservoirs

The ecological and water quality relationships in a reservoir are complex. The succession of trophic state within an aquatic system is characterized by quality parameters that include dissolved oxygen, nutrients, suspended solids, detritus and sediments. The transformations of mass and energy are associated with the processes of primary production, growing, respiration, mortality, predation and decomposition, which in turn are governed by environmental parameters such as temperature, light availability and nutrients. In the following paragraphs an overview of the processes that govern oxygen and nutrient dynamics in lotic water bodies is presented.

2.5.2 Oxygen

Among water quality parameters, oxygen is of key importance not only because its concentration, presence or absence, dictates the type of living organisms present, as in its absence only anaerobic microbial activity is possible, but also because it rules some of the chemical processes such as the oxidation of organic matter.

The oxygen cycle in a reservoir is a complex phenomenon with important differences in its distribution, as a function of diurnal and seasonal cycles and of the trophic state of the system.

Horizontal variation in oxygen content can be great in reservoirs where the photosynthetic production of oxygen by littoral vegetation exceeds that of open water algae, that is, when benthic and infra-littoral processes associated with algae and riparian vegetation dominate the photosynthetic pelagic production. A schematic division of the reservoir is presented in Figure 2-6. The profile of dissolved oxygen concentration at surface will vary strongly with the horizontal morphology of the reservoir as well as with its bathymetry.

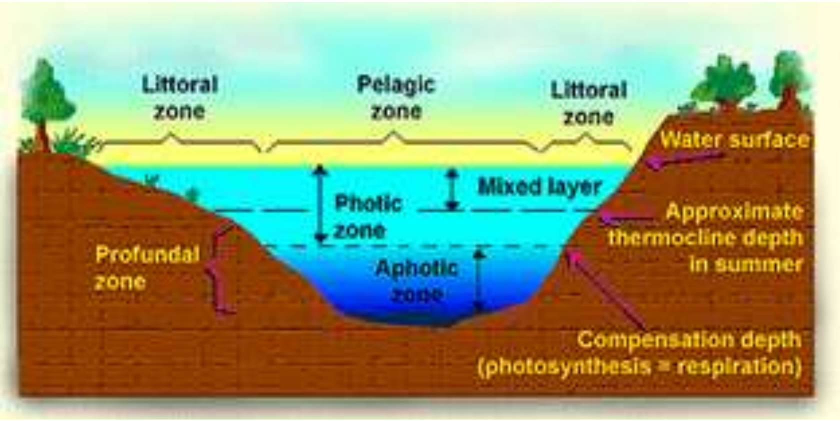

Figure 2-6: Horizontal Variation of dissolved oxygen concentrations

Extensive and rapid decay of littoral plants or phytoplankton can result in large reductions in the oxygen content in particular in small, shallow reservoirs leading to the death of large numbers of aquatic animals often known as summerkill.

Vertical distribution of DO concentrations in the water column has a series of typical patterns. As diffusion of oxygen from the atmosphere into and within water is a relatively slow process, turbulent mixing of water is required for dissolved oxygen to be distributed in equilibrium with that of the atmosphere. Subsequent distribution of oxygen in the water of thermally stratified water bodies is controlled by a number of solubility conditions, hydrodynamics, photosynthetic activity and sinks due to chemical and biochemical oxidation reactions.

In summer, in stratified oligotrophic reservoirs the oxygen content of the epilimnion decreases as the water temperature increases due to the decreased of solubility and often to the more quiet wind conditions that also decrease the rate of re-aeration in the water-atmosphere interface. The oxygen content of the hypolimnion is higher than that of the epilimnion because the saturated colder water from spring turnover experiences limited oxygen consumption. This oxygen distribution is known as an *orthograde oxygen profile* (Figure 2-7)

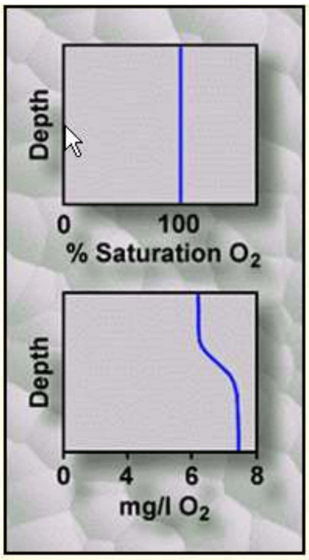

Figure 2-7: Orthograde Oxygen Profile

In eutrophic reservoirs, the loading of organic matter and of sediments to the hypolimnion increases the consumption of dissolved oxygen. As a result, the oxygen content of the hypolimnion of thermally stratified lakes is reduced progressively during the summer stratification period - usually most rapidly at the deepest portion of the basin where a lower volume of water is exposed to the intensive oxygen consuming processes of decomposition at the sediment-water interface. This oxygen distribution is known as a clinograde oxygen profile (Figure 2-8).

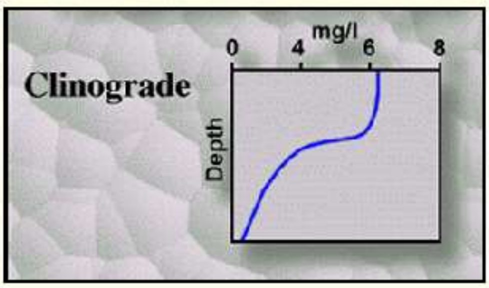

Figure 2-8: Clinograde Oxygen Profile

Oxygen saturation, at existing water temperatures, returns throughout the water column during *fall overturn*. The oxygen concentrations at lower depths in productive water bodies are reduced, but not to the extent observed in the summer because of colder water temperatures throughout the water column, resulting in greater oxygen solubility and reduced respiration by aquatic organisms. In the spring, the water is mixed and oxygen becomes saturated throughout the water column.

The metalimnetic oxygen maximum distribution occurs when the oxygen content in the metalimnion is supersaturated in relation to levels in the epilimnion and hypolimnion. The resulting positive heterograde oxygen curve is usually caused by extensive photosynthetic activity by algae in the metalimnion.

Epilimnetic oxygen concentrations vary on a daily basis in productive lakes. Rapid fluctuations between super-saturation and under-saturation of oxygen can result when daily photosynthetic contributions and night respiratory oxygen consumption exceed turbulent exchange with the atmosphere.

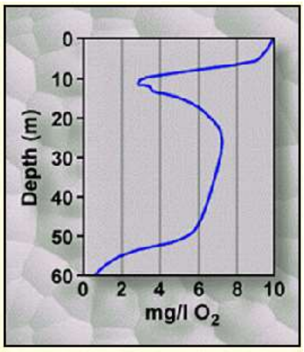

Figure 2-9: Metalimnetic Oxygen Maximum

2.6 NUTRIENT DYNAMICS

2.6.1 Nitrogen

Figure 2-10 presents the nitrogen cycling that occurs in a reservoir. The dissolved inorganic forms present in the water column are ammonia (NH_4), nitrite (NO_2) and nitrate (NO_3), all derived from organic nitrogen compounds by a series of chemical reactions presented, in a simplified form, in Figure 2-11.

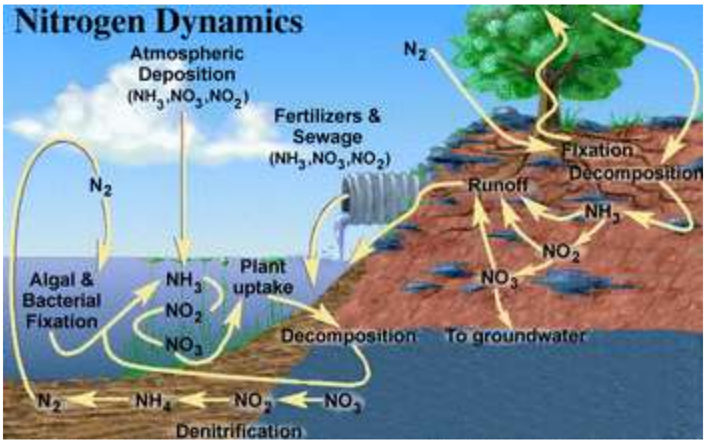

Figure 2-10: Nitrogen cycling in a reservoir

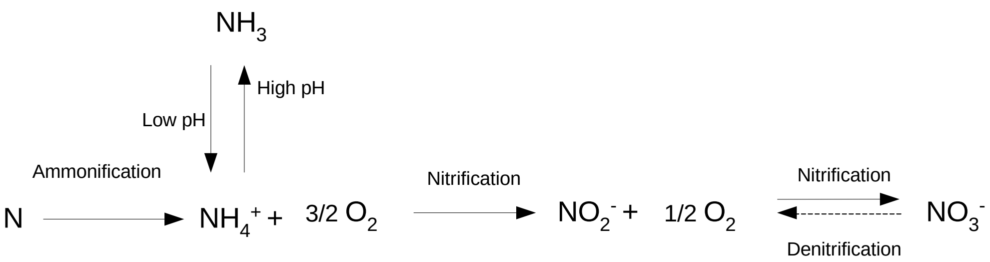

Figure 2-11: Nitrogen chemical transformations

Nitrification is the process that transforms ammonia, directly input into the water body from sewage or produced by the ammonification of organic nitrogen compounds, into nitrite and nitrate, in the presence and with the consumption of oxygen. If dissolved oxygen concentrations are depleted creating anaerobic conditions, denitrification occurs with the production of molecular nitrogen that is diffused to the atmosphere. This is a process occurring predominantly in the sediments, although it may also occur in the deoxygenated hypolimnia of some reservoirs. In eutrophic stratified reservoirs, concentrations of N_2 may decline in the epilimnion because of reduced solubility as temperatures rise and increase in the hypolimnion from denitrification of nitrate (NO_3) to nitrite (NO_2) to molecular inorganic nitrogen (N_2). Nitrite (NO_2) rarely accumulates except in the metalimnion and hypolimnion of eutrophic systems. Concentrations of nitrite are usually very low unless organic pollution is high.

2.6.2 Phosphorous

Although it is only needed in small amounts, phosphorus is one of the more common growth-limiting elements for phytoplankton in fresh waters. These shortages arise as there is no biological pathway enabling phosphate fixation similar to the process of nitrogen fixation and due to geochemical shortage of phosphorus in many drainage basins. The anthropogenic addition of phosphorous to fresh water bodies is one of the causes of the increase of their trophic state as previously referred. Figure 2-12 presents the dynamics of phosphorous in the aquatic environment.

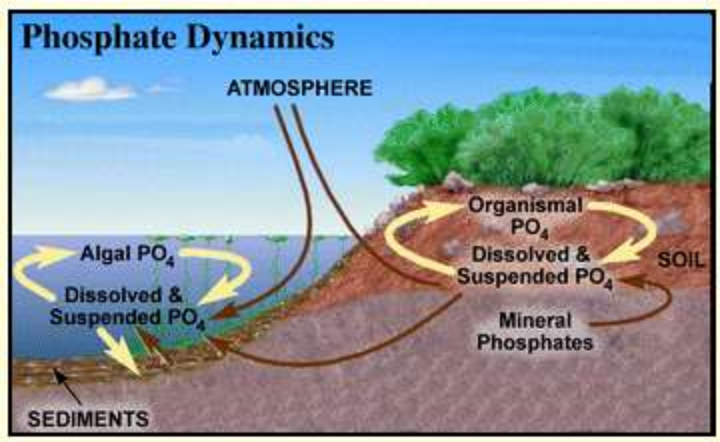

Figure 2-12: Phosphorous dynamics in a reservoir

In deep stratified systems surface waters may have limited sources of phosphate and the quantity of "available" phosphorus in late winter may determine the level of phytoplankton primary production in summer. Intensive algal growth in spring usually depletes phosphate levels in the surface waters. Hence, phytoplankton growth during the summer usually consumes recycled phosphate, excreted by animals feeding on phytoplankton. Direct benthonic fluxes from the sediments may be the most important source of this nutrient in the summer in shallow areas.

Rooted aquatic plants get phosphorus from sediments and can release large amounts of this element to the water column. Phosphate (in contrast to nitrate) is readily adsorbed to soil particles and high inputs of total phosphorus are due to erosion of erodible soils and from run-off. Agricultural, domestic, and industrial wastes are major sources of soluble phosphate and frequently contribute to an increase of the trophic state and to the occurrence of algal blooms.

2.7 OVERVIEW OF WATER QUALITY MODELS OF RESERVOIR

> *...in science, a model has as objective to uncover what structure or what set of relationships are a genuine representation although partial of reality.*

This definition (McFague, 1982, cited by Thoman e Mueller, 1987) enhances three characteristics of models:

- Models are about “discovery”.
- Models are about behaviour.
- Models are at the same time true and not true.

In fact, a model is no more than a representation of reality that contains some of the characteristic of a system representing in a more or less detailed way, our understanding of the system and of the processes that govern its state and of the relations between its components (Cardoso da Silva, 2002).

Three main reasons can be stated to build water quality models (Schooner, 1996):

- To get a better understanding of the destiny and transport processes of substances present in the aquatic environment

- To determine concentrations of substances to which are exposed humans and aquatic organisms.

- To forecast future environmental state under different scenarios of pressures as a consequence of the adoption of alternative courses of action and management measures.

The growing capability of models to forecast the behaviour of aquatic systems was the main reason for presenting these techniques as decision support tools. *Prognostic modelling* is the use of models to simulate consequences of alternative courses of action, in one of the most attractive roles of modelling. Another use of models is made in the context of diagnostic modelling, where the conceptual and mathematical representation aims to help the understanding of available information in order to better identify cause-effects relationships for the observed phenomena.

Although diagnostic modelling does not posses the appeal of the capability of prognosis, it is not less relevant (Baptista, 1994). The credibility of a forecast will be dependent on the degree of calibration and validation of the model that produced them.

Dynamic simulation models incorporate mathematical descriptions of physical, chemical and biological processes in lakes or reservoirs. If properly designed and calibrated, these models can assist with management decisions that require considering alternative scenarios. Moreover, they often offer sufficient spatial and temporal resolution to model algal blooms and other responses to eutrophication. Conversely, the data requirements and process-level understanding demanded by dynamic models can be formidable. While such models have been in existence for decades and continue to be developed, it is prudent to be sceptical of their predictive power and realism. If a model is to be used, it should be selected based on the information available about the lake or reservoir and the questions to be answered. The most complex model is seldom necessary.

As a consequence, and although models never replace observations they can be very useful to guide in the definition of strategies to design monitoring programs and contribute to increase efficiency of field work.

Adequate management of water resources and, in particular, aspects related with water quality, should not exclusively depend upon modelling. In fact, due to the complexity of the problem, and although the models constitute an important tool, management should always result from a global, weighted and multidisciplinary analysis of several aspects.

A new predictive technique for remediation of aquatic environment, which comes from the field of Information Technology, was recently described. This technique, known as the "knowledge-based" (K-B) approach, faces the problem from a different perspective to mathematical modelling. Prediction by the mathematical modelling is a common choice in countries, which have a rich, reliable data base, the scientific capacity for the modelling, and experienced management. These are usually not available in developing countries. On the other hand, the "knowledge-based" prediction focuses on the use of local and domain knowledge. As the use of mathematical models in developing countries usually requires a foreign expert, the use of the K-B approach builds a local expertise in predictive techniques. Details and advantages of the K-B technique were recently discussed by Ongley and Booty (1999).

An overview of the types of models more commonly used for the study of environmental problems in reservoirs is presented below.

2.8 LAKE STABILITY

2.8.1 The Wedderburn and Lake Numbers

The simplest model of a stratified lake comprises a warm surface layer (epilimnion) overlying a cooler bottom layer (hypolimnion), separated by a sharp thermocline. In this model, wind blowing over the lake moves the surface water, tilting the thermocline. The response of the lake is determined by the relative strength of the restoring baroclinic force, due to the density difference between the two layers, and the overturning force of the wind. This ratio is the Wedderburn number (Imberger and Hamblin, 1982):

$$W = \frac{g' h^2}{u_*^2 L}$$

where $g' = \Delta\rho/\rho g$, $\Delta\rho$ is the density difference between the layers, h is the depth to the thermocline, L is the length of the lake (in the direction of the wind) and u_* is the shear velocity induced by the wind.

According to this model, if W<1, the baroclinic restoring force is insufficient to prevent the thermocline tilting so far that the hypolimnetic water upwells to the surface at the windward end of the lake, accompanied by significant mixing.

In many lakes, however, this two-layer model is too simple and the epilimnion and hypolimnion are separated by a much thicker gradient layer, the metalimnion. In these lakes, some upwelling of metalimnetic occurs even when W>1.

For a continuous stratification a more useful measure of stability is the Lake number (Imberger and Patterson, 1990):

$$L_N = \frac{g S_t (1 - h/D)}{\rho_0 u_*^2 A^{3/2} (1 - z_g / D)}$$

where A is the surface area of the lake, h is the depth to the centre of the thermocline, D the depth of the lake, z_g is the height of the centre of volume of the lake and S_t is the stability of the lake, given by:

$$S_t = \int_0^D (z - z_g) A(z) \rho(z) dz .$$

For large Lake numbers (L_N>>1) the stratification is so strong that the lake is very stable and there is no upwelling and little mixing. When the Lake number is very small (L_N<1), cold hypolimnetic water will upwell and will be accompanied by significant mixing. There is an intermediate regime in which L_N>1 but W<1 and the wind will bring the metalimnetic water to the surface, but not the deeper hypolimnetic water.

The Lake number generally follows a seasonal trend reflecting the stratification and wind conditions, increasing to a maximum in late summer (in temperate lakes) when the stratification is most stable. The Lake number has been used as an indicator of mixing and vertical transport in lakes and reservoirs and as a predictor of water quality parameters such as dissolved oxygen, nutrient and metal concentrations. The Lake number is typically calculated using profiles of temperature and is well suited to automated calculation from thermistor chains or CTD profiles.

2.8.2 Monitoring and Control

Thermistor chains

Since the thermal stratification of a reservoir is central to vertical fluxes, and hence to the biological and chemical processes that determines water quality, it is surprising that the evolution of the temperature profile is often overlooked in regular monitoring programs. Many reservoir operators include temperature profiles in their monitoring program, but this is often restricted to quarterly measurements to coincide with other water quality parameters. The usual technique during such sampling exercises is to drop an instrument through the water column, continuously measuring temperature and depth (and often conductivity) at a spatial resolution of the order of one centimetre. The relatively high cost of collecting and analyzing water samples for chemical composition usually ensures that any monitoring is restricted to the absolute minimum necessary.

An alternative to obtaining temperature profiles using a single thermistor on a probe is to employ an array of thermistors permanently fixed at depths in the reservoir – a thermistor chain. A single thermistor chain might include thermistors at vertical spacing of one to two meters near the surface and at greater spacing at depth. The thermistor chain is fixed to a mooring that allows for the anticipated changes in water level. Where large operating ranges are expected, systems of weights and floats are necessary to ensure the thermistor chain remains approximately vertical. Each thermistor measures the temperature at periods of typically several minutes, although some applications allow sampling periods of as little as ten seconds. The individual thermistors are connected to a data-logger that either stores the data locally on the chain for manual retrieval, or relays it to a shore station via telemetry.

A permanent thermistor chain allows a reservoir manager to measure a wide range of physical processes from the seasonal stratification to internal waves. In this way it is possible to understand important issues that effect water quality such as: how the seasonal thermocline evolves, when autumn turnover is likely, the amplitude of large-scale internal waves. When a thermistor chain is linked to a shore station by telemetry the temperature data can be made available in real-time. This aids reservoir managers in deciding operating strategies such as the choice of off-take or the use of an artificial destratifier.

In addition to the advantages of greater temporal resolution, thermistor chains can provide a cost-effective monitoring program where the cost of manually profiling is high, for example in remote locations.

Weather stations

We have described how the dynamics of a reservoir is determined by the balance between the stabilising effects of thermal stratification, caused by solar radiation, and the destabilising effects of wind and cooling. The measurement of the thermal stratification, ideally using a thermistor chain, provides only part of the story; it describes the net effect of meteorological forcing on the thermal stratification but provides no record of the forcing itself. The major meteorological data of relevance to water quality in reservoirs are: air temperature, wind speed, solar radiation and humidity. All of these contribute to the thermodynamics of the surface layer and the wind speed also contributes energy and momentum for driving internal waves and mixing.

In many locations high quality meteorological data is collected at a nearby station by the relevant government agency. However, in some instances it is desirable to measure at the reservoir site, preferably on the lake itself. Since wind plays such an important role in mixing and is often highly local, it is becoming more common to include at least a wind anemometer at the site, often on a thermistor chain mooring. The combination of temperature data from a thermistor chain and wind data from an anemometer allows the reservoir operator to calculate the Lake number, from which reservoir dynamics, mixing and even water quality can be inferred. The collection of more complete meteorological data is usually reserved to those sites where numerical models are used.

Lake number correlation model

This is a simple computer model that uses temperature data measured by the thermistor chain in a lake and wind speed over the lake. This allows the Lake Number to be computed. From the Lake Number and correlations with historical records of biological and chemical variables, it is possible to predict oxygen, manganese and iron levels and, most recently, phytoplankton biomass. The correlation model is based on the premise that if the lake stability is weak then the geochemical variables vary only due to mixing, and if the stability of the lake is strong then the variation in the variables is predominantly due to changes in the rate of biogeochemical fluxes. This simple correlation model has been applied to a number of lakes and yields excellent results. This technique could be extended to cover transport of potentially other chemicals and micro-organisms by inflows. The model will need to be calibrated for each reservoir.

The main objective of such techniques is to provide ongoing rapid simple indicator measurements which are then used to control the operations of the lake such as water level, off-take level and possibly alert the operators of the treatment plant downstream of changes in water quality.

Inflow characteristics

In some circumstances it is important to be able to predict the depth at which an inflow will insert in a reservoir; an inflow may be of poor water quality or even contaminated by an event in the catchment. As we have described above, the depth at which an inflow inserts depends on the stratification in the reservoir and the temperature of the inflow. The stratification can be measured by a temperature profile, or preferably a thermistor chain, but this information must be combined with the temperature of the inflow. Although it is possible to infer inflow temperatures from air temperatures during rainfall events or to directly measure the stream water temperature at the time of interest, it is now possible to install small self-logging thermistors to continuously record the inflow water temperature. This is particularly important if numerical models are being used to predict the dynamics of the reservoir.

Auto-samplers and auto-analysers

The instruments described above collect physical data and are well established. Recent advances in instrument development have resulted in robust automatic sampling and analysis systems able to provide a continuous record of chemical and nutrient concentrations at selected locations. Although still relatively expensive, this technology has a place in the management of critical drinking water resources and in the collection of high quality data for the calibration and validation of numerical models. Recent advances in sensor technology also allow measurement of various additional water quality parameters including light at depth, fluorescence, dissolved oxygen and pH.

2.8.3 Real-Time Data Acquisition, Modeling and Control

Recent advances in our understanding of reservoir dynamics, in instrumentation and in techniques to control reservoir dynamics provide us with all the elements necessary to develop an integrated real-time data-acquisition and control system for the management of reservoirs. As the value of some water resources increases and the threat to the quality of those water resources also increases, the need for such a system may not be as far in the future as we might think.

Real-time data acquisition and display systems are already widely available. Useful data would include reservoir stratification and water quality, meteorological forcing and inflows. The data would be automatically transferred to a database that could be accessed through a computer network. The data acquisition system could also include some simple instrument checks and alarms to notify operators and managers of sensor failure. This would allow timely maintenance and repair of instruments and minimise gaps in an otherwise valuable data set.

The next step would be to link the data acquisition to hydrodynamic and water quality models of the reservoir. Access to real time continuous temperature, inflow and meteorological provides the opportunity to continuously check the validity of the hydrodynamic and water quality models and to adjust calibration coefficients if necessary. Such checks could be automated at a regular (weekly) interval to ensure the models remain well calibrated. The same real time data can also be used to initialise the models, allowing predictive simulations to commence from real time. The models would use a historical database of inflows and meteorological forcing to step forward from any given initial condition. This would allow a reservoir manager to predict future temperature structure and water quality in a reservoir following a particular event and to investigate a range of operating strategies.

Finally, telemetry would allow the reservoir manager to implement the operating strategy recommended by the modelling, activating control measures required, such as a bubble-plume destratifier or changing the selective withdrawal depth.

2.9 WATER QUALITY MODELS

2.9.1 One-dimensional Temperature Models

These models simulate the energy balance in a reservoir, forecasting vertical temperature distribution and variation, considering the reservoir as a one-dimension system.

When stratification is strong and the reservoir is deep with a relatively reduced surface, results are, in general, satisfactory. On the contrary, when stratification is weak or even inexistent, or when the reservoir is long and narrow, the hypothesis of horizontal homogeneity is sometimes far away from reality. For such cases, two and three-dimensional representations are required.

Simulation of vertical temperature variations has been well achieved by the use of one-dimensional advection-diffusion equation, and the energy conservation equation.

There are basically two mathematical models with very similar structures that although from the sixties or early seventies are still very used: one, developed by the company Water Resources Engineers, Inc (WRE, 1968), and other by the Parsons Laboratory, Massachusetts Institute of Technology, MIT (HUBER, 1972). Both use the heat budget procedures that were developed by the Engineering Laboratory of the Tennessee Valley Authority (TVA, 1972), and both are well documented.

2.9.2 One-dimensional Water Quality Models

Once the annual thermal cycle in stratified reservoirs could be represented, the next step in modelling was to extend the one-dimensional temperature models towards the characterization of the corresponding water quality cycles. This was first achieved using the one-dimensional advection-diffusion equation and the same conceptual structure as the used for temperature models, adding terms for other processes related with water quality.

According with Orlob (1983), a possible criterion about the applicability of a one-dimensional representation is based on the calculation of the reservoir densimetric Froude number. This dimensionless parameter compares the inertia forces, represented by an average flow velocity, with the forces that tend to maintain the densimetric stability.

Modelling water quality parameters in reservoirs was a logic sequence of temperature simulation, and some authors carried it out during the seventies namely WRE or MIT. An ecological water quality model was developed by Chen for the Environmental Protection Agency (US-EPA) (Chen and Orlob, 1975) and latter became the LAKECO model. This model includes 22 different biotic and abiotic state variables.

The MIT group made an extension of the temperature model to include the simulation of dissolved oxygen (DO) and biochemical oxygen demand (BOD), and demonstrated its application at the Fontana reservoir, in the water resources system of the Tennessee Valley Authority (Markofsky and Harleman, 1973).

Baca and Arnett (1976) introduced an improvement in the solution technique for the one-dimensional water quality models, incorporating the finite element method. The resulting model avoids problems of numerical diffusion, instability and adaptation to high gradients.

The one-dimensional dynamic model DYRESM appeared in the eighties, developed by Imberger (Imberger, 1981), and was successfully applied for temperature and salinity forecast in lakes and reservoirs of small and average size. More recently, the Environmental Laboratory in Vicksburg developed the CE-QUAL-R1 model, which describes the vertical distribution of temperature and chemical and biological substances of a reservoir along the time. More recent examples of the application of these models, using improved versions, were reported by, e. g. Hamilton and Schladow, 1997, Bo-Ping Han et. al, 2000 and Gal et al., 2003.

Currently, other one-dimensional ecological-water quality models for stratified reservoirs are in use all over the world. One model representative of these was originally developed by WRE (Chen and Orlob, 1975) and it formed the basis of the WQRRS (Water Quality for River-Reservoir Systems) model (HEC family of models). This model describes the vertical distribution of thermal energy and of concentrations of substances, and is meant to be used as a planning tool to study water quality before and after the construction of a certain dam, as well as for the evaluation of effects of reservoir operation. The model also incorporates the water quality issues associated with eutrophication and anaerobic conditions.

2.9.3 Multi-layer Models

The final goal on the dynamic modelling of reservoirs or large lakes is to allow an adequate description for the simulation of ecological and water quality balances of a limnological system. Due to the stratification introduced by the effects of temperature, salinity or suspended solids, one-dimensional and two-dimensional models are only sufficient in special cases.

A large number of reservoirs and lakes, relatively small, with a clear thermal stratification, may be well modeled in one dimension. However, when the reservoir is long and narrow, or when stratification is strongly affected by the momentum transferred by large inflows, the one-dimensional approach is not satisfactory anymore.

In shallow lakes and reservoirs this problem is not so relevant, once vertical homogeneity is ensured. In this case, the two-dimensional (in the horizontal) circulation models may be sufficiently adequate to describe the current fields and the mass transport. That is the case of models like Leendertse, 1967 and Masch, 1969, originally developed to simulate the circulation in shallow water systems like estuaries.

However, even the shallow systems may require a vertical resolution, for instance to deal with the biological cycles that are related with the solar radiation at the air-water interface, as well as with the benthic processes at the lower part of the water column. Stratification due to water density requires a greater accuracy on the mathematical representation of the hydrodynamic phenomena of the reservoir.

Models where hydrodynamics of the thermally stratified flow is the main issue are generally included in the multi-layer models (Simons, 1973, Cheng et al., 1976). In these models the thickness of the layers may be constant or variable and the number of layers may also differ.

The multi-layer model developed by Simons is well representative of such models, which were used with reasonable success to some of the Great Lakes in North America and to Lake Vanern in Sweden (Simons, 1977, Orlob, 1977).

The two-dimensional circulation models in stratified flows used to simulate the behaviour of long shaped and narrow reservoirs are well represented by the finite element model RMA2, developed by King and Norton (1975), and by the finite difference model of Edinger and Buchak (1975). The RMA2 model has been improved along the years and is currently available in a commercial version.

2.9.4 Two and Three-dimensional Water Quality Models

The modelling of transport and conservative substances in shallow lakes is represented by the model of Lam and Simons (1976), which was applied to Lake Erie. The problem of non-conservative substances, including nutrients and phytoplankton, was solved in the Green Bay model by Patterson (1975), and in the phytoplankton productivity model of Lake Erie developed by DiToro (1975).

In each of these examples models were run from a known field of currents obtained by field measurements or a circulation model. The Lam and Simons model treated the lake system as having vertical mixture (one layer) or having stratification (two layers), while the other models assumed vertical homogeneity.

The eutrophication phenomena have been modeled using the principle of general nutrient balance, which was firstly presented by Vollenweider (1975) and later by Snodgrass and O´Melia (1975). The models of Thomann (1975) and Chen (1975), for Lake Ontario are examples of a more comprehensive two and three dimensional representation of the nutrients-biota time varying interactions in lake systems.

Three different types of models were identified by Thomann, ranging from a simple three-layer model (epilimnion, hypolimnion, and benthos), up to a seven-layer model with 67 segments and up to 15 variables.

CLEANER, an ecological model for lakes, which includes up to 34 state variables, reduces the water body to a one square meter water column that may be divided up to ten cells to allow vertical resolution. This model was used in a variety of situations and countries like the USA, Scotland, Scandinavia, Lake Balaton in Hungary, and also other lakes in Czech Republic and Italy.

The "state-of-the-art" of ecological or water quality modelling is probably well represented, even today, by the phytoplankton productivity models of Ditoro (1975), Thomann (1975), and Chen (1975). The above-mentioned model CLEANER adds to those models the biological characterization in reservoirs.

Buchak and Edinger developed the model LARM2 (Edinger and Buchak, 1975) for the simulation of hydrodynamics and transport of pollutants in reservoirs. This model is laterally averaged, being two-dimensional in the X-Y plane (longitudinal - vertical), and has the possibility of adding or eliminating longitudinal segments during the rising or the falling of the reservoir water level. More recently, Cole and Buchak developed the CE-QUAL-W2 model (Cole and Buchak, 1995), an extension of LARM2, which includes the possibility of simulating reservoirs with several branches.

Several versions of RMA models have been used for different water quality studies (*e.g.* King and Norton, 1975). For example, the above mentioned RMA2 model was used as the hydrodynamic basis for a water quality model, the RMA4 model, which has been used with success both in estuarine systems as in reservoirs. RMA7 was developed to simulate water quality variables in a two-dimensional, laterally averaged, reservoir.

2.9.5 Eutrophication Models

Nutrient enrichment in lakes and reservoirs has been a growing concern among the pollution control experts, biologists and environmentalists in general. However, it has been only recently that, in some countries, a combined effort has been set up to quantify the effects and to establish alternative control strategies in terms of nutrient balances in reservoirs.

The previously mentioned model of Vollenweider (1975) for the phosphorus is among the first eutrophication models of nutrient mass balances, which has a wide application. Taking the balance of phosphorus as the sum of external, effluent and sedimentation sources, as well as the reservoir residence time, Vollenweider proposed a relatively simple equation to evaluate the time evolution of the phosphorus concentration.

Jørgensen (1976) made an analysis of various approaches to the eutrophication problem and concluded that it is crucial that eutrophication models include, at least, three trophic levels, phytoplankton, zooplankton and fish. They should also allow the nutrient exchange between sediments and water. Such models may give a more accurate description of the system response to the seasonal variations of nutrient inputs.

A comprehensive review of the available models of this type was presented by Reckhow and Chappra (1999).

2.9.6 Special Models

There are a relatively large number of special models for reservoirs, or models used for particular purposes. Among them are those that simulate water quality in a system of reservoirs, or models that simulate water quality in a reservoir with back pumping in a pump-storage reservoir system. The latter may be used to define pumping rules that can be used to improve reservoir water quality (Chen and Orlob, 1972). One model of this type was used for the recently built Alqueva reservoir, in Portugal, (Diogo and Rodrigues, 1997).

Some other special models refer to sedimentation, or even to the forecast of the consequences of landslides into the reservoir. HEC-6, developed by the U. S. Army Corps of Engineers (HEC, 1991), is one of the models that allows the simulation of sediment deposition in reservoirs (Scour and Deposition in Rivers and Reservoirs). This model was developed to forecast the long term hydro-morphological behaviour of fluvial systems and is not adequate to evaluate short-term responses due to certain events, like floods.

2.10 FINAL REMAKS

It seems to be evident that the "state-of-the-art" of water quality mathematical modelling in lakes and reservoirs is reasonably well represented by certain simulation models, which range from the one-dimensional temperature and water quality models in stratified systems, to the multi-dimensional, wind driven, and ecological models, for large water bodies.

Water quality models may be extremely useful during the planning phase of a dam, anticipating some measures that will contribute to minimise negative impacts or even to promote some potential benefits both in the reservoir and in the downstream river reach. These models may also play an important role as part of the management tools used for the reservoir operation, including the potential to forecast the water quality response to different pressure scenarios or remediation works.

In general, model calibration and validation is not a precise science. For this reason, it is crucial that the most appropriate data is collected in order to produce a good water quality forecast.

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3 MANAGEMENT OF THE IMPACT OF HYDRAULIC PROCESSES

3.1 INTRODUCTION

3.1.1 Gas Supersaturation

Water in streams and rivers can become supersaturated with the gasses that make up the atmosphere as a result of both natural and man-made actions that cause air to be entrained in the flow at great depths. The solubility of gas increases with pressure and thus when air is introduced at depths of several meters below the water surface, a higher amount of total gasses will be dissolved than at atmospheric pressure. This condition, when the amount of dissolved gas exceeds the maximum amount of dissolved gas at atmospheric pressure, is called “total gas supersaturation“.

While the condition of supersaturation requires that air be introduced to water at an elevated pressure, the condition is not easily reversed when the supersaturated water mass moves to shallower depths or near atmospheric conditions. Water in a river may remain supersaturated for many kilometres down stream of the location where the supersaturation condition is generated.

Natural conditions that can result in gas supersaturation include deeply plunging waterfalls. Masses of air drawn into the plunge pool by the plunging jet of water contribute to the supersaturated condition. Hydraulic structures can also contribute to gas supersaturation. Deeply plunging spillway discharge and deep stilling basins operating with submerged hydraulic jumps have been known to cause supersaturation that contributed to fish mortality.

Fish that are exposed to the supersaturated water accumulate the dissolved gasses in their blood stream in their natural respiration process. Symptoms of the gas bubble disease occur when the fish swim at shallower depths where the gasses expand in their circulatory system and cause ruptures that are often fatal. The amount of supersaturation that can be tolerated by fish depends on the species and the environment to which they are exposed. Fish can adapt to some level of supersaturation by sounding down to deeper water if a deep channel exists in the river. If, however, the downstream river channel is relatively shallow, little supersaturation can be tolerated. Case studies and a discussion of the issues are given in Section 3.2.

3.1.2 Control of Floating Debris

Floating debris comes in many forms, from rafts of timber transported into the reservoir from the catchment by the river system, to floating peat bogs and reed rafts generated from within the reservoir. The management and control of floating debris is an important aspect of reservoir operation through its ability to clog outlets and spillways. Case studies are presented of various forms of floating debris and some of the actions which have been taken to control them.

3.1.3 Fish Passage

The conservation of fishlife in rivers is a concern which is reflected in the policy of sustainable development adopted by ICOLD. The ICOLD Position Paper on Dams and the Environment specifes that: “...more and more we also recognise an urgent need to protect and conserve our natural environment as the endangered basis of all life...“. The conservation of fishlife in rivers and lakes can only be considered from a holistic point of view, taking into account the entire life cycle of the species concerned: reproduction, feeding, movement and migration, which in the latter case has to consider the whole river system from the source to the sea. It is thus preferable to adopt a comprehensive approach to the aquatic environment and develop a piscicultural plan for the entire river in question.

The impact of dams on the environment, and in particular on fishlife, has been discussed in some detail at several ICOLD Congresses and in various Bulletins of ICOLD, particularly Bulletin 116, Dams and Fishes. This latter Bulletin provides more detailed information on fishlife and draws up an outline of the existing knowledge and experience of dam constructors and operators. However given the diversity and range of environmental, climatic and hydrological conditions, it was not intended to be an exhaustive treatise on the subject. The Bulletin provides more of an introduction to engineers and dam owners so that they can understand the scope of the studies and investigations necessary before a successful fish management programme can be implemented. Three areas are examined;

- The reservoir: the conditions necessary for fishlife, including food and reproduction'
- The dam: fish passage techniques
- The river downstream of the dam: flow conditions required to maintain fishlife.

Certain of the techniques described in the Bulletin are relatively recent and the approaches described should be regarded as a first step, to be further refined as research into the particular application develops.

The maintenance and development of fish life is one of the important aspects to be considered in developing dam projects. The Bulletin notes that the objectives of the dam developer should be threefold;

- Conserve the diversity of living species
- Enable riverside communities to fish for food
- Provide for the development of water based recreational activities

The Bulletin goes on to note that these objectives must be adapted to the size of the dam, the particular environmental and social situations that exist and the regulations in force in the country concerned.

3.1.4 Reservoir Operating Strategies

Section 3.4 outlines a range of measures that can be used to manage water quality in reservoirs. These range from various means to implement artificial destratification and mixing in reservoirs, to structural methods of managing water quality such as selective withdrawal through various forms of offtake works. The paper proceeds further to discuss the options for monitoring and representation of real time data with the prospects to further integrate the data gathering and modelling to enable real time forecasts of reservoir behaviour and its response to management strategies to be made.

3.2 REDUCTION OF GAS SUPERSATURATED WATER

3.2.1 Case History

(a) Western United States

Spillway operation at several dams on the Pacific Northwest contributed to gas bubble disease related fish mortality in the 1970's. The majority of problems were related to the operation of spillways with hydraulic jump energy dissipaters. In these cases, the stilling basin elevations were selected to provide sufficient tail water depth to contain the hydraulic jump during the maximum design flood. Since the conjugate depth curve is typically steeper than the tail water curve, the hydraulic jump is drowned for all spillway discharges lower than the design flood. Higher saturation rates generally occur when the ratio of tail water depth to the conjugate depth (d_2) increases.

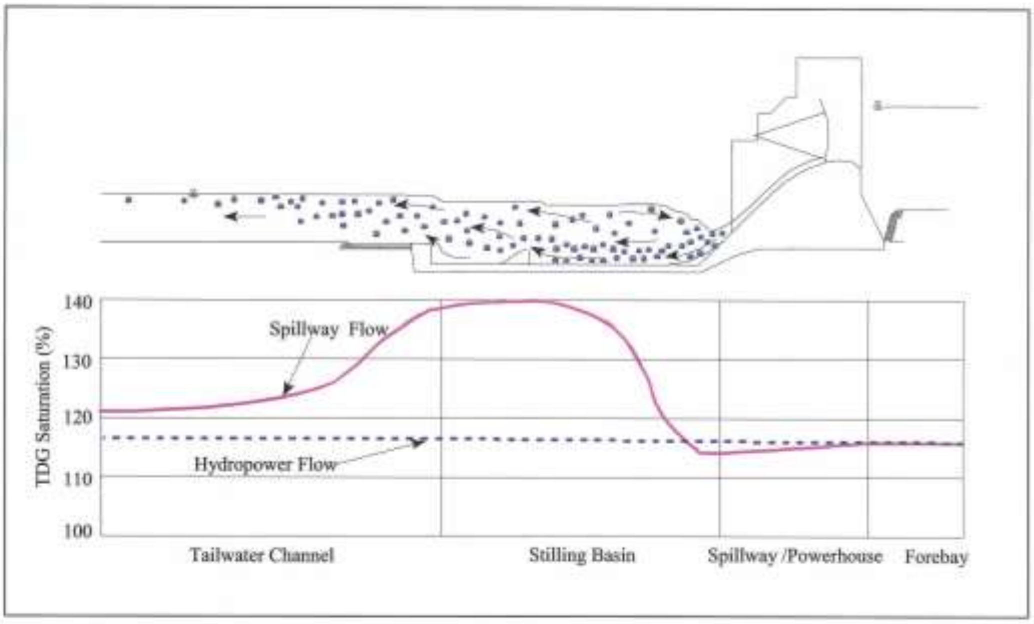

Figure 3-1 Total Dissolved Gas Exchange in Spillway and Hydropower Releases

Measurement of saturation in the Columbia and Snake Rivers that commenced in 1968 detected supersaturation of more than 130%. The highest concentrations occurred during high flow years when the greatest volumes of water were passed over the spillways. Large fluctuations in spillway operations which caused significant decreases in depth following supersaturation conditions caused fish to lose the ability to sound down to depths that would protect them, thus increasing fish mortality.

Laboratory experiments were conducted to determine the tolerance of both adult and juvenile salmonoids to the level of supersaturation. Studies showed that when both adults and juveniles were confined to shallow water (1 meter or less), substantial mortality occurred at 115% saturation of total dissolved gas. When salmonoids were allowed to sound to deeper water to obtain higher hydrostatic compensation, significant mortality did not occur until saturation reached 120%.

(b) Case History in Australia - Lower Pieman Power Scheme

The Lower Pieman Power Scheme near the West Coast of Tasmania, Australia was built in the period 1973 to 1986. Two short power tunnels convey water from the storage to two 119MW turbines in the Reece power station. Below the power station the Pieman River flows a further 30km to the sea.

In 1989 a number of dead trout were reported at Corinna, 15km downstream of the power station. Immediate investigations by the Inland Fisheries Commission determined that the trout died from gas-bubble disease, while native species were largely unaffected. The source of the gas bubbles was traced to supersaturated water emerging from the power station tailrace.

Each turbine in the station is fitted with a system to admit or inject air below the runner, to combat rough running of the turbine during start-up and at certain power outputs. It was the use of these systems which caused supersaturation of the water and the demise of the fish. The degree of supersaturation was increased by the aeration of the water from the reservoir. This aeration was caused by the unusually low level of the reservoir (drawn down for maintenance reasons) and the passage of water through an accumulation of logs and debris at the tunnel intakes.

As a temporary measure to protect the fish, the air admission and injection systems were disconnected. This action, while necessary, had an adverse impact on station operation. The station is very suitable for frequency control of the Tasmanian electricity grid, as the station has a relatively large capacity and its response time to changes in demand is rapid. Operation of the station in frequency control mode involves a fluctuating station output with a high probability of extended periods requiring either air injection or air admission. If its role in frequency control were continued without air, the machines would be subjected to severe vibration and additional wear and tear.

Studies were therefore commissioned to determine both the conditions under which supersaturation of the water occurs, and the tolerance of the fish to various levels of supersaturation. These studies are outlined below.

Gas saturation investigations were conducted on site. The power station was run under a variety of conditions, and gas saturation levels were measured in the tailrace with a tensionometer (to measure total gas saturation) and a dissolved oxygen meter. The readings confirmed that supersaturation only occurred when the air admission/injection facility was used. Passive air admission increased total gas saturation to about 110%, and forced air injection increased total gas saturation to about 120%. The water was generally less saturated with dissolved oxygen than dissolved nitrogen, probably indicating that the dissolved oxygen concentration in the water leaving the storage was low.

Fish exposure tests on site were primarily designed to establish whether relatively short-term exposures to the range of supersaturated conditions produced by the operation of the power station were harmful to fish. Rainbow trout were held in a flow-through tank fed with water pumped from the tailrace. Fish held in an identical tank fed with water from the intake side of the power station were used as a control. Measurements of total gas saturation, dissolved oxygen and temperature were made in both tanks.

The auto-start procedure takes about 17 minutes to bring the machine up to efficient load, during which air is admitted passively or forcibly into the draft tube for about 12 minutes. As the tensionometer is slow to react to changes in saturation, it is estimated that the actual level of saturation may have reached 120%, but no mortality or signs of stress was noted in the fish.

- Two hours of operation in the range requiring air admission, producing about 110% saturation, caused no mortality or signs of stress.
- Two hours of operation in the range requiring air injection, producing about 120% saturation, also did not result in any mortality or signs of stress.
- Six hours of frequency control mode, during which the machine was predominantly in the range requiring air injection, produced no mortality. However there were some signs that the fish were becoming stressed, e.g. loss of balance and erratic swimming behaviour.

Fish exposure tests at were conducted at the Salmon Ponds Hatchery. Here again two identical tanks were set up, an experimental one in which the degree of supersaturation of the inflow could be varied, and a control tank fed from the same water source.

- When the trout were exposed to a saturation level of 120%, mortalities began after about six hours and 91% of the fish had died after 24 hours.
- When the fish were exposed to a saturation level of 115% for 48 hours, mortalities began after 30 hours and final mortalities were 12% and 24% in two tests.
- Finally the fish were subjected to a cycle of six hours at 120% saturation followed by six hours at 100% saturation, repeated four times over a 48-hour period. None of the fish died from gas bubble disease.

It was concluded that the fish would be unaffected if

- the saturation level was generally below 110%, and
- any period of 120% saturation was limited to six hours and followed by a period of exposure to 100% saturation in which to equilibrate.

These conclusions were also consistent with overseas experience that 110% is a tolerable saturation level in natural streams and lakes, where depth compensation for the effects of supersaturation is normally possible for fish.

The results of the tests provided considerable scope for relaxing the restrictions imposed after the original fish kill.

Under normal conditions passive air admission operates between about 15 and 75MW output for each turbine. Within this range, air injection is required between about 40 and 70 MW. With two machines in the power station, it was realized that the only times during which the saturation level is likely to exceed 110% are when both machines are operating on frequency control, or when one machine is on frequency control and the other shut down. Therefore, provided that the station load exceeds the output of one machine at its most efficient load (>75MW), the other machine may be operated indefinitely on frequency control, furnishing up to 100MW of output to meet fluctuating demand.

The power station is once more able to operate as an efficient frequency control station. No further fish kills have occurred and the possibility of a recurrence due to gas bubble disease is considered unlikely.

(c) Case History in Australia - King River Power Development

The King River Power Development was constructed in the period 1983-1993 near the West Coast of Tasmania, Australia. The scheme comprises a large storage covering $54 km^2$, a 7km long headrace tunnel and a single-machine power station with an installed capacity of 143MW. The tunnel intake is at a relatively low level in the reservoir because the tunnel was excavated at a rising grade from the upstream end for economic and environmental reasons.

As soon as the power station was commissioned, the foul smell of hydrogen sulphide gas from the tailrace water was immediately apparent. Although the production of hydrogen sulphide gas was a temporary phenomenon, caused by rotting vegetation in the newly-filled reservoir, the gas was also a health hazard. Being heavier than air, the gas could concentrate in the confined valley immediately downstream of the station. While the presence of hydrogen sulphide is initially all too apparent from the smell, that sense becomes dulled by exposure and heightened awareness is essential to avoid the risk of a fatality.

Monitoring of the water quality then found that the tailrace water was low in dissolved oxygen. The concern was that slugs of oxygen-depleted water would be discharged into Macquarie Harbour 20 km downstream where fish farming is an important industry. While the farms are normally located kilometers away from the river mouth, fish pens in transit could pass through the danger zone.

Various methods of increasing the level of oxygen in the water were considered. The adopted solution made use of the existing air injection system installed on the turbine. When required jet pumps inject air immediately below the turbine runner, to combat rough-running conditions during start-up and at particular power outputs. Operation of the jet pumps was not without cost, as the pumps absorb about 3MW of the station output.

The injection of air also helps to reduce the release of H_2S by precipitating the sulphide as FeS and the oxidation of H_2S to sulphate, which is essentially non-toxic to the aquatic environment.

Air injection is now utilized on a seasonal basis to increase dissolved oxygen concentrations during periods of stratification in the lake, and is one of the formal operating rules of the power station. Continuous monitoring of the water quality being discharged by the power station ensures the timely utilization of the air injection facility.

(c) Aeration weir in Nam Theun 2

Due to lack of dissolved oxygen and excess dissolved methane in the reservoir of the Nam Theun 2 (Laos), an aeration structure was implemented for transfer of water of $375 m^3/s$. The dimensions of the basin were 205 x 50 m. The effectiveness of aeration through analysis of formation and repartition of air bubbles were tested. A model test at scale 1/20 was undertaken (See figure 3-2 and 3-3). Figure 3-4 gives the aeration weir in operation for the half of the nominal discharge;

Figure 3 -2: Plan view of the model test 150 m³/s at the scale 1/20 (Hydraulic Laboratory of Constructions; University of Liège Belgium)

Figure 3 -3: View of the flows detail on the aeration weir model test for 150 m³/s Hydraulic Laboratory of Constructions; University of Liège Belgium) and on site implementation

Figure 3 -4: On site view of the aeration in operations for 150 m³/s (EDF)

3.2.2 Retrofit Solutions for Spillways with Deep Stilling Basins

The physical process that causes supersaturation associated with a submerged hydraulic jump is related to the form of the flow in the submerged jump. The shear force at the air water interface along the upper nappe of the flow over the spillway crest and chute combined with the reverse roller of the submerged jump causes air to be drawn to the bottom of the stilling basin where the hydrostatic pressure is high. In a free jump, air is not carried in such large quantities to areas of elevated hydrostatic pressure. Redirecting the flow along the surface so that air is not dragged to the bottom of the stilling basin can avert saturation caused by the submerged jump condition.

The US Army Corps of engineers designed flow deflectors for 7 spillways with stilling basin energy dissipaters that contributed to the supersaturation problems using physical hydraulic model studies to determine the dimensions. The purpose of the deflectors, also called „flip lips“ is to direct flow for lower more frequent discharges along the water surface. The deflectors are of simple step geometry with a horizontal floor and vertical downstream face.

The location of the deflector on the spillway surface and the dimensions (length, height) are dependent on the depth of flow on the spillway at the location of the ramp and the variation of tail water level over the range of flows for which it is intended to be effective. If the deflectors are positioned too low with respect to the tail water level, the flow will penetrate too deeply in the basin and supersaturation will not be averted. If the deflectors are set too high, the flow will plunge into the basin with the same effect. If the length (and height) of the deflectors is too small in comparison to the thickness of the flow on the chute, the deflectors will not effectively turn the flow. If the deflectors are too large, they will compromise the energy dissipation during the Spillway design flood. The optimum dimensions are best determined by physical model studies**.**

Deflectors were designed for flows equivalent to the 10 year flood or less for spillways at the Bonneville, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose and Lower Granite dams. These devices were installed at all of the above projects except John Day and Ice Harbor. The deflectors are installed below the water surface and proportioned using the physical model to deflect the flows in the design range along the water surface, but allow the Hydraulic jump to form normally for the Spillway Design Flood.

Similar deflectors have been designed following physical model studies of the Brazo Principal and Brazo Ana Cua spillways of the Yacyreta Hydroelectric Project in Argentina. The deflectors have been installed and perform effectively in the Brazo Ana Cua spillway. Other design considerations include lower unit discharge, divider walls and low discharge bays with higher basin elevations. Operational considerations include the avoidance of abrupt change in spillway flow and non uniform gate operation to provide the balance of best operation and maintenance practice with best environmental practice.

Options combining the use of stepped spillways that improves energy dissipation allows for shallower stilling basins also have some potential for mitigating the problem.

3.3 CONTROL OF FLOATING DEBRIS

3.3.1 Type and origin of debris

Rivers carry not only water and sediments but also various kinds of debris, which may constitute both an operational problem and a dam safety problem. On a number of occasions floating debris has blocked spillway openings and lead to significant reductions in effective discharge capacity at the very time that capacity was needed. The possibilities and consequences of spillway blockage with floating debris therefore need to be considered. In some cases also action needs to be taken to stop, divert, pass or otherwise remove floating debris.

Precipitation, type of terrain, vegetation, reservoir treatment and other human activities around reservoirs and rivers are factors governing the potential amounts of floating debris. During major floods both the debris flux and the size of individual items of debris tend to increase which may affect cooling water intakes, trash racks and even large structures like spillways. The debris may be floating on the water surface or carried at some depth. It may comprise diverse bits and pieces of vegetation, such as grass, bushes, sunken logs or entire trees and manufactured items, such as boats, piers and houses. Ice runs may cause similar problems in some rivers.

However the role of smaller debris in clogging intakes cannot be ignored. A report from China (Prof. Jun Guo, Personal communication) highlights problems experienced in that country that are typical of those that are experienced on a world wide basis. Professor Guo reported that they have experienced clogging of hydro power plant intakes with debris comprising tree branches, logs, brush or grasses, stalks, straw and ice that floats towards the intakes and accumulates on the trash racks. The accumulation of trash can be several metres deep and cause the collapse of trash screens in extreme cases. Significant head losses have been shown to occur and, in some cases, the trash screens are damaged. The head loss in the intakes to power stations can lead to significant losses in energy generation resulting in substantial economic losses.

Mires are the source of another type of floating debris in some countries. On occasion large chunks of mires may lift to form floating islands covering several hundred square meters each and with a depth of a few meters. Floating mires tend to be released either when the ice cover is smelting in the spring or when the water is getting warmer in the summer, apparently lifted by expanding gas bubbles previously dissolved in the cooler water.

Floating rafts of reeds, such as bullrushes, other aquatic plants and materials such as peat bog can also break loose and cause problems with the operation of hydraulic structures. There are numerous examples around the world, but only a few specific examples will be referenced in this report.

Figure **3**-5: Floating rafts of bulrushes along Shoreline

Figure 3-5 shows floating rafts of bulrushes (Typha domingensis) growing out from the shoreline, which together with floating pondweed in deeper water outside, combine to block access to the shoreline on Lake Kununurra in Western Australia.

3.3.2 Case histories

Case histories of clogged or damaged spillways come from northern countries with temperate climates, but it would be reasonable to assume that similar problems occur in other climates.

(a) Norway experienced a large flood in 1789. It covered a number of the bigger rivers in the south-eastern part of the country and is estimated to have been of a size with present-day spillway design floods

(PMF) for major structures. Witness accounts from the time reported that normally clean rivers were 'thick as gruel and dead animals and houses, timber and trees floated in the current'. – Norway's biggest lake, the 'Mjosa, was almost entirely covered with bushes and trees and the water was so dirty that the fish died and became uneatable. In May 1790 the water had not yet cleared. Rivers and streams fell over the steep valley sides and brought mill houses and bridges along. - People thought it was Armageddon'.

(b) In November 1955 the Alouette dam in British Columbia, Canada was exposed to a flood, which caused the water to rise 1.5 m above the ungated fixed weir of a concrete spillway[i]. A large tree got stuck on the weir and damaged a concrete weir panel, probably by the changed flow conditions. The resulting seepage lifted a number of panels and finally caused 25 m of the weir to fail and the underlying clay foundation to be severely scoured. The failure occurred towards the end of the flood, which prevented a catastrophe. The Alouette dam is considered a high-hazard dam and the reservoir area had previously been cleared of trees and debris. The reservoir banks are however steep and heavily forested. The same storm also caused the 5.2m wide spillway openings of the nearby Jordan dam to become clogged with floating debris from the poorly cleared reservoir. The dam was overtopped by 0.6 m and this initiated erosion at the base of the dam. The Jordan dam is a 40m high Ambursen dam with an adjoining embankment.

(c) In 1978 the Palagnedra dam in Switzerland was exposed to a major flood, which caused an embankment dam adjoining the main concrete arch dam to fail due to overtopping after all the thirteen spillway openings measuring 5m by 3m had clogged up with floating debris, mostly logs. The amount of debris carried during the flood was estimated to some 25,000 m^3.

Figure 3-6: Debris in Palagnedra Dam , Switzerland following record floods

(d) In October 1987 part of south-eastern Norway was hit again by a flood estimated to have a return period of around 100 years. The rivers carried a lot of debris. Significant blockage of spillways by floating debris occurred at six dams (Svendsen, 1987), most of which were equipped with several smaller spillway openings. At one of the dams with a number of 2m wide openings, 20 men equipped with chain-saws, 2 excavators, 2 forest harvest machines and 5 trucks could not keep the spillways clean. At another dam floating debris collected on top of the partially open radial gate in the early part of the flood before the gate was fully opened. The debris got wedged in between the gate and the walkway on top of it and could not be cleared away with manpower and chain-saws.

(e) The example in Figure 3-7 shows the effect of a substantial flood in the Derwent River in Australia that carried with it a large number of logs which clogged the river diversion openings during the construction of Cataguna Dam. Catagunya Dam is a concrete gravity dam on the Derwent River in the Australian State of Tasmania. When the dam was under construction in 1960, a 1 in 100 AEP flood occurred. At that time the structure consisted of a series of alternate high and low blocks across the valley, with normal river flows diverted by an upstream cofferdam through four 5 m by 3 m openings in the dam.

The peak flow at Catagunya greatly exceeded the diversion capacity, and the excess water passed over the low blocks of the dam itself. The upstream cofferdam and the formwork erected for the next concrete pours on the dam were damaged.

Upstream of the dam the Derwent Valley is heavily timbered, and the flood brought with it a vast assortment of trees, logs and branches of all sizes. Tasmanian eucalypts are quite dense and many logs travel at or below the surface. Much of this material passed over the dam, but when the flood subsided, a great mass of timber had built up across the diversion openings. See photograph below.

At first sight it was thought that the diversion capacity had been reduced to about 25%, but a check on the pond level and river flow produced the surprising result that about 70% of the design flow was still finding its way through the maze of logs. Removal of the timber, log by log, was a slow and somewhat dangerous task.

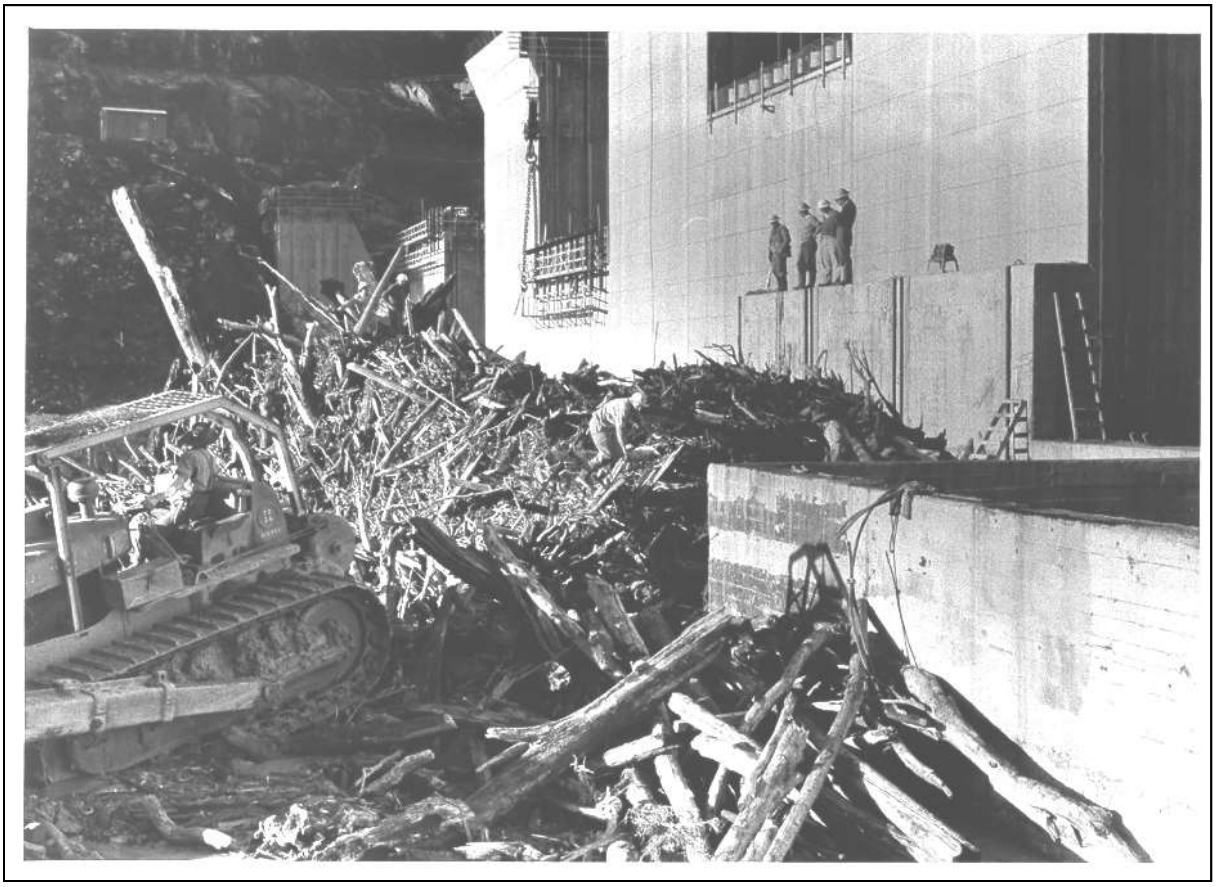

Figure 3-7: Catagunya Dam, Australia, April 1960, accumulation of logs at diversion openings after a major flood

(f) Reports from China (Guo, 2003) indicate that the Gezhouba Power Plant, that is located on the Yantze River 43 km downstream from the Three Gorges Project has suffered from loss of energy production due to clogging of the intake screens. The energy loss due to clogging of the intake screens in the period 1982 to 1984 was 79.1 GWhr per annum. The clogging was sufficient to stop some units from running. The clogging of intakes with debris causing head losses of up to 6.2m was reported during the initial operations at the Yantan Hydropower Plant, located on the Hogshuihe River in south west China.

(g) In the Australian state of New South Wales, the structural failure of the Wingecarribee Swamp peat bog in a storm event early August 1998 resulted in almost 6000 ML of peat and sedimentary material being deposited in Wingecarribee Reservoir, which previously had a storage capacity of 34500 ML. The peat flowed into the reservoir as floating blocks several metres thick and ranging in size from individual tussocks to clumps of several hectares. Increases in turbidity in the water body forced the cessation of raw water supply to the treatment plant. However the floating peat posed a significant threat to the security of the dam, having the potential to block the narrow single gated spillway. In order to contain the peat a 1.2km long steel mesh barrier was built across the reservoir to contain the peat.

3.3.3 River transport of debris

While it might be tempting to try and describe debris transport with formulae developed for sediment transport, the mechanism of initiation of motion is quite different as logs are often delivered into the stream by slides in the banks rather than direct erosion. Moreover, debris tends to be transported midstream at the water surface rather than along the bed or throughout the whole body of water. Although the surface velocity is usually slightly higher than the mean stream velocity, the debris transport velocity measured over substantial distances may be only a fraction of the mean stream velocity.

Floating uprooted trees tend to align themselves with the stream with the larger of the root wad and the canopy at the prow. However, not all trees float like that. Trees with heavy root wads have also been known to be transported standing up.

Generally, the transport of individual debris pieces is subject to a significant random element. Some debris may get temporarily stranded at a bend or other obstruction, while other debris may pass the same point. However, with some debris stuck there is an increased probability for more debris to get stuck at the same point. When a significant amount of debris has gathered, it will obstruct the flow and eventually may become unstable so that a slug of debris is released. Where floating debris is transported over longer distances there is accordingly a tendency for it to be transported entangled in slugs or rafts, especially when there is much debris in the river.

3.3.4 Debris transport through flow control structures

The behaviour of floating material approaching flow control structures such as spillways has been the subject for hydraulic model testing on many occasions over the years. Most of the earlier studies dealt with logs floating through specially designed log outlets designed to extract only surface water and to line up the logs to avoid blockage. The problem is similar to that of clogging of bridge decks where there is a body of information to be drawn on, a typical study is that of Schmocker and Hager (2011). More recent hydraulic model studies have also been made to investigate the ability of common types of spillways to discharge floating debris.

In Scandinavia hydraulic model tests (Godtland and Tesaker, 1994: Johansson and Cederstrom, 1995) have been made involving single trees, pairs of trees travelling together and larger slugs of trees. The tests dealt with passage of debris over both gated and ungated spillways and possibilities to stop slugs of trees with the help of floating boom arrangements. for several years starting in

The models used young plants of spruce, Picea Abies, of around 0.3m length with root systems less than 0.05 m in diameter, to simulate grown-up trees of 25-30m length, typical for Scandinavia. It was noted that the model trees were proportionally stiffer and stronger than the prototype trees, especially at the top ends and the model trees may therefore have stuck easier at spillways. It were suggested therefore that not only the root but also the top portion of prototype trees having trunk diameter less than 0.05 m should be disregarded to establish an effective tree length, *L*. Figure 3-8 gives some test results for *single* and *multiple* spillway openings with a single tree or, where indicated, two trees together approaching a spillway Trees stuck across a spillway opening from one pier to the next are denoted as '*definite*'. Some trees were caught by a combination of actions involving also roots and branches caught by bridges and spillway sills; they are marked with unfilled symbols and denoted as '*doubtful*'.

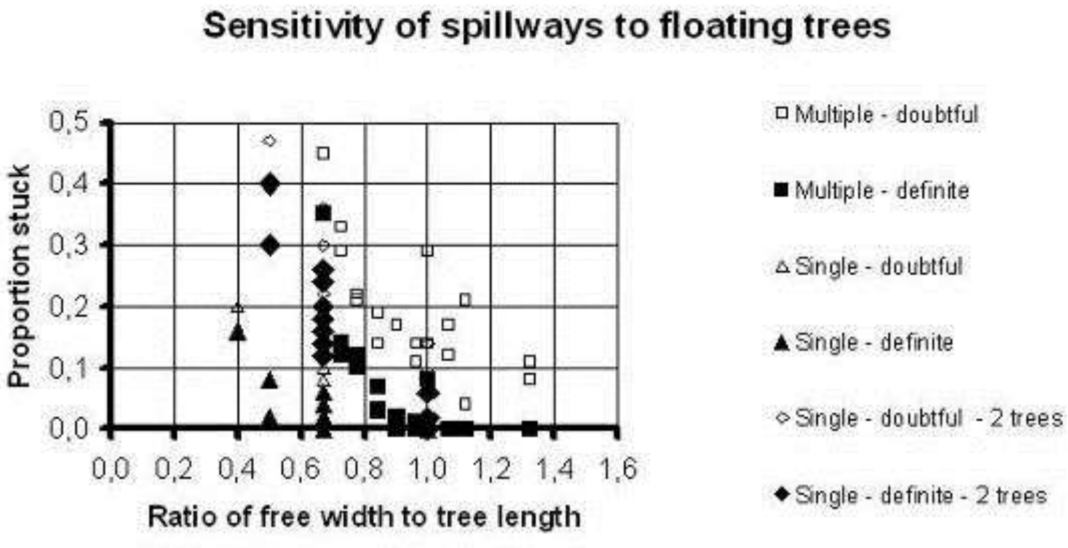

Figure 3-8: Model test results for floating trees at spillways

The approach flow to the spillway was found to be important in two respects. High flow velocities in the approach zone tend to increase the momentum of the trees, which reduced the risk of jamming. On the other hand a certain acceleration of the flow velocities tends to line up the trees parallel to the flow, which also increased passage rates. As can be seen in the graph above a somewhat larger free width may be required where there are multiple spillway openings next to each other so that the flow acceleration upstream is less pronounced.

The following dimensions were required to allow *single* trees a 95-100 % probability of passing through fixed sill spillway structures:

- A free distance between piers not less than 0.75 L for single spillway openings and 1.0 L for multiple spillway openings separated by piers
- A head of the upstream pool over the fixed sill and a free height between sill and overlying bridge not less than 0.15 L.

Passage of 80 % of tested *slugs of trees* required a minimum head of the upstream pool over the fixed sill of 0.15 L - 0.20 L and a free distance between piers of 1.1L.

Also the capability of bottom outlets was tested to pass trees sucked down from the water surface to outlets placed in a vertical front of a dam. The outlet had a rectangular shape with the free height equal to half the free width and a slightly bell-shaped approach with no sharp corners where trees could get stuck. Single trees were safely passed as long as the free width of the outlet exceeded 0.5 L. The higher flow velocities and the marked flow acceleration in front of the outlet may be the reason for the improved performance compared to that of the surface spillways.

The results are relevant only to passage of trees of the species used in the model tests. Other species of tree with different sizes, shapes and strengths require separate investigations.

3.3.5 Proposed counter- measures

The first step would be to try and assess if a potential for debris problems exists at a particular dam. If the upstream river runs through forested terrain and there are no lakes or reservoirs upstream, where the debris is collected and removed, such a potential usually exists unless spillway dimensions are extremely large. If the terrain around the reservoir is steep and prone to erosion the problem may be severe.

A debris management plan may be developed to limit the amounts of floating debris. There are a number of different methods (CDSA, 1995) which may be employed to counteract clogging of spillways:

Control of debris inflow by

1. Cooperation with forestry companies to promote suitable practices such as

    - leaving standing timber barriers
    - providing adequate drainage of slopes
    - minimizing strip clearing
    - rapid replanting

2. Identification and protection of reservoir slopes prone to slides, especially those influenced by human activities such as road construction, logging and mining operations

3. Creation of debris traps on streams entering the reservoir

4. Cooperation and joint approach to debris management with other dam projects in the same river.,

Measures to manage the inflow of debris to reservoirs from areas around the rim and from tributaries have not been very successful.

Collection and removal of debris on and around the reservoir by

1. Construction of bag shear and containment booms

2. Construction of containment dykes in shallow water

3. Clearing of snags and stumps in shallow parts of the reservoir

4. Controlled raising of reservoir to float off debris around reservoir rim

Protection of spillways by

1. Booms to restrain, deflect and stop debris

2. Diverting debris to other weirs

3. Construction of visor structures at spillways

The design of booms is critical as gathered debris may be released in slugs after boom failure or after reaching a depth sufficient to pass under booms. Boom arrangements are therefore presently not favoured as a single-line of defence (Rundqvist, 2006). The concept of visors is based on the idea of allowing the spillways to function, perhaps at some reduced capacity, although large amounts of debris has been collected against some visor structure just upstream.

Check of existing spillways' ability to pass debris by

1. Model test spillways to assess their sensitivity to the expected debris

2. Increase free width or height of spillway, for instance by removal of piers, lowering of crest or raising/removal of bridge or gate lip in top position

3. Modify spillway approach zone to improve debris passage

4. Revise operating procedure to reduce likelihood of debris jams, for instance by early complete raising of gates

5. Introduce new spillway with better capability to pass debris, perhaps a bottom outlet.

A number of possible spillway approach improvements have been model tested in Germany and Switzerland. These include patterns of piers constructed upstream (Strobl, 2003) to better align floating debris with the flow and improved pier shapes.

3.4 RESERVOIR OPERATING STRATEGIES

3.4.1 Artificial Destratification

One approach to mitigating the adverse water quality caused by the prolonged stratification of a reservoir is to artificially mix, or destratify the water column. By removing the stratification dissolved oxygen concentrations are maintained throughout the water column and the depth of the photic zone is increased, reducing algal growth. By preventing anoxia, iron and manganese levels can be reduced with a consequent reduction in phosphorus release. The two main destratification techniques are bubble plumes and mechanical mixers.

Bubble Plume Mixers

Bubble plumes are the most common method of destratification and involve the release of compressed air from a series of diffusers at the bottom of the reservoir. The resultant buoyant bubble plume entrains water as it rises, transporting colder water to the surface where it is released into the surface layer. A well designed bubble plume destratifier will introduce sufficient buoyancy to lift the oldest water just to the surface, resulting in an efficiency of the order of 5-10%. A bubble plume destratifier does not increase the dissolved oxygen concentration by dissolution of gas from the bubbles, but by allowing atmospheric oxygen transfers to be mixed through the full depth of the reservoir.

Mechanical Stirrers

A less commonly used technique is the use of mechanical stirrers; usually large low-speed impellers designed to pump the surface water downwards. These systems use either an open impellor or an impeller in a draft tube. An open impeller system creates a jet that impinges on the thermocline, gradually eroding it. A draft tube enables lower velocity impellors to transport surface water to depth, where it forms a positively buoyant plume.

Until recently mechanical stirrers were considered to be less efficient than bubble plumes, but the use of low-speed impellers makes this technique potentially more efficient. It has been suggested that downward impellers may have the advantage of allowing oxidised metals to settle from the water column at a lower depth than would be the case using a bubble plume since the latter transports the anoxic hypolimnetic water to the surface. There remain some important unanswered questions as to the relative effectiveness of each of these techniques.

Jet Diffusers

David Horn – How about something along the lines of the effect of the Mundaring pump back on water quality

Curtains

Flexible curtains can be used to control mixing and to separate inflows or withdrawals. For example, surface suspended curtains can separate cold inflows from the epilimnion of the main reservoir, preventing the entrainment of the warmer water as the inflow plunges. This technique has been used to reduce the hypolimnetic temperature in a reservoir in which cold environmental releases were required for sustaining downstream fish populations.

Typically temperature control curtains are positioned around intake structures where they control withdrawal elevation. Curtains may also be positioned at other locations within a reservoir or downstream of outlets, particularly in the tailraces of hydro power stations, to control hydrodynamics that might otherwise affect reservoir release water quality. Curtains potentially offer substantial cost savings over traditional selective withdrawal structures. However the considerable uncertainties about their performance was examined in one recent study of three reservoirs (Vermeyen, 1997). This study concluded that the performance of curtains was complex and not easily characterized.

Hypolimnetic Aeration and Oxygenation

In some instances it is desirable to maintain the thermal stratification and yet increase the dissolved oxygen (DO) concentration in the hypolimnion. For example some fish require cold water temperatures but high DO concentrations. Although destratification would increase the DO at depth, it would also increase the temperature. Another important example is when the low DO concentration leads to increased nutrient release from the sediments. In such a case destratification would mix the high nutrient concentration water to the surface layer, increasing the possibility of an algal bloom.

The DO concentration in the hypolimnion can be increased by the introduction of air or pure oxygen. The use of pure oxygen is significantly more efficient, although a supply of compressed oxygen is required. In shallow systems low DO water is pumped from the reservoir, oxygen is injected using a venturi and then returned to the reservoir. In deeper reservoirs the oxygen is introduced directly into the hypolimnion although usually through a venturi to ensure dissolution

3.4.2 Lake Nyos Example

On 21 August 19Rfi, a massive release of carbon dioxide from Lake Nyos in Cameroon killed about 1,700 people. II was suggested hat the CO^2, released was initially dissolved in the hypolimnion (dense lower layer) of the lake, and was released by eruptive outgassing. Because of its violence, the Nyos outburst was at first though° to have been volcanic. Recent experiments have shown that decompression of CO^2-saturated water is able to power expulsive eruptions.

To decrease the concentration of CO^2 in the hypolimnion, a degassing pipe has been implemented shown in Figure 3 – 9.

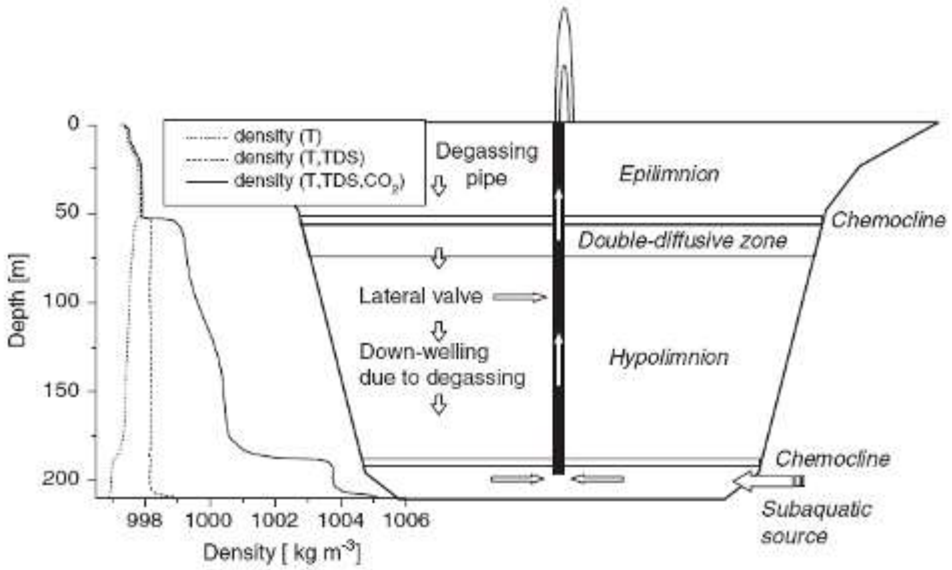

Figure 3-9. Overview of Lake Nyos showing TDS, CO_2 and Stratification.

The graph to the left shows the contributions of temperature, total dissolved solids (TDS) and CO_2 to the density stratification of Lake Nyos in December 2002. The operation of the degassing pipe causes a down-welling of 1–3myr. The figure 3-10 and 3-11 show respectively the rate of CO_2 accumulation below 175 m at Lake Nyos since 1986 and the degassing pipe in action.

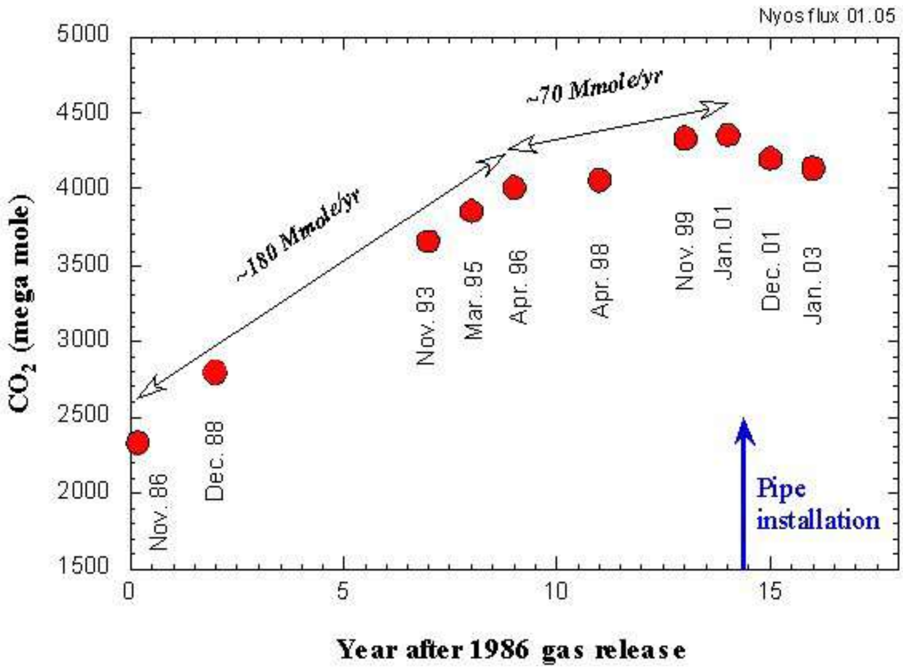

Figure 3-10: The rate of CO2 accumulation below 175 m at Lake Nyos since 1986.

Figure 3-11: Degassing pipe in action

3.4.3 Management of reservoir filing

Study case: Turbidity generated during the filling of a reservoir – The Péribonka case (Québec-Canada)

The Péribonka hydro-electric installation includes a dam of 80-m- height by 700-m-crestlength, two closing dykes, one underground power plant equipped of three Francis turbines of 385 MW total installed power generating 2,2 TWh annual energy, a dual pass spillway summarising 5 300 m^3/s of maximum capacity and a reservoir of 35-km-length laying on 32 km^2.

Filling the reservoir required 37 days, from September 27th to November 3rd 2007. Due to the proximity of a large reservoir upstream (Figure-3-12), the water naturally contains very few suspended load at the Péribonka power plant site (Pelipaukau means in the Montagnais dialect "*a river digging in the sand and where the sand moves"*.)

During the filling process of the reservoir, landslides occurred on the river (Figure 3-13 and 14) resulting in a temporary increase in the water turbidity. The plume of the brown water could be followed from day to day by satellite images (Figure-3-15) and by punctual measurements. Without immediate and appropriate actions undertaken by Hydro-Quebec, this turbidity would have an important impact on the drinking water supply of the surrounding inhabitants living downstream. Their water treatment systems were not been designed to take account of high turbidity.

The Péribonka river, indeed, is the main source of fresh water for two municipalities located next to the river mouth. The municipality of Sainte-Monique draws its drinking water from the Chute-à-la-Savane power plant reservoir (Figure 3-10), whereas the municipality of Péribonka draws water directly downstream of this last power plant. Both water treatment systems by chlorination became inefficient when the suspended load increased.

Special measures using tanker trucks were used during the period of time required to reach the normal concentration of suspended load. Set up of these corrective actions was facilitated by the delay of the reservoir filling and the time taken by the turbidity plume to progress downstream. Normal concentrations were reached two months after the turbidity front had reached the water supply installations of the two municipalities (Figure3-16a and b).

Lessons were drawn from this experience.

- Despite of the geological surveying, the geomorphological study and the deforestation of the reservoir banks, it has been impossible to predict such a level of turbidity. Indeed, sources of suspended load were limited over a few zones with silt and clay contents, very hard to detect
- Emphasis of the importance of the communication system between the developer and the concerned population which allowed for an excellent cooperation in order to limit adverse effects.
- About the erosion and landslides, this experience shows the importance to have an efficient environmental follow up program during the filling phase of this reservoir so as to ward off all eventualities. It was surely through an efficient environmental follow up that the impact on drinking water supply was controlled.
- Observation of the great capacity of the marine fauna to temporarily tolerate and sustain unusual environmental conditions.

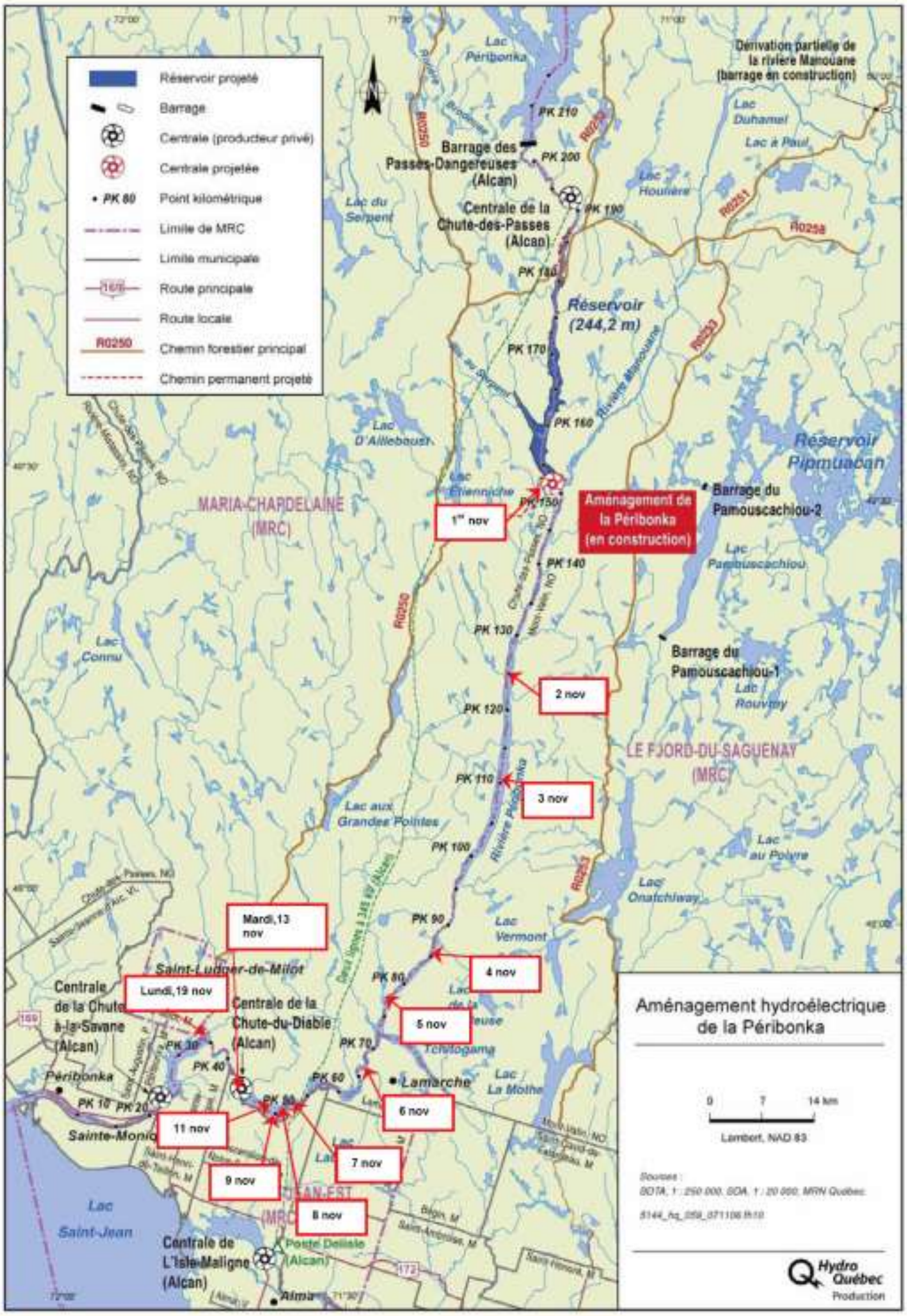

Figure 3-12: General layout of the installations on the Péribonka river

Figure 3-12 also shows the progression of the turbidity front during the filling of the reservoir.

Figure 3-13: Landslides in a sandy bank at K.P 177,5 (Réf. H.-Q.-Polygéo-2007

Figure 3-14: Landslides in a sandy bank with silt content at K.P 174,5 (Réf. H.-Q.-Polygéo-2007)

Figure 3-15: Satellite image of November 5th 2007

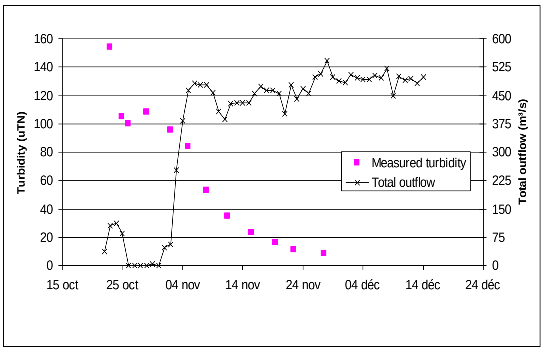

Figure-3-16a: Turbidity progression in the Péribonka power plant reservoir

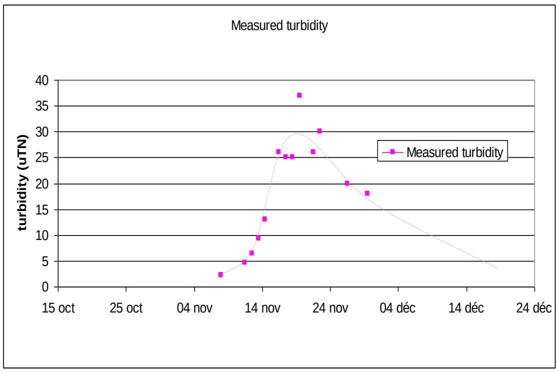

Figure-3-16b: Turbidity in the Chute-du-Diable reservoir (105km downstream)

3.4.4 Structural Options - Multi Level Offtake Towers

There are ranges of structural options available for the selective withdrawal of specific layers of water from the reservoir. These range from floating offtakes, to multi level fixed offtakes and continuous screen systems.

Floating Offtakes with Pivot arms or Trunnions

The basic concept consists of a pipe off-take that is attached to a float. The concept is shown diagrammatically in Figure 3-17. Generally, for this type of option the diameter of the intake is limited to about 1000 mm or flow rates of up to about 2m^3/sec, which does not provide sufficient capacity for the bulk water discharges required for major water storages, hydro power stations or irrigation dams. In addition there is a practical feasibility that limits the length of the pipe to about 25 meters and hence it is only suitable for withdrawals at shallower depths. This option would be suitable for smaller volume town water supply

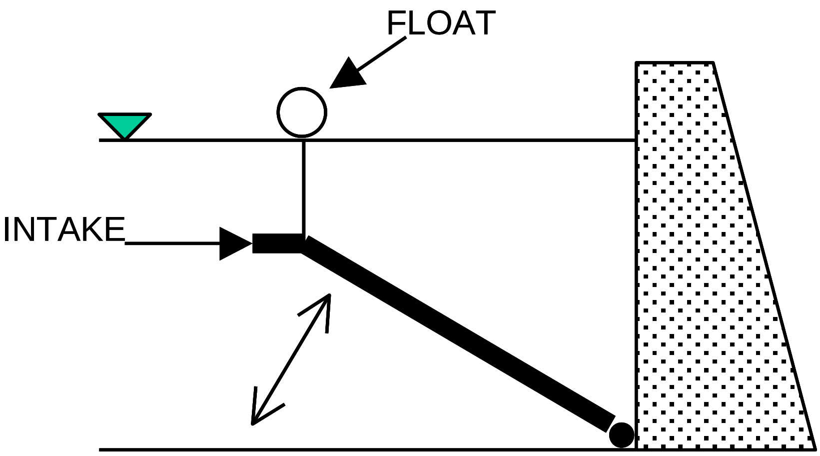

Figure 3-17 Pivoting Arm Option

Dry Tower Multi Port Intake Towers

In Australia a recent survey indicated that the preferred method for achieving selective withdrawal is via a "dry" tower consisting of multi-leveled bell-mouth inlet ports connected to an internal conduit that passes vertically down inside the tower (Figure 3-18). Inflow into each inlet port is controlled by a butterfly valve or penstock gate that is either fully open or closed. Operation of the valves and maintenance of the system is easily carried out from within the tower structure with access being from either the top platform or via a tunnel under the embankment. Many of these structures can also be operated remotely from the tower platform or from control rooms by SCADA. In Australia, the majority of these types of dry intake structures are used for drinking water supply, however some authorities do operate this type of inlet for irrigation water.

Figure 3-18: Two Intakes Exposed on a Dry Multi Port Intake Tower

Dry intake structures have limited flexibility in being able to only selectively withdraw from the specific levels at which the ports are set. Typically, dry intakes may have no more than about 6 draw off levels. The acceptability of the arrangement will depend on the specific conditions within the storage and the objectives for the withdrawal conditions. The main drawback though for the dry type intakes is the limited draw off capacity. This capacity is limited by the cost to provide sufficiently large intakes, valves and conduits. For this reason dry intake structures are typically not suited to the flow rates in excess of 10 to 12 m^3/sec.

Continuous Baulk and Screen Options

These structures incorporate a method of selective withdrawal by using a trashrack and baulk system (Figure 3-19). The trashracks and baulks are positioned vertically within a slot located on the upstream side of the intake tower and line up with the corresponding inlet ports, depending on the withdrawal level or depth that has been selected. This style of intake tower is considered to be the best design and practice for the required discharge volumes, having been used to control discharges up to 50 m^3/sec. In practice, however, design limitations pose potential significant constraints to operating these structures for effective downstream thermal and water quality management. Changing the withdrawal level is a slow and manually intensive task involving some significant occupational safety issues

All of the structures consist of either one or two vertical columns of intake ports on the upstream side of the tower. Positioned in front of each column of intake ports is a single slot that permits the trashracks and baulks to be vertically stacked one on top of the other in line with the port openings. The baulks prevent water entering the intake structure at the corresponding depth and are positioned above and below the desired release depth. The trashracks screen coarse material and reservoir debris and are set at a height corresponding to the desired intake level. The trashracks on some dams have been retrofitted with finer screens suitable for use with mini hydro schemes. The intake structures are described as being “wet” since water fills the entire internal cavity and gravitates down to the base of the tower, through the bulkhead and into the outlet tunnel. Flow through the intake structure is controlled with the penstock valve. Lowering of the main bulkhead gate enables the penstock to be dewatered. Figure 3- is a diagrammatic representation of the system.

In the United States a survey of selective withdrawal systems undertaken by the Bureau of Reclamation (2003) gathered basic design and operational data for large selective withdrawal dams in the US. Many of the dam operators canvassed in the USBR survey indicated that it would not be practical to automate the operation of the selective withdrawal gates at their dams. The most common reason given for not automating the operation of systems was that the infrequency of operation made it difficult to justify the cost. The majority of respondents indicated that intake level change was undertaken on average once every month.

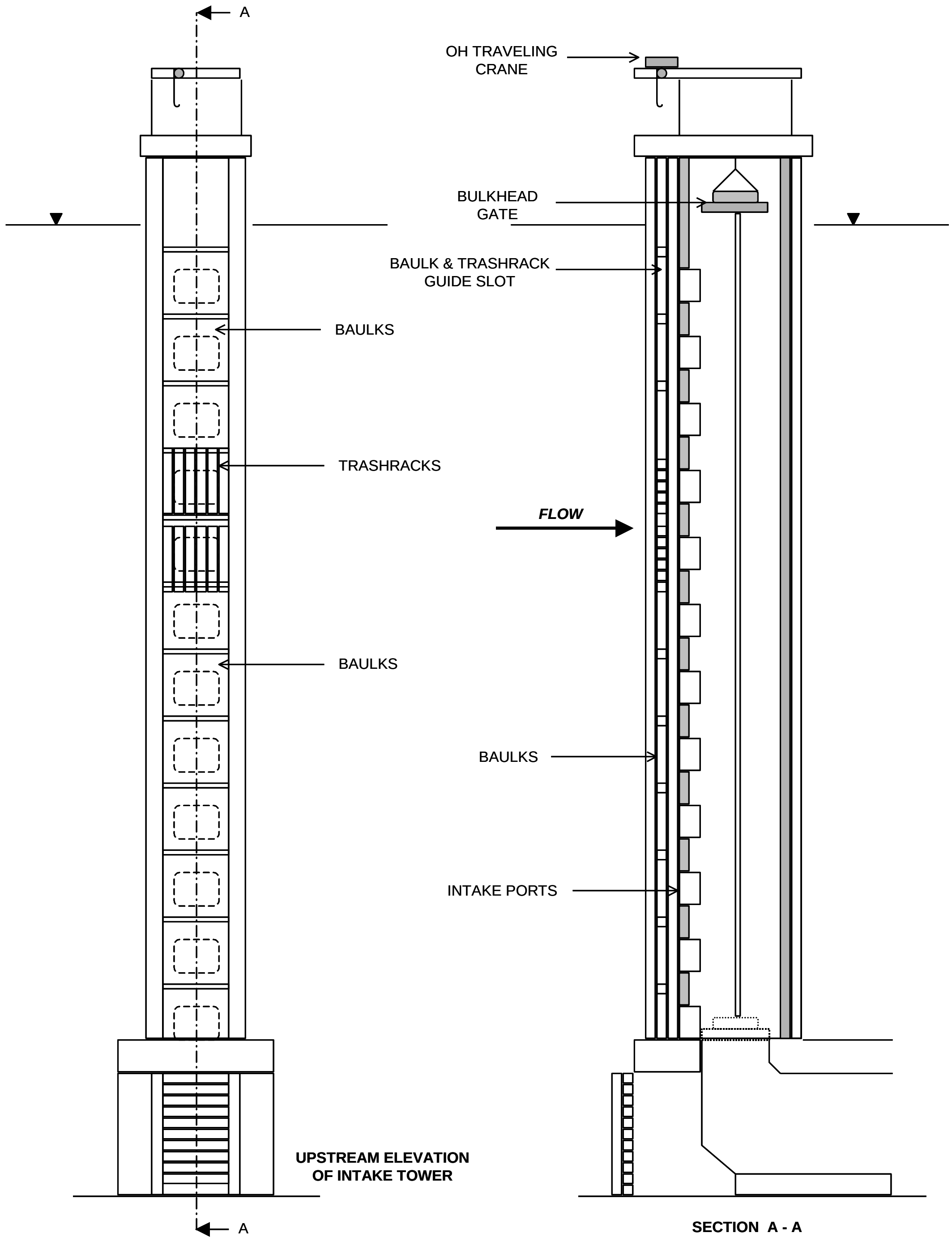

Figure 3-19: Basic Operation of Selective Withdrawal

A number of intake structures in the US have undergone major retrofitting to add selective withdrawal capability to improve release water quality. A selection of these is briefly described below

Shasta Temperature Control Device, California

Completed in 1998, this is a retrofitted multi-level water intake structure (Figure 3-20). Water withdrawal is controlled by a 91 meter tall and nearly 80 meter wide shutter structure that was added to the upstream face of this concrete dam. The shutter extends about 15 meters upstream from the face of the dam, and is open between units to permit crossflow in front of the existing trashrack structures. It was manufactured off-site and lowered into the water and assembled by divers and attached to the upstream face of the dam. The total cost of the project was US$80M.

 

Figure 3-20: Shasta Dam Multi Level Offtake Structure

Glen Canyon Dam, Arizona

This is the fourth highest dam in the US. The proposal is for an uncontrolled overdraw design where flow enters the top of the intake tower (built on the upstream face of the dam) 50 meters above the existing intake. The operational flexibility of this design is limited due to reservoir elevation fluctuation

Flaming Gorge Dam, Utah

Completed in 1978, the retrofit consists of electrically controlled gates that allow the release of water from different depths in the reservoir.

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4 DOWNSTREAM IMPACTS OF LARGE DAMS

4.1 INTRODUCTION

Riverine ecosystems are important centres of biodiversity; freshwaters support a relatively high proportion of species, and more per unit area than other environments; 10% more than land and 150% more than oceans. While only about 45,000 species of freshwater animals, plants microorganisms have been scientifically described and named, it is estimated that an additional million species remain to be named.

Changes in ecological processes, arising as a consequence of the change in flow regime, can have profound social and economic repercussion for people dependent on the natural resources and ecosystem functions of floodplains and wetlands to sustain their livelihoods.

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

In 1970s concerns about large dams began to be raised, contemporary thinking regarding integrated water resources management strongly supports the river basin as the logical basic unit for water planning and management.

Analysis of the operation of the world’s 45.000 large dams and their associated infrastructure (e.g. irrigation, water supply systems) shows that operational efficiencies can be improved by upgrading and modifying operations. Countries also are exercising the option to de-commission some dams when they have reached the end of their useful lives, or their environmental impacts have been judged unacceptable[20].

4.2 RIVER ECOSYSTEMS

4.2.1 Ecosystem Interconnectivity

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

4.2.2 The parts of flow regime

The flow regime is the pattern and timing of high and low flows in a river. Each river’s flow regime is different, depending on the characteristics of its catchments and the local climate, although regional trends do emerge. The different river flow characteristics play an essential role in river system conservation, manipulations of the flow regime will affect the river ecosystem; therefore, the efforts should be focused to avoid these unwelcome changes as the river responds, or trying to predict the potential changes and managing them.

River ecologists recognise that different parts of the flow regime play different roles in maintaining a river of which, low flows, small floods, large floods and variable flow, which can be described as follows:

The low flows are the daily flows that occur outside of high-flow peaks. They define the basic seasonality of the river: its dry and wet seasons, and degree of perenniality. The different magnitudes of low-flow in the dry and wet seasons create more or less wetted habitat and different hydraulic and water-quality conditions, which directly influence the balance of species at any time of the year.

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

In some rivers, dry-season low flows are periodically completely eradicated by damming or direct abstraction. Such reaches will lose their fish, and other river life will be drastically reduced in diversity and numbers because most cannot cope with periods of drying out, even for a few hours.

In ephemeral rivers, dams or other abstractions may halt the movement of groundwater along the channel, killing ancient riparian trees. This has happened in the *Luvhuvhu* River, Kruger National Park (which should be a perennial river), and could happen to the linear oases of trees along the rivers flowing east to west across Namibia that support the large desert mammals and local indigenous peoples [3].

Small and medium floods are usually of great ecological importance in semi-arid areas in the dry season. They mobilise smaller sediments and contribute to flow variability, stimulate spawning in fish, flush out poor-quality water. They re-set a wide spectrum of conditions in the river, triggering and synchronising activities as varied as upstream migrations of fish and germination of riparian seedlings.

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

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

Large floods trigger many of the same responses as do the small ones, but additionally provide scouring flows influence the form of the channel. They mobilise coarse sediments, and deposit silt, nutrients, eggs and seeds on flood plains. They inundate backwaters and secondary channels, and trigger bursts of growth in many species. They recharge soil moisture levels in the banks, inundate flood plains, and scour estuaries thereby maintaining links with the sea.

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

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

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

It is often claimed that dams cannot harness the larger floods, which will spill over. They may well reduce their size, however, so that ones of a magnitude that occurred on average every two years could occur as a spill of that magnitude only once in five to ten years.

4.2.3 Flow Variability

Fluctuating discharges constantly change conditions through each day and season, creating mosaics of areas inundated and exposed for different lengths of time. The resulting physical heterogeneity determines the local distribution of species: higher physical diversity enhance biodiversity.

4.3 DAMS AND RIVER SYSTEMS

4.3.1 The role of dams

If water is life, rivers are its arteries. Dams regulate or divert the flow through these arteries, affecting the life-blood of humanity.

In many countries dams provide reliable supplies of electricity and water. The main purposes of dams are:-

- Hydropower: Globally hydropower provides about 19% of electricity generated (That is 2.650 TWh/y). The remaining economically exploitable potential is 5.400 TWh/y, of which about 90% is in the low-income regions (IEA).
- Irrigation: About 30-40% of irrigated land worldwide relies on dams (WCD, 2000), about 40% of food produced is from irrigated land (about 150 million hectares, or 17% of agricultural land). In the next 25 years about 90% of food production is anticipated to come from existing land. This implies a need to double the productivity of irrigated land, particularly in Asia and Africa.
- Flood and drought management: nearly 2 billion people live in areas of high flood risk. Due to climate change, scientists expect that, the frequency and intensity of extreme weather events-including floods and droughts- will increase. Dams can play an important role in strategies to adapt to climate change by storing water and regulating flow.
- Drinking water.

Table 4-1: Dam's purposes globally distribution [10]

• Irrigation only	37%
• Multi-purpose	22%
• Electricity generation only	16%
• Water supply only	12%
• Flood control only	6 %
• Recreation only	3 %
• Other	4 %
• Total	100%

Despite all these positive effects, many dam projects have fallen into disrepute because of their various drawbacks.

4.3.2 Scale and variability of impacts

There are different types of dams each with their own operating characteristics. Similarly, dams have been built in a wide array of conditions, from highlands to lowlands, temperate to tropical regions, fast flowing to slow flowing rivers, urban and rural areas, etc. the combination of dam types, operating systems, and the contexts where they are located, yields a wide array of conditions that are site specific and very variable. This complexity makes it difficult to generalize about the impacts of dams on ecosystems, as each specific context is likely to have different types of impacts and to different degrees of intensity.

Types of dams, in descending order of impacts on ecosystems:

- Storage dams : large reservoirs with or without river diversions,

- Diversions (run-of-river): uses flow with limited or no storage; diverts all or part of river flow through turbines,
- River barrage: low level storage; no river diversion, and
- Run-of- river: uses flow with limited or no storage; no river diversion.

In addition to dam type the height of dams and their reservoir areas are extremely variable

4.3.3 Problems associated with large dams

The effects of dams on the river downstream usually include a decrease in both, the magnitude, frequency and duration of flood flows, and, the quantity and calibre of the sediment load (Petts and Lewin 1979). If these process changes are of sufficient magnitude they should induce a readjustment of channel form.

Dams impact indirectly on the downstream river ecosystem by potentially affecting every part of the flow, sediment, thermal and water-quality regimes. They may also impact the ecosystem directly by, for instance, blocking fish passage. As a result, the problems can be summarised as follows:

- Flow regime transformation.
- Impacts on flow patterns.
- River Ecosystems impacts.
- Socioeconomic impacts.

However, these concerns and impacts can be reduced or eliminated by careful planning, and the incorporation of a variety of mitigation measures.

4.3.4 Flow regime transformation

Dams have an impact on the hydrological cycle, replacing natural high and low flows by an artificial regime. In general discharge control resulting from the damming of rivers reduces flow variability downstream from the dam. Although for major flood plain rivers, dams may increase flood peaks it is normally the case that the magnitude and timing of flood peaks is reduced. The effect of a reservoir on individual flood flows depends on both storage capacity of the dam relative to volume of flow and the way the dam is operated as mentioned above.

The nature hydrological effects vary with the purpose of the dam and the seasonal regime of the river regime of the river. Dams come in many different shape and size. A critical distinction between types of dams reflects their purpose. Dams for flood control exacerbate peak flow moderation effects, particularly in such torrential rivers; hydroelectric dams are designed to create a constant flow through turbines, and therefore tend to have a similar effect on discharge patterns. However, if the intention is to provide power at peak periods, variations in discharge of considerable magnitude can occur over short timescales, such hydropeaking creates artificial freshets or floods downstream.. Dams for irrigation cause moderate variations in flow regime on a larger time scale, storing water at seasons of high flow for use at times of low flow. Discharge beyond storage capacity is usually spilled, allowing some flood flows to pass downstream, albeit in routed and hence attenuated form; dams are often designed to have multiple functions, in which case their impacts will be a combination of the above forms.

Reservoirs having a large flood-storage capacity in relation to total annual runoff can exert almost complete control upon the annual hydrograph of the river down stream. However, even small-capacity detention basins can achieve a high degree of flow regulation through a combination of flood forecasting and management regime. In addition to altering the flow regime of rivers, dams also affect the total volume of runoff. These changes may be either temporary or permanent. Temporary changes arise primarily from filling the reservoir, which may take several years where reservoir storage greatly exceeds the mean annual runoff, Permanent changes occur because of:

- Water is removed for direct human consumption and not returned to the river (e.g. for irrigation or interbasin transfer).
- Water is lost from the reservoir through evaporation.
- Under certain geological conditions there are increased transmission losses down stream of the dam.

The hydrological effects of a dam become less significant the greater the distance downstream (i.e. as the proportion of the uncontrolled catchments increases). The frequency of tributary confluences below the dam and the relative magnitude of the tributary streams, play a large part in determining the length of the river affected by an impoundment. Catchments in semi arid and countries with significant storage may never recover their hydrological characteristics even at the river mouth, especially when dams divert water for agriculture or municipal water supply.

Flow regimes are the key driving variable for downstream aquatic ecosystems. Flood timing duration and frequency are all critical for the survival communities of plants and animals living downstream, therefore, the main forms of flow regime transformation can be observed in case of flood regime and low flow regime.

4.3.5 Flood regime

Uncontrolled floods cause tremendous damage and flood control is therefore often an added social and environmental benefit of dams. Dams and reservoirs can be effectively used to regulate river levels and flooding downstream of the dam by temporarily storing the flood volume and releasing it later.

Radically altered flood regimes may also have negative impacts. Controlled floods may result in a reduction of groundwater recharge via flood plains and a loss of seasonal or permanent wetlands. Changes to the river morphology may result because of changes to the sediment carrying capacity of the flood waters. This may be either a positive or negative impact. As a consequence, a series of impacts is expected impacts resulting from a change in the flow regime of rivers, or a change in the movement of the water table, through the seasons.

It should be noted that other the critical point is that most dams moderate and delay the incoming flood peak because of the flood-routing effect of the impoundment. Such effects can be particularly significant where river regime is flashy and such peaks are common, for example, some rivers in the semi-arid tropics such as River Nile after constructed High Aswan Dam, The outflow from the dam was completely controlled and the maximum monthly discharge has been reduced by 30 %, while the minimum monthly discharge has been increased by 40 % which led to serious impacts in terms of river's behaviour downstream [16].

It is also important to recognize the interrelationship between river flows and the water table, during high flow periods; recharge tends to occur through the river bed whereas groundwater often contributes to low flows.

4.3.6 Low flow regime

The natural varying discharges over the year may have certain disadvantages for certain users, such as too small discharge for navigation in the dry season, flooding during peak discharges, etc. By means of a reservoir water can be stored during the peak discharges and released during the dry season, thus adapting the discharge hydrograph of the river, downstream of the reservoir.

A reduction in the natural river flow together with a discharge of lower quality drainage water can have severe negative impacts on downstream; changes to the low flow regime may have significant negative impacts on downstream users, whether they abstract water (irrigation schemes, drinking supplies) or use the river for transportation or hydropower.

Minimum demands from both existing and potential future users need to be clearly identified and assessed in relation to current and future low flows. The quality of low flows is also important, therefore, low flows need to be high enough to ensure sufficient dilution of pollutants. Large changes to low flows (± 20%) will alter micro-habitats of which wetlands are a special case. It is particularly important to identify any endangered species and determine the impact of any changes on their survival. An example is the Senegal River downstream of the Manantali Dam where the extent of wetlands has been considerably reduced, fisheries have declined and recession irrigation has all but disappeared [1].

4.3.7 Impacts on flow patterns

River response to flow regulation and sediment abstraction is often complex, with channel adjustments varying spatially and changing with time, therefore, Complex relationships exist between channel form and processes. Due to that regulation of river's natural flow a series of impacts are expected downstream which can summarized as impacts on river morphology itself, flood plains and costal delta:

In general the frequency of flood discharges, the magnitude and particle-size distribution of the sediment load, are the dominant control of channel and floodplain morphology. Reservoirs alter the processes operating in the downstream river system, by isolating upstream sediment sources, controlling floods and regulating the flow regime. A unique combination of climate, geology, vegetation, size of impoundment and operational procedures produce the effect of any individual dam upon the fluvial processes downstream. Hence, a wide range of geomorphological responses can be generated by river regulation.

Some physical changes caused by dams are immediate and obvious while others are so gradual that they may go unrecognized by humans using the river for many years. As an example of these slow and not always intuitive impacts is blocking sediment transport, which can be resulted in lowering of the river bed and deepening of the channel as a consequence of sediment starvation. This channel incision impacts the frequency of floodplain inundation, as the deeper channel requires a higher discharge to overtop its banks and spill out on the floodplain. (i.e. Amazon floodplain).

4.4 DOWNSTREAM IMPACTS OF DAMS ON RIVER MORPHOLOGY:

4.4.1 introduction

Changes to the river morphology may effect downstream uses, in particular navigation and abstraction for drinking, industry and irrigation. The river ecology may also be adversely affected.

The capacity and shape of rivers result from its flow, the river bed, bank material and sediment carried by the flow. A fast flowing river has more energy and is able to carry higher sediment loads (both more and larger particles) than a slow moving river. Hence, sediments settle out in reservoirs and in deltas where the flow velocity decreases. A river is said to be in regime when the amount of sediment carried by the flow is constant so that the flow is not erosive nor is sediment being deposited. On the other hand, the regime condition changes through the year with changing flows.

The main impacts of dams on river morphology include

- Change of sediment load concentration.
- Erosion and sedimentation.
- Changes in the thalweg line and flow direction characteristics.
- Changes in bed forms and resistance to flow.
- River bed degradation.
- Changes in the length and stability of river banks.

Reductions in low flows and flood flows may significantly alter the river morphology, reducing the capacity to transport sediment and thereby causing a build up of sediments in slower moving reaches and possibly a shrinking of the main channel. Increasing flows will have the reverse effect. Where the sediment balance changes over a short distance, perhaps due to a reservoir or the flushing of a sediment control structure, major changes to the local river morphology are likely to occur. The release of clear water from reservoirs may result in scour and a general lowering of the bed level immediately downstream of the dam, the reverse of the effect that might be expected with a general reduction in flows.

The geomorphological effects of changes in flow and sediment can be recognized if the post-regulation flows remain competent to move bed material; the initial effect is degradation downstream from the dam, because the entrained sediment is no longer replaced by material arriving from upstream.

According to the relative erodibility of the streambed and banks, the degradation may be accompanied by either narrowing or widening of the channel. A result of degradation is a coarsening in the texture of material left in the streambed; in many instances, a change from sand to gravel is observed and, in some, scour proceeds to bedrock. On most rivers these effects are constrained to the first few kilometres or ten of kilometres below the dam. Degradation of up to 7.5 m has been observed on large rivers (e.g. the *Colorado* below the *Hoover* dam). Further downstream, increased sedimentation (aggradation) may occur because material mobilized below a dam and material entrained from tributaries can not be moved so quickly through the channel system by the regulated flows. Channel widening is a frequent concomitant of aggradations [9].

High Aswan Dam on river Nile illustrates these changes which occurred after finishing construction and still running on the river's behaviour for instance the sediment concentration was changed from 3000 ppm in 1959 to 65 ppm after construction, as well as diameter of the bed material which increased from 0.22 mm before dam constructed to (0.23-0.42) mm, and there are enough evident showed the fact that reveals the river's bed may get coarser [16].

The Yellow River provides another example of unfavourable changes to the river regime such as shrinking of the river channels due to the regulation of upstream reservoirs made peak floods decrease greatly. In the lower Yellow River during the period 1986~2000, the combined operation of Liujiaxia reservoir, Longyangxia reservoir and other middle or small reservoirs, lead most of the sediment to be deposited in the main river channel. This, together with additional reclamation of flood plain along the river, caused a shrinking of the channels. The lip of floodplain becomes even higher than the bed elevation at the levee toe, forming "a secondary perched river" (see Figure 4-1).

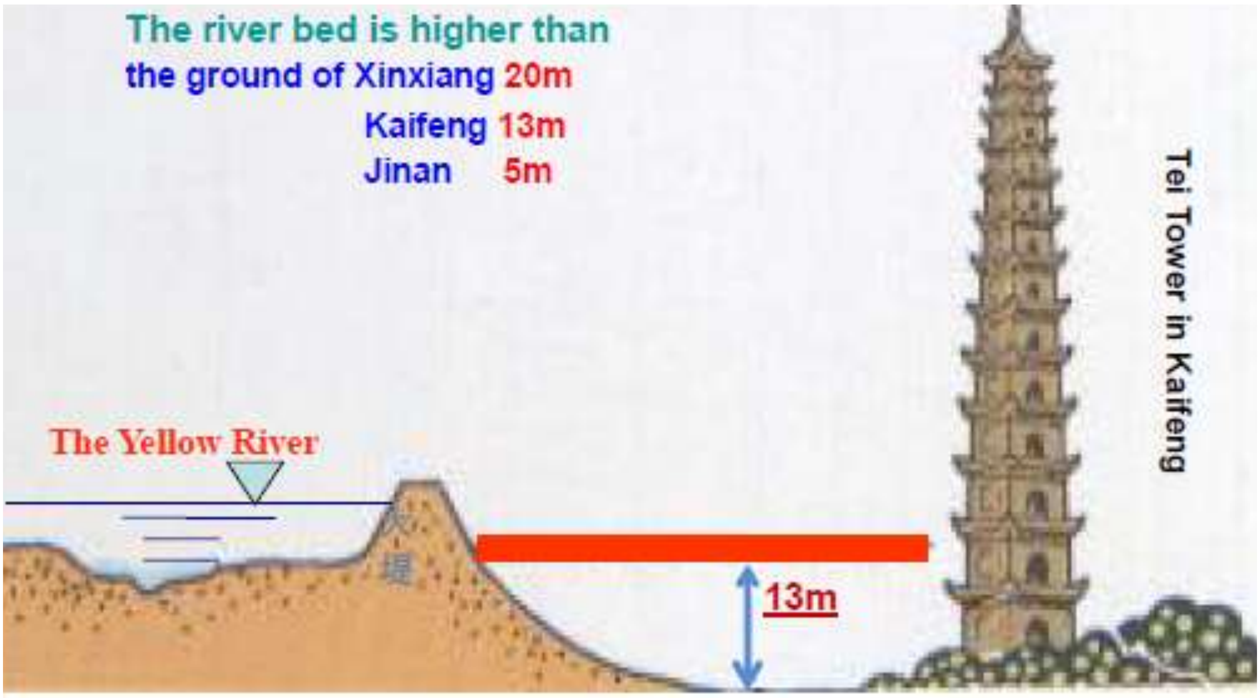

Figure 4-1 Yellow River – Suspended River

The river capacity for flood conveyance and sediment transport was sharply reduced; the bank full discharge decreased from 7000m3.s-1 in 1985 to 2600-3000m3.s-1 at present. Channel shrinking as well as over abstraction of water upstream, which made the lower Yellow River dry up during the drought season, deteriorated the water ecosystem. Similar phenomena occurred also in the lower Weihe River, the largest tributary of the Yellow River, in Haihe River and the middle Huaihe River [13]. However, with the operation of Xiaolangdi reservor in 2000, the sediment-water regulation project was carried out every year. In the flood season the large clear flow was discharged into the lower river channel and most of the channel was scoured. In non-flood season, the low sediment-laden flow only caused little deposition. Up to 2012, the channel bed has been scoured more than 2m and the bank full discharge has been increased to 4200~7000m3/s. The channel section has transformed from wide-shallow type to narrow-deep type (see Figure 4-2).

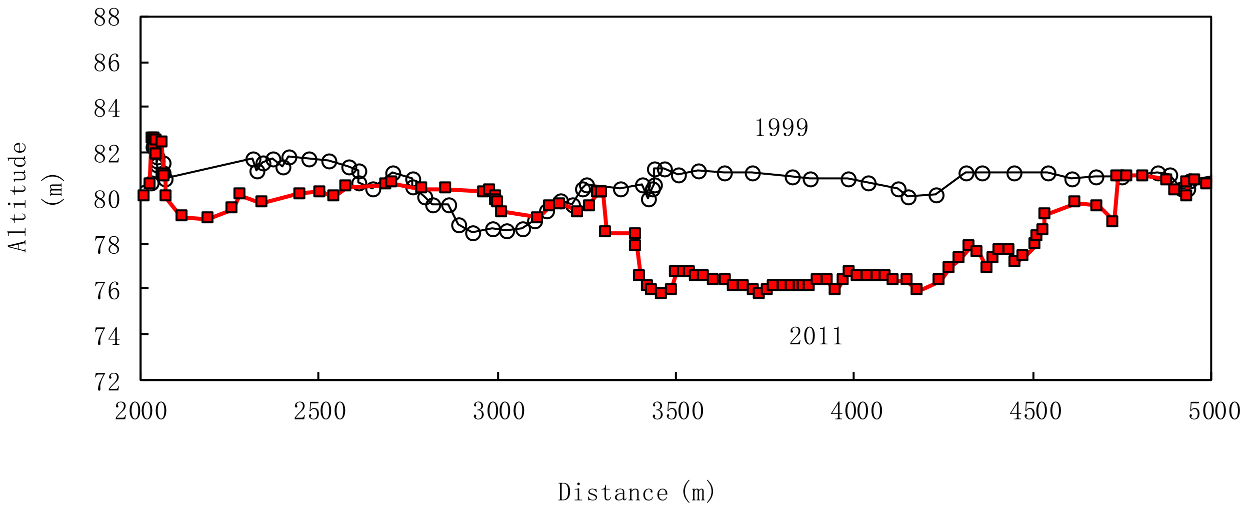

Figure 4-2 Typical Cross Section of the Lower Yellow River Reach

One significant impact also is river carrying capacity and channelling response downstream the dam when there is sediment injection and runoff from an unregulated tributary, which frequently initiates channel changes at a discrete point along a river downstream of the confluence, the channel may not only contracted and degraded but also migrated laterally, reworking some of the floodplain sediment. Degradation has been associated with a progressive coarsening of the bed material. The remaining cross-section sites have exhibited little morphological change due to the constraints outlined above, although there also has been a winnowing of fines and coarsening of the bed material, an example of such case is river Hunter downstream of Glenbawn Dam in Australia [5].

4.4.2 Floodplains

Under natural conditions sediments feeds floodplains, creates dynamic successions, and maintains variability and instability. Changes in sediment transport have been identified as one of the most important environmental impacts of dams. The reduction in sediment transport in river downstream of has impacts on channel flood plain.

Damming a river can alter the character of floodplains. In some circumstances the depletion of fine suspended solids reduces the rate of overbank accretion so that new floodplains take longer to form and soils remain infertile. In other circumstances, channel bank erosion results in loss of flood plains. For example, between 1966 and 1973, some 230 ha of land were lost from 10% of the total bank-length of the Zambezi below the Kariba dam. Erosion was particularly pronounced at alluvial sites with non-cohesive sandy bank materials and was attributed to: the release of silt free water; the maintenance of unnatural flow-levels, sudden flow fluctuations, and out –of- season flooding. However, in some places the reduction in the frequency of flood flows and the provision of stable low flows may encourage vegetation encroachment which will tend to stabilize new deposits, trap further sediments and reduce flood plain erosion. Hence, depending on specific conditions, dams can either increase or decrease floodplain deposition/erosion [15].

River Nile, as well, shows this significant reduction was happening in the total length of the river bank, from 2409 km in 1950 to 2048 in 1978, and a further reduction to 2035 km in 1988 [16].

4.4.3 Coastal Deltas

In contrast to the impact on river and floodplain morphology, where aggradation may occur, impounding river invariably results in increased degradation of at least part of coastal deltas, as a consequence of the reduction in sediment input for example, the slow accretion of the Nile Delta in Egypt was reversed with the construction of the Delta Barrage in 1868. Today, other dams on the Nile including the high Aswan dam have further reduced the amount of sediment reaching the delta from 129 million tons/year before 1968 to 94 million tons/year. As a result much of the delta coastline is eroding at rates up to 5-8 meters per year, but in places this exceeds 240 meters per year. Similarly [16], erosion part of the Rufiji Delta, Tanzania, by up to 40 meters per year, is attributed to the construction of dams (Horrill, 1993). The consequences of reduced sediment may also extend to long stretches of the coastline eroded by waves which are no longer sustained by sediment input from rivers. It is estimated that the entire coastline of Togo and Benin are being eroded at a rate of 10-15 meters per year because the Akosombo dam on the Volta river in Ghana has halted the sediment supply to the sea (Bourke 1988).another example is the Rhone river, where a series of dams retains much of sediment that was historically transported into the Mediterranean and fed the dynamic processes of coastal accretion there. It is estimated that theses dams and associated management of the Rhone and its tributaries have reduced the quantity of sediment transported by the river from 12 million tons in the 19th century to only 4-5 million tons today. This has led to erosion rate of up to 5 meters per year for the beaches in some regions [1].

4.4.4 The impacts of dams on downstream river ecosystems

There are different classifications for the ecosystems components and the interaction between theses components and the functions of each. The general classification of ecosystems functions can be grouped into four main categories of which:

- Regulation functions
- Habitat functions
- Production functions
- Information functions

Dams are intended to alter the natural distribution and timing of stream flow in order to meet human needs. As such, they also alter essential processes for natural ecosystems. Dams constitute obstacles for longitudinal exchanges along rivers. By altering the pattern of downstream flow (i.e. intensity, timing and frequency), they change sediment and nutrient regimes and alter water temperature and chemistry. Storage reservoirs flood terrestrial ecosystems, killing terrestrial plants and displacing animals. As many species prefer valley bottoms, large scale impoundment may eliminate unique wildlife habitats and extinguish entire populations of endangered species. Terrestrial ecosystems in reservoir area are replaced by lacustrine, littoral and sublittoral habitats and pelagic mass-water circulations replace riverine flow patterns. Consequently, there are manifold impacts on the natural ecosystem of which:

- Effects of stopping the flow of nutrients downstream.
- Reduced biological activity downstream (in arid areas often an increase in quantity of flora and fauna).
- Reduction in downstream flooding may result in less natural submergence for flood-recession agriculture, reduction in groundwater recharge and reduction in removal of parasite by natural flooding.
- Impacts on quantity of water needed for maintaining downstream ecology.
- Anaerobic decomposition of vegetation and production of greenhouse gases.
- Environmental degradation from increased pressure on land such as irrigated agriculture, industries and municipalities
- Dams form obstacles to passage of trees, floating debris, ice and ships.
- Water loss due to evaporation.
- Induced seismicity.
- Rivers may dry up.

A good example for the link between changing flow regime, patterns and ecosystems impact is river Nile and aquatic weeds problem, which observed after construction High Aswan Dam and attributed to the clearness of water because of sediment blocking, therefore, water became clear and free of suspensions and consequently allowing deeper penetration of light, which led to serious problems such as water losses and decreasing of irrigation efficiency by convey this weeds to the irrigation canals [16].

4.4.5 Socioeconomic impacts

The main role of dams is considered in the context of sustainable development, this involves dealing not only with environmental and social issues but also economic aspects associated with the benefits of dams.

Due to the fact that dams alter and divert rivers flows, affecting existing rights and access to water, and resulting in significant impacts on livelihood and environment.

As with other forms of economic activity, dams can have both positive and negative social aspects. Social costs are mainly associated with transformation of land use in the project area, and displacement of people living in the reservoir area.

Therefore, dams' constructions have serious impacts on the spatial and social changes as well as demographic dynamics and people health.

As an example of such impacts, the region of Tucurui in Brazil has undergone quantitative and qualitative alterations in its demographic structure and composition that are directly related to the various planning and implementation stages of the Tucurui hydropower complex. During the period prior to the announcement of the construction of this hydropower complex and the series of government intervention through road – building and settlement projects, the most heavily populated in the entire region was Cometa, with almost 50,000 inhabitants. The reminder had less than 8,000 inhabitants. News of construction of this hydropower complex drew large inflows of migrants, with Turcurui absorbing a significant portion of them, increasing its population, appreciable growth was also noted at Jacunda and Itupiranga, with annual growth rates of around 20.90% and 11.33% respectively. Overall this region doubled its population in less than ten years, and this trend has continued, despite certain shrinkage during subsequent decades [21].

It should be noted that, dams' projects may represent a significant source of revenue for local communities. The access roads, local availability of electricity and other activities associated with the reservoir are all possible sources of sustainable economic and social development. But there must be good co-operation between proponents, authorities, political leaders and communities, and long-term benefits must be directed to affected communities.

4.5 THE COMPLEXITY OF DOWNSTREAM IMPACTS

4.5.1 The Issues

The river characteristics, in particular the frequency of flow extremes, exert important controls upon every physical, chemical and biological attribute of riverine, riparian and in many instances coastal ecosystems downstream of the impoundment. The changes induced by large dams may affect ecosystem and people who depend on them for tens to hundreds of kilometres downstream

Downstream impacts of dams are complex, and have knock-on secondary and tertiary impacts on aquatic and flood plain ecosystems. These often go unrecorded, except by those left coping with them. There are relatively few studies of downstream degradation following dam construction in the third world. Downstream impacts can extend for many hundred kilometres downstream, and well beyond the confines of the river channel. Transformation or modifications of discharge patterns and stream environments have a range of significant effects on those ecosystems.

These impacts involve a change in a dynamic element of the environment (variable river flows within and between years) rather than gross change (a lake where there used to be dry land). A critical problem therefore is the issue of uncertainty. There is inevitably a high degree of uncertainty in predicting the nature of the downstream environmental impacts of dams at any given point in space and time. A key challenge is how to convey the fact of uncertainty to stakeholders and decision makers, and how to devise planning frameworks that take into account.

There are difficulties with the concept of downstream impacts in case of river basins where flights of dams, or linked sets of dams have been built. There are also conceptual difficulties where these upstream and downstream dams are linked, and are dependent on each other for their functioning (e.g. using headwater storage and release to a downstream dam). A good example of this is Bio-Bio River in Chile and *Parana* River in Brazil [2].

4.5.2 Principles for Taking Account of Downstream Impacts

Most of the impacts can be managed through good design and effective mitigation measures. Recommendations should ensure that decision-making results in a more balanced outcome, giving equal weight to environmental and social factors as to economic and financial factors. However, they are yet to be applied in a consistent manner.

Five principles are suggested below that indicate how downstream impacts could be taken into account by dam planners, of which [2]:

1. Analysis of the impacts of dam's impacts should be holistic, in spatial, *social* and economic senses.
2. A program to monitor and periodically re-examine the impacts of dam development in downstream communities should be an integral element of the planning and process, and should be matched by resources to mitigate impacts not addressed fully by the planning process.
3. All people who depend on the natural flow of the river and its associated natural resources for their subsistence should be adequately compensated for losses resulting from dam construction, or be among the primary recipients of benefits generated.
4. The existing individual and community rights of riverine populations to natural resources to be affected by planned dams should be recognized in assessing potential losses and in devising mitigation measures, whether these rights are codified or informal, whether they relate to ownership or usufruct rights.
5. Project planning should allow for the participation of people affected by project development in downstream areas.

Due to wide range of impacts and its consequences, its important to find a common classification aims to categorize these impacts depending on their effects, WCD suggested the following classification:

- First order impacts: are the immediate abiotic effects that occur simultaneously with dam closure and influence the transfer of energy and material into and within the downstream river and connected ecosystems (e.g. changes in flow, water quality and sediment load).
- Second order impact: are the abiotic and biotic changes in upstream and downstream ecosystem structure and primary production, which result from first order impacts. These depend upon the characteristics of the prior to dam closure (e.g. changes in plankton,), and these changes may take place over many years.
- Third order impacts: are the long-term biotic changes resulting from the integrated effect of all the first and second order changes. Complex interactions may take place over many years before new ecological equilibrium is achieved.

In general terms the complexity of interacting processes increases from first – to- third order impacts. Since the ecosystem functioning is guided by abiotic steering variables related to hydrology (i.e. water quantity and flow regime), geomorphology and water quality, observations related to these ecosystem components can be used as primary indicators of river ecosystem condition. Such changes are the key to understanding the long-term ecological consequences of dams as they are the underlying mechanisms by which many habitats are maintained.

4.6 Responding to the Ecosystem Impacts of Dams

The impact of dams upon natural ecosystems and biodiversity has been one of the principal concerns raised by large dams. Over the course of the past 10 years in particular, considerable investments have been made in the development of measures to alleviate the impacts.

The precise impact of any single dam is unique and dependent not only on the dam structure and its operation, but also upon local hydrology, fluvial processes, sediment supplies, geomorphic constraints, climate and the key attributes of the local biota. There is therefore no normative or standard approach to address ecosystem impacts and these have to be looked at one a case by case basis. In addition the importance attached to some ecosystem changes will vary with the nature of human societies, cultures, and expectations. However, each global review to understand the dam's performance should considered five major headings of which:

- Technical performance.
- Financial and economic performance.

- Environmental performance.
- Social performance.
- Institutional and decision making processes.

Within this framework of avoidance, mitigation, compensation and restoration, there are a wide range of specific measures that can be taken appropriate to specific circumstances of each dam.

While there is experience of good mitigation, this success is nevertheless contingent upon stringent conditions of:

- A good information base and competent professional staff available to formulate complex choices for decision-makers;
- An adequate legal framework and compliance mechanisms;
- A co-operative process with the design team and stakeholders;
- Adequate financial and institutional resources.

If any one of these conditions is absent, then the ecosystem values will likely be lost. In practice the extent to which these conditions are met varies enormously from country to country and dam to dam.

4.7 MITIGATION MEASURES

4.7.1 Options

Engineers, environmentalists and ecologists have developed a broad range of technical measures to reduce the most damaging impacts of dams. For new dams these can be conceptualised within hierarchical framework comprising three types of measures:

- Mitigation measures reduce the undesirable effects of a dam by modification of its or operation, or through changes the management of catchments within which dam is situated.
- Measures compensate for effects that can neither be avoided nor sufficiently mitigated. Principle approaches include preservation of existing ecologically important areas and rehabilitation of previously disturbed land either around reservoirs.
- Avoidance measures result in no change to the existing environmental functioning of a particular area by avoiding anticipated adverse effects.

Mitigation measures are implemented as part of impact management. This process is accompanied by monitoring to check that impacts are ‘as predicted’. When unforeseen impacts or problems occur, they can require corrective action to keep them within acceptable levels. However, to be successful, mitigation measures require a great deal of understanding of complex processes and their interaction. Strategies are often has limited effectiveness, or may even result in undesirable effects, if detailed scientific and engineering studies are not conducted before hand.

4.7.2 Environmental flows

Provision for environmental flows is currently becoming a central issue in the debate of integrated water resources management in river basins. The term of environmental flows has come into some usage. To some this term applies to releases from dams which are specifically for environmental benefit, or the flow which achieves an environmental benefit, or the flow at the end of a river system, or any flow event which should be protected. Environmentally important characteristics can be maintained by constraining the volume, rate and timing of flow. The flow rules in water sharing plans for unregulated rivers typically specify how this should be done.

In the regulated section of a river the flow regime is totally changed by the operation of the dam, therefore, restoration is important. The principle tool used in mitigation the negative downstream impacts of dams is the environmental Flow Requirements (EFR).which represents the water regime provided within the river, wetland or coastal zone to maintain ecosystem (e.g. to encourage seasonal fish migration or maintenance of flood plains downstream) and their benefits where there are competing water users and where flows are regulated. Environmental flow characteristics normally requires releases of water to be made at times which are less optimal for other uses of water from the dam because water demands frequently occur at different times to natural peak flows.

EFR usually covers three major hydrological variables: water quality, minimum flows and managed flood releases. Using EFR requires a good understanding of a particular ecosystem's response to change in river flows and water quality. As dam releases for ecosystem benefits may reduce hydropower production, for example, there will be a willingness to reduce such direct project benefits for the greater indirect social and environmental good.

EFR are increasingly being applied retroactively, currently used in 25 countries worldwide, many dams can be managed differently to provide or restore downstream ecosystem and economic benefits, while not jeopardizing their original function of power generation or water storage and supply, an example for such mitigation the Itezhi-Tezhi Dam, Zambia, which provides partial river regulation for the 900 megawatt *Kafue* Gorge hydropower plant. The dam was completed in 1977 with an additional storage volume of 20% to allow managed flood release to simulate natural cycles in the Kafue flats, a wetland area of exceptional conservation and socio-economic importance at the heart of Zambia's agricultural and industrial zone. To develop and implement the third iteration of dam's operating rules and thereby increase the benefits from managed flood releases, a partnership was formed between the owner and operator, the regulator and an international NGO. The partnership successfully developed new rules that mimic natural cycles better while not affecting power generation [1].

4.7.3 Managing floods

By storing or diverting water, dams alter the natural distribution and timing of stream flows downstream from a dam, the most common effect is a reduction of the flood peak and, therefore, a reduction of the frequency, extent and duration of floodplain inundation. This reduction in downstream annual flooding may reduce the natural productivity of floodplains and deltas. The effects are particularly significant for strongly seasonal, flood-related ecosystems.

In the past ten years, efforts have been made to alleviate the negative impacts of dams, some of these adverse impacts are reversible and managed flood releases from the reservoirs can restore downstream productivity.

Effective flood management demanded an integrated control programme, for example using embankments and levees to protect some areas, while enhancing flooding in areas where more water was required. Regulation could be best achieved by an independent body.

By maintaining artificial flood in the river's downstream, and determining the water management scenario to rehabilitate the degraded estuarine and floodplain ecosystems and so reconcile the interests of a diversity of stakeholders.

The managed flood releases have to take into consideration environmental sustainability, economic efficiency and social equity. Practically, the questions were:

- How much water to release and when,
- How to adapt the management to observed and perceived,
- Impacts of the artificial flood releases,
- How to promote equitable access to the restored natural resources and, at the same time, enhance biodiversity.

In addressing the problems faced by downstream communities, some dam authorities have attempted to simulate the effects of the annual rains, by deliberately releasing large amounts of water during the normal flooding period. In the majority of cases, managed releases are quite a recent strategy, but in Zambia, flood releases have been made from the Kafue River's Itezhi-tezhi dam for over twenty years. This is an exceptional case as the concept of flood flow releases was incorporated into the design of the dam; 15% of the water held by the dam was designated for flood releases [1].

Other river basins have shown clearer benefits from flood releases. In Cameroon, the Waza-Logone floodplain ecosystem and farming systems have been substantially restored following a re-inundation programme. In Kenya managed releases are being considered in the design of the Grand Falls dam on the Tana River [1].

The Tana River is the largest in Kenya. It rises in the highlands near Nairobu and Mt Kenya and then flows for more than 250 km over the flat, dry coastal plain to the Indian Ocean. The Tana has an extensive floodplain and delta, which is the mainstay for thousands of people who use the results of the floods for their survival through subsistence agriculture, fishing, livestock rearing and horticulture. The wetlands of the lower floodplain and delta are the main refuge of livestock and wildlife from a wide area that is extremely arid for most of the year. Planning is underway to dam the Tana upstream of the floodplain at Mtonga (or Grand Falls) to accommodate several hydropower plants to satisfy the increasing electricity demand within Kenya. Investigations by the designers and developers have shown that the floodplain and its floods are a very significant resource both locally and nationally and that they should be retained if possible. Consequently, a dam is being designed that will store enough water to produce a flood downstream through substantial releases as well as produce the necessary electricity. Furthermore, recognising that silt is as important as water for the maintenance of the productivity of the floodplain, the dam designers are looking at the potential for releasing silt together with the flood water.

Apart from the engineering details, the main problem faced by the engineers is inadequate knowledge of the amount of water required to simulate a flood and the timing of this in relation to upstream and local rainfall. The lower Tana is not a simple channel that overflows onto the floodplain. Furthermore, the contribution to flooding from parallel channels, from short-lived local streams and from subsurface flows is still poorly understood. However, a modelling study is currently underway to address these limitations using data from historical and recent floods. These data show that similar “normal” floodplain inundations (as measured by the flood hydrograph at Garissa) have resulted from a range of different flows from the dam site. The figure below shows three possible flood release hydrographs (A, C & D - broken lines) varying enormously in volume, which can all produce the desired flood downstream (solid line) depending on the hydrological conditions in the rest of the catchments. This means that regional rainfall, soil moisture and flows from tributaries must all be monitored if the optimum release is to be made. Despite this complexity, it is anticipated that the final design will result in a dam that meets the demand for electricity and respects the needs of its floodplain downstream

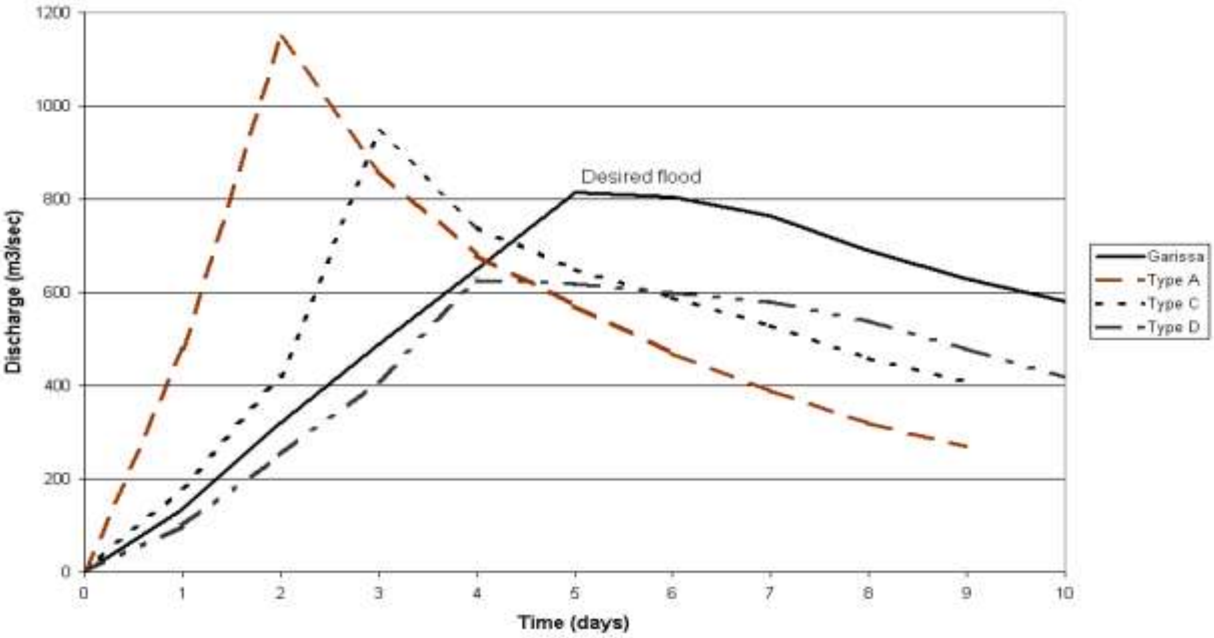

Figure 4-1: Three release flood hydrographs giving the same floodplain inundation

Managed flood releases involve a trade-off with other potential uses of the water. Whether or not managed floods are appropriate - and if so what their size, frequency, duration and timing should be - requires an appropriate decision-making process that includes directly quantifiable monetary values and non-monetary measures of biodiversity and human welfare.

The main recommended guidelines that need to be undertaken to achieve effective managed flood releases from reservoirs are:

1. Define objectives for flood releases.
2. Assess overall financial feasibility.
3. Develop stakeholder participation and technical expertise.
4. Define links between floods and the ecosystem.
5. Define flood release options.
6. Assess impacts of flood options.
7. Select the best flood option.
8. Design and build engineering structures.
9. Make releases.
10. Monitor, evaluate and adapt release program.

Optimal results would be achieved by releasing water from the reservoir to supplement periods of natural high runoff from the catchment's area downstream of the dam. Consequently, releasing managed floods is not straight-forward. It requires technical expertise, a detailed understanding of the land-use and ecology of downstream ecosystems and close collaboration with the users of floodplain resources.

Reproducing the natural flooding regime downstream of a dam is not possible, even if desirable. The aim of managed floods is to find a compromise in the allocation of water between managed flood releases and retaining sufficient water within the reservoir to support activities for which the dam was originally built or, in the case of new dams, for which it is being built. The successful management of flood releases require co-ordination of the various institutions involved. In many cases, there are gaps or overlaps in responsibilities of institutions that need to be addressed to achieve the desired outcomes.

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