

## Chapter 33

# Environmental Impacts of Reservoirs

Gordana Dević

**Abstract** The construction of reservoirs is one of the most important practices for the development and management of water resources. Many large reservoirs were built without a thorough or systematic evaluation of the long-term environmental, social, and economic interactions of different alternatives.

Up to the last quarter of the twentieth century, those responsible for the construction of dams and creation of reservoirs – entrepreneurs, decision makers, engineers, investors – were praised for the acknowledged benefits of their works: water supply, irrigated agriculture, flood control, improved navigation and firm hydroelectric generation (considered clean and unequivocally renewable energy). However, on the other hand, alarmist, especially environmental groups and organizations, have been exaggeratedly stating that infrastructure works, in general, and dams and reservoirs, in particular, cause serious and intolerable environmental impacts. Reservoir construction leads to a number of environmental issues, both during building and following completion. The physical, chemical character and water quality of rivers draining into lakes and reservoirs are governed in part by the velocity and the volume of river water. In these last decades of industrialization and rapid population increase, human intervention on the balance of nature has never been so various and so extensive as it is today.

This chapter reviews a large range of potential impacts linked to the exploitation of reservoirs and dams, such as: (1) Climate-changing greenhouse gases emissions; (2) Changes in the Temperature Regime (3) Reservoir sedimentation; (4) Water pollution; (5) Destruction of Eco-systems, and (6) Planning and reservoir management.

**Keywords** Reservoirs • Water resources • Environmental impacts

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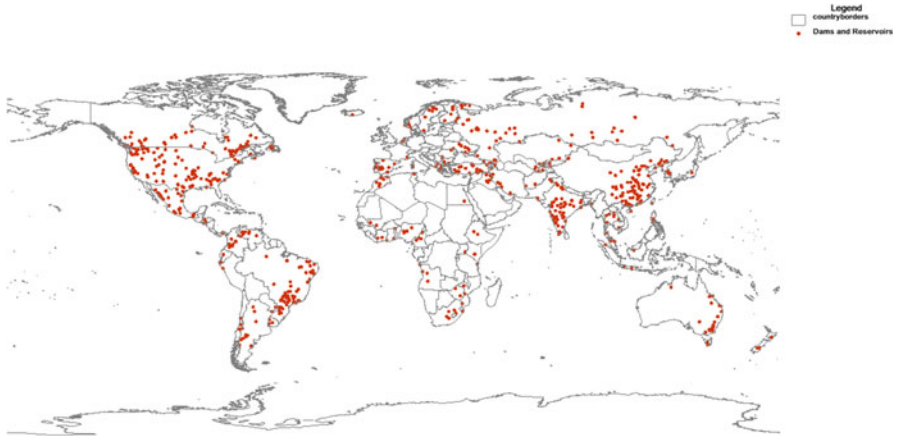
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### 33.1 Introduction

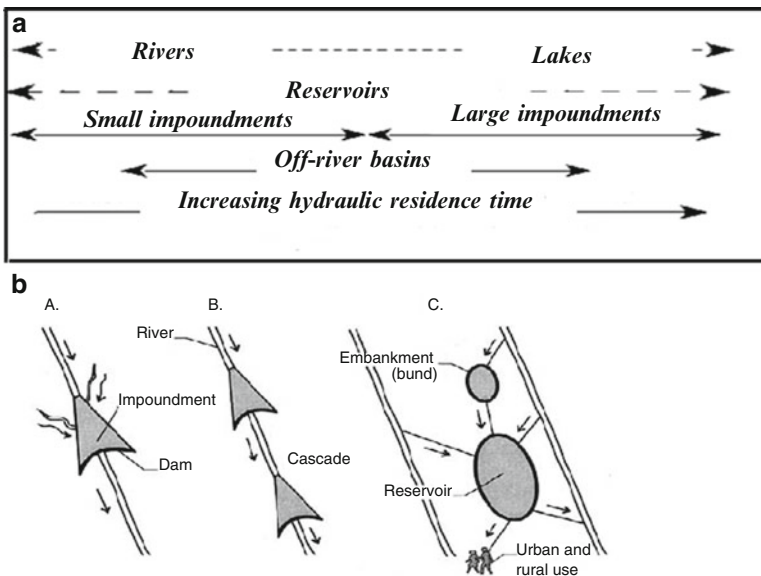
Reservoirs are found primarily in areas with relatively few natural lakes, or where the lakes are not suitable for human water requirements. They are much younger than lakes, with life spans expressed in historical terms rather than geological time. Although lakes are used for many of the same purposes as reservoirs, a distinct feature of reservoirs is that they are usually built by humans to address one or more specific water needs. These needs include municipal and drinking water supplies, agricultural irrigation, industrial and cooling water supplies, power generation, flood control, sport or commercial fisheries, recreation, aesthetics and/or navigation (UNEP 2000). The reasons for constructing reservoirs are ancient in origin, and initially focused on the need of humans to protect themselves during periods of drought or floods. Small reservoirs were first constructed some 4,000 years ago in China, Egypt, and Mesopotamia, primarily to supply drinking water and for irrigation purposes (Sumi and Hirose 2009). Simple small dams were constructed by blocking a stream with soil and brush, in much the same manner as beavers dam a stream. Larger reservoirs were constructed by damming a natural depression, or by forming a depression along a river and digging a channel to divert water to it from the river. Dams have made important contributions to human development, and the benefits derived from them have been considerable (WCD 2000). It has been estimated that the volume of water in impoundments increased by an order of magnitude between the 1950s and the present (Downing et al. 2006). The volume of fresh surface water on the earth is only 0.0075 % of the total global water: 104,620 km<sup>3</sup>, distributed in lakes (90,990 km<sup>3</sup>), swamps (11,510 km<sup>3</sup>) and rivers (2,120 km<sup>3</sup>). According to the International Committee on Large Dams – ICOLD, the total water storage in man-made lakes is around 6,620 km<sup>3</sup> (White 2010).

Most reservoirs are concentrated in the temperate and sub-tropical zones of the northern and southern hemisphere. Nearly all major river systems in the world have reservoirs in their drainage basins, and a number of river systems also have cascades of reservoirs within their basins. It has been estimated that approximately 25 % of all the water that previously flowed to the oceans is now impounded in reservoirs. Reservoirs exist on all continents and in all countries, except Antarctica (Fig. 33.1), although their distribution within specific countries and regions is irregular.

Man-made reservoirs constitute an intermediate type of water-body between rivers and natural lakes (Fig. 33.2a). Like lakes, reservoirs range in size from pond-like to very large water-bodies. The variations in type and shape, however, are much greater than for lakes. Reservoirs formed by a dam across the course of a river, with subsequent inundation of the upstream land surface are often called impoundments. Water bodies not constructed within the course of a river and formed by partially or completely enclosed water-proof banks are often referred to as off-river, or banded, reservoirs (Morley 2007). Reservoirs created by dams serially along a river course form a cascade (Fig. 33.2b).



**Fig. 33.1** Distribution of dams and reservoirs that have been digitally georeferenced as part of an ongoing collaborative development of a comprehensive global database on dams and reservoirs (Lehner et al. 2011 (unpublished data))



**Fig. 33.2** (a) The intermediate position of reservoirs between rivers and natural lakes, (b) Different types of reservoirs systems

Depending on their use, the water level of reservoirs may be either more or less stable, or it may fluctuate according to a periodicity linked to the water cycle and its exploitation – from full to empty in the extreme case (Wildi 2010).

Reservoirs typically receive larger inputs of water, as well as soil and other materials carried in rivers, than do lakes. As a result, reservoirs usually receive

larger pollutant loads than lakes. However, because of greater water inflows flushing rates are more rapid than in lakes. Thus, although reservoirs may receive greater pollutant loads than lakes, they have the potential to flush the pollutants more rapidly than lakes do. Reservoirs may therefore exhibit fewer or less severe negative water quality or biological impacts than lakes for the same pollutant load.

In these last decades of industrialization and rapid population increase, human intervention in the balance of nature has never been so varied and extensive as it is today. Reservoir construction leads to a number of environmental issues.

This chapter reviews a large range of potential impacts linked to the exploitation of reservoirs and dams, such as: Climate-change, greenhouse gases emissions, Changes in the Temperature Regime, Reservoir sedimentation, Water pollution, and Destruction of Eco-systems.

### **33.2 Environmental Impacts of Reservoirs**

For thousands of years, reservoirs and dams have been important tools for the management of extreme hydrological events. Water-related disasters, such as floods and droughts, have been successfully mitigated by the intelligent use of the storage provided by reservoirs. Up to the last quarter of the twentieth century, those responsible for the construction of dams and the creation of reservoirs – entrepreneurs, decision makers, engineers, investors – were praised for the acknowledged benefits of their work: water supply, irrigated agriculture, flood control, improved navigation, and reliable hydroelectric generation (considered clean and unequivocally renewable energy). However, on the other hand, alarmists, especially environmental groups and organizations, have been exaggeratedly stating that infrastructure works, in general, and dams and reservoirs, in particular, cause serious and intolerable environmental impacts (Palau 2006; Gomide 2012). Reservoir construction leads to a number of environmental issues, both during building and following completion (Table 33.1). The construction of a dam results in post-impoundment phenomena that are specific to reservoirs and do not occur in natural lakes. One difference is that during the first reservoir filling terrestrial habitats are submerged and destroyed. Thus, dams and the creation of reservoirs require the relocation of potentially large human populations if they are constructed close to residential areas. The record for the largest population relocation is held by the Three Gorges Dam built in China. Its reservoir submerged a large area of land, forcing the displacement of over a million people (Tan and Yao 2006). Another difference is that level fluctuations may be much larger than those normally found in a natural lake. Non-earth storage dams often have a bottom outlet. This may enable both sediment flushing and water release from deep below the surface. Major changes in the river system occur both upstream and downstream.

**Table 33.1** Environmental changes associated with reservoirs and dams

Cause of Impact	Possible direct effects	Possible indirect effects		
Creation of dam	Creation of a major obstacle in the river	Barrier to migration for certain aquatic vertebrates (fish)		
	Associated construction work	Disruption of habitat Increased sediment erosion and temporary effects on river water quality		
	Population displacement	Population reduction in the vicinity of the reservoir		
	Modification of landscape	Presence of new water body in landscape Presence of newly-built associated structures (turbine plants, treatment plants) Change in slope gradient Creation of a tourist attraction (recreation-seasonal population influx)		
Reservoir impoundment	Flooding of land	Habitat destruction Destruction of archaeological and historical features Decomposition of organic material Splitting of continuous forested areas in two belts Possible migration barrier for terrestrial fauna		
		Presence of a permanent still water body	Creation of a still water habitat	Change from riverine to lacustrine ecosystem Stratification of the water body with associated changes to the ecosystem
			Creation of a micro-climate	Increased humidity and attenuated temperature changes upstream of the reservoir
		Rice in groundwater levels upstream of the reservoir	Possible flooding of land and increased salinization Changes in groundwater flow regime	
		Effect on bedrock	Possible induced seismic activity (in the largest impoundments)	
Water use	Change in downstream land use due to the availability of a new water resource			
Accumulation in the reservoir	Sediment trapping	Sedimentation of the reservoir with associated water volume reduction Leaching of nutrients and other substance		
		Nutrient enrichment-causing eutrophication	Evolution of ecosystem. Appearance of water detrimental to recreation uses-toxic algae	
	Atmospheric acidic deposition	Acidification of reservoir, low pH and effects on ecosystem		
	Chemical pollution	Accumulation of heavy metals, pesticides and other micro-pollutants		
	Biological pollution	Possible presence of pathogens		

Modified data: European Environment Agency 1999

### ***33.2.1 Climate-Changing Greenhouse Gases Emissions***

The construction of a reservoir results in the total inundation of all areas upstream of the dam. These regions are often rich in trees and forests. The process of deforestation actually emits carbon dioxide into the atmosphere, and is responsible for 20 % of the world's greenhouse gas emissions. There is growing interest and concern regarding greenhouse gas emissions from lakes and reservoirs (St. Louis et al. 2000; Huttunen et al. 2002; Tremblay et al. 2005). The fact that CH<sub>4</sub> has a global warming potential up to 25 times stronger than that of carbon dioxide on a 100-y scale has made the monitoring of this greenhouse gas of particular importance. Atmospheric CH<sub>4</sub> concentrations are currently at the highest levels observed in the last 650 ky and have an ever-growing list of natural and anthropogenic sources (Forster et al. 2007).

Greenhouse gases, primarily methane (CH<sub>4</sub>) and carbon dioxide (CO<sub>2</sub>), are emitted from all of the dozens of reservoirs where measurements have been made (Bastviken et al. 2011). A first estimate indicated that for global large dams, area of  $1.5 \cdot 10^6$  km<sup>2</sup>, about 69.3 Tg CH<sub>4</sub> (1 Tg = 1,012 g) could be released annually by bubbling and diffusion processes (Lima et al. 2008).

Despite the uncertainties about upstream emissions, the growing consensus is that emissions downstream from dams might be responsible for a substantial release of CH<sub>4</sub> into the atmosphere (Abril et al. 2006; Lima 2005; Lima et al. 2008).

The current state of knowledge shows that N<sub>2</sub>O emissions from the great majority of freshwater reservoirs are negligible (Guérin et al. 2008). N<sub>2</sub>O has the potential (over a period of 100 years) to contribute 298 times more than CO<sub>2</sub> to global warming.

Gases are emitted from the surface reservoirs, at turbines and spillways, and for tens of kilometres downstream. Emissions are the highest in hot climates. Hydro plants in the tropics with large reservoirs relative to their generating capacity can have a much greater impact on global warming than fossil fuel plants generating equivalent amounts of electricity. Emission levels vary widely between different reservoirs depending on the area and type of ecosystems flooded, reservoir depth and shape, the local climate, and the way in which the dam is operated. For instance, China's reservoirs are often deep but sludge-filled, while Brazil's reservoirs are shallow and in a tropical zone. Both cases lead to high gas emissions (International Rivers 2007).

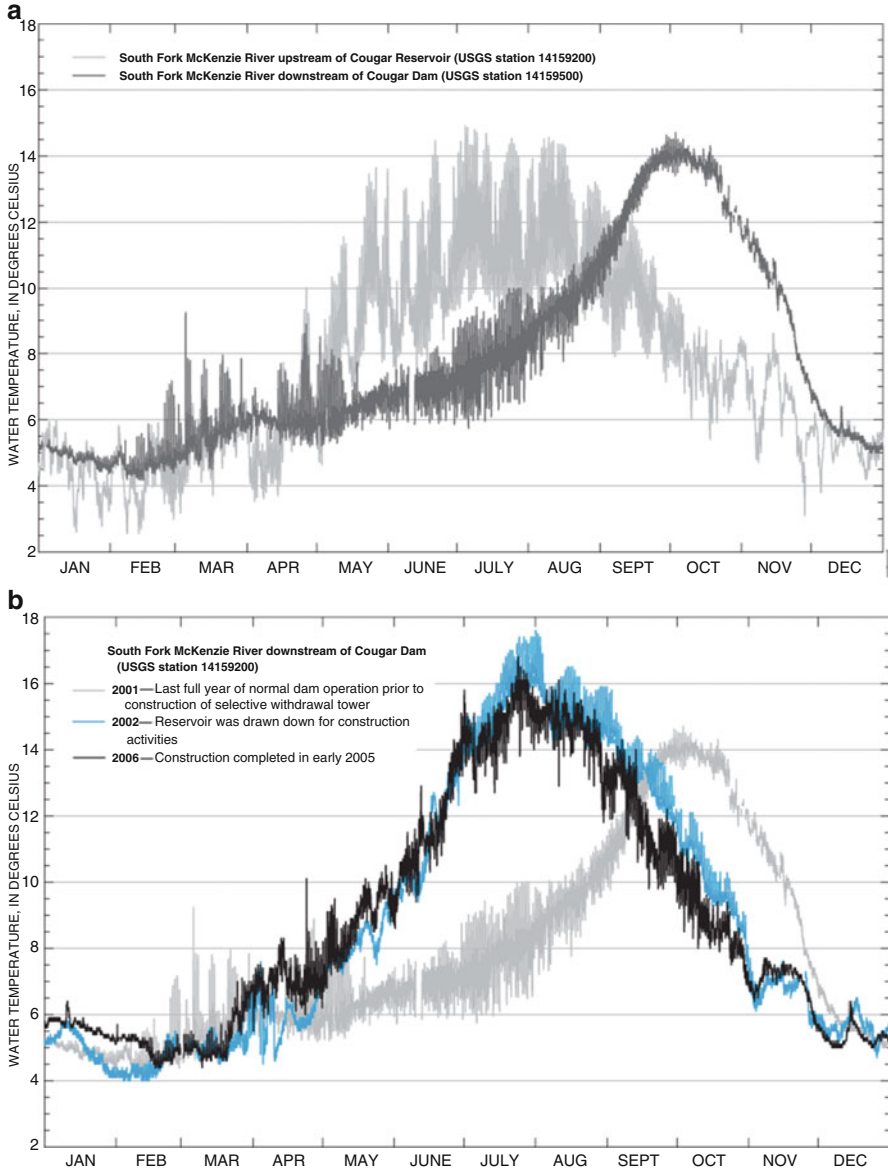
### ***33.2.2 Changes in the Temperature Regime***

Temperature affects a number of physical, chemical, and biological processes in natural aquatic systems. The temperature regime of a lake is a function of seasonal/diurnal ambient air temperatures and the morphology and setting of the reservoir. One of the most important effects of temperature is the decrease in oxygen

solubility with increasing temperature. Increasing temperature can also increase the oxygen demand of biological organisms, such as aquatic plants and fish. The rate of chemical reactions generally increases at higher temperatures. Some compounds are also more toxic to aquatic life at higher temperatures. Reservoirs act as thermal regulators that may fundamentally alter the seasonal and short-term fluctuations in temperature that are characteristic of many natural rivers. Depending on the geographical location, water retained in deep reservoirs has a tendency to become thermally stratified (Hutchinson 1957). Reservoirs closest to the equator are the least likely to become stratified. Many deep reservoirs, particularly at mid and high latitudes, do become thermally stratified, as do natural lakes under similar climatic and morphological conditions. However, the release of cold water into the receiving river from the hypolimnion of a reservoir is the greatest non-natural consequence of stratification.

An example of thermal stratification is shown in Fig. 33.3, which compares the annual temperature pattern at monitoring sites on the South Fork McKenzie River upstream and downstream of the Cougar Dam. The Cougar Dam on the South Fork McKenzie River, Oregon, USA, is a multi-purpose dam and reservoir impounding 270 million m<sup>3</sup> of water. The Cougar Dam controls the flow of and greatly influences the temperature in the South Fork McKenzie River downstream of the dam. The Cougar Reservoir becomes thermally stratified in summer, with warmer, less dense water near the surface and colder, denser water at the bottom. The warm and sunny summer weather of Western Oregon's adds additional heat to the surface of the reservoir, stabilizing its stratification throughout the summer. As the dam was built with its major release point at a relatively low elevation, the dam historically released relatively cold water from near the bottom of the reservoir in mid-summer. As the reservoir was drawn down in autumn to make room for flood-control storage, the heat that was captured in the upper layer of the reservoir's during the summer was released downstream. As a result, the seasonal temperature pattern downstream of the Cougar Dam through 2001 was quite different from the pattern upstream of the Cougar Reservoir (Fig. 33.3a), (Rounds 2007).

The McKenzie River supports the largest remaining wild population of Chinook salmon in the upper Willamette River Basin, and the South Fork McKenzie River provides good spawning habitat. The altered temperature pattern downstream of the Cougar Dam, however, can create problems with regard to the timing of migration, spawning, and egg hatching (Caissie 2006). To restore the suitability of this reach for salmon spawning, the U.S. Army Corps of Engineers added a sliding gate assembly to the intake structure of the Cougar Dam. To allow for construction, the reservoir was drawn down from 2002 to 2005; the construction was completed in early 2005. The new selective withdrawal tower allows dam operators to blend warm water from the top of the reservoir with cooler water at the other levels, or simply to select a depth from which to withdraw water, in an attempt to match a downstream temperature target (Rounds 2007). The selective withdrawal tower was employed successfully in 2005 and 2006 to restore a more-natural seasonal temperature pattern to the South Fork McKenzie River downstream of the Cougar dam (Fig. 33.3b).



**Fig. 33.3 (a)** Seasonal water temperature patterns in the South Fork McKenzie River upstream and downstream of Cougar Reservoir, Oregon. The *light grey line* shows, for the upstream site, a pattern as you might expect – temperatures heating up in late spring and rising during the summer with the fall bringing lower temperatures. It shows a normal bell-curve type of pattern that closely follows seasonal air temperature patterns. Fish living in this reach of the river would be adapted for these normal temperature patterns. Cougar Reservoir becomes thermally stratified in summer, with warmer, less-dense water near the surface and colder, denser water at the bottom. Western Oregon’s warm and sunny summer weather adds additional heat to the reservoir’s surface, stabilizing its stratification throughout the summer. Because the dam was built with its major release point at a relatively low elevation, the dam historically released relatively cold water from near the bottom of the reservoir in mid-summer. As the reservoir was drawn down in autumn to



### 33.3 Reservoir Sedimentation

The construction of >800,000 dams over the past century has reduced sediment loads to the oceans by  $\approx 50\%$  (Vörösmarty et al. 2003). About 1,100 km<sup>3</sup> of sediment has accumulated in the world's reservoirs, taking up almost 20% of the global storage capacity (WCD 2000). In China, 8 billion m<sup>3</sup> of storage capacity of 20 large reservoirs have been lost due to sedimentation, which is 66% of the total reservoir capacity of these reservoirs (Wang and Chunhong 2009). The storage capacity of reservoirs is being lost at an annual rate of 2.3% in China and 1% worldwide (White 2001). A wide range of sedimentation-related problems occurs upstream from dams as a result of sediment trapping. Sediment can enter and obstruct intakes and greatly accelerate abrasion of hydraulic machinery, thereby decreasing its efficiency and increasing maintenance costs. Dam construction is the largest single factor influencing sediment delivery to the downstream reaches. The cut-off of sediment transport by dams can cause stream bed degradation, accelerate the rates of bank failure, and increase scouring at structures such as bridge pillars. Stream morphology downstream of dams can be dramatically impacted by reduction in the supply of sediment. Clear water in the river channel, downstream of the dam tends to scour the stream bed causing it to coarsen, degrade, and become armoured. Channel degradation can raise bank heights, increase bank erosion rates, increase the severity of scouring at downstream bridges, lower water levels at intakes, reduce navigational depth in critical locations, and lower ground-water tables in riparian areas (Wang and Chunhong 2009).

Sedimentation reduces reservoir storage worldwide, causing serious problems not only for water and electricity supply, and flood control, but also for ecosystem development up-and down-stream of large dams. The consequences are especially precarious in (semi-) arid environments, where many reservoirs have been built for irrigation, water supply, flood control, and production of electricity. However, also in other areas sediment storage behind dams can have large implications for ecosystem and coastal development downstream of large river systems (Vörösmarty et al. 2003). Furthermore, storage of possibly contaminated sediments in a reservoir and subsequent chemical reactions occurring within the sediments due to long term storage cause serious problems for water quality and the possibilities for using the sediments further after dredging or flushing operations (de Vente et al. 2005). Therefore, it is of utmost importance to be aware of sediment yield on the basin scale and the composition of the sediments, and to understand which factors determine the sedimentation rate of reservoirs. This knowledge will enable

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**Fig. 33.3** (continued) make room for flood-control storage, the heat that was captured in the reservoir's upper layer during the summer was released downstream. As a result, the seasonal temperature pattern (*darker line* on chart) downstream of Cougar Dam through 2001 was quite different from the pattern upstream of Cougar Reservoir. (b) Seasonal water temperature patterns in the South Fork McKenzie River downstream of Cougar Dam in 2001, 2002, and 2006 (Data from Rounds 2007)

the probable lifespan of a reservoir to be estimated and moreover, allow proper measures against reservoir sedimentation, water shortage, and river bank and coastal erosion to be undertaken (de Vente et al. 2005).

### 33.4 Water Pollution

Water storage in reservoirs induces physical, chemical, and biological changes in the stored water. As a result, the water discharged from a reservoir could have a different composition to that flowing into the reservoir. Temperature changes relate to the thermal mass and surface area of the reservoir for radiant exchange, retention time, thermocline development, and whether the released water originates from the surface or a depth (Quinn, et al. 2004) (see Sect. 33.2.2). Chemical changes include altered nutrient levels and dynamics, modified water-column and sediment oxygen regimes, nitrogen supersaturation in downstream waters, and increased mobilization of certain metals and organic contaminants. Nutrients (phosphorous and nitrogen) are released biologically or leached from flooded vegetation and soil. Eutrophication of reservoirs may occur as a consequence of large influxes of organic loading and/or nutrients (Camargo et al. 2005; Perkins and Underwood 2000; Huang et al. 2012). In many cases, these are a consequence of anthropogenic influences in the catchments rather than a direct consequence of the presence of the reservoir. Nutrient pulses in conjunction with specific environmental conditions can cause oxygen depletion and increased concentrations of iron and manganese in the bottom layer and increased pH and oxygen in the upper layers of stratified reservoirs. Although the oxygen demand and nutrient levels generally decrease over time as the organic matter decreases, some reservoirs require a period of more than 20 years for the development of stable water-quality regimes. After maturation, reservoirs, like natural lakes, can act as nutrient sinks particularly for nutrients associated with sediments.

Heavy metal contamination has recently been highlighted as a major reservoir problem in some countries (Müller et al. 2000; Audry et al. 2004; Akoto et al. 2008; Feng and Qiu 2008; Larssen et al. 2010). Among environmental pollutants, metals are of particular concern, due to their potential toxic effects and ability to bioaccumulate in aquatic ecosystems (Censi et al. 2006). These metals may be introduced into a fluvial environment as a result of natural weathering, erosion, and transport processes, as well as from a range of anthropogenic activities (Audry et al. 2004). The release of heavy metals can occur both in dissolved and particulate form. When released in particulate form or adsorbed to particles, heavy metals can settle down and be deposited in the river bottom sediments under the favourable hydraulic conditions provided by natural and reservoir lakes. Reservoir sediments usually accumulate at high rates (typically  $> 2 \text{ cm a}^{-1}$ ), compared to lacustrine sediments (often  $< 3 \text{ cm a}^{-1}$ ; Audry et al. 2004). Due to these rapid sedimentation rates, reservoir sediments are considered to be little affected by early diagenesis processes and to provide preserved historical heavy metal inputs. A special problem

is the contamination of newly formed reservoirs with mercury. When the terrestrial landscape is flooded to create a reservoir, the organic carbon within the soil and vegetation begins to decompose. Under the anoxic conditions prevalent in new reservoirs, sulphur-reducing bacteria thrive causing microbial methylation of inorganic mercury, naturally accumulated through long-term wet and dry atmospheric deposition, into the highly toxic form, methyl mercury (MeHg) (Mailman et al. 2006). Elevated production of MeHg in new reservoirs may last for more than 13 years and be rapidly transferred through the food web, causing increased metal levels in fish, which may persist for up to 30 years after flooding (Mailman et al. 2006).

A major impact on the surface water quality may stem from biological processes, such as bacterial contamination. Water turbidity could be increased by high plankton concentrations and there may be a proliferation of mosquitoes and other insects, as well as rats and other nuisances. In the surrounding area and downstream of the reservoir, groundwater levels generally rise due to damming, increased infiltration, and rise in the hydraulic base level (Wildi 2010).

For many reservoirs that are found in arid or semi-arid areas where the surface water is naturally scarce, the problem of salinization could be severe. The salinisation of water below dams in arid climates is particularly problematic and is exacerbated in areas of marine sediments and where saline drainage water from irrigation schemes is returned to the rivers downstream of dams. Salinisation has also proved to be a problem on floodplain wetlands in the absence of periodic flushing and dilution by flood water. If sufficiently high and prolonged, elevated salinity will affect aquatic organisms (Akindele et al. 2013). The South African Department of Water Affairs (DWA 1986) gives a range of median total dissolved solids (TDS) concentrations, for 13 major reservoirs throughout the country, of between 137 and 955 mg l<sup>-1</sup>. The extreme values of TDS measured in these reservoirs ranged from 99 to 2,220 mg l<sup>-1</sup>. Salinity in this range limits the possible employment of the water because all but a few salt-tolerant crops, and most industrial and other uses, of the water are seriously affected by high salinity.

### 33.5 Destruction of Eco-systems

Changes in the physical and chemical characteristics of water from impoundment inevitably affect the distribution and abundance of aquatic biota and the resulting community structure (Morita et al. 2000; Dudgeon 2000; Tullios 2008). Within new reservoirs, fish populations are often quite large during the first few years, largely because of increased nutrients leached from flooded soils and vegetation, enhanced productivity throughout the food chain, and provision of secure sites for spawning and predator protection. Once established, the new physical/chemical characteristics of a reservoir could pose challenges to biota, primarily because they are not in synchrony with natural cycles. Disturbance to spawning results from the drawdown/raising of water levels, changes in seasonal temperature cycles, and blocked migration for fish (Walks et al. 2000; Quinn, et al. 2004).

Some reservoirs also provide habitats for birds and other fauna, but this often does not outweigh the loss of habitat downstream.

Eutrophication can lead to algal blooms in reservoirs that may have numerous adverse consequences for both the operational efficiency and the wildlife of the reservoir (Baxter 1977). In particular, toxic products produced by algae can cause mass fish and invertebrate mortality. The role of harmful algal blooms in animal mortality and disease events has only recently begun to be understood (Landsberg 2002). Mercury and other heavy metals can have a dramatic effect on parasite transmission and host–parasite relations in aquatic habitats (Morley 2007).

### 33.6 Planning and Reservoir Management

Proper water management is of vital importance to human society in a world where increasing demands are being placed on a relatively finite but potentially renewable resource. Moreover, effective water management demands transboundary coordination in the context of the fact that a total of 276 international river basins cover almost half the earth's surface (WWAP 2012).

Reservoirs represent an important component of the social and economic structure of both developed and developing countries. Many large reservoirs were built without a thorough or systematic evaluation of the long-term environmental, social, and economic interactions of different alternatives. The “dead storage” concept has been used in the planning and design of reservoirs to store sediment for a predetermined useful life, say 50–100 years. However, many existing reservoirs have reached, or may soon reach, their designed useful life. For instance a significant amount of sediment storage capacity at the Japanese reservoirs, which were designed for a life span of 100 years, has already been lost because sedimentation has occurred faster than expected (Sumi et al. 2004). Reservoir sedimentation is one of the most crucial issues to be solved this century to realize sustainable water resources management. The reservoir sedimentation problem has been a challenging issue for many countries worldwide; however, only a limited number of countries have been actively playing roles in reservoir sedimentation management. In the present situation, for those countries which have progressively developed various techniques and possess example cases, key issues are not to put off dealing with this problem but to make a continuous effort toward developing techniques further and putting them into practice, and to share the resulting information and knowledge widely with every country in need of them (Kantoush and Sumi 2010).

In addition, environmental, social, economic, and political considerations, and the fact that suitable dam sites are now scarce, necessitate new and innovative approaches for the development and management of water resources. To cope with population increases and the increasing demands of higher standards of living, more reservoirs will be built, especially in developing countries (Yang 2006). Reservoir construction has been largely completed in North America and Europe, but continues in the developing world, and most new reservoirs in the future will be located in Asia, Africa, and Latin America (White 2005).

## References

- Abril G, Richard S, Guérin (2006) In situ measurements of dissolved gases (CO<sub>2</sub> and CH<sub>4</sub>) in a wide range of concentrations in a tropical reservoir using an equilibrator. *Sci Total Environ* 354:246–251
- Akindele EO, Adeniyi IF, Indabawa II (2013) Spatio-temporal assessment and water quality characteristics of Lake Tiga, Kano, Nigeria. *Res J Environ Earth Sci* 5:67–77
- Akoto O, Bruce TN, Darko G (2008) Heavy metals pollution profiles in streams serving the Owabi reservoir. *Afr J Environ Sci Technol* 2:354–359
- Audry S, Schäfer J, Blanc G, Jouanneau JM (2004) Fifty-year sedimentary record of heavy metal pollution (Cd, Zn, Cu, Pb) in the Lot River reservoirs (France). *Environ Pollut* 132:413–426
- Bastviken D, Tranvik LJ, Downing JA, Crill PM, Enrich-Prast A (2011) Freshwater methane emissions offset the continental carbon sink. *Science* 331(6013):50. doi:10.1126/science.1196808
- Baxter RM (1977) Environmental effects of dams and impoundments. *Annu Rev Ecol Syst* 8:255–283
- Caissie D (2006) The thermal regime of rivers – a review. *Freshw Biol* 51:1389–1406
- Camargo JA, Alonso A, Puente M (2005) Eutrophication downstream from small reservoirs in mountain rivers of Central Spain. *Water Res* 39:3376–3384
- Censi P, Spoto SE, Saiano F, Sprovieri M, Mazzola S, Nardone G, Di Geronimo SI, Punturo R, Ottonello D (2006) Heavy metals in coastal water system. A case study from the north western Gulf of Thailand. *Chemosphere* 64:1167–1176
- de Vente J, Poesen J, Verstraeten G (2005) Evaluation of reservoir sedimentation as a methodology for sediment yield assessment in the Mediterranean: challenges and limitations. In: Soil conservation and protection for Europe, pp 139–145
- Downing JA, Prairie YT, Cole JJ, Durate CM, Tranvik LJ, Striegl RG, McDowell WH, Kortelainen P, Caraco NF, Melack JM, Middelberg JJ (2006) The global abundance and size distribution of lakes, ponds and impoundments. *Limnol Oceanogr* 51:2388–2397
- Dudgeon D (2000) The ecology of tropical rivers and streams in relation to biodiversity and conservation. *Annu Rev Ecol Syst* 31:239–263
- DWA (1986) Management of the water resources of the Republic of South Africa. Department of Water Affairs, Government Printer, Pretoria
- Feng XB, Qiu GI (2008) Mercury pollution in Guizhou, southwestern China – an overview. *Sci Total Environ* 400:227–237
- Forster P, Ramaswamy V, Artaxo P, Bernsten T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S et al (eds) *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on climate change*. Cambridge University Press, Cambridge/New York
- Gomide F (2012) Water storage for sustainable development and poverty eradication, GWF discussion paper 1223. Global Water Forum, Canberra. Available online at: <http://www.globalwaterforum.org/2012/06/19/water-storage-for-sustainable-development-and-poverty-eradication-part-1-of-2>
- Guérin F, Abril G, Tremblay A, Delmas R (2008) Nitrous oxide emissions from tropical hydroelectric reservoirs. *Geophys Res Lett* 35, L06404. doi:10.1029/2007GL033057
- Huang YL, Huang GH, Liu DF, Zhu H, Sun W (2012) Simulation based inexact chance constrained nonlinear programming for eutrophication management in the Xiangxi Bay of Three Gorges Reservoir. *J Environ Manag* 108:54–65
- Hutchinson GE (1957) *A treatise on limnology. Geography, physics and chemistry*. Wiley, New York

- Huttunen JT, Väisänen TS, Heikkinen M, Hellsten S, Nykänen H, Martikainen PJ (2002) Exchange of CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O between the atmosphere and two northern boreal ponds with catchments dominated by peatlands or forests. *Plant Soil* 242:137–146
- International Rivers (2007) 4% Global warming due to dams, says new research, <http://www.internationalrivers.org/node/1361>. Cited 03 March 2013
- Kantoush SA, Sumi T (2010) River morphology and sediment management strategies for sustainable reservoir in Japan and European Alps. *Annals of Diass. Res. Inst., Kyoto Universitet*, 53B
- Landsberg JH (2002) The effects of harmful algal blooms on aquatic organisms. *Rev Fish Sci* 10:113–390
- Larssen T, Zhang H, Feng X (2010) An integrated survey on mercury pollution and its impacts in Guizhou Province, China. *Geochim Cosmochim Acta* 74 (Suppl) ISSN 0016-7037
- Lima IBT (2005) Biogeochemical distinction of methane releases from two Amazon hydroreservoirs. *Chemosphere* 59:1697–1702
- Lima IBT, Ramos FM, Bambace LAW, Rosa RR (2008) Methane emissions from large dams as renewable energy resources: a developing nation perspective. *Mitig Adapt Strat Glob Chang* 13:193–206
- Mailman M, Stepnuk L, Cicek N, Bodaly RA (2006) Strategies to lower methyl mercury concentrations in hydroelectric reservoirs and lakes: a review. *Sci Total Environ* 368:224–235
- Morita K, Yamamoto S, Hoshino N (2000) Extreme life history change of whites – potted char (*Salvelinus leucomaenis*) after damming. *Can J Fish Aquat Sci* 57:1300–1306
- Morley NJ (2007) Anthropogenic effects of reservoir construction on the parasite fauna of aquatic wildlife. *Ecohealth* 4:374–383
- Müller J, Ruppert H, Muramatsu Y, Schneider J (2000) Reservoir sediments – a witness of mining and industrial development (Malter Reservoir, eastern Erzgebirge, Germany). *Environ Geol* 39:1341–1351
- Palau A (2006) Integrated environmental management of current reservoirs and regulated rivers. *Limnetica* 25:287–302
- Perkins RG, Underwood JC (2000) Gradients of chlorophyll A and water chemistry along an eutrophic reservoir with determination of the limiting nutrient by in situ nutrient addition. *Water Res* 34:713–724
- Quinn F, Day JC, Healey M, Kellow R, Rosenberg D, Saunders OJ (2004) Chapter 1. Water allocation, diversion and export. In: Threats to water availability in Canada, NWRI scientific assessment report series No. 3; ACSD science assessment series No. 1. National Water Research Institute and Meteorological Service of Canada, Burlington
- Rounds SA (2007) Temperature effects of point sources, riparian shading, and dam operations on the Willamette River, Oregon. U.S. Geological Survey Scientific Investigations Report 2007–5185, 34 p. Available online at: <http://pubs.usgs.gov/sir/>
- St. Louis VL, Kelly CA, Duchemin E, Rudd JWM, Rosenberg DM (2000) Reservoir surfaces as sources of greenhouse gases to the atmosphere: a global estimate. *BioScience* 50:766–774
- Sumi T, Hirose T (2009) Water storage, transport, and distribution, In: Yutaka Takahasi (ed) *Encyclopedia of life support systems (EOLSS)*, Developed under the Auspices of the UNESCO, vol 1, Eolss Publishers, Oxford, p 486, <http://www.eolss.net>, ISBN 978-1-84826-176-1 (eBook)
- Sumi T, Okano M, Takata Y (2004) Reservoir sedimentation management with bypass tunnels in Japan. In: Proceedings of the ninth international symposium on river sedimentation, Yichang, China, 18–21 October 2004
- Tan Y, Yao F (2006) Three gorges project: Effects of resettlement on the environment in the reservoir area and countermeasures. *Popul Environ* 27:351–371
- Tremblay A, Varfalvy L, Roehm C, Garneau M (2005) Greenhouse gas emissions: fluxes and processes – hydroelectric reservoirs and natural environments. Springer, New York
- Tullos D (2008) Assessing the influence of environmental impact assessments on science and police: An analysis of the Three Gorges Project. *J Environ Manag* 90:1–16

- UNEP (ed) (2000) Lakes and reservoirs: similarities, differences and importance. United Nations Environment Programme (UNEP IETC), Osaka
- Vörösmarty CJ, Michel M, Fekete B, Sharma K, Green P, Syvitski JP (2003) Anthropogenic sediment retention: major global impact from registered river impoundments. *Glob Planet Chang* 39:169–190
- Walks DJ, Li HW, Reeves GH (2000) Trout, summer flows, and irrigation canals: a study of habitat condition and trout populations within a complex system. In: Cowx IG (ed) *Management and ecology of river fisheries*. Blackwell Science, London, pp 115–125
- Wang ZY, Chunhong HU (2009) Strategies for managing reservoir sedimentation. *Int J Sediment Res* 24:369–384
- WCD (2000) World commission on dams report: dams and development – a new framework for decision-making. Earthscan Publications, London/Sterling
- White R (2001) Evacuation of sediments from reservoirs. Thomas Telford, London, 280
- White WR (2005) A review of current knowledge: world water storage in man-made reservoirs. FR/R0012. Foundation for Water Research, Marlow
- White WR (2010) World water: resources, usage and the role of man-made reservoirs. Foundation for Water Research, Marlow
- Wildi W (2010) Environmental hazards of dams and reservoirs. *Curriculum in Natural Environmental Science, Terre et Environment*, 88:187–197
- WWAP (World Water Assessment Programme) (2012) The United Nations World Water Foundation for water research development report 4: managing water under uncertainty and risk. UNESCO, Paris
- Yang TC (2006) Sustainable development and use of reservoirs. In: *Erosion and sedimentation manual*. U.S. Department of the Interior Bureau of Reclamation Technical Service Center Sedimentation and River Hydraulics Group, Denver