

Getting into hot water: Water quality in tropical lakes in relation to their utilisation

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Abstract. Over-exploitation of tropical lakes and reservoirs ('lakes') causes water quality problems that occur as a result of competing socio-economic demands and the presence of feedback loops within the system that exacerbate the situation. We review well documented case studies from Brazil, India, Indonesia, Kenya, Malaysia and Mexico to examine the effect that changes in water quality and quantity have had on the utilisation of these tropical lakes. By comparing the different approaches used to improve their sustainable management, we have found that nutrient enrichment is one of the most important and widespread water quality problems, causing adverse effects such as algal blooms, nuisance levels of aquatic plants, low oxygen levels and elevated greenhouse gas emissions. These effects restrict the use of these lakes for water supply, fisheries, recreation, tourism and wildlife. We conclude that tropical lakes require better management, urgently, to restore the ecosystem services that they deliver to man and nature. However, to be effective, the development of sustainable management programmes needs to be underpinned by reliable scientific evidence and the results of extensive stakeholder engagement activities. We note that, currently, there is little information available on how tropical lakes respond to management interventions that can be used to guide these activities. Further research is needed to address this knowledge gap.



1. Introduction

The world's tropical lakes deliver a range of important benefits to people. These are known as environmental services [1] and they include provision of important aquatic habitats; delivery of food and livelihoods for millions of people; supply of clean water for domestic, industrial and irrigational use; and regulation of floods and droughts. Also, they have important historical and traditional values, and they offer economically important opportunities for recreation and tourism¹ [3-5]. The socio-economic importance of these lakes often far outweighs their physical size. However, like other lakes and reservoirs ('lakes') across the world, tropical systems are being degraded by external pressures such as nutrient enrichment (eutrophication) [6], water stress (due to abstraction and climate change), impoundment (to deliver sustainable energy and water supplies), and the development of fisheries and aquaculture [7] to provide food security for growing populations. Competing demands on available resources among a range of different users are accelerating the rate of degradation of the natural environment and the ecosystem services that it provides [5]. Often, this degradation is accentuated by complex feedback mechanisms within the system. These include, for example, the increased levels of eutrophication caused by expanding aquaculture facilities in lakes whose natural fish resources have been degraded by eutrophication problems [7, 8].

A better understanding of the uniqueness of tropical lakes is crucial for their sustainable management [9]. Historically, limnologists have tended to focus on temperate regions. However, more recent studies on tropical inland waters have suggested that these waterbodies are fundamentally different to temperate systems [9]. Their warmer waters, higher levels of solar radiation and wide intra-annual variations in precipitation rates, augmented by climate change, are having important impacts on biogeochemical processes within these lakes and their catchments. Rapid increases in population sizes, land use change and economic growth in many tropical countries has resulted in increasingly high levels of anthropogenic pressures on these systems; this has led to an inadequate supply of good quality water [9].

In this paper, we review some of the best documented case studies from across the tropics (Brazil, India, Indonesia, Kenya, Malaysia and Mexico) to examine the impact that changes in water quality have had on the utilisation of lakes and reservoirs, and the effect that utilisation has had on the water quality of these systems. Also, we highlight lessons learned from the different approaches used in these case studies to improve the sustainable management of these systems in relation to supporting local communities and developing sustainable blue economies.

2. Case studies

2.1 Valle de Bravo, Mexico

2.1.1. Background. The Valle de Bravo reservoir in Mexico (Figure 1) is a high altitude waterbody that was created by flooding 2900 ha. of land in 1947. Lying at 1,830 m.a.s.l., it has a surface area of 18.6 km², a mean depth of 21.1 m and a maximum depth of 38.6 m [10]. With a storage capacity of 391 x 10⁶ m³, the reservoir provides a reliable water supply to about 4 million people in Mexico City [11]. Since the 1980s, when hydro-electric power generation was discontinued at this site, water levels have fluctuated by about 10 m per year [12]. Water level is regulated by the balance between inputs from rainfall (836 mm y⁻¹) and runoff, and losses due to evaporation (1,620 mm y⁻¹) [13], abstraction and discharge. The water retention time of this reservoir is about 2.2 years.

¹ The travel and tourism industry was one of the first sectors to be affected by COVID-19. Historically, tourism demand is known to rebound after a crisis, although the recovery time may vary. In this instance, the tourism sector can expect substantial changes in supply and demand patterns emerging from this crisis [2]. As the sector recovers, long term opportunities for lake-related recreation and tourism are expected to rebound too. In this publication, we refer to lake-related tourism opportunities for each of the case studies without assessing the impact of COVID-19.

In addition to providing a water supply, Valle de Bravo reservoir is of economic importance as a tourist attraction, a sailing resort and a popular recreational fishery (tilapia (*Oreochromis niloticus*), carp (*Cyprinus carpio*), trout (*Oncorhynchus mykiss*), bass (*Micropterus salmoides*) etc.).

2.1.2. Water quality problems. The Valle de Bravo drains a catchment area of 547 km², which is mainly forest. A detailed nutrient budget for the reservoir and its catchment concluded that, between 1992 and 2002, increases in human activity within the River Amanalco subcatchment had increased phosphorus (P) inputs by 276% and nitrogen (N) inputs by 203% [13]. Also, the authors of this study found that, between 2002 and 2005, the average annual nutrient loads to the reservoir were about 121 t P and 592 t N, with more than 50% of these inputs coming from the River Amanalco subcatchment. The main sources of these nutrients were identified as sewage (treated and untreated) and agricultural runoff. While it was estimated that abstraction removed about 22% of P and 54% of N inputs to the system, it was found that rates of N fixation were greater than those of denitrification, effectively doubling the N inputs from other sources.

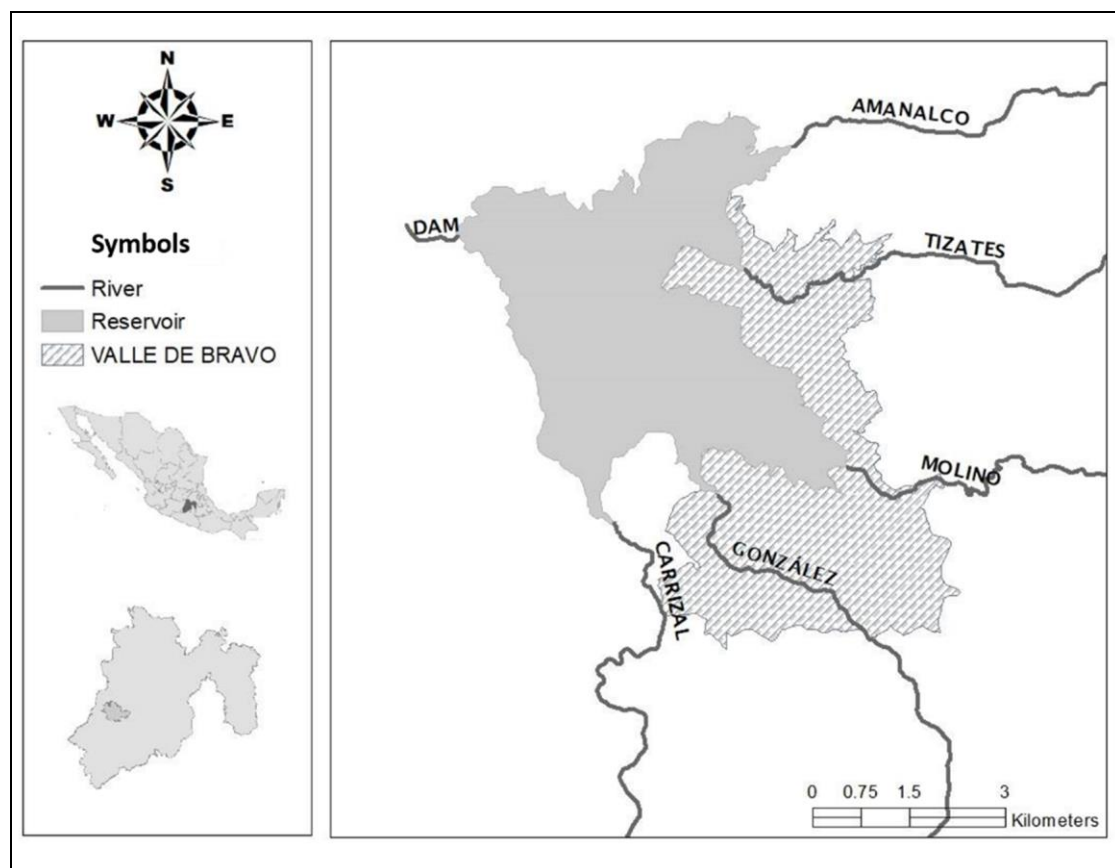


Figure 1. Location of the Valle de Bravo Reservoir in Mexico

Due to its rapid nutrient enrichment (eutrophication) in recent years, the water quality status of the Valle de Bravo has changed from oligotrophic to mesotrophic [12] and, now, to eutrophic. As a result, the hypolimnion becomes anoxic every year when the system is stratified (March to October) and even when fully mixed, at other times of year, dissolved oxygen [DO] concentrations rarely exceed 60%. Other water quality problems include high chlorophyll *a* concentrations (0.13 – 0.18 mg L⁻¹), low water clarity (1.5 m – 2.5 m) and frequent, and sometimes toxic, cyanobacterial blooms. These include the highly toxic strains *Dolichospermum planctonicum* and *Woronichinia naegeliana* [14].

2.1.3. Impacts of water quality problems on lake utilisation. Eutrophication and its impacts have had marked and deleterious effects on the utilisation of the reservoir for water supply, tourism/recreation and fishing. A particular problem is that the cyanobacterial blooms that are becoming more common due to eutrophication problems are also being exacerbated by the effects of climate change (especially warming). The symptoms of this degradation include poor water quality, high levels of water turbidity and fish kills. While bioaccumulation of cyanotoxins, especially microcystins, has the potential to limit the use of fish from the reservoir as a food resource [15], the more direct health effects of these toxins on humans restricts the use of this waterbody for recreation and tourism. There is evidence that rising temperatures may also be leading to increases in toxin production by tropical cyanobacterial species [16].

2.1.4. Management recommendations. A study of the causes and effects of water quality problems in Valle de Bravo [13] concluded that use of this reservoir as a safe and sustainable water resource could be improved if the following management interventions were implemented:

- improved monitoring of the quality and quantity of water entering the system from inflows and sewage discharges, including nutrient source apportionment
- improved treatment of sewage effluent prior to discharge
- better regulation of fertiliser use within the catchment

In addition, the use of floating islands and littoral macrophytes is being trialled as an in-lake method of reducing nutrient and cyanobacterial concentrations in the water [17, 18]. Also, a particular focus of research at this site has been the development of a new biomonitoring method for cyanobacterial toxins. This is based on the rotifer *Brachionus calyciflorus*, which is routinely used in ecotoxicological bioassays globally and aims to improve the routine monitoring of these compounds within the reservoir and in the water abstracted from it [14].

2.2 Urban tropical coastal lagoon and semi-arid man-made lakes, Brazil

2.2.1. Background. Jacarepaguá Lagoon is situated in the Municipality of Rio de Janeiro, Brazil. It is part of an urban system that comprises three lagoons that are connected in sequence and flow to the sea [19] (Figure 2). The Jacarepaguá Lagoon has a surface area of 3.7 km², an average depth of 3.3 m and a drainage area of 103 km². Its tributaries flow through urban settlements that surround the lagoon and deliver sediment, and industrial and household wastewater to the system [20]. The intense, disorganised and growing urban occupation of this area over recent decades has resulted in the rapid and on-going degradation of the environment. Artisanal fishing activity, which was of great economic importance until the mid-2000s, is now badly affected by the pollution that it receives from untreated effluents; these have led to the local extinction of most of the 89 species of fish recorded here in the early 1990s and fish kills are common.

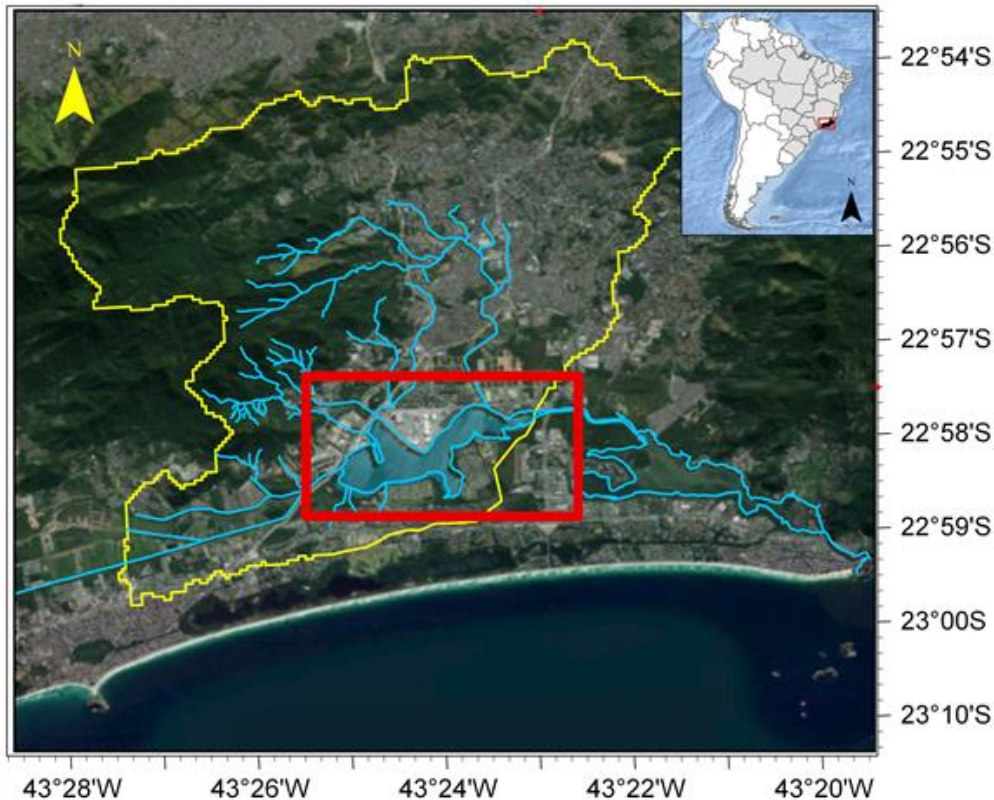


Figure 2. The location of the Jacarepaguá Lagoon in Brazil.

Gargalheiras and Cruzeta Reservoirs are located in northeastern Brazil (Figure 3), in the semi-arid climatic region [21, 22]. The Gargalheiras Reservoir has a maximum capacity of 44.4 million m^3 and a maximum 26.5 m depth. The Cruzeta Reservoir has a maximum capacity of $35 \times 10^6 \text{ m}^3$ and a maximum depth of 14.5 m. Both reservoirs have multiple uses, including water supply (priority use), irrigation, fishing, recreation and animal watering. The semi-arid region of Brazil, with an estimated population of 28 million people in 2017, has the highest rural population density in the country. During the wet season (January-May), the area receives $550\text{-}700 \text{ mm y}^{-1}$ of rain; however, in the dry season, evaporation rates exceed $2,000 \text{ mm y}^{-1}$ causing a negative water balance that leads to conflicting demands among the multiple users of the lakes.

The multiple pressures on these systems affect water quality and availability by increasing the symptoms of eutrophication. These pressures include nutrient pollution from wastewater discharges, agricultural runoff and waste from livestock rearing. These water quality problems are exacerbated by the lack of a sustainable approach to the development and management of water resources in this area and the prolonged periods of severe drought that occur, the last of which lasted for eight consecutive years (2011-2019) [23]. This drought, which had a strong negative effect on water supply for human and agriculture use, occurred with an intensity that had not been seen in previous decades [24] and resulted in both reservoirs drying up completely.

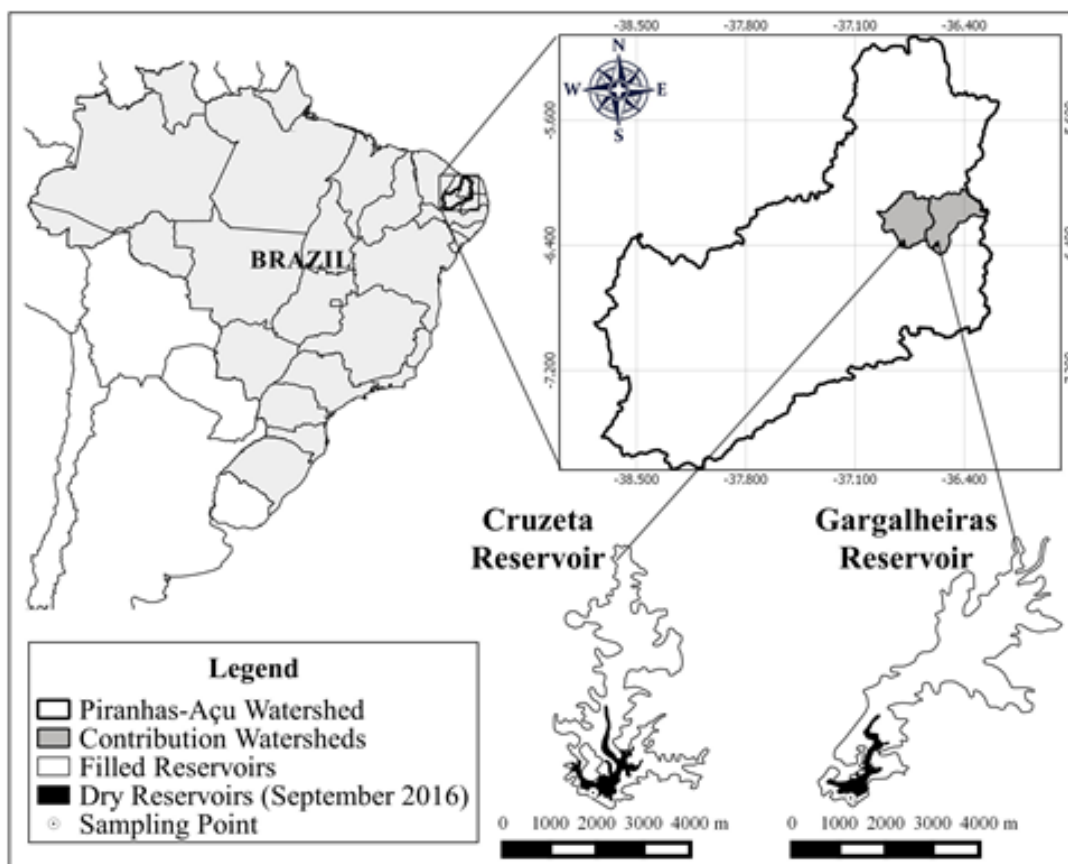


Figure 3. Location on the Cruzeta and Gargalheiras Reservoirs, in Brazil [15]

Despite advances in sanitation in recent decades, about 50% of municipal and industrial wastewater discharges in Brazil are still untreated and, in rural areas, this percentage is higher [25, 26]. In developing countries, such as Brazil, with reduced or inefficient wastewater treatment infrastructure, reducing in the external load of nutrients and other materials to these systems is not an easy task.

2.2.2 Water quality problems. Both of these reservoirs are classified as eutrophic [21, 27], with the key factor challenging the health of Jacarepaguá lagoon being the discharge of untreated industrial and domestic effluents. These deliver high loads of nutrients and organic matter to the system, accelerating eutrophication problems and causing toxic, long-lasting and perennial blooms of cyanobacteria and opportunistic pathogenic bacteria; these pose a serious risk to the environment and to public health [28, 29].

A recent study showed that the main inflows to the lagoon deliver a high external P input of about 55 t yr^{-1} . Also, Jacarepaguá has an almost continuous flux of P from its sediment, yielding an internal load of 6.2 t P yr^{-1} (about 11% of the total P load). This equates to an average internal load of $4.6 \text{ mg P m}^{-2} \text{ day}^{-1}$, which is high in comparison to other eutrophic systems [19]. Because inflows to lakes in this area flow intermittently and there are long periods of drought, Jacarepaguá there are often long periods when the lagoon has little or no flushing; this increases the internal P loading [22, 30].

Total P (TP) and chlorophyll-*a* concentrations are higher in the Gargalheiras Reservoir than in the Cruzeta Reservoir, although concentrations of soluble reactive phosphorus [SRP] and inorganic suspended solids [ISS] are greater in Cruzeta Reservoir [21]. The high ISS values in Cruzeta Reservoir are caused by collapses in the phytoplankton biomass when water levels are low during periods of drought and light availability is low [31]. Vulnerability to climatic variability in these

semi-arid regions is characterised, mainly, by an increase in the frequency of prolonged droughts and decreases in water flow, both of which cause a deterioration in water quality and restrictions on its use.

2.2.3. Impacts of water quality problems on lake utilisation. Decades of eutrophication and its impacts have shifted the Jacarepaguá lagoon from a more natural environment into a system for the disposal of the domestic effluents from 700,000 people, and of industrial effluents from chemical, pharmaceutical, metallurgical, food and electronic industries. This high population density, coupled with a lack of sanitation, releases 45 t d^{-1} of organic load, measured as biochemical oxygen demand (BOD), and 80 t d^{-1} of other waste materials into the lagoon [32]. The symptoms of this degradation include bad water quality (i.e., high nutrient levels; low oxygen concentrations), odours and fish kills, which restrict recreation/tourism and other economically important activities such as fisheries. In addition, toxic cyanobacterial blooms and pathogenic microorganisms threaten public health.

Water security is achieved when water of sufficient quantity and quality is available to meet human needs, support economic activities and support aquatic ecosystems. It is an indispensable part of social and economic development, as demonstrated by the impact of the extreme hydrological events that occurred in Brazil over the current decade. In regions where water availability is reduced naturally, such as in the Semi-Arid region, water crises have been occurring for increasing periods of time. Recently (2011-2019), the northeast of Brazil experienced a prolonged drought that is considered to be one of the most severe in the last 60 years, which caused the degradation of aquatic ecosystems (mainly eutrophication) and an inability to meet the water demands of the region [33]. Rainfall variability, land degradation, desertification, and socio-economic change are some of the factors that, together, could make this region one of the world's most vulnerable to climate change [34]. Several studies have indicated that this semiarid region has already been affected by the intensification of eutrophication problems due to these extreme drought events [31, 35-37]. In addition, droughts cause the high concentrations of P in lake sediments in this area to become a constant problem by increasing internal loading [22].

In this context, eutrophication allied with an insufficient capacity to meet the population's demands for water and a lack of sustainable management of water resources generates conflicts of interest among water users; these include problems exacerbated by lack of sanitation, issues of public health and the overall deterioration of aquatic ecosystems.

2.2.4. Management recommendations. Reduction of the external P load from its inflows is absolutely essential for the restoration of the Jacarepaguá lagoon, although sediment P release (internal loading) may still be sufficient to fuel cyanobacterial blooms for some time after external inputs are reduced. In reducing internal P load, *in-situ* geo-engineering techniques (e.g., addition of aluminum sulfate modified clay) appear to be far more cost-effective than standard dredging procedures [19, 38].

Another problem is that internal P loading can delay recovery for many years even if external inputs are reduced. To address this, natural P-adsorbent materials are being tested in terms of their ability to remove bio-available SRP from the water column and speed up recovery processes. Studies have concluded that natural adsorbents from this semi-arid region, such as luvisol, planosol and scheelite tailings, have a high potential to adsorb SRP when applied to natural systems [39]. Also, recent studies on tropical waterbodies [38, 40, 41] have shown that combining coagulants with modified clays or natural soils could help to:

- remove cyanobacterial biomass from the water column
- remove P from the water column, and/or
- block P-release from the sediment (internal load).

However, because each system is unique, a full systems analysis is required before these types of geoenvironmental tools are applied.

In addition to the control of internal loading, other actions are also required. These include:

- determining the support capacity of reservoirs by calculating the water balance and mass balance of nutrients
- estimating the P concentrations of the tributaries and the vertical flow of P within the system
- improving wastewater treatment systems so that treated effluent can be re-used for non-drinking water purposes, such as irrigation and animal watering.
- managing water resources more effectively to meet demand while preserving aquatic ecosystems
- supporting the effective dissemination of scientific evidence and running educational workshops for local communities, in formal and non-formal settings, to develop a community-based approach to sustainable reservoir management.

2.3 Urban lakes in Bangalore, India

2.3.1. Background. Bangalore does not have a perennial river; instead, it relies on water brought from the Cauvery River, 140 km away, to supply drinking water. However, the safe disposal of wastewater is a huge problem for the city [42]. Although there were once about 262 lakes (artificial reservoirs, known locally as “tanks”) in Bangalore 30 years ago, only 81 still exist today. Of these, Jakkur Lake and Bellandur Lake, which lie within the city boundary, are the focus of this case study.



Figure 4. Bellandur Lake (left) and Jakkur Lake (right)

Bellandur Lake is the largest lake in Bangalore and was constructed, about 130 years ago, in a relatively undeveloped part of what is now Bangalore city. Originally, its waters were clear and it was full of wildlife [43]. However, as the city expanded, it became surrounded by urban development and its natural water supply was disrupted [43]. Although originally covering about 329 ha., weed growth and siltation have reduced its area to about 154 ha. [42] and its volume to about $6,786 \times 10^3 \text{ m}^3$. It has a water retention time of 30 days. Although Bellandur Lake still receives some runoff from rain (859 mm y^{-1}) falling over its 148 km^2 catchment, its main hydrological input comes from approximately 300 Megalitres per day [MLD] of waste water (mainly sewage) that is discharged into it from Bangalore city. As a result, the lake is heavily polluted – a problem that led to foam on the surface of the lake catching fire and burning for several hours in May 2015 [43].

Jakkur Lake is situated in north-eastern Bangalore. It covers an area of 55 ha. and has an estimated volume of $894 \times 10^3 \text{ m}^3$ and a water retention time of about 90 days. The lake has three inlets and two outlets, and there is a waste water treatment plant close to its main inlet. This feeds into an algal pond (5 ha.), fringed with macrophytes, through which secondarily treated (15 MLD) and untreated (0.01 MLD) wastewaters enter the lake [44].

2.3.2 Water quality problems. Bellandur Lake has an average phosphate ($\text{PO}_4\text{-P}$) concentration of about 0.22 mg L^{-1} , which classifies it as severely hyper-trophic according to the OECD which has set an upper limit of 0.03 mg P L^{-1} for lakes to be classified as eutrophic [45]. Similarly, the average nitrate ($\text{NO}_3\text{-N}$) concentration of Bellandur Lake is about 9 mg L^{-1} , which is far in excess of that usually found in tropical lakes because rapid denitrification in these systems generally results in concentrations of less than 0.5 mg L^{-1} , a level at which lack of N is starting to limit algal growth. In addition, the nitrate concentrations in this lake are very close to the WHO standard of 11.3 mg L^{-1} , above which nitrate levels become a risk to human health [46, 47]. More importantly, the lake is anoxic due to the extremely high loads of untreated wastewater that it has been receiving for several decades [42].

Jakkur Lake has a high nutrient load, most of which is assimilated into algal growth and/or sedimentation processes and is retained in the lake. This has led to hyper eutrophication, with chlorophyll *a* levels of up to 0.125 mg L^{-1} being recorded [48]. A recently constructed nutrient budget for the system suggests that the current P load needs to be reduced by about 96% to control nuisance algal blooms and reduce the number of deoxygenation events that lead to fish kills [48].

2.3.3. Impacts of water quality problems on lake utilisation. Poor water quality is threatening the benefits that people derive from both of these lakes in Bangalore, including:

- refugia for biodiversity
- fisheries
- groundwater recharge
- water for irrigation
- green spaces for recreation

Bellandur Lake is no longer able to support a fish community because the water has become anoxic. To support a successful fishery, the dissolved oxygen (DO) concentration in the lake would need to be above 4 mg L^{-1} [49]. In contrast, the less polluted Jakkur Lake is still suitable for fish, although DO levels often fall below 4 mg L^{-1} at night in the deeper water, restricting fish to the upper 1.25 m of the water column. This causes stress and fish kills are common. Jakkur Lake currently supports a small fishery, but this may not be sustainable in the long-term unless oxygen conditions improve.

The highly polluted water from Bellandur Lake is used for irrigating agricultural lands, coconut trees, etc. However, several episodes of disease in coconut trees have been reported to have occurred as a result of using this water for irrigation [42]. In addition, the water is unsuitable for drinking, bathing or supporting the ecosystem as a whole due to the high discharges of sewage and other effluents into this system [42]. Public access to Bellandur Lake is now forbidden and the area is fenced off due to its heavily polluted waters emitting high levels of methane, and thus creating a high risk of fire. Also, the anoxic conditions and the absence of most forms of animal life mean that it is of limited use as a haven for biodiversity within the city.

In contrast, Jakkur Lake is very popular for recreational use and, as a biodiversity hotspot, it supports pelican roosts on its island. However, the lake still has persistent problems with algal blooms and with fish and bird deaths caused by low oxygen levels and, possibly, toxins from cyanobacteria. These problems indicate that the current uses of the lake may not be sustainable in the longer term unless the water quality improves. In addition to its direct uses, Jakkur Lake recharges (and potentially contaminates) local groundwater [50]. Groundwater is abstracted close to the lake and used as a supply of drinking and irrigation water. However, boreholes have had to be dug to a depth of about 200 m in some parts of Bangalore to compensate for rapidly falling ground water levels. These have been created by changes in the hydrological balance of the system, especially over-abstraction to supply local residents with drinking water.

2.3.4. Management recommendations. A number of management recommendations have been made to improve the future quality and utilisation potential of water from Bellandur and Jakkur lakes. These include:

- installing, or improving, municipal wastewater treatment systems to reduce organic loading, especially to Bellandur Lake
- incorporating tertiary treatment (e.g., constructed wetlands) into these systems to lower nutrient inputs and reduce the occurrence of harmful algal blooms
- setting up realistic water quality restoration goals for scaling up, and monitoring the efficacy of, interventions aimed at water quality improvement; given the high levels of secondarily treated wastewater that these urban lakes receive, setting water quality targets that are suitable for swimming and water-based recreation is unrealistic [51]
- supporting lake community action groups; these are already a strong force for change but require access to good monitoring data and to expert advice on its interpretation, to inform the development of sustainable solutions to their water quality problems [52]
- promoting Citizen Science by creating open data platforms (e.g. lake dashboards for data collection, monitoring and decision making) and by training volunteers to monitor lake water quality, biodiversity, etc. [52]

2.4 Winam Gulf of Lake Victoria, Kenya

2.4.1 Background. Lake Victoria, with a total surface area of 68,000 km², is shared among the three East African countries of Tanzania (51%), Uganda (43%) and Kenya (6%). The Winam (Kavirondo or Nyanza) Gulf is an area of Lake Victoria that sits wholly within Kenya (Figure 5). It has a surface area of 1,920 km², mean and maximum depths of 6 m and 43 m, respectively, and an estimated volume of about 6 km³. The catchment of the Winam Gulf covers an area of 11,994 km² [53] 62% of which is covered by natural vegetation, 31% is used for agriculture and the remaining 6% comprises urban areas and scattered settlements [54].

The Gulf delivers a range of ecosystem services such as transportation routes, recreation, tourism, and food and water security. Like other gulfs in Lake Victoria, limnological conditions within the Winam Gulf are different from those of the main lake and there is limited water exchange between the two systems due to a causeway that was constructed to link Rusinga Island to the mainland. This, together with many river inlets, results in the Gulf being more turbid than the open lake. Also, being the direct recipient of high levels of nutrients from catchment runoff and municipal waste, the Gulf is more eutrophic than the rest of the lake [55]. The Gulf influences the productivity of the wider lake, to a large extent, due to its unique physical nature and its location within the Lake Victoria basin.

2.4.2 Water quality problems. Although nutrient concentrations within the Gulf vary temporally and spatially [56, 57], there are sufficient historical data to show that levels of eutrophication have been increasing since the 1980s. This is demonstrated by the fact that soluble reactive P (SRP) concentrations rose from about 0.005 mg P L⁻¹ to about 0.07 mg P L⁻¹ between the 1960s and the 2010s. The most likely cause of these eutrophication problems is a rapidly growing population and a correspondingly large increase in agricultural production over this period [58]. The most recent estimates of P inputs to the Gulf are 716 t y⁻¹ from various sources, including wastewater (56%), agriculture (30%), natural vegetation (11%) and farm animals (3%) [59].

2.4.3. Impacts of water quality problems on lake utilisation. Nutrient enrichment within the Gulf has resulted in an overgrowth of algae, including potentially toxic cyanobacteria [60-62], and invasion by water hyacinth [63]. These problems have reduced the use of the Gulf for a variety of purposes. Firstly, water hyacinth accumulates in sheltered bays, making piers and harbours inaccessible to

shipping. Secondly, it blocks access to fishing grounds and landing sites, and damages fishing gear [64-66]. Thirdly, it reduces biodiversity [67, 68].

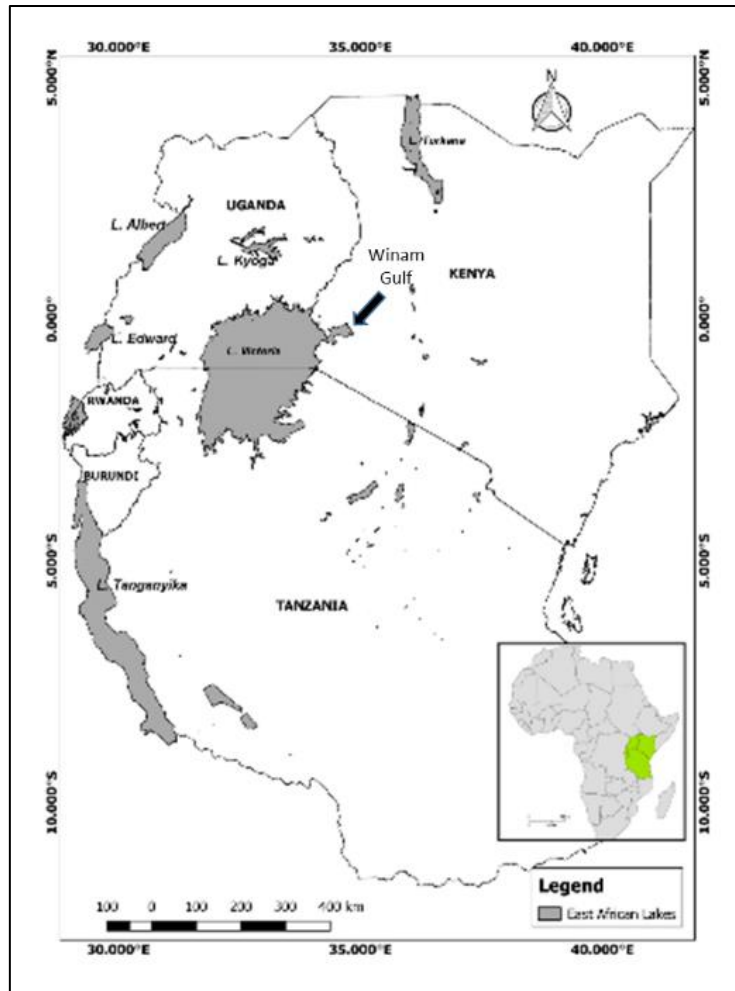


Figure 5. The location of the Winam Gulf of Lake Victoria, Kenya.

The potential risk of cyanobacterial toxins from *Microcystis* spp. and *Dolichospermum* (formerly *Anabaena*) spp. to the health of communities living around Kisumu Bay has been explored [69]. It was found that 50% of local households use raw lake water for drinking and domestic purposes, and that 30% of water samples taken from those households exceeded World Health Organisation (WHO) safe levels for microcystins (cyanobacterial toxins). In addition, it has been found that microcystin levels in fish from Lake Victoria often exceed the Tolerable Daily Intake (TDI) recommended by the WHO, thus potentially contributing to chronic exposure to microcystins among the communities living around the lake [70].

All of these problems have had serious socio-economic impacts on food security, and on the livelihoods and health of the local population. Often, they have caused fishing communities to migrate away from stricken areas [71], but other impacts include the social problems that arise from the competition that is generated by less access to areas of open water, fewer tourists, and blocked irrigation channels [71].

To compensate for the loss of income, and to secure food for a growing population, local fisherman have turned to aquaculture. As a result, the number of fish cages in the Kenyan part of Lake Victoria has risen from just a few cages in 2008 to about 4,400 by 2018 [72]. Because the fish are fed with

poor quality food and productivity levels are high, these caged fisheries exacerbate the increasing eutrophication problems by discharging nutrient laden wastes into the water; these encourage the growth of algal blooms and water hyacinth [73].

2.4.4. Management recommendations. To improve water quality within the Winam Gulf, and to reduce the impacts of the water hyacinth invasion, several potential solutions have been recommended. These include:

- reducing the level of nutrient laden discharges into the Gulf [74]
- implementing a multi-faceted approach to controlling water hyacinth that includes biological control, mechanical removal and the use of harvested weed for cottage industries and energy generation [75]
- zoning the lake according to its suitability for different uses, especially aquaculture [76]
- reducing the water retention time of the system by increasing the connectivity between the Gulf and the rest of Lake Victoria [74]

2.5 Tasik Chini Wetland, Malaysia

2.5.1. Background. Tasik Chini is a rare example of a flood pulse wetland in Malaysia. It comprises many different types of wetland habitat (Figure 6) and lies within an area that has a humid tropical climate and an average rainfall of 2,500 mm y⁻¹ [77]. The lake, itself, comprises about 2 km² of open water that has a maximum depth of 2.7 m and is surrounded by 7 km² of freshwater swamp and swamp forest. The catchment of Tasik Chini covers an area of about 50 km² that comprises low hills and undulating land with a maximum elevation 641 m.a.s.l. This includes the Tasik Chini State Park Forest Reserve, which consists mainly of tropical rainforest.

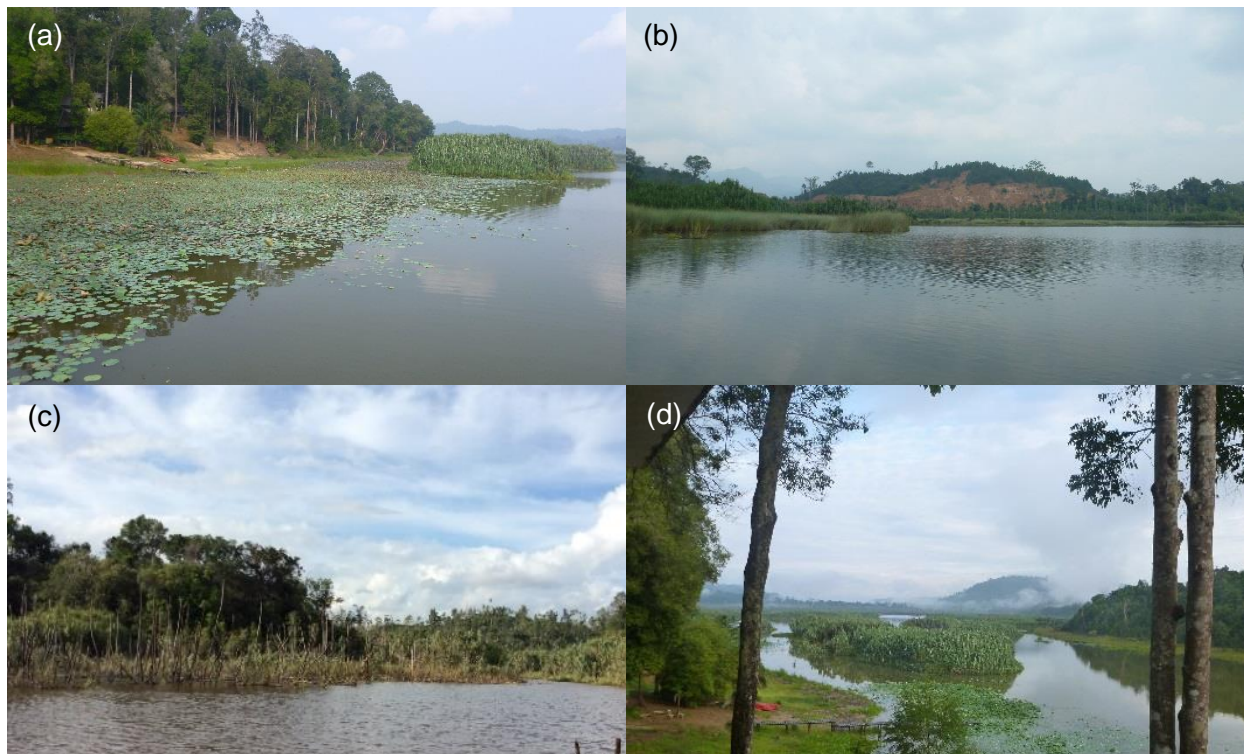


Figure 6. Tasik Chini, Malaysia, showing (a) Hydroserie of secondary dipterocarp forest, sedge at the lake margins, and floating vegetation, (b) evidence of local mining activity (c) marginal vegetation and (d) overview of Tasik Chini from the tourist hotel.

Water is discharged from the lake into the larger Pahang River via the Chini River, which can become an inflow during periods of high rainfall (November to March) [78]. When this happens, it creates a “flood pulse” that generates high concentrations of suspended solids within the system [79, 80] and can increase lake levels by more than 1 m in a day. Diatom records from the sediments of Tasik Chini suggest that conditions in the lake were stable until 1938, with the system being maintained by runoff from heavy and frequent rainfall events [81]. However, since then, the hydrology of the system has changed several times [81]. Variations in annual rainfall led to the drawdown and isolation of one of the lake’s basins between 1940 and 1980, although this was reconnected in 1995 when a small dam was built on the outflow to stabilise water levels and enhance the potential for ecotourism. This increased the size of the wetland by 2.4 km² and decreased its flushing rate [77, 83]; it also disrupted the natural flood pulse. It has been suggested that this decline in flushing rate caused the trophic state of the lake to change from nutrient poor (oligotrophic) to nutrient rich (eutrophic) [82].

Changes in the hydrology of the system have been driven, primarily, by variations in rainfall. However, the hydro-ecological response of the system has been exacerbated by land disturbance. Since the 1930s, soil erosion and nutrient runoff have increased because about 15% of the catchment has been converted from primary forest to oil palm and rubber agriculture [81, 83]. Since the 1980s, mining for iron ore has also increased soil erosion and water pollution problems in the area [83].

2.5.2 Water quality problems. In recent years, concerns have been raised about the sustainability of Tasik Chini with pollution, especially from sewage and agricultural runoff, being blamed for its deterioration. Conditions at Tasik Chini are now very turbid (total suspended solids 6–23 mg L⁻¹; Secchi depth <1 m). In the past this has probably been due to sediment entering the system from its numerous inflows. However, more recently, the motorised boats of tourism operators have disturbed the lake sediments. A recent survey of stakeholders suggested that the main problems in the area were perceived to be fewer forest products, a decline in fish, invasion by non-native plants, weir construction, mining, logging and increased levels of water pollution [84]. Climate change has exacerbated any potential water quality problems by reducing water levels and flushing rates [81].

2.5.3. Impacts of water quality problems on lake utilisation. The Tasik Chini basin has been designated as a UNESCO Man and Biosphere Reserve, with the aim of encouraging economic and social benefits for local people whilst demonstrating sustainable development and environmental conservation [85]. A stakeholder consultation found that local communities, of approximately 400 people [86], were once highly dependent on the lake, rivers, and forests in this area for their livelihoods with many earning a living as boatmen, fishermen or collectors of forest produce. In addition, clean water used to be supplied by the lake, its inflows and groundwater. In recent years, delivery of these ecosystem services has decreased due to the deteriorating quality of the lake and its inflows. As a result, about 40% of the local community are now engaged in agriculture (including oil palm cultivation), mining and tourism. In addition, tourist numbers have fallen due to the deterioration of water quality in the lake, as characterised by the perceived loss of the iconic water lotus (*Nelumbo nucifera*) [87] and the invasion of the system by a non-native macrophyte (*Cabomba furcata*) that has hindered navigation by tourist boats [88]. Changes in water level and increasing levels of nutrient enrichment have also changed the lake’s ecology, including the expansion of benthic habitats and greater coverage by swamp plants; this has made the site less attractive to visitors.

2.5.4. Management recommendations. In the absence of any long-term records, the main drivers of the historical deterioration of the Tasik Chini wetland were identified by exploring palaeolimnological evidence from the lake sediments [81]. These data showed that:

- sedimentation rates had increased markedly since the 1960s, exacerbated by land disturbances

- the ecology of the lake had been disrupted by fluctuations in lake levels, caused by hydrological interventions and changes in rainfall

The data suggest that these changes had led to eutrophication problems, losses of open water habitat and an expansion of benthic areas and swamp plants.

In terms of developing a plan for the sustainable management of this, and similar systems, in the future [81] it was concluded that:

- baseline conditions need to be defined before rare habitats can be restored effectively
- if long term records are not available, useful information can be derived from palaeolimnological evidence
- where a combination of local (e.g. land disturbance, damming) and regional (e.g. climate change) drivers have degraded water quality and disrupted ecosystem service delivery, restoration should focus on solving the local (more manageable) problems first.

2.6. Lake Toba, Indonesia²

2.6.1. Background. Lake Toba is Indonesia's largest lake and one of its most important freshwater resources [89 - 91]. Situated in North Sumatra Province (Figure 7), Lake Toba is a volcanic lake that reaches depths of 505 m and is surrounded by steep cliffs that rise to a height of 1,200 m above the surface of the lake. The lake has a rich cultural heritage and supports numerous social, environmental, and economic functions. It is one of Indonesia's priority tourism destinations for development and its waters support a 180 MW hydropower plant, aquaculture production of more than 80,000 tonnes of fish per year, domestic water supplies and livelihoods for about 0.5 million people living around its shores.

² This case study is based on World Bank, 2018a [91]



Figure 7. Location of Lake Toba in North Sumatra, Indonesia

The natural state of Lake Toba is oligotrophic and government regulations (Governor Regulation 1/2009) require nutrient inputs to be managed within these limits. However, Lake Toba’s P and DO concentrations are already above the threshold for mesotrophic conditions. This deterioration in water

quality is causing recurrent algal blooms and large fish kills, both of which threaten tourism potential and the long-term sustainability of the lake [91 – 93].

2.6.2. Water quality problems. The point and non-point sources of water pollution to Lake Toba (especially inputs of N and P) are caused by intensive and extensive caged aquaculture, livestock rearing (manure) and runoff of domestic wastewater. Important contributing factors include rapid changes in land use, including deforestation, which have exacerbated erosion problems within the catchment. An assessment of changes in water quality have identified aquaculture, livestock, and domestic wastewater as primary sources of increased N and P concentrations since the mid-1990s [91]. In 2015, it was estimated that 76% of N loads and 68% of P loads to the lake were derived from aquaculture (fish feed, manure, carcasses). In contrast, P inputs from livestock manure and wastewater were only 19% and 11%, respectively. Managing the nutrients inputs to Lake Toba is central to addressing its eutrophication problems and sustaining its long-term economic and environmental value.

A confounding problem is that Lake Toba has a long water residence time of about 80 years. Also, it is not well mixed, so the impacts of nutrient inputs on water quality vary across space and time. In 2016, chlorophyll *a* concentrations increased, surface water temperatures rose, and transparency fell due to localised algal blooms [94]. Examination of long-term historical data confirmed that the quality of the lake's surface and deep waters had been deteriorating since the 1930s.

2.6.3. Impacts of water quality problems on lake utilisation. Managing the emission of nutrients into Lake Toba is essential to addressing its eutrophication problems and their negative environmental impacts. The Government of Indonesia has given high priority to the future development of Lake Toba as a tourist destination and, prior to the COVID-19 pandemic, it has been estimated that its warm clear waters, stunning scenery, and recreational opportunities could attract 3.3 million visitors per year by 2041 [95]. However, the successful development of Lake Toba as a sustainable tourist destination depends on marked improvements being made in its water quality.

2.6.4. Management recommendations. A scenario based analysis was undertaken to identify the potential impacts of different types of interventions on water quality and to quantify the level of investment required to reduce nutrient concentrations to the level required to support the development of Lake Toba as a tourist attraction [91]. These scenarios were developed through a collaborative process that involved local stakeholders, national agencies and international experts. All five scenarios acknowledged the need for improving information flow and institutional coordination, and for creating an Integrated Lake Basin Management Platform. Also, it was concluded that:

- nutrient emissions from aquaculture need to be controlled by reducing fish production from 80,000 t y⁻¹ to 10,000 t y⁻¹, in line with government regulations
- a comprehensive and integrated water quality monitoring plan is required to assess the outcomes of any intervention and enable adaptive management
- new and innovative techniques, such as remote sensing, should be integrated with *in situ* water quality measurements
- better coordination is needed among government agencies and other stakeholders to ensure that actions to improve water quality are functional, financially viable, and cooperative.

3. Discussion

These case studies illustrate how increasing levels of anthropogenic pressures on tropical lakes and reservoirs can cause a degradation of water quality and quantity that adversely affects the health and welfare of the local communities that depend on them. A common driver of many of these problems is nutrient enrichment. While phosphorus (P) and nitrogen (N) are needed in sufficient quantities to support food and energy production, in excess they can cause water quality problems that limit the

utilisation of these systems for water supply, fisheries, recreation and tourism. These problems include potentially harmful algal blooms [6], proliferation of nuisance aquatic macrophytes, invasive species, low oxygen levels and excessive production of greenhouse gases such as methane. It is likely that climate change will exacerbate these impacts by increasing water temperatures and reducing flushing rates.

In contrast to many temperate systems, lakes and reservoirs in tropical countries are an important part of local economies, with the potential to improve food and water security, and to generate income that supports the livelihoods of local communities. However, as populations grow, development of these water resources needs to be managed in such a way that competing demands can be balanced within a sustainable framework. Realising this aim requires a comprehensive approach that can accommodate the needs of all relevant stakeholders in relation to defining a desired future state and agreeing an appropriate set of management interventions that can meet stakeholder expectations. Practical examples of this type of approach are provided by the Tasik Chini [85] and Lake Toba [96] case studies.

Eutrophication continues to be the most significant threat to the sustainable development of tropical lakes and reservoirs, as illustrated by most of the case studies. In particular, sustainable solutions are needed for reducing nutrient loads from waste water and runoff, from the internal recycling of nutrients from lake sediments and from the by-products of aquaculture. Potential solutions that are being explored include upgrading waste water treatment facilities (including the installation of constructed wetlands [44]), better regulation of fertiliser use within sensitive catchments, the more sustainable use of water and geoengineering solutions (e.g. with P adsorbent materials) [38, 40, 41]. Floating islands and macrophyte beds can also be used to remove of nutrients from contaminated lake water [17, 18].

However, it is important to establish the main cause of the problem and set realistic water quality targets, first. Where historical monitoring data are not available to identify the drivers of change and provide baseline conditions for a water body, the Tasik Chini case study demonstrates that this information can be obtained from palaeolimnological records [81]. The baseline conditions of water bodies will differ according to their type and geographical context, so these must be determined on a site specific basis.

The safe use of water for recreation and water supply is affected by the presence of algal toxins, because these can cause a wide range of health issues such as skin rashes, nausea and neurological problems. This problem has been highlighted as an issue in many of our case studies and is a widespread problem across the tropics [6]. However, the monitoring of toxins to determine an unsafe level can be difficult and expensive. As part of the Valle de Bravo Reservoir case study, tests are being carried out to determine whether biomonitoring can be used for this purpose [14]. Studies are also underway to investigate the potential bioaccumulation of cyanotoxins in fish, which can affect food safety [15].

The Task Chini case study found that the main drivers of change at this site ranged from local disturbances, such as land use change and damming, to regional drivers such as climate change [81]. The study concluded that the best way forward, in terms of water body restoration, was to address local, more manageable, issues first. The case study from Bangalore illustrates that local interventions can be implemented successfully by community action groups, if they have access to good data and the expert advice needed to develop sustainable solutions from those data; a particular challenge is the setting of realistic restoration targets that are fit for purpose [51].

The need to find a solution to water quality problems is all the more urgent now that it has been predicted that one impact of climate change will be the substantial migration of people into areas that are close to water sources by 2050 [96]. Climate change also exacerbates water quality problems by increasing water temperatures and decreasing flushing rates, both of which enhance the growth of cyanobacteria [31, 35-37].

Tropical lakes are strongly affected by catchment pressures, and their restoration and sustainable management requires an holistic approach that is applied to both terrestrial and aquatic ecosystems and

includes both natural and socio-economic systems. In addition, although the water quality problems in tropical lakes may look very similar to those seen in temperate systems, the solutions to those problems may be very different. For example, most of the restoration measures applied to temperate lakes assume that those lakes are P limited, whereas most tropical systems are N limited. Tropical systems also have very different stratification patterns, which has implications for anoxia and nutrient cycling. So, restoration methods that are effective in temperate systems may not be transferrable to tropical systems, and recovery trajectories may differ too. Tropical lakes need urgent, careful and evidence based management, but information on restoration and recovery processes in these systems is sparse. This requires further research.

4. Conclusions

Increases in anthropogenic pressures on tropical lakes and reservoirs are degrading the quality and quantity of the water that they contain; this is adversely affecting the health and welfare of communities that depend on them. Eutrophication is a particularly widespread problem. It limits the use of these systems for water supply, fisheries, recreation and tourism, and its effects are likely to be exacerbated by climate change. Delivering effective solutions to eutrophication problems requires a good understanding of nutrient sources and their impact so that management interventions (such as source control and/or nutrient removal) can be applied appropriately. Extensive stakeholder engagement is also an important part of this process.

Tropical lakes are strongly affected by catchment pressures, and their restoration and sustainable management requires an holistic approach to be applied across terrestrial and aquatic ecosystems, and includes both natural and socio-economic systems. Also, it needs to be recognised that solving water quality problems in tropical lakes may require different approaches to those used in temperate systems. Tropical lakes need urgent, careful and evidence based management interventions, but the lack of information on restoration and recovery processes in these systems makes this difficult to achieve. Further research is needed to address gaps in our knowledge on how to manage these systems sustainably.

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