Executive summary

1. River dolphins live in south and east Asia (Bangladesh, Cambodia, China, India, Indonesia, Myanmar, Nepal & Pakistan) and in South America (Bolivia, Brazil, Colombia, Ecuador, Peru, and Venezuela). They inhabit some of the world’s largest rivers, with very high water flows: the Amazon, Ayeyarwady, Indus, Ganges/Brahmaputra/Meghna, Mahakam, Mekong, Orinoco, and Yangtze. River dolphins formerly lived in other countries such as Laos.

2. Dolphin numbers have declined in recent decades. There are only six extant species of river dolphins left in the world today and they are all classified by IUCN as endangered or critically endangered. The major factors in the decline of river dolphins include aquatic pollution, poaching, by-catches, prey-fish depletion and habitat destruction due to river dredging, and fragmentation due to dams, and water extraction of water for irrigation. Restoring dolphin populations must include preventing or reducing river water pollution.

3. Wetlands have been described as ‘the kidneys of the landscape’ because they can remove pollutants from water. Floating wetlands, as the name suggests, consist of floating vegetation that has very limited contact with the bed of the pond or river and therefore derive their nutrients and other elements from the water column alone. Floating wetlands occur naturally in many locations, but their pollutant removal properties have not been fully studied. However, the effectiveness of constructed or highly managed floating wetlands has been tested in urban storm water ponds, mining and refinery plant wastewater, meat processing plants, poultry or livestock effluent, polluted rivers and water supply reservoirs, agriculture and aquaculture environment and aquaculture ponds.

4. The objectives of this study were to answer three questions using published scientific evidence: Q1: How effective are floating wetlands for reducing water pollution? Q2: What characteristics of floating wetlands alter their effectiveness? Q3: Are the results applicable to large flowing rivers supporting dolphin habitat? Searches of international databases, including Web of Science and Google scholar, yielded 3043 publications, all of which were reviewed at least at title and abstract level by applying predefined inclusion/exclusion criteria. This reduced the total to 185 publications relevant to the study. A further 20 were rejected on full text reading, leaving 165 papers. Of these, 16 were review papers, 40 of a general nature and 56 were on the ecology of river dolphins. Importantly, the 165 included 53 scientific publications containing data mainly from Asia (Bangladesh, China, India, Indonesia, Korea, Pakistan, Sri Lanka, Taiwan) but also from other countries worldwide (Australia, Belgium, Egypt, German, Italy, Netherlands, Portugal, UK, Costa Rica, Mexico, USA and Brazil). Studies from non-dolphin countries were included where information could be relevant to constructing wetlands in dolphin rivers, such as potential plant species, design of plant holders and buoyancy. Findings presented in this report are based on information from these publications. No further analysis of data was undertaken and no inferences were made beyond statements reported in the publications.
5. Most publications reported studies in which polluted water is introduced for treatment to a tank, lagoon or pond containing floating wetlands. In practice, treated water would then be released to a water course. In these studies, there is little flow or replenishment of polluted water; the plants remove pollutants from the same water over a period of time. Only four studies were of wetlands within rivers. Almost all publications reported pollutant removal in terms of change in concentration in the water, which is applicable to critical levels in dolphin rivers. Almost all the studies concluded that floating wetlands can remove significant amounts of pollutants from water, including heavy metals (Fe, Mn, Zn, Cu & Pb), nutrient pollution (N&P), Biological Oxygen Demand (BOD), chemicals (PFAS) and bacteria (E Coli). Effectiveness rate varied greatly; some tank studies reported 100% removal, others no removal. One study reported floating wetlands reduced cadmium and iron concentrations below national permissible thresholds for rivers. None referred to pollutants affecting dolphins. Some publications also reported pollutant concentrations in the wetland plants after uptake; these data do not indicate water concentrations that are critical for dolphins, however they can indicate differential pollutant uptake by plant species.

6. Only three river studies reported data. In China, a wetland across the entire channel width removed 36.9% of total nitrogen, 44.8% of ammonia, 25.6% of nitrate and 43.3% of total phosphorus. A canal study in the USA, where the floating wetland covered only part of the channel, reported lowering of nitrate-as-nitrogen and phosphate by 6.9% and 6.0% respectively. A further study of floating wetland covering part of the channel in India reported a “slow flowing or almost stagnant river”; total nitrogen, ammonia and nitrate were reduced by 37.7%, 39.7% and 10.5% respectively but measurements were taken adjacent to the wetland, so not encompassing flow that would by-pass the facility.

7. In tanks and ponds, the size of a floating wetland, in terms of % plant coverage of the water surface, has an influence on pollutant removal effectiveness, the relationship is not definitive. Ideally floating wetland volume as a proportion of water volume might be a better metric. Generally, studies suggest 50-70% surface cover provided the maximum uptake from the water column, although 40-50% coverage produced good performance in some studies. In some studies, higher coverage reduced dissolved oxygen and caused anoxia, whilst lower coverage produced little treatment effect. Of the three river studies, the one with a wetland across the entire width of the channel showed greater pollutant removal than those that cover part of the channel. Theoretically the required size of floating wetland for a river would be proportional to the discharge or catchment area but insufficient river studies were available to quantify this relationship.

8. In tank and pond studies, the time taken to absorb pollutants depended on pollutant type. However, generally, the minimum retention time recommended was 5 days after which time the duration seemed less important for pollutant removal. Some studies recommend a water depth of at least 0.8–1.0 m to prevent plants rooting in the bed and reducing pollutant uptake from the water column.

9. Plant species differ in their effectiveness to take-up pollutants. Species reported to be particularly effective at nutrient take-up were common reed (Phramites Australis), water hyacinth (Eichhoria crassipes), yellow flag iris (Iris pseudacorus), jointed rush (Baumea articulata) and broadleaf cattail (Typha Latifolia), although figures from different studies were inconsistent, perhaps reflecting the influence of other variables. Plant species with highest take-up of heavy metals were frogbit (Hydrocharis dubia), water hyacinth (Eichhirnia crasslpes) and water lettuce. (Pisitia stratiotes). Generally, the highest pollutant removal rates were amongst those plants with the highest biomass production and high transpiration rates. Floating wetlands containing a diversity of species were more effective than single species wetlands. The presence of microbes within a biofilm in the wetland enhanced pollutant removal significantly.

10. Continued pollutant removal efficiency can be enhanced by regular plant harvesting, which stimulates regrowth and prevents pollutants being re-mobilised back to the water. Whilst harvesting both roots and shoots could maximize nutrient removal, it can be difficult, time consuming, and costly; harvesting the plant shoots is the most practical and cost-effective option.
11. In addition to pollutant removal, floating wetlands can provide important habitat for birds, fish and invertebrates and plant harvesting produces raw materials for animal feed and biofuel production. However, maintaining these functions (e.g. avoiding harvesting during bird nesting) may not be consistent with management for optimum pollutant removal.

12. Whilst floating wetlands can be beneficial, potential trade-offs must be considered. Some plants, such as water hyacinth are very invasive and have become a nuisance in water bodies such as water hyacinth in Lake Victoria, so they would not be recommended for floating wetlands outside of enclosed tanks. Some floating wetlands have been found to emit significant nitrous oxide, whilst others absorb methane. One bacterium, *Pseudomonas pneumoniae*, that is effective at removal of copper in wetlands, can cause illness, particularly in people with weakened immune systems. Pollutant take-up by plants can lead to bioaccumulation in the aquatic food chain. Care must be taken when using waste from bioremediation or animal feed to avoid contamination from pollutants absorbed by the plants. Use of some wetland plants may be restricted by their lack of tolerance to polluted conditions, such as high copper concentrations.

13. Few publications provided details of manufacturing and installation costs of floating wetlands. One study in India suggested a cost of US$60 per m$^2$ locally compared with US$220 in USA.

14. Given that only three publications reported data from experiments where the floating wetland was actually in a river, it is not possible to draw firm recommendations for future installations. The two most relevant studies (River Kshipra, India and river in Jiaxing City, China) suggest that where a floating wetland spans the entire river width pollutant might be reduced by 30-40% and around 5% if it spanned 10% of the river. However, constructing a similar floating wetland across major rivers supporting dolphins, which could be more than 1 km wide, would not be practical in many ways, including construction, anchorage in high flows, allowing navigation and wetland management. The limited evidence suggests distributed wetlands on point sources of pollution, such as factory discharge canals or urban stormwater ponds are likely to be more realistic. Further studies are required of floating wetlands within rivers, particularly those where dolphins live, to test these conclusions.

15. The significance of percentage reductions in pollutant loads for dolphin health also depends on the initial concentration or load. Analysis of data available in the publications could be undertaken. Multivariate analysis may, for example, reveal patterns or tendencies or explain differences in effectiveness from different studies that were due to factors such as design, climate, initial pollutant concentrations and plant type.

16. Further studies of the effectiveness of floating wetlands need to be undertaken in dolphin rivers to augment information from the literature. A single large wetland immediately upstream of dolphin habitat cleaning the river water flowing into it, is unlikely to be practical given the large size of rivers involved; a demonstration project on a small tributary would be more realistic, with a small wetland downstream of pollution sources, which might be in a lagoon or in the water course. The wetlands can be designed initially using information from the literature. To establish effectiveness, water quality measurements should be taken upstream and downstream of the wetland and discharge data obtained. Measurement of pollutant levels in harvested plants samples would provide additional data on effectiveness. Related investigations could include use of harvested material for bioenergy or animal feed, particularly amongst local people, mindful of the potential toxicity of the plants, plus general biodiversity surveys.
Project title: Artificial floating wetlands to increase river water quality, for dolphins and people.

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Rob McInnes is an internationally respected expert on wetlands and particularly on constructing wetlands to improve water quality. Rob is a Chartered Environmentalist and has been Director of RM Wetlands & Environment Ltd since 2011. He possesses specialist knowledge and understanding of the benefits wetland ecosystems provide to human society and how to protect, manage, restore or create multifunctional-multibenefit wetlands. This includes recent work on floating wetlands and designs for the UK Water Industry to remove pollutants from rivers. Rob was formerly President of the Society of Wetland Scientists and remains a member of the Ramsar Convention’s scientific advisory panel (STRP).
River dolphin extent and populations

River dolphins live in Asia and South America, in 14 countries and 8 of the world’s largest river basins. They are important indicators for the health of the rivers they live in, which are also the lifeblood of huge economies and hundreds of millions of people. Where freshwater dolphin populations are thriving, it is likely that the overall river systems will be flourishing too – as well as the people and countless wild species that depend on them. But river dolphins are at risk. There are only six extant species of river dolphins left in the world today and they are all classified by IUCN as endangered or critically endangered.

Hydrological habitat of river dolphins

Searches of the literature provided some information on hydrological habitats of river dolphins.

Ganges river dolphins (*Platanista gangetica*) historically occurred throughout the Ganges-Brahmaputra-Meghna and Karnaphuli-Sangu River basins from their tidal deltas in India and Bangladesh, to the plains at the Himalayan foothills (Figure 1), where rocky barriers, shallow water, and fast currents prevented upstream movement. They do not normally occur in coastal waters when salinity is above 10–12 ppt (Smith *et al*. 2009), but they have been observed occasionally in waters with salinity up to 23 ppt (Smith *et al*. 2010).

![Figure 1 Range of Ganges river dolphin *Platanista gangetica* (Kelkar *et al.*, 2022)](image_url)

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1 Bangladesh, Bolivia, Brazil, Cambodia, China, Colombia, Ecuador, India, Indonesia, Myanmar, Nepal, Pakistan, Peru, and Venezuela. River dolphins formerly lived in other countries such as Laos.

2 Amazon, Ayeyarwady, Indus, Ganges/Brahmaputra/Meghna, Mahakam, Mekong, Orinoco, and Yangtze
Ganges river dolphins generally favour deep pools (Paudel et al., 2015), particularly with counter-currents, and below channel convergences and sharp meanders (Kasuya & Haque 1972, Smith 1993, Smith et al. 1998; 2000) and above and below mid-channel islands, bridge pilings, and other engineering structures that cause scouring (Smith et al. 1998, Smith & Reeves 2012). Adults can grow to nearly 3 m in length and prefer river sections with thalweg depths of 5–12 m in larger river channels (Kelkar et al. 2010). In shallower tributaries, dolphins were found in river channels with depths from 2.5 to 5 m (Choudhary et al. 2012).

The Indus river dolphin (Platanista minor), also known as the bhulan in Urdu and Sindhi, is endemic to the Indus River Basin of Pakistan and northwestern India. It is patchily distributed in five sub-populations that are separated by irrigation barrages. These dolphins inhabited around 3,400 km of the Indus River and the tributaries attached to it in the past, but today, it is only found in one fifth of this previous range (Figure 2), with a range decline by 80% since 1870 (Braulik, 2006). This dolphin prefers a freshwater habitat with a water depth greater than 1 meter and that have more than 700 meters squared of cross-sectional area. The Indus river dolphin has most recently been assessed for the IUCN Red List of Threatened Species in 2021 and listed as Endangered under criteria A2abcde; C1 (Braulik et al., 2022).

Figure 2. Range of Indus river dolphin Platanista minor (Braulik et al., 2022)

Amazon river dolphins (Inia geoffrensis) also called boto, bufeo, and pink dolphin are found throughout the Amazon and Orinoco basins (Figure 3) and can grow to over 2.4 m in length. Whilst they stay in the main river during low flows, they can swim into the flooded forests in the high-water season (Layne 1958, Best & da Silva 1989a) in search of prey among the roots and trunks of partially submerged trees (da Silva 1984). Females with dependent calves spend more time inside the flooded forest and in lakes and small tributaries during the high-water season, while most adult males at any one time occur in the main rivers.

When the water is receding, dolphins leave the lakes and the shallow habitats, perhaps in order to avoid getting trapped (Martin & da Silva, 2004a,b; Mintzer et al., 2016). During the low-water season, Inia are often concentrated below channel confluences (Best & da Silva, 1989a,b; Leatherwood, 1996; Vidal et al., 1997; McGuire & Winemiller, 1998; Leatherwood et al. 2000). In the main rivers they occur most often within 150 m of the banks, with lower
densities in the centre of large rivers (Martin et al., 2004a; Gómez-Salazar et al., 2012a). Some individuals are resident to specific areas year-round (Martin & da Silva, 2004a; Gómez-Salazar et al., 2011), whereas others move several thousand kilometres within the rivers, but there does not appear to be any rigid seasonal migration patterns (Martin & da Silva, 2004a).

Irrawaddy river dolphins occurs in varied habitats (Figure 4) including in the Mekong, Ayeyawady and the Mahakam River. In some rivers, they inhabit relatively deep (10-50 m) pools located at confluences or above and below rapids. In coastal waters, Irrawaddy dolphins most commonly occur in areas with freshwater inputs and they may enter the lower reaches of rivers (Smith, 2017). In the Rajang River in Sarawak, Malaysia, Irrawaddy dolphins were observed both in the lower reaches of the river and as far as 86 km upriver (Bali et al. 2017).

Figure 3. Range of Amazon River Dolphin *Inia geoffrensis* (IUCN Red List)
Yangtze river dolphins, also known as Baiji (*Lipotes vexillifer*) are now possibly extinct. They were found throughout the lower reaches of the Yangtze River (Figure 5). They grew to around 2.4 m in length and were generally found in eddy counter-currents below meanders and channel convergences (Hua *et al*. 1989, Zhou and Li 1989, Zhang *et al*. 2003). They were known to prey on fish of many sizes and various species, including both surface and bottom feeders (Chen *et al*. 1997). The Yangtze finless porpoise (the only freshwater porpoise in the world) is still living in the Yangtze River, occupying the same habitat as Baiji once did.
River discharge data indicate the general size of the river and rate of flow of water. Discharge data are publicly available for most dolphin rivers, but not for India where these data are confidential. Discharge data were obtained from the Global Runoff Data Centre for several measurement stations to give an indication. Table 1 shows that minimum flows are in the region of 100 to 55,000 m$^3$s$^{-1}$. Clearly discharge will decrease further upstream, but given their size, dolphins are limited to the more downstream parts of the rivers. Even the upper reaches of the Amazon are around 0.7 km wide, increasing to 3 km wide in its mid-reaches. Other dolphin rivers also exceed 1 km in width in their lower reaches.

Table 1. Maximum and minimum monthly discharge for some dolphin rivers

<table>
<thead>
<tr>
<th>River</th>
<th>Station location</th>
<th>Approximate maximum monthly mean discharge (m$^3$s$^{-1}$)</th>
<th>Approximate minimum monthly mean discharge (m$^3$s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ganges</td>
<td>Paksey</td>
<td>48,000</td>
<td>2,500</td>
</tr>
<tr>
<td>Brahmaputra</td>
<td>Bahadurabad</td>
<td>59,000</td>
<td>2,600</td>
</tr>
<tr>
<td>Indus</td>
<td>Kotri barrage</td>
<td>22,600</td>
<td>100</td>
</tr>
<tr>
<td>Rio Atiparana</td>
<td>Barreirinha</td>
<td>5,250</td>
<td>240</td>
</tr>
<tr>
<td>Rio Negro</td>
<td>Curicuriari</td>
<td>27,400</td>
<td>2,400</td>
</tr>
<tr>
<td>Amazon</td>
<td>Jaturana</td>
<td>217,000</td>
<td>55,000</td>
</tr>
</tbody>
</table>
Water quality data including a large, but inconsistent, range of nutrients and heavy metals, are available at station, country or catchment level from the UNEP GEMStat Data Portal. Some example values are given in Table 2. However, these are individual sample values rather than broad statistics. Consequently, data analysis would be required to assess general water quality and pollutant levels that would affect dolphins, which was beyond the scope of this study. Any site-based interventions would need to collect and analyse local water quality data.

Table 2. Example water quality data for some dolphin rivers

<table>
<thead>
<tr>
<th>River</th>
<th>Sampling location</th>
<th>total phosphorus (mg l⁻¹)</th>
<th>dissolved reactive phosphorus (mg l⁻¹)</th>
<th>ammonia nitrate (mg l⁻¹)</th>
<th>nitrite &amp; nitrate (mg l⁻¹)</th>
<th>cadmium (mg l⁻¹)</th>
<th>lead (mg l⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ganges</td>
<td>Padha</td>
<td>0.1 – 0.4</td>
<td>0.0</td>
<td>0.9 – 2.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brahmaputra</td>
<td>Dhubris Assam</td>
<td>1.1 – 1.9</td>
<td>7 – 23</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indus</td>
<td>Kotri barrage</td>
<td>0.2 – 2.3</td>
<td>2.0</td>
<td>0.0 – 4.2</td>
<td>1.6 – 8.3</td>
<td>0.0</td>
<td>0.005 – 0.05</td>
</tr>
<tr>
<td>Amazon</td>
<td>Manaus</td>
<td>0.05</td>
<td>0.04</td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yangtze</td>
<td>Chang Jiang</td>
<td>0.04 – 0.12</td>
<td>0.0</td>
<td>0.05 – 0.12</td>
<td>0.2 – 0.9</td>
<td>0 – 0.002</td>
<td>0.005 – 0.05</td>
</tr>
</tbody>
</table>

Factors influencing river dolphin populations

The major factors in the decline of river dolphins include aquatic pollution, poaching, by-catches and interactions with fisheries including prey-fish depletion, dam and impoundment construction and habitat destruction due to river dredging and extraction of water for irrigation (Smith et al., 1998; Brownell et al., 2017; Chaudhury et al., 2019, Braulik et al., 2021).

Focusing on water quality issues relevant to this analysis, untreated domestic sewage discharged to the River Ganges, India, contains butyltin, used in wood preservative and anti-fouling paint, which is an endocrine disrupting compound that influences biological activities such as growth, reproduction and other physiological processes. Concentrations in
fish and invertebrates were 3-10 times greater than in sediment. Total butyltin concentration in the tissues of dolphins (Platanista gangetica) was 5-10 times higher than in their diet, reaching 2000 ng g⁻¹, due to biomagnification in the freshwater food chain (Kannan et al., 1998). Perfluoro chemicals, used in many sectors, e.g. aerospace and defence, automotive, aviation, textiles, leather, were found in the liver of Ganges River dolphins at concentrations of 27.9 ng g⁻¹ (Yeung et al. 2009).

The River Beas, India, receives untreated sewage from the surrounding villages and agricultural run-off containing fertilizers and pesticides posing threat to river dolphins. Both the Ganges river dolphin and Irrawaddy dolphin were predicted to have a moderate risk of plastic ingestion (Roman et al., 2022). The River Ganges also suffers pollution by plastics from fishing gear (Nelms et al., 2021).

The subpopulation of the Irrawaddy dolphin (Orcaella brevirostris) living in the Mekong River, Cambodia, is considered to be critically endangered due to pollutants such as organochlorines and polybrominated diphenyl ethers and organic mercury (Schnitzler et al., 2021).

In China large dams, including the Three Gorges High Dam, have affected fisheries stocks and endangered fish species and may have contributed to the extinction of the endemic and highly endangered Yangtze river dolphin (Lipotes vexillifer), exacerbated by overfishing and increasing pollution of rivers by sewage, pesticides and industrial wastes (Dudgeon, 1995). Threats to river dolphins in the Yangtze River from water pollution include eutrophication, heavy metals, and organic pollutants (Wang et al., 2016). Dichlorodiphenyltrichloroethane (DDT) and persistent organic pollutants (POPS) pose a high risk to dolphins (Zhang et al., 2020).

Wavelength-dispersive X-ray fluorescence (WD-XRF) spectrometry has detected heavy metals in blood and milk samples of a free-ranging female Amazon river dolphin (Inia geoffrensis) from Central Amazon, Brazil. In all, 14 elements (Na, Mg, Al, Si, P, S, Cl, K, Ca, Cr, Mn, Fe, Zn, and Cu) in the samples analysed, in which 13 elements were in the blood and 14 were in the milk. However, no mercury was detected (Silva et al., 2023). However, mercury was found in the muscle tissue 46 individuals of genera Inia and Sotalia in the Arauca and Orinoco Rivers, Colombia, the Amazon River, Colombia, a tributary of the Itenez River, Bolivia and the Tapajos River, Brazil (Mosquera-Guerra et al. 2019). Mercury has been released from artisanal and industrial gold mining since colonial times, as well as being a result of deforestation and burning of primary forest, that release natural deposits of methyl mercury.

Heavy metals can be toxic to dolphin species (Lavery et al., 2009). In the River Amazon near Manaus, Brazil, high concentrations of K, Mg, Na and Ca have been detected in river dolphins. Mercury concentration found in the dolphin’s milk (176 ng/ml) was very close to the minimum level of methylmercury toxicity for non-pregnant human adults (Rosas & Lehti, 1996).

The literature found does not provide critical levels of pollutants above which they are toxic to river dolphins.

Floating wetlands as a potential solution to falling river dolphin populations

The studies described above demonstrate a need for targeted and practical interventions to limit the pollutants in major river systems that are home for dolphins. Stopping pollution at source would be preferable, but this is a broad issue requiring action from governments and industries (including farming) and environment protection agencies. Treating pollutants once they reach a water course is another potential intervention.

Wetlands have been described as ‘the kidneys of the landscape’ (Mitsch & Gosselink, 1995) because of these hydrological and chemical functions they perform removing pollutants from water. In a review of the effectiveness of
wetlands as nature-based solutions in Africa (Acreman et al., 2021) seven case studies of natural wetlands reported changes to total nitrogen in downstream water course; all were decreases. Five of these reported numerical values, which ranged from 33.0% to 53.0% reductions. Six case studies of natural wetlands reported changes to total phosphorus in downstream water courses; three reported decreases from 5.0% to 50.0, though one study of Natete wetland Uganda (Kanyiginya et al., 2010) reported an increase in nutrients due possibly to remobilisation from sediments. Eight case studies of natural wetlands reported changes in heavy metal (cadmium, copper, iron, lead, manganese, uranium and zinc) in downstream water courses; all were decreases ranging from 61% reduction to full removal (-100%). As an example, the Nakivubo swamp, Uganda, receives partially treated sewage from the city of Kampala and removes nutrient and pathogens with an effectiveness of 56% for nitrogen, 40% for total phosphorus and 91% for faecal coliforms (Kansiime & van Bruggen, 2001; Mugisha et al., 2007). Wetlands have also been constructed specifically to treat water pollution and this usually involves adapting conditions to enhance pollutant removal. Many constructed wetlands can remove 60-100% of ammonia, nutrients (nitrogen and phosphorus), heavy metals (e.g. cadmium, lead, zinc, copper, iron, manganese, mercury), oil and grease, \textit{E. coli}, parasite eggs, Salmonellae and faecal coliforms (Acreman et al., 2021).

Floating wetlands, such as floating islands (Figure 6), provide one nature-based aquatic phytoremediation device that can help reduce pollutants (Shahid et al., 2018; Kumar et al., 2020). This has been considered an effective, aesthetically pleasing, cost effective and environmentally friendly technology for the remediation of potentially toxic metals from the environment (Ali et al., 2020). Studies in Pakistan have shown artificial, floating wetlands in stagnant water, close to the outlet of polluting industries can be effective (Azfal et al., 2019).

Figure 6. Representation of an artificial floating island, presenting (A) shoots, (B) floating device, (C) roots under the surface water, allowing biofilm formation. The system remains floating in water flow (D) (after Demarco et al., 2023).

In some places floating islands occur naturally, such as floating reed islands in Srebarna Lake, Bulgaria (Ivanova et al. 2018), the Kuttanad–Vembanad Wetland, India (John et al., 2009) and mats of water hyacinth in Lake Victoria (Luilo, 2008). These can be very biological diverse, for example floating mats in the Abobral and Miranda Pantanal Wetlands of Brazil contained 66 species of epiphytic aquatic macrophytes, distributed in 27 families, \textit{Cyperaceae} and \textit{Poaceae} being the most representative, with the number of species per mat varied from 7 to 39 (Pivari et al., 2008). The Mississippi River delta in coastal Louisiana, USA and particularly Lake Boeuf, which covers 640 ha, supports one of the largest floating marsh systems known worldwide, occupying around 100,000 ha (Sasser et al., 2019) with an
average of 20 species recorded from ten 0.25 m² plots (Visser & Sasser, 2009). Nitrogen and phosphorus transformations in this floating system are important to the nutrient budget of the whole delta ecosystem (Sasser et al., 1991). The floating meadows of Keibul Lamjao National Park, India, located in the Indo-Burma Biodiversity Hotspot are crucial for the survival of the globally threatened Eld’s deer, Rucervus eldii, and the hog deer, Axis porcinus (Tuboi & Hussain, 2018).

Some natural floating plants such as Water hyacinths (Eichhornia crassipes), a native of the Amazon, but a widespread invader across Africa, can reduce nutrient concentration significantly, as shown for the Hartbeespoort Dam water, South Africa (Auchterlonie et al., 2021). However, the pollutant reduction properties of natural floating wetlands are not widely reported and some natural floating wetlands, such as Sphagnum palustre, are sensitive to high levels of nutrients and the Mizorogaike wetland, Japan, has decreased significantly due to eutrophication (Tsujino et al., 2020). Consequently, in this report the focus is on floating treatment wetlands fabricated or managed specifically to treat water pollution. Such floating wetlands or islands are small artificial platforms that allow aquatic emergent plants to grow in water that is typically too deep for them to root in the bed. Their roots spread through the floating islands and down into the water column creating a dense mass of roots with a large surface area (Figure 12). Because these roots do not reach the pond, lake or river bed, all plant nutrients and other requirements are taken from the water column, thus generating an absorption mechanisms for contaminants. In addition, the plant roots and floating island material provide an extensive surface area for microbes to grow as a slimy layer of biofilm that services pollutant degradation.

The concept of constructing a floating platform on which plants could be grown to improve water quality originated in China, Japan, Taiwan and UK in the 1990s (Headley & Tanner, 2006; Masters, 2012). Floating beds of Canna generalis were placed on fishponds and their biomass production was measured (Wu et al., 2000). Similar soil-less floating beds planted with Canna were also used to control eutrophic water in China, with coverage of 20% to significantly improve water quality (Bing & Chen 2001). This eco-technology has been installed around 2000 lakes and ponds in USA covering 24,000m² (Kamble & Patil, 2012). Floating wetlands can remove phosphorous at up to 4.6 g m⁻²d⁻¹ and ammonia at up to 8.1 g m⁻²d⁻¹ with simultaneous denitrification of nitrate to nitrogen gas (Masters, 2012).

The effectiveness of floating wetlands for pollution removal has been tested in storm water ponds, mining or refinery plant wastewater, meat processing, plants, poultry or livestock effluent, lakes, rivers and water supply reservoirs, agriculture and aquaculture environment (Yeh et al., 2015) and aquaculture, loach (Misgurnus anguillicaudatus) rearing ponds (Zhang et al., 2015).

Floating wetlands containing a mix of rush species in the USA were shown to significantly reduce nitrate (Messer et al., 2022). Floating wetlands can also remove emerging contaminants, such as per- and polyfluoroalkyl substances, which are not always filtered by treatment plants and are linked to elevated cholesterol levels, problems with reproductive health, and kidney and testicular cancers in humans. In Australia, Phragmites australis reeds placed in a floating wetland were shown to absorb these pollutants into their tissues in less than a month (Cosier, 2022).

Study objective

The overall objective of this study was to assess the effectiveness of floating wetlands as nature-based solutions to remove pollutants from river water where dolphins live. According to IUCN, nature-based solutions are “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016).
Floating wetlands are nature-based solutions that have the potential to protect river dolphins, maintain wider biological diversity and provide numerous additional community benefits.

Study approach
The study focused on addressing the following three key questions and three supplementary questions.

Q1: How effective are floating wetlands for reducing water pollution?
Q2: What characteristics of floating wetlands alter their effectiveness?
Q3: Are the results applicable to large flowing rivers supporting dolphin habitat?

Supplementary questions were:

a. How is effectiveness measured?
b. What surface area of floating wetland is needed to improve water quality significantly?
c. How can effectiveness be maximised?

Given the budget available, a first phase of this work focused on the effectiveness of floating wetlands for removing nutrients and pollutants such as heavy metals. Research into and development of guideline on the design of floating wetlands and benefits to/involved from local communities may be addressed as a separate later stage of the project.

This study will follow the principles of systematic evidence reviews as detailed in Annex 1.

Numbers and distribution of published studies
Searches of Web of Science (see Annex 1) were undertaken using the term ‘floating wetland’ returned 2635 publications in English language. Most reported studies of changes in nutrient levels and in BOD or COD in water bodies holding floating wetlands, whilst 1628 publications referred to changes in heavy metals. Further searches were undertaken using Google scholar and the top 200 publications were added to the pool. Finally, searches were undertaken using ‘river dolphin’ and ‘pollution’, which returned 208 publications, to provide contextual information.

Table 3. Publications retained for the report after applying inclusion/exclusion criteria.

<table>
<thead>
<tr>
<th>Type of publication</th>
<th>Details</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reviews</td>
<td>Published reviews of available literature</td>
<td>16</td>
</tr>
<tr>
<td>Technical studies</td>
<td>Results of studies of effectiveness</td>
<td>53</td>
</tr>
<tr>
<td>General</td>
<td>Useful general information on the topic</td>
<td>40</td>
</tr>
<tr>
<td>Dolphin studies</td>
<td>Details of dolphin ecology and habitat</td>
<td>56</td>
</tr>
</tbody>
</table>
All 3043 publications were reviewed at least at title and abstract level by applying the inclusion/exclusion criteria, when there was any doubt the publications with included. This reduced the total to 185 publications that at first screening were relevant to the study. For each of the 185 publications, the full text was assessed and categorised as shown in Table 3. These numbers exceed, but are broadly in line with, the agreed limits for the project of 1500 publications to be screened at title/abstract level and 100 to be assessed at full text level, which, it was assumed, would yield around 50 publications holding relevant data.

These numbers are broadly consistent with a search of Web of Science using the term “Floating Treatment Wetlands” undertaken in September 2019 (Colares et al. 2020), which used different inclusion/exclusion criteria. That search found 396 publications, of which 359 were articles, 51 proceedings papers, 16 reviews, three meeting abstracts, two abstracts, one data paper and one early access. Another review based on Web of Science (Oliveira et al., 2021) also used the term “Floating Treatment Wetlands” and returned 440 articles.

The technical studies included cover a range of applications of floating wetlands, such as to treat domestic sewage (e.g. Huth et al., 2021), highway runoff containing heavy metals (e.g. Ladislas et al., 2015), textile waste (e.g. Wei et al., 2020), acid mine waste (e.g. Palihakkara et al., 2018) and polluted river water (e.g. Lin et al., 2019). The water bodies studied included Ramsar designated wetlands, rivers, lakes, reservoirs, lagoons and ponds.

Publications rejected reported subjects such as computer modelling (e.g. Xavier et al., 2018), detailed processes studies of contaminant dispersion (e.g. Wang et al., 2022), survey methods (e.g. vonBank et al., 2017), effects of elevated CO$_2$ on floating wetland plant growth (e.g. Middleton & McKee, 2012), vegetation succession in natural floating wetlands (e.g. van Diggelen et al., 1996) and sediment influx (e.g. Carpenter et al., 2007). Table 4 shows that the majority of 53 studies were from Asia, with a few from Meso and South America, so covering regions inhabited by dolphins. Studies from non-dolphin countries (e.g. USA, African and European countries) were retained where information could be relevant to constructing wetlands in dolphin rivers, such as potential plant species, design of plant holders and buoyancy or where they used species that exist dolphin home countries.

<table>
<thead>
<tr>
<th>Continents</th>
<th>No</th>
<th>Countries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
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<td>Egypt</td>
</tr>
<tr>
<td>Asia</td>
<td>26</td>
<td>Bangladesh, China, India, Indonesia, Korea, Pakistan, Sri Lanka, Taiwan</td>
</tr>
<tr>
<td>Australasia</td>
<td>4</td>
<td>Australia</td>
</tr>
<tr>
<td>Europe</td>
<td>8</td>
<td>Belgium, German, Italy, Netherlands, Portugal, UK</td>
</tr>
<tr>
<td>Meso America</td>
<td>2</td>
<td>Costa Rica, Mexico</td>
</tr>
</tbody>
</table>
Research study design
Before detailing the findings of the studies of the effectiveness, it is important to describe the design of the studies. In the vast majority of cases, polluted water was taken from a river or lake or waste discharge channel and introduced to a constructed tank, pond or lagoon holding the floating wetland. In practice, treated water would then be released from the treatment lagoon to a water course. The wetlands ranged in size: 19 smaller than 1 m$^2$, 8 between 1 and 10 m$^2$, 7 between 10 and 100 m$^2$ and 7 greater than 100 m$^2$. The smallest, shown in Plate 1a, was 0.06 m$^2$ using water hyacinth to treat acid mine waste in Sri Lanka (Palihakkara et al., 2018). A further small-scale example is shown in Plate 1b from Pakistan using reeds to reduce pollutants from textile effluent. A large lagoon experiment, for which no image is available, was 1741 m$^2$ using water lettuce and water hyacinth to treat wastewater from a dairy farm, paper plant and landfill in Costa Rica (Nahlik & Mitsch, 2006).

Three examples of larger-scale experiment are shown in Plate 2a, a 722 m$^2$ wetland of southern cattail to treat domestic sewage in Brazil (Benvenuti et al., 2018), in Plate 2b, islands of around 160 m$^2$ of reeds to treat a lake algal bloom in Korea (Park et al., 2018) and in Plate 2c, islands of 1858 m$^2$ of reeds and canna to treat an urban waste water in Pakistan (Afzal et al., 2019).

In most cases water quality variables were measured before and after a set period, ranging from 1 or 460 days, often referred to as hydraulic retention time. Only in 7 experiments was there any mention of flow through the system, so it was assumed that water was static in the other experiments. In the larger-scale experiment in Brazil (Plate 2a) the inflow rate (referred to as hydraulic loading) was 67.4 m$^3$d$^{-1}$ or 0.09 m$^3$d$^{-1}$ m$^{-2}$ for each m$^2$ of wetland. In an experiment to treat pollution in the urban River Yitong, China (Bai et al., 2020), a 150 m$^3$ floating wetland was constructed in a tank on the floodplain into which river water was diverted, with an inflow rate of 100 m$^3$d$^{-1}$ or 0.67 m$^3$d$^{-1}$m$^{-2}$.
Plate 2 Large-scale experiments. a. Brazil (Benvenuti et al., 2018) b. Korea (Park et al., 2018) c. Pakistan (Afzal et al., 2019).
Plate 3. Floating wetlands a. on the Chicago River, USA (Cosier, 2022), b. in the River Kshipra, India (Billore et al., 2009), c. in a eutrophic river in Jiaxing City, China (Zhao et al., 2012), d. canal, Chicago, USA (Peterson et al., 2021).

Only three publications reported results of experiments where the floating wetland was actually in a river (Plate 3). A fourth, a study of a floating wetland in the Chicago River, USA (Cosier, 2022), gave qualitative information but no data. The three with data were (1) a study of the River Kshipra, India (Billore et al., 2009), which was described as “slow flowing or almost stagnant river”; (2) a study of a river in Jiaxing City, in the northern subtropical monsoon climate zone of China (Zhao et al., 2012), where the ‘flow rate’ can be calculated from the reported velocity (0.2 m s\(^{-1}\) to 1.5 m s\(^{-1}\)) and cross-section (55 m\(^2\)) to give 11 to 83 m\(^3\)s\(^{-1}\); and (3) a canal in Chicago (Peterson et al., 2021) with a 90 m\(^2\) artificial floating wetland and a mean discharge of 0.88 m\(^3\)s\(^{-1}\) (or 76032 m\(^3\)d\(^{-1}\)).

Two papers by Shahid et al. (2019a,b) refer to remediation of polluted River Ravi water using floating treatment wetlands, however this study was achieved by taking samples of river water and introducing them to tanks with floating wetlands, rather than the wetlands being in the river itself. Water samples are taken from Kerukan River (Banjarmasin, South Kalimantan Indonesia Prihatini et al., 2019). Yang et al. (2010) reported nutrient reductions in the Bailianjing River, Shanghai, China but only the abstract was available in English, so the experimental design was not clear.

Research study pollutant measurement and effectiveness

For the purposes of this report, the ideal result of research would be the effectiveness of floating wetlands in terms of their ability to reduce pollutant levels from above those critical for dolphins to below those critical for dolphins. No studies provided this information. One study in Pakistan (Afzal et al., 2019) reported floating wetlands reduced cadmium and iron concentrations below national permissible thresholds in rivers, but it was not clear how these thresholds were defined.

Most studies reported measurements of pollutant concentrations in water. These concentrations provide a direct means of assessing the effectiveness of floating wetlands on aquatic habitat. In the cases of tanks and ponds, water samples were taken at set intervals or at the start and end of experiments, which ranged from 4 days to 426 days. Pollutant concentrations in the samples indicate water quality change (improvement in most cases) over time. This time period was often referred to as hydraulic retention time (i.e. how long water is held in the system before it flows
out/is replaced), but in most cases, as described above, there was little throughput of water into and out of the ponds and tanks. Thus, the floating wetlands were removing pollutants from the same water during the experiments. In the studies where the wetlands were in rivers, measurements from water samples taken upstream and downstream providing a measure of effectiveness longitudinally in the river.

Plate 4. Sampling points in the River Kshipra, India (from Billore et al., 2009)

In Korea, water samples for chemical analysis were collected from two sampling holes within the floating wetland (Parks et al., 2018), but no indication of water flow or throughput was given.

In the River Kshipra, India (Billore et al., 2009), the water quality was compared between two points, sampling point 1 located at 40m upstream of the wetland receiving the input from an adjoining sewage stream, and sampling point 2 lying below the distal end of the reed bed in the water (Plate 4). However, it is not clear how much of the water sampled at point 1 would pass through the wetland to point 2 and how much would by-pass the wetland. Likewise, water samples of influent and effluent were collected from the river in Jiaxing City, China (Zhao et al., 2012).

After analysing medium-sized storm water ponds in North Carolina, USA, Maxwell et al. (2020) concluded that limited discrete sampling can lead to partial information and potentially erroneous conclusions when assessing floating wetland treatment effectiveness.

Some studies measured the take-up of pollutants by plants. Such data do not directly indicate the effectiveness of the plants in improving water quality as will be dependent on other factors such as total plant mass and water volume/flow. However, plant uptake data are useful for calculating a pollutant budget and for differentiating pollutant removal effectiveness between species.

Pollutant removal rates from water

Almost all publications reported that floating wetlands can remove significant amounts of pollutants from water. They have the ability to effectively remove heavy metals (Fe, Mn, Zn, Cu), nutrient pollution (N&P), chemicals (PFAS) and bacteria (E Coli) (Zhao et al., 2012; Awad et al., 2022). In Australia, floating wetland of
Jointed twig rush, *Baumea articulata*, can successfully remove significant amounts of nutrients from domestic wastewater (Huth *et al*., 2021). Most studies reported percentage changes in concentrations. **The significance of these percentages for dolphin health depends partly on the initial concentration or load.** For example, a low percentage removal from a high concentration may be more important ecologically than a high percentage from a low concentration. In some publications, more data were given but much additional work would be required to extract and analyse this information for all studies. As examples, floating wetlands removed heavy metals in water from the River Ravi in Pakistan by 79.5% for iron, 91.4% for nickel, 91.8% for manganese, 36.14% for lead, and 85.19% for chromium (Shahid *et al*., 2019b). In China, floating treatment wetlands reduced total nitrogen by 83.5% and total phosphorous by 91.0% in urban storm water runoff (Xu *et al*., 2017).

The mean and range of reduction across the 53 technical studies is given in Table 5. Many studies did not report % reductions in this way but detailed pollutant concentration in wetland plant tissues.

Data are reported for three floating wetland studies from within rivers. For the River Kshipra, India (Billore *et al*., 2009), described as “slow flowing or almost stagnant river”, total nitrogen, ammonia and nitrate were reduced by 37.7%, 39.7% and 10.5% respectively, but dissolved oxygen was also reduced by 14.6% (see chapter 12). In the river in Jiaxing City, China (Zhao *et al*., 2012), total nitrogen, ammonia, nitrate and total phosphorus were reduced by 36.9%, 44.8%, 25.6%, 43.3% respectively. The study of the canal in Chicago, USA, comparison of upstream and downstream waters showed that the floating wetland lowered the concentrations of nitrate-as-nitrogen and phosphate during the growing season by 6.9% and 6.0% respectively (Peterson *et al*., 2021).

In Italy, floating wetland had an important role in total nitrogen and ammonia nitrogen abatement (Barco & Borin, 2020). Treated effluents from floating wetlands in Pakistan met the water quality guidelines for irrigation and aquatic life Shahid *et al*., (2019b) as total nitrogen, nitrate and total phosphorus concentrations decreased to 1.77 mg/L, 0.80 mg/L and 0.60 mg/L, respectively. Additionally, the concentration of iron, nickel, manganese, lead and chromium in the water lowered to 0.41, 0.16, 0.10, 0.25, and 0.08 mg/L, respectively. In contrast, studies of medium-sized storm water ponds in North Carolina, USA, revealed no significant differences in total nitrogen and total phosphorus between two ponds, one with floating wetlands and the other without (the control).

**Table 5. Mean reduction of pollutants across 53 studies**

<table>
<thead>
<tr>
<th>Water quality variable</th>
<th>No of studies recording variable</th>
<th>Mean and range % reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD</td>
<td>9</td>
<td>71.8 (92.0 – 33.4)</td>
</tr>
<tr>
<td>COD</td>
<td>11</td>
<td>67.3 (93.6 - 67.3)</td>
</tr>
<tr>
<td>Total phosphorus</td>
<td>16</td>
<td>59.1 (100.0 - 0.0)</td>
</tr>
<tr>
<td>Total nitrogen</td>
<td>16</td>
<td>52.6 (100.0 - 0.0)</td>
</tr>
<tr>
<td>Phosphate</td>
<td>3</td>
<td>64.3 (97.5 - 6.0)</td>
</tr>
<tr>
<td>Ammonia NH₄-N</td>
<td>10</td>
<td>61.8 (97.5 – 5.5)</td>
</tr>
</tbody>
</table>
Size and coverage

The size of a floating wetland, in terms of percentage cover of the water surface, is theoretically an important factor in its effectiveness in removing pollutants. Size is most usefully indexed as percentage cover of a lagoon, tank or pond. Data from the scientific studies are displayed in Figure 7. For flowing water bodies, including rivers, size would be best indexed in relation to river discharge or catchment area or residence time for water flowing through lakes, but these data are not provided for the studies in the literature.

In Asia, installation over large surface areas, with coverage ranging from 10% to 30% of lakes and reservoirs, helped mitigate the effects of eutrophication (Nakamura & Mueller, 2008). In the USA, a computer model of floating wetland in a storm water pond was used to assess the effect of surface area coverage on nitrogen removal and indicated that over the range 0.7% to 100% coverage, efficiency increased with surface area of wetland (McAndrew & Ahn, 2017).

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Value</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrate NO₃-N</td>
<td>7</td>
<td>39.2 (99.0 – 6.9)</td>
</tr>
<tr>
<td>Total suspended solids</td>
<td>4</td>
<td>78.1 (97.6 – 43.0)</td>
</tr>
<tr>
<td>Dissolved oxygen</td>
<td>2</td>
<td>15.4 (16.2 – 14.6)</td>
</tr>
<tr>
<td>Arsenic Ar</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Cadmium Cd</td>
<td>3</td>
<td>75.3 (91.8 – 58.0)</td>
</tr>
<tr>
<td>Chromium Cr</td>
<td>4</td>
<td>70.0 (95.2 – 33.4)</td>
</tr>
<tr>
<td>Copper Cu</td>
<td>4</td>
<td>57.2 (75.0 – 23.0)</td>
</tr>
<tr>
<td>Iron Fe</td>
<td>6</td>
<td>66.4 (83.0 – 40.0)</td>
</tr>
<tr>
<td>Mercury Hg</td>
<td>1</td>
<td>29.4</td>
</tr>
<tr>
<td>Lead Pb</td>
<td>4</td>
<td>67.7 (88.9 – 36.1)</td>
</tr>
<tr>
<td>Magnesium Mn</td>
<td>3</td>
<td>58.6 (91.8 – 14.0)</td>
</tr>
<tr>
<td>Nickle Ni</td>
<td>4</td>
<td>78.4 (91.4 – 67.0)</td>
</tr>
<tr>
<td>Vanadium V</td>
<td>1</td>
<td>79.9</td>
</tr>
<tr>
<td>Zinc Zn</td>
<td>4</td>
<td>66.5 (86.9 – 33.0)</td>
</tr>
</tbody>
</table>
In Korea, a 20m² floating wetland in a pond of surface area 1,000 m² (i.e. 2%) produced little change in water quality; a 40% coverage of the pond reportedly eliminated 100% of nutrients from the inflow (Park et al. 2001). Similarly, in a review, low vegetation cover, 9–18%, was found to contribute insignificantly to treatment efficiency (Sharma et al., 2021). In Africa, a plant coverage of 50% of a tank showed a good performance regarding the bioaccumulation of biochemical parameters (Gaballah et al., 2021). However, total nitrogen and total phosphorus were only reduced by 4.1 and 8.0%, respectively in a pond in the USA with 50% floating wetland coverage (Maxwell et al. 2020).

Overall, a floating wetland with 70% coverage (of E. crassipes) and a retention of 3–5 days was identified as the optimum design for effective remediation of the polluted water in Marriott Lake, Egypt (Gaballah et al., 2021).

Tanks treating urban storm water in the USA removed 48% total nitrogen with only 9% island cover and this increased to 88% with 18% cover (Winston et al., 2013). In India, the effect of coverage of tanks by floating wetland on pollution from domestic sewage was examined systematically (Samal et al. 2020). Coverage of zero, 25%, 50%, 75% and 100% reduced COD by 60.8%, 85.4% 96.2%, 93.6% and 86.4% respectively. Furthermore, ammonia was reduced by 65.3%, 88.2%, 97.1%, 97.5% and 92.5%, respectively and phosphate by 52%, 81.2%, 91.6% and 96%, respectively. It is noteworthy that even with no plants, removal exceeded 50% and maximum removal of ammonia was with 75% coverage (Figure 7).
Figure 7. Pollutant removal rates as a function of floating wetland plant coverage

Large percentage cover of floating wetlands can restrict oxygen diffusion from the air into the water in tanks and ponds (Smith and Kalin, 2000). High cover (>50%) can cause anoxia, while low cover (9 to 18%) may produce little additional treatment effect (Winston et al., 2013). When floating wetlands occupied 50% or more of the surface water area, the reduction in treatment efficiency due to anoxia was found in several studies (Borne et al., 2014). These findings probably explain the reduction in efficiency at high percentages shown in some graphs in Figure 7. Chang et al. (2017) suggested that coverage as low as 20% could be optimal if a pond or lagoon to be maintained as an aerobic system without artificial aeration, and still achieve good removal efficiency.

The issue of anoxia was not discussed in the three river studies reporting data. In flowing rivers with water arriving from upstream, floating wetlands may not alter oxygen levels.

In rivers, floating wetlands need to be sufficiently large to intercept most of the flow; otherwise untreated water will bypass the installation. However, constructing a floating wetland across the entire width of a large river could be impractical in most instances. Even if it were possible, in deep rivers, significant amounts of polluted water may still underneath the wetland. None of the publications addressed this topic.

Other ways to assess pollutant removal effectiveness would be in terms of additional variables such as inflow rate or floating wetland area as a percentage of the catchment area draining to the facility. However, insufficient data were available to make any assessment of this. Such factors may not be as effective as improving the efficiency of the floating wetland design (Lucke et al., 2019).

Retention time and depth

In general, increasing the hydraulic retention time, or the time water spends in contact with floating wetland plants, increases the overall removal of some pollutants (Abed et al. 2017). However, if the water volume below the plant roots is high, then less water will be in contact with the biofilm present at the roots’ surface (Colares et al., 2020). The minimum retention time recommended is 5 days for wastewater treatment, after which time the duration seems less important for pollutant removal (Olguin et al., 2017). Reducing the retention time from 14 to 7 days did not lead to significant changes in pollutant removal (Colares et al., 2020).
Gaballah et al. (2021) studied floating wetlands in laboratory tanks with water depths of 15, 25 and 35 cm to assess their effectiveness at remove nutrients and heavy metals from water taken from Marriott Lake, Egypt. Overall, the floating wetland with 70% E. crassipes coverage, 25-cm water depth, and a retention of 3–5 days was identified as the optimum design. However, such depths may not be appropriate for floating wetlands in lakes and rivers. 

A depth of 0.8–1.0 m was recommended for functioning of floating bed wetlands with fluctuating water levels (Samal et al., 2019). If the water becomes shallow macrophytes roots can extend into sediment, replacing some pollutant uptake from the water with uptake from the bed, and attach to the bed; when the water level increases, there is a chance that roots may not be able to get detached from the benthic zone and macrophyte may submerged in the water body (Samal et al., 2019).

Plant species

Plant uptake plays a major role in overall nutrient removal by floating wetlands (Keizer-Vlek et al., 2014). Some studies measured the take-up of pollutants by different plant species, for example Lin et al. (2019) reported concentrations of Vanadium, Chromium and Cadmium in Acorus calamus shoots were 9.32, 51.17 and 0.78 mg kg⁻¹, respectively. In stormwater retention ponds, total nitrogen uptake by Carex virgata was 14 mg g⁻¹ (Borne et al., 2013). Wetland plant species also differ in their ability to diffuse oxygen from the atmosphere to the water column. Where there is a risk of anoxia (see chapter 12), the selection of the appropriate species should be a consideration (Rehman et al., 2017).

Many different plant species have been shown to be effective in pollutant removal studies, but uptake differs, which strongly influences treatment efficiency (Oliveira et al., 2021). Plant uptake data can also be useful for differentiating pollutant removal effectiveness between different species and different pollutants. However, the large number of combinations of species and pollutants studied in the literature and inconsistencies in results make it very difficult to identify the most effective species for removing a particular pollutant.

When comparing three plant species, the highest overall perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid removal efficacies were for Phragmites australis (0.21, 0.33 μg g⁻¹) followed by Baumea articulata (0.13, 0.18 μg g⁻¹), and then Juncus krausii (0.09, 0.11 μg g⁻¹) with uptake rate changing with initial exposure concentrations (Awad et al., 2022). Plant communities including Oenanthe hookeri outperformed other communities in removing phosphorus (Geng et al., 2017).

Hubbard et al. (2004) found that cattail (Typha latifolia L.) was more effective than maidencane (Panicum hematomon Schult ‘Halifax’) at nutrient removal from pig wastewater. Cattail removed 534, 79, and 563 g m⁻² of nitrogen, phosphorus and potassium, respectively, whilst maidencane removed 323, 48, and 223 g m⁻². Hubbard et al. (2004) compared nutrient uptake from pig wastewater of five species, common bermuda grass (Cynodon dactylon (L.) Pers.), Tift on 85 bermuda grass (Cynodon dactylon (L.) Pers.), St. Augustine grass (Stenotaphrum secundatum (WalterKuntze)), fall panicum (Panicum dichotomiflorum (L.) Michx.) and giant reed (Arundo donax L.). The greatest annual nutrient uptake was by Tift on 85 bermuda grass, which removed 69 and 25 g m⁻² of nitrogen and phosphorus respectively.

Karstens et al. (2021) compared nutrient uptake in Bolboschoenus maritimus, Carex acutiformis, Iris pseudacorus, Juncus effesus, Lythrum salicaria, Schoenoplectus lacustris and Typha latifolia. Phosphorus concentrations were highest in L. salicaria 247 mg m⁻² and nitrogen in I. pseudacorus 8188 mg m⁻².
Floating wetlands containing 70% water hyacinth (*Eichhornia crassipes*) coverage was identified as the optimum design for effective remediation of the polluted water from Marriott Lake, Egypt (Gaballah et al., 2021). It has great ability to remediate contaminants like arsenic, zinc, mercury, nickel, copper and lead from industrial and domestic wastewater streams (Ali et al., 2020). In studies of polluted riverine wetland water in China, flat-topped bog moss (*Sphagnum fallax*) had the greatest ability to accumulate iron, whilst spikey bog moss (*Sphagnum squarossum*) was superior potential for manganese accumulation (Li et al., 2016). Duckweed (*Lemnoidae*), which can survive in high pH (3.5), and water fern (*Salvinia natans*) both readily take-up heavy metals such as nickel, manganese, zinc, uranium, arsenic, and copper (Ali et al., 2020). As with water hyacinth, some species of water fern are recognised as invasives (see chapter 19).

Water lettuce (*Pistia stratiotes*) has the capacity for reducing/removing nutrients such as nitrogen, ammonia, nitrite, nitrate and phosphate from sewage water and industrial wastewater (Ali et al., 2020). In the River Yangtze delta, China, alligator flag (*Thalia dealbata*) outperformed canna lily (*Canna indica*) and purple loosestrife (*Lythrum salicaria*) in nutrient removal (Ge et al., 2016). In China, floating wetlands including water dropwort (*Oenanthe hookeri*) outperformed others in removing phosphorous (Geng et al. 2017). In Mexico, vetiver (*Chrysopogon zizanioides*) removed significant heavy metals landfill leachate (Álvarez-Ascencio et al. 2022), whilst in the UK, common reed (*Phragmites australis*) significantly reduced COD in highly polluted urban runoff (Abed et al., 2021). In a study of 10 plant species in Australia, two, twig rush (*Baumea articulata*) and the common reed (*Phragmites australis*) showed the highest uptake of nitrogen and phosphorus of any floating wetland (Huth et al., 2021). *Baumea articulata* uptake of nitrogen in its shoots was 104 g m$^{-2}$ and roots 23.9 g m$^{-2}$ and phosphorus in its shoots was 12.9 g m$^{-2}$ and roots 5.54 g m$^{-2}$. Uptake was slightly less in *Phragmites australis* with nitrogen uptake in the shoots 52.5 g m$^{-2}$ and 17.1 g m$^{-2}$ in roots, whilst phosphorus uptake was 7.69 g m$^{-2}$ in shoots and 2.82 g m$^{-2}$ in its roots.

### Table 6. Nutrient uptake by different plant species

<table>
<thead>
<tr>
<th>plant species (common and latin names)</th>
<th>part of plant</th>
<th>nitrogen (g m$^{2}$)</th>
<th>phosphorus (g m$^{2}$)</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jointed or twig rush <em>Baumea articulata</em></td>
<td>roots</td>
<td>24</td>
<td>5.5</td>
<td>Huth et al. (2021)</td>
</tr>
<tr>
<td></td>
<td>shoots</td>
<td>104</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Common reed <em>Phragmites australis</em></td>
<td>roots</td>
<td>17</td>
<td>2.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>shoots</td>
<td>53</td>
<td>7.7</td>
<td></td>
</tr>
<tr>
<td>Lesser bulrush <em>Typha augustifolia</em></td>
<td>whole</td>
<td>1.2</td>
<td>0.48</td>
<td>Keizer-Viek et al. (2014)</td>
</tr>
<tr>
<td>Yellow flag iris <em>Iris pseudacorus</em></td>
<td>whole</td>
<td>19</td>
<td>0.51</td>
<td>Gao et al. (2017)</td>
</tr>
<tr>
<td></td>
<td>whole</td>
<td>52</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Sea clubrush <em>Bolboschoenus maritimus</em></td>
<td>whole</td>
<td>3.3</td>
<td>0.11</td>
<td>Karstens et al. (2021)</td>
</tr>
<tr>
<td>Species</td>
<td>Form</td>
<td>Plant parts</td>
<td>Take-up rate (g kg(^{-1}))</td>
<td>Source</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>------</td>
<td>-------------</td>
<td>--------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Lesser pond sedge Carex acutiformis</td>
<td>whole</td>
<td>3.0</td>
<td>0.13</td>
<td>Hubbard et al. (2004)</td>
</tr>
<tr>
<td>Broadleaf cattail Typha latifolia</td>
<td>whole</td>
<td>5.3</td>
<td>0.25</td>
<td>Hubbard et al. (2004)</td>
</tr>
<tr>
<td>Broadleaf cattail Typha latifolia</td>
<td>whole</td>
<td>534</td>
<td>79</td>
<td>Hubbard et al. (2004)</td>
</tr>
<tr>
<td>Yellow flag iris Iris pseudacorus</td>
<td>whole</td>
<td>110</td>
<td>4.2</td>
<td>Xu et al. (2017)</td>
</tr>
<tr>
<td>Alligator-flag Thalia dealbata</td>
<td>whole</td>
<td>86</td>
<td>3.9</td>
<td>Zhang et al. (2016)</td>
</tr>
<tr>
<td>Edible canna Canna indica</td>
<td>whole</td>
<td>62</td>
<td>12</td>
<td>Zhao et al. (2012)</td>
</tr>
<tr>
<td>Water hyacinth Eichhormia crassipes</td>
<td>whole</td>
<td>33</td>
<td>8.2</td>
<td>Zhao et al. (2012)</td>
</tr>
<tr>
<td>Water lettuce Pistia stratiotes</td>
<td>whole</td>
<td>14</td>
<td>4.1</td>
<td>Zhao et al. (2012)</td>
</tr>
<tr>
<td>Jussiaea repens</td>
<td>whole</td>
<td>23</td>
<td>7.7</td>
<td>Zhao et al. (2012)</td>
</tr>
<tr>
<td>Whorled pennywort Hydrocotyle verticillata</td>
<td>whole</td>
<td>30</td>
<td>7.1</td>
<td>Zhao et al. (2012)</td>
</tr>
<tr>
<td>Frogbit Hydrocharis dubia</td>
<td>whole</td>
<td>7.8</td>
<td>2.0</td>
<td>Zhao et al. (2012)</td>
</tr>
<tr>
<td>Parrot’s feather Myriophyllum aquaticum</td>
<td>whole</td>
<td>49</td>
<td>9.1</td>
<td>Zhao et al. (2012)</td>
</tr>
<tr>
<td>Pickerel weed Pontederia cordata</td>
<td>whole</td>
<td>29</td>
<td>5.9</td>
<td>Garcia Chance &amp; White (2018)</td>
</tr>
<tr>
<td>Edible canna Canna indica</td>
<td>whole</td>
<td>31</td>
<td>8.2</td>
<td>Garcia Chance &amp; White (2018)</td>
</tr>
<tr>
<td>Alligator-flag Thalia dealbata</td>
<td>whole</td>
<td>57</td>
<td>8.2</td>
<td>Garcia Chance &amp; White (2018)</td>
</tr>
<tr>
<td>Golden canna Canna flaccida</td>
<td>whole</td>
<td>45</td>
<td>7.6</td>
<td>Garcia Chance &amp; White (2018)</td>
</tr>
<tr>
<td>Soft rush Juncus effusus</td>
<td>whole</td>
<td>22</td>
<td>3.9</td>
<td>Karstens et al. (2021)</td>
</tr>
<tr>
<td>Purple loosestrife Lythrum salicaria</td>
<td>whole</td>
<td>4.5</td>
<td>0.25</td>
<td>Karstens et al. (2021)</td>
</tr>
<tr>
<td>Purple loosestrife Lythrum salicaria</td>
<td>whole</td>
<td>3.3</td>
<td>0.20</td>
<td>Karstens et al. (2021)</td>
</tr>
</tbody>
</table>

Table 7. Plants species with high effectiveness to take-up heavy metals (after Zhao et al., 2012)
Table 6 contains plant uptake data (when given as g m$^{-2}$) for nitrogen and phosphorus from the 53 studies, which potentially allows their effectiveness to be compared. It is noteworthy that widely differing values are presented for the same species – e.g. two orders of magnitude different for Typha latifolia by Hubbard et al. (2004) and Karstens et al. (2021) and one order of magnitude difference for Iris pseudacorus by Karstens et al. (2021) and Xu et al. (2017). This may show that other conditions, such as biomass, experimental design, temperature or initial pollutant concentrations, may significantly influence plant take-up. Other studies presented effectiveness in terms of g pollutant per kg of plant material; data on the plants with highest take-up rate of heavy metals (Zhao et al., 2012) are provided in Table 7.

### Plant biomass and diversity

Diversity and species richness can be important for purification effectiveness. Floating wetlands containing a diversity of species removed nitrate at more than twice the rate of simple Rush wetlands (Messer et al., 2022). Similarly, high plant species richness enhanced phosphate removal (Geng et al., 2017) due to higher biomass production. Schück & Greger (2020) compared heavy metal removal capacity of 34 different plant species but found no correlations with the uptake of metals; results generally indicated removal would be increased by selecting plants with high transpiration and high total biomass.

Geng et al. (2017) used four common species (Rumex japonicas, Oenanthe hookeri, Phalaris arundinacea and Reineckiacarnea) and compared 15 combinations (4 monocultures, 6 two-species mixtures, 4 three-species mixtures and 1 four-species mixture). Results showed that total P removal increased with increasing species richness, primarily due to higher biomass production, but species composition exerted a stronger effect than species richness.

Pollutant removal by floating wetlands also depends strongly on plant biomass production (Keizer-Vlek et al., 2014), such as nitrogen removal (McAndrew & Ahn, 2017). In France, higher plant biomass production observed in greater pond sedge (Carex riparia) compared to common rush (Juncus effusus), due to better tolerance of the conditions, led
to a greater heavy metal removal in highway stormwater ponds (Ladislas et al., 2015). Also due to its high biomass, alligator flag (Thalia dealbata) showed the greatest nutrient uptake in studies in China (Zhao et al., 2012). Also in China, floating wetlands with softstem bulrush (Scirpus validus Vahl), spiked loosestrife (Lythrum salicaria Linn.), yellow-flowered iris (Iris wilsonii) and dwarf cattail (Typha minima) had a strong capacity for the removal of nitrogen and phosphorus (Yao et al. 2011).

Studies of floating wetlands in Italy (Barco & Borin, 2020) assessed the performances of 11 wetland species and found that Canna (Canna indica), pickerel weed (Pontederia cordata) and alligator flag (Thalia dealbata) were the most suitable species for floating wetlands due to their high vigour and colonization of the floating mats. In contrast, sweet flag (Acorus calamus), bur weed (Sparganium erectum) and calla lily (Zantedeschia aethiopica) did not present adequate features for use in FTWs.

**Time of year can influence pollutant removal effectiveness in floating wetlands** because pollutant loads change, plant processing changes and environmental factor such as temperature alter. In China, phosphorus concentrations of influent water increased quickly from February to August with the increases in water temperature and then decreased with the decreases in water temperature. The average total phosphorus removal rate in the summer–autumn season was 43.3%, which was 2.6 times that in the winter–spring season with 17.0% average removal rate, due to high growth, and associated nutrient uptake, of emerged plants on the floating island in the summer–autumn season (Zhao et al., 2012).

**Bacterial biofilms and invertebrates**

Biofilms are communities of microorganisms (bacteria, fungi, algae) that get attached to each other and to stable surfaces. They provide mechanical stability, enhance water retention, improve nutrient sorption, give protection against viruses and possess antimicrobial activity (Samal et al., 2019). After a review of literature, Masters (2012) concluded that ‘bacterial biofilms develop on all physical surfaces within a wetland and it is bacteria, supplemented by oxygen and carbon from plants, which do the bulk of the work (pollutant removal) within wetlands including within and beneath floating islands’. **Whilst the right plants can be critical to pollutant removal efficiency, this can be enhanced by the natural development of, or the inoculation with, specific bacterial strains** (Wei et al., 2020).

In China, it was found that integrating plants and biofilm carriers enhanced the nutrient (nitrogen, phosphorus and ammonia) removal efficiency (Zhang et al., 2015), although previous work suggested the bacterial community parameters of the biofilms were not related to pollutant removal (Zhang et al., 2014). A global review found that rhizosphere microbial communities promoted the removal of phosphorus (Shen et al., 2022). In the Ravi River study in Pakistan, inoculation of plants with bacteria enhanced their natural ability to utilize their metabolic mechanisms to eliminate various types of pollutants from wastewater (Shahid et al., 2019a). Similarly, in Pakistan augmentation with bacteria of reeds (Phragmites australis) and cattail (Typha domingensis) enhanced their heavy metal removal efficiency from textile wastewater (Tara et al., 2018). Additionally, in Pakistan inoculation with bacterial strains significantly increased removal of heavy metal from the treated dye-enriched wastewater (Nawaz et al., 2020).

Whilst many publications endorsed the ability of biofilms to enhance pollutant uptake and processing, they provided no details of biofilm types, conditions required or inoculation methods.
Invertebrate species can also be influential. In a study of algal blooms in a lake in Korea, with floating wetlands containing a strong zooplankton community, rotifers biomass had increased BOD reduction (Park et al., 2018). The major mechanisms for improving water quality were found to be inhibition of phytoplankton growth by attenuating light, top-down control by zooplankton grazing and active decomposition of organic matter in the rhizospheric zone.

Technical design of artificial floating wetlands
The most common construction of floating wetlands is a raft or pontoon that consists of a buoyant frame enclosing a permeable material into which wetland vegetation can be planted and harvested. In many cases, a floating frame is constructed using sealed lengths of PVC or other plastic pipes. These may be joined together to form a buoyant square or rectangular frame, or used as individual linear sections that are connected in some other way to form a floating frame. Additional buoyancy is often provided by use of a floating structure or raft which supports the growth of the plants filled with expanded polystyrene foam (Headley & Tanner, 2006). Other floating wetlands consisted of 2.4 m by 4.8 m frames constructed from timber with plastic snow fencing or fish netting stapled across the bottom to support the developing vegetation mat. Styrofoam and plywood panels were attached to the sides to provide artificial buoyancy for the first few growing seasons after which mat became thick enough and had trapped sufficient gas to be self-buoyant. Rafts were lined with burlap to hold the growth medium (Smith & Kalin, 2000).

Most floating wetlands are not stable enough to support maintenance personnel, so extra buoyancy is needed to give a high degree of stability (National Aquarium, 2021). Buoyancy also means the wetlands can cope with fluctuating water depths during heavy or scanty rainfall events and helps floating and bottom-rooted emergent plants to submerse or sail on water depending upon the conditions required to survive. This advantage makes them suitable to be constructed in the form of an extended detention basin so that when events of runoff are quite large, runoff water can be captured for a while and then released slowly over time in the right manner, and hence increasing retention time for treatment (Sharma et al., 2021).

Many artificial floating wetlands use polyethylene, polypropylene, polyurethane or polyvinyl alcohol foam as a base in which to plant vegetation (Pavlineri et al., 2017), to give buoyancy, or a combination of these materials (Kamble & Patil, 2012). Karstens et al. (2021) used an artificial polymer-free island, whereas, in the Netherlands, floating mats were made of Styrofoam 4 cm thick (Keizer-Vlek et al. 2014), whilst in Korea polystyrene foam has been used (Lee et al., 1999). Coconut palm fibres, known as coir, are most often used as the vegetation base.

In Chicago, floating wetlands were installed to improve aquatic habitat and the aesthetics of a canal, using interconnected tubes of coconut husk that provide a buoyant substrate for various plant species (Peterson et al., 2021).

One of the key design challenges for floating wetlands in flowing rivers is anchoring. This was not highlighted in the studies.

Several papers suggested additional technology to enhance removal of pollutants by floating wetlands. For example, in Baltimore, USA, a central channel with moving water within the wetland was included that mimics shallow-water habitat for native wildlife and an aeration system to mix the upper portion of the water column (National Aquarium, 2021). A solar-powered aerator device was incorporated within a floating wetland in a lake at Ming Dao University Taiwan (Lu et al., 2015) and in a constructed floating wetland in the Ju-Liao Stream, one of the most contaminated streams in
Kaohsiung City, Taiwan (Lin et al., 2015). Aeration enhances the removal rates, particularly of oxygen demanding substances. Aeration also enhances root development below floating mats and produces aerobic zones that allow the formation of biofilms in a multi-medium substrate which ultimately contributes to increased pollutant removal. For instance, by aerating 20% of a floating wetland, a substantial improvement in organic matter removal was observed (Sharma et al., 2021). However, use of power sources other than solar may be unsustainable. Appropriate choice of plant species can also help with diffusing oxygen beneath the floating wetland.

Floating wetland management
Floating wetlands require management to maintain their pollutant removal capability. Nitrogen generally escapes to the atmosphere as a gas after bacterial degradation of ammonia, nitrite and nitrate compounds. However, phosphorous is taken up within bacteria and plant material eventually falling to the bottom of the wetlands to create an organic-rich sediment. This phosphorous can become biologically available and return to the water, so physical removal and safe disposal of wetland plants and sediments is important to avoid algal blooms (Masters, 2012). Furthermore, the purification phase of plants is followed by a decay phase during which nutrients incorporated into plant tissues can re-enter the water. Continued pollutant removal efficiency can be enhanced by regular plant harvesting (Zhou & Wang, 2010). The proper disposal of this biomass after removal is a key part of ensuring that there is no generation of secondary pollution.

For some species, significant proportions of extracted nutrients are held in the roots, so whole plant harvesting can be a good management tool (Pavlinen et al., 2017). In China plant harvesting facilitated complete removal of nutrients (Xu et al., 2017). In Lake Paldang, Korea, cutting off and removing the above ground part of macrophytes twice a year removed nitrogen and phosphorus and reduced algal blooms (Park et al., 2018). A study in China (Ge et al., 2016) concluded that harvesting of either the above-ground or whole plant tissues should be developed. Whilst harvesting of both roots and shoots could maximize nutrient removal, it can be difficult, time consuming, and costly (Huth et al., 2021). Harvesting only the plant shoots appears to be the most practical and cost-effective option in most cases and assists the plants to regrow from the remaining root systems.

Wider benefits
Harvesting of plant material allows the generation of value-added by-products for local communities. Pyrolysis of biomass, subjecting it to high temperatures to facilitate thermal decomposition, promotes the stabilization of metals within the carbon matrix, producing biocoal, which can be used as corrective for the soil, considering the presence of basic nutrients, such as N, P, and K (Demarco et al., 2023).

In addition to pollutant removal, floating wetlands can provide other benefits to biodiversity. Floating wetlands can provide a habitat for fish and bird species- indirectly benefiting river dolphins and fishing communities. There has been evidence of fish spawning and larval fish life stages in floating wetlands in China (Huang et al., 2021).

Free-floating aquatic plants (such as Azolla spp., Wola spp., Spirodela sp. and Duckweeds) can be used as a food source for water birds. They also provide shelter for insect larvae and small molluscs. Fishes also use the mats of these plants as cover and use their shade for reproduction. Floating aquatic plants can also improve the aquaculture in
fishponds (Ali et al., 2020). The total individuals of larvae fish *Cyprinus carpio* and *Cyprinus Auratus* in a floating wetland in China totalled 12,122 and was higher than in the non-wetland areas (Huang et al. 2021).

Periodic inundation, producing temporary (i.e. seasonal) floating islands, USA, favoured the germination of more species-rich seed banks, emergent wetland plant assemblages (Cherry & Gough, 2006). Because these islands persisted long enough for several species to set seed, their formation may be one mechanism by which the seed bank is replenished and populations of otherwise uncommon species are maintained.

Floating islands in lagoons on the coast of Germany were used by juvenile eels and shrimps as a refuge from predators, as a resting and hunting place for grey herons (*A. cinerea*) and provided habitats for other birds, amphibians, crustacean, molluscs and insects (Karstens et al., 2021).

Harvested plants can be used as animal feed, raw materials for biofuel production and fertilizer (Samal et al., 2020; Harun et al., 2021). A major practical challenge is how to access the floating wetlands for management purposes, such as cutting. This needs to be considered during the design phase.

Another possible benefit of floating wetlands is their ability to mitigate and buffer wave erosion. This facility is widely reported for other wetland types, such as mangroves in coastal zones, but the literature on floating wetlands did not refer to it.

**Trade-off**

It is important to understand the limitations of any intervention. As indicated above, some plants, such as water hyacinth are very invasive and have become a nuisance in water bodies such as Lake Victoria, so would not be recommended for floating wetlands outside of enclosed tanks.

One bacterium, *Pseudomonas pneumoniae*, is effective at the removal of copper, but causes illness, particularly in people with weakened immune systems.

Whilst highly effective at pollutant removal and suitable in containers, great care should be applied in advocating the use of water hyacinth and other non-native species due to it being an aggressive invasive species in many parts of the world, such as Lake Victoria.

Floating wetlands can provide important habitat for birds, fish and invertebrates and plant harvesting produces raw materials for animal feed and biofuel production. However, maintaining these functions may not be consistent with management for optimum pollutant removal (e.g. avoiding harvesting during bird nesting).

It is clear from data on pollutant concentrations in wetland plants and they often store pollutant. This has the potential to bio-accumulate in the food chain and pose a risk to other species in the food web.

It is noteworthy that whilst reduction of pollutants is a positive benefit of floating wetlands, lowering of dissolved oxygen levels may be detrimental.

Although the biomass of these wetland plants may be used for bioenergy generation or as animal feed, care must be taken when using contaminated waste from bioremediation to avoid polluting other environments (Demarco et al.,
2023) and driving bioaccumulation in the food chain (Wang et al., 2019). Physical harvesting of plants can also be a major health and safety challenge across large floating wetlands.

Use of some plants may be restricted by their lack of tolerance to polluted conditions. For example, water hyacinth has the capability to reduce both Cu and Cd concentrations, but concentrations of 4 mg/L of Cu are toxic to this plant (Palihakkara et al., 2018). Likewise, some wetland plants are susceptible to Perfluorooctanoic Acid (Mudumbi et al., 2014).

Floating wetlands may also be sinks or sources of greenhouse gases. In China, methane emission rates were lower in duckweed plots than in the non-duckweed plots (Wang et al., 2015) but average nitrous oxide emission rate was found to be significantly higher. In Canada, constructed floating wetlands did not change greenhouse gas production (Jacobs & Harrison, 2014).

**Costs**

Only one publication provided details of manufacturing and installation costs of floating wetlands. In India, costs of US$60 per m$^2$ locally were suggested compared with US$220 per m$^2$ in the USA (Billore et al., 2009).

**Implications of floating wetland study results for rivers supporting dolphins**

Almost all studies of pollutant removal by floating wetlands report a significant effect with some achieving 100% reduction, although some report a modest decrease and a few found no effect. Generally, it can be concluded that well-designed and managed floating wetlands have a high ability to improve water quality through pollutant uptake.

However, most of the studies were undertaken in tanks, lagoons or ponds in which there was very little flow, except for experiments in Brazil (Benvenuti et al., 2018) and China (Bai et al., 2020). In the absence of flow or water replenishment, wetland plants can remove pollutants continually from the same water. In a flowing river, water is continually replaced, so it is difficult to extrapolate these findings to assess the effectiveness of such floating wetlands in rivers that where dolphins live, which have very high flow rates and the total load of a pollutant removed may be insignificant in terms of positive enhancement of the riverine ecology (see section 2).

Only four publications reported experiments where the floating wetland was actually in a river. These are much smaller rivers with lower discharge than those where dolphins live or lived, so great care must be taken when extrapolating the results of these studies to dolphin rivers.

The Chicago River, USA study (Cosier, 2022) presented no results; so only three presented data.

The River Kshipra, India study (Billore et al., 2009) used a 200 m$^2$ floating wetland planted with local reed grass (*Phragmites karka*). The study recorded a 43% reduction in total sediment, 38% reduction in total organic nitrogen and ammonium and 39% reduction in BOD. The Kshipra was described as a “slow flowing or almost stagnant river”, so not a large flowing river, such as the Ganges or Amazon. Although the publication contains an annotated photo of the sampling points (Plate 4), it is difficult to know what the recorded data represent. It is likely that the data show the removal of pollutants from the water passing through the wetland, but the wetland only covers part of the river (Plate
3b). If the wetland covers 10% of the width of the river, at best only 10% of the flow will pass through it and the remaining 90% will by-pass the wetland. Consequently, for the river as a whole, the reduction in pollutants could be say 4% based on a 40% difference upstream and downstream of the wetland. These approximated figures are consistent with the study of a canal in Chicago (Peterson et al., 2021) with a 90 m² artificial floating wetland, which also only covers part of the river (Plate 2a). The canal has a mean discharge of 0.88 m³s⁻¹ (or 76032 m³d⁻¹) and comparison of upstream and downstream waters showed a lowering in concentrations of nitrate-as-nitrogen and phosphate during the growing season by 6.9% and 6.0% respectively.

Figure 8. Implications of different water sampling strategies on defining the pollutant removal effectiveness of a floating wetland covering part of a river width.

The generic situation Is shown In Figure 8. Sampling at SP1 would provide data on the untreated water quality. Sampling at SP2 would define the quality of water passing through the wetland, whilst sampling at SP3 would define the quality of water by-passing the wetland. Only by sampling at SP4 would the effectiveness of the wetland on water quality in the river as whole be recorded. Data from SP2, SP3 and SP4 would likely be different, with those from SP4 being some combination of results from SP2 and SP3. In Figure 9, data from SP2, SP3 and SP4 would likely be similar.

The study of the river in Jiaxing City, China (Zhao et al., 2012), reported a flow rate in terms of velocity (0.2 m s⁻¹ to 1.5 m s⁻¹) within a mean cross section of 55 m², which suggests a flow rate of around 11 to 83 m³s⁻¹. The experiment began in June 2008 and was completed in November 2008, so it is possible that the river and floating wetlands experienced flows across this range as well as differences in temperature and growing season. Reported reductions in pollutants were 43.3%, 36.9%, 44.8% and 25.6% for total phosphorus, total nitrogen, ammonia and nitrate respectively. Importantly, a photo of the wetland (Plate 2c) suggests that the wetland covers most of the river width, so water by-passing may be limited. But it is not possible to assess how much of the water flow is treated by the wetland. There may be a high vertical gradient with water passing more rapidly along the riverbed than through the wetland itself.
Figure 9. Implications of different water sampling strategies on defining the pollutant removal effectiveness of a floating wetland covering the entire river width.

Figure 10. Siting of a floating wetland immediately upstream of dolphin habitat.
These few studies suggest that significantly reducing pollutants (>40%) in a river requires a floating wetland that covers the entire river width. Installing such a wetland in the very large rivers where dolphins live, or used to live, would be impractical (Figure 10). Furthermore, the high flow rates in these rivers would likely mean far lower pollution reduction than 40%.

**Use of floating wetlands might be best targeted at pollution sources**, such as on the channels carrying effluent from factories to rivers or within lagoons temporarily holding urban runoff (Figure 11). This would require many smaller floating wetlands distributed around the catchment feeding dolphins habitats. Some analysis would need to be undertaken of flow rates, pollution sources, reduction rates, suitable locations for wetlands to determine the most effective distribution network as well as the appropriate wetland design.

**Summary and conclusions**

The study focused on addressing the following three key questions and associated three supplementary questions.

**Q1: How effective are floating wetlands for reducing water pollution?**

The available scientific literature returned from the searches shows that floating wetlands are, in most cases, very effective at removing pollutants from water including nutrients and heavy metals, with some reporting 100% removal. Some report a modest improvement of around 40-50% and a few found no effect. Most of these studies were undertaken in tanks or ponds with limited or no flow or throughput of water, so that the floating wetland plants were removing pollutants from the same water throughout the experiment.
Q2: What characteristics of floating wetlands alter their effectiveness?

Contrary to expectations, surface area, or % coverage of the water body, was only weakly correlated with pollutant removal rate. Indeed, the highest removal rates in tanks were with surface area coverage of around 75%. It was reported that high coverage can lead to anoxia. However, the sole use of % reduction can be misleading as a small reduction of a high concentration may be ecologically more significant than a high % reduction at a low concentration.

Many different plant species were used in the experiments, so it is difficult to quantify the effect of plant type. Generally, species such as common reed (*Phramites Australis*), water hyacinth (*Eichhornia crassipes*), yellow flag iris (*Iris pseudacorus*), jointed rush (*Baumea articulata*) and broadleaf cattail (*Typha Latifolia*) were reported as being particularly effective, but data were inconsistent between studies. Generally, effectiveness was most closely related to plant biomass, with the fastest growing plants removing the most pollutants. Species composition exerted a stronger effect than species richness. The presence of microbes within a biofilm in the wetland enhanced removal significantly. In addition to just effectiveness, which may be the major criteria in an enclosed system, selection of suitable plants for a nature river environment must be placed in the wide context of other issues such as invasive nature of many of the plants, their ability to enhance dissolved oxygen and propensity to develop important associated biofilm communities.

Q3: Are the results applicable to large flowing rivers supporting dolphin habitat?

Only four publications reported experiments where the floating wetland was actually in a river. The Chicago River, USA study presented no results. The study of the River Kshipra, India, reported around a 40% reduction in pollutants, but this river was described as "slow flowing or almost stagnant river", so not a large flowing river, such as the Ganges or Amazon. The Chicago study was in a canal where the floating wetland covered only part of the river and was undertaken in an eco-climate different from dolphin rivers. The study of the river in Jiaxing City, China, possibly contains the most relevant data, where a floating wetland spanning the entire river width under a flowing water regime reduced total nitrogen, ammonia, nitrate and total phosphorus by 36.9%, 44.8%, 25.6%, 43.3% respectively. However, constructing a similar floating wetland across major rivers supporting dolphins would not be practical. The limited evidence suggests distributed wetlands on point sources of pollution such as factory discharge canals, industrial settlement lagoons or urban stormwater ponds is likely to be more realistic and deliverable.

Supplementary questions were:

a. How is effectiveness measured?

No studies reported the effectiveness for improving habitat for dolphins, such as reducing pollutant concentrations below critical levels for this species. One study in Pakistan reported floating wetlands reduced cadmium and iron concentrations below national permissible thresholds in rivers.

In the studies assessed, effectiveness is measured in two ways. First by taking water samples and analysing pollutant concentrations. These were upstream and downstream of floating wetlands in rivers or at the start and end of experiments in tanks and ponds. Second, the pollutant content of harvested plants was measured. Although scientifically sound it is not easy to convert these data into implications for river water quality, which was the focus of this study. However, plant uptake data can indicate relative effectiveness of species. As discussed above, in most publications, effectiveness is presented in terms of % change in concentration in the water samples, but this should ideally be related to initial or final total concentrations.
b. What surface area of floating wetland is needed to improve water quality significantly?
The surface area, or % coverage of the water body, was provided in many studies but these were in tanks, ponds and lagoons. There was not a strong linear relationship and highest removal rates were with coverage of around 50-75%. In some cases, higher coverage led to low oxygen conditions that suppressed plant activity. For rivers, the size of floating wetland needed should be a function of the flow rate or catchment area upstream and the initial and target final pollutant concentrations.

c. How can effectiveness be maximised?
Selection of plants with high biomass and fast growth rates were the most effective at removing pollutants from water (see Tables 6 and 7). The presence of microbes within a biofilm in the wetland enhanced removal significantly. Constructing floating wetlands that cover the entire river width would avoid untreated water by-passing the wetland laterally, although water may still pass below the wetland in deep rivers. An alternative approach would be to locate floating wetlands immediately below point sources of pollution such as factories or urban areas. This would support design that is appropriate to the specific local conditions and pollutant/contaminant under consideration. Selecting the correct plant species should include knowledge of the prevailing environmental conditions, avoiding unintentional consequence, such as use of potentially invasive species. Ensuring appropriate anchorage and robust design, especially in relatively high energy environments such as large rivers and access for management are also crucial. Harvesting of plants can enhance uptake and provide material for local fodder to bio-energy production.

Recommendations
Although only three studies reported the effectiveness of floating wetlands from in-river studies, from these and from studies in tanks and ponds there is sufficient evidence available to warrant further investment in this initiative.

Analysis of data available in the publications could be undertaken. Multivariate analysis may, for example, reveal patterns or tendencies or explain differences in effectiveness from different studies that were due to factors such as design, climate, initial pollutant concentrations and plant type.

A pilot demonstration project would be a good next step to test the level of effectiveness of floating wetlands specifically in rivers providing dolphin habitat. This project could include the following steps.

1. Select a river or rivers that supports dolphins, where levels of pollutants have been or can be measured at various locations and key sources of pollutants are known. This is likely to involve a range of issues, such as access rights to the river, willingness of governments and polluters to engage, and availability of and access to river flow and water quality data. Analysis of water quality data analysis would be to identify a river with pollutant levels that are detrimental to dolphins, but for which floating wetlands could reduce pollutants significantly.

2. Design a network of floating wetlands. This will involve considering various configurations including two extremes. One extreme will be a single large wetland immediately upstream of the dolphin habitat as in Figure 10, or, more realistically at a strategic point in the river that makes a pilot project manageable, such as on a small tributary. The other network extreme would have a small wetland downstream of one or more pollution source as in Figure 11 with the wetland in the river or in a pipe/channel discharging the polluted water to the river or in a lagoon holding polluted water temporarily (before discharge to a river). Intermediate designs can include a few wetlands midway along the river network. Ideally, this strategy should be tested by running several pilot studies with different designs.
3. Use approximate pollutant removal rates of wetland plants from the literature together with river flow and water quality data and ideally critical pollutant toxicity levels for dolphins to compare the likely overall effectiveness of different network designs.

4. For each network, consider the practicality of constructing a floating wetland at each location, including the size of river (width and depth), discharge rate and its variability, plus access to the river for installation and management, availability of laboratories to test water and plant samples.

5. Design the floating wetlands using information in the literature including buoyancy, structures for holding plants and tethering in flowing water, plus allowing navigation and other uses of the river.

6. Select plants guided by information in the literature (see, for example, Table 6) and local environmental conditions, such as the type and concentrations of pollutants in the water. Avoid use of non-native nuisance plants. Consider whether biofilms need to be added to the floating wetland.

7. Before installation, take water quality measurements at the sites to define a baseline against which to assess pollutant removal. Develop a way to either monitor river discharge or estimate it, such as by employing a hydrological model.

8. After installation, take water quality measurements upstream and downstream of each floating wetland and calculate pollutant loading using available discharge data. Also measure pollutant levels in harvested plants samples and calculate a simple pollutant balance to reconcile the data from plants with changes in water quality.

9. Manage the wetlands using information in the literature or local knowledge of plant growth and ecology. Investigate the use of harvested material for bioenergy or animal feed, particularly amongst local people, mindful of the potential toxicity of the plants. Undertake general biodiversity surveys of the floating wetlands to assess additional ecological benefits.

10. Assess broad benefits of floating wetlands for improving dolphin habitat, particularly achieving pollutant levels within the tolerance of dolphins, plus wider benefits to biodiversity and local people.
Annex 1 Research protocol

This study will follow the principles of systematic evidence reviews, so that outputs are robust, defensible, objective, transparent, repeatable and provided in an easily accessible manner that facilitates an audit trail from summary statements to underpinning knowledge. Systematic reviews have been used previously by WWF to assess evidence on, for example, the impacts of riverine aggregate mining on freshwater ecosystems (Koehnken et al., 2020) and the effectiveness of nature-based solutions to water issues (Acreman et al., 2021). Evidence was reviewed that was available from international databases (such as Web of Science), literature lists from other books, papers and reports (snowballing) and from experts in the topic. We cannot guarantee that sufficient information will be found to address all questions comprehensively.

The Defra guidance shows that a Quick Scoping Review (Collins et al., 2015) is appropriate for time scales of 3-5 months and funding of £10-30,000. A QSR aims to provide an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to the questions. The QSR method does not include, for example, further analysis of data from reports and papers.

Basic steps in the method are as follows:

1. Define the question(s) to be answered.
2. Specify the scope, geographically e.g. worldwide, South America & Asia, and technically e.g. floating wetlands.
3. Produce a protocol to search for and assemble evidence. This will include internet searches (such as Web of Knowledge, Google scholar) and other methods, such as snow-balling references from textbooks or reviews and contacting experts.
4. Undertake pilot searches to assess the likely number of returns. Steps 1-3 and/or may be revised if the numbers are too small or too large to complete all steps below within budget.
5. Collate titles and abstracts and screen publications for relevance to questions.
6. Collate full papers/reports from short-listed literature in step 5.
7. Extract information from papers/reports of studies.
8. Classify studies according to key criteria such as location, type of floating wetland, methods used, whether results are quantitative or qualitative etc.
9. Design an evidence base to hold information, a summary statement, which can include contextual information such as location, type of floating wetlands, plant species, effectiveness.
10. Populate the evidence base.
11. Assess all knowledge and organise according to relevance to different questions.
12. Distil recommendations for WWF-NL programme.
13. Identify gaps that preclude answering questions fully.
14. Produce report that includes questions, protocols, search results, summary statements, evidence base details and recommendations.

A key step in a systematic review is to define the review protocol. The PICO (Population, Intervention, Comparator and Outcome) framework is a common part of a QSR protocol as it helps to focus the study and define methods. The PICO framework used is provided as Table 1.

Given the financial constraints of the project it was agreed that the number of publications assessed at title abstract level would be limited to around 1500 from Web of Science, and assessment at full text level of around 100
publications, which would yield approximately 50 publications holding relevant data according to the PICO inclusion/exclusion criteria. This number of publications would be used to answer the questions posed.

Table A1.1 PICO framework

<table>
<thead>
<tr>
<th>Collation criteria</th>
<th>Inclusion criteria</th>
<th>Exclusion criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Population</strong></td>
<td>floating wetlands globally in freshwaters and estuaries, but focusing on Asia and South America, other habitats that have similar characteristics to floating wetlands or found in other locations relevant to Asia and South America</td>
<td>Floating vegetation in marine zones, habitats with characteristics different from floating wetlands, evidence from regions not relevant to dolphin rivers in Asia or South America, such as boreal or arid zones</td>
</tr>
<tr>
<td><strong>Intervention</strong></td>
<td>the presence or establishment or construction of floating wetlands or changes to the characteristics or management of existing floating wetlands</td>
<td>other environmental changes that could influence habitat for freshwater dolphins</td>
</tr>
<tr>
<td><strong>Comparator</strong></td>
<td>natural habitat condition or reference conditions without floating wetlands or before management changes or comparisons upstream and downstream of the floating wetland or pollutant content of plants before and after experiments</td>
<td>single measurements with no comparator to assess effectiveness or management</td>
</tr>
<tr>
<td><strong>Outcome</strong></td>
<td>quantitative measurements or qualitative assessments of changes relevant to habitat conditions for freshwater dolphin habitats and local people, particularly pollutants</td>
<td>personal views without evidence, changes in conditions inferred from other measurements</td>
</tr>
</tbody>
</table>
Annex 2 References

A2.1 Publications on river dolphin ecology

Bali, J., Jaaman, S.A., Saleh, E. et al. 2017 Distribution, abundance and density of 41aters41dy Dolphin (Orcaella brevirostris) in Rajang River of Sarawak, East Malaysia Malaysian Applied Biology 46, 2, 105-114


Best R.C. & Da Silva, V. 1989a Amazon river dolphin, boto Inia geoffrensis (de Blainville, 1817). In Handbook of Marine Mammals


Yeung, L.W.Y., Miyake, Y., Wang, Y., Taniyasu, S., Yamashita, N. & Lam, P.K. 2009 Total fluorine, extractable organic fluorine, perfluorooctane sulfonate and other related fluorochemicals in liver of Indo-Pacific humpback dolphins (Sousa chinensis) and finless porpoises (Neophocaena phocaenoides) from South China. Environmental Pollution 157, 1, 17-23. doi.org/10.1016/j.envpol.2008.08.005


A2.2 Publications of general interest to the project


Cosier, S. 2022 *How Floating Wetlands Are Helping to Clean Up Urban Waters*. Yale Environment 360, Yale University, USA. https://e360.yale.edu/features/ floating-wetlands-cities-pollution


Ivanova, I., Nedkov, R., Borisova, D. & Stankova, N. 2018 Using SAR and optical data from Sentinel satellites for precise modeling of seasonal floating reed islands dynamics in Srebarna Lake Proc. SPIE 10790, Earth Resources and Environmental Remote Sensing/GIS Applications IX, 107900E (9 October 2018); doi.org/10.1117/12.2325703


Lin, J.L., Tu, Y.T., Chiang, P.C., Chen, S.H. & Kao, C.M. 2015. Using aerated gravel-packed contact bed and constructed wetland system for polluted river water purification: A case study in Taiwan Journal of Hydrology, 525, 400-408 doi.org/10.1016/j.jhydrol.2015.03.049


**A2.3 Review publications**


Chang, Y., Cui, H., Huang, M. & He, Y. 2017 Artificial floating islands for water quality improvement *Environmental Reviews* 25, 3 doi.org/10.1139/er-2016-0038


Yeh, N., Yeh, P. & Chang, Y-H. 2015. Artificial floating islands for environmental improvement *Renewable and Sustainable Energy Reviews* 47, 616-622 doi.org/10.1016/j.rser.2015.03.090

A2.4 Publications reporting technical studies


Ge, Z., Feng, C., Wang, X. & Zhang, J. 2016 Seasonal applicability of three vegetation constructed floating treatment wetlands for nutrient removal and harvesting strategy in urban stormwater retention ponds *International Biodeterioration & Biodegradation* 112, 80-87 doi.org/10.1016/j.ibiod.2016.05.007


Hubbard, R.K., Gascho, G.J. & Newton, G.L. 2004 Use of floating vegetation to remove nutrients from swine lagoon wastewater Transactions of ASAE, 47, 6, 1963-1972


Prihatini, N.S., Mizwar, A., Riduan, R., Irawan, C. & Arifin, Y.F. 2021. Performance of Floating wetland to reduce the organic matter in river water *MATEC Web of Conferences* 2 doi.org/10.1051/mateconf/20192800501 80


### A2.5 Rejected publications


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