CHAPTER 5

# Mitigation measures in freshwater ecosystems

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# Chapter 5 Contents



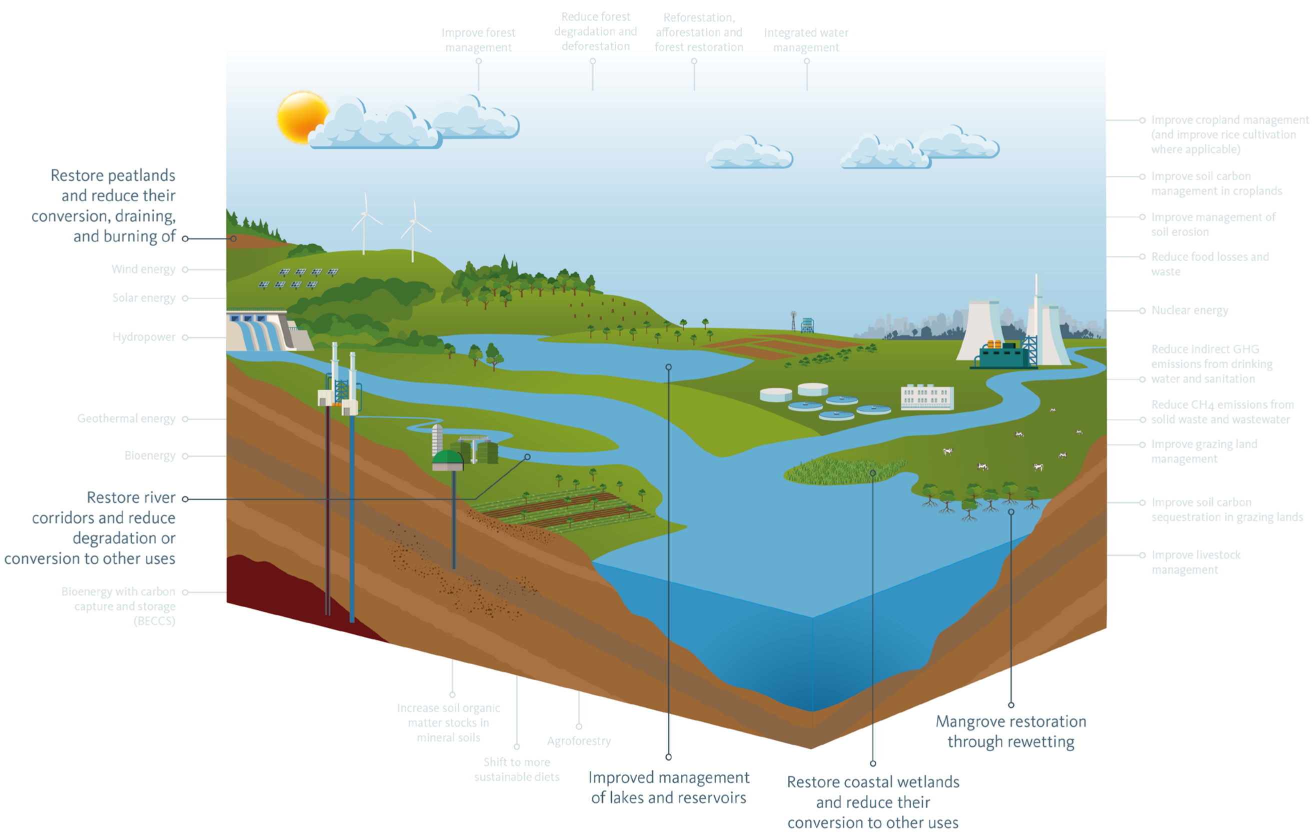



Figure 5.0. Mitigation measures in inland freshwater ecosystems and freshwater-dependent coastal and marine ecosystem. Source: SIWI.

## Highlights

- Freshwater ecosystems can function as greenhouse gas (GHG) sources and sinks based on their environmental state and management. While restoration of wetlands and floodplains is an effective measure for mitigation, stronger priority should be given to protecting existing natural wetlands and floodplains to avoid additional GHG release. Freshwater ecosystems, such as peatlands, marshes, swamps, lakes, streams, rivers, and tidal wetlands, have high potential for mitigation when managed well, but can contribute additional emissions when managed poorly. Land use, surrounding vegetation, pollution, human activities, hydrologic regime, and climate can influence the emissions profile of freshwater ecosystems. Mitigation-relevant data and research on rivers, lakes, and dams is scarce, while wetlands are more acknowledged and researched.
- It is important to promote a concerted effort nationally and internationally to account for the GHG emissions from freshwater ecosystems. In addition to 'blue carbon' ecosystems (BCE), which include freshwater-dependent coastal and marine systems, the emission reduction potential of freshwater ecosystems needs to be more commonly included as a measure to reduce atmospheric GHG emissions alongside sectors outside of land use, such as energy and transport.
- The potential (or use) of catchment and coastal zone policies, programmes, and investments to support effective and sustainable emission reduction strategies needs to be recognized and adopted. GHG production in aquatic systems is driven by nutrient and organic carbon inputs from watersheds. Effective emission reduction strategies may entail integrated approaches for land management and regenerative agriculture, restricting nutrient loading (including improved wastewater treatment capacities), and maintaining and improving ecohydrological connections.
- Natural solution schemes (both nature-based solutions and green-grey infrastructure) need to include the full range of ecosystem services, alongside carbon sequestration, to reduce the risk of maladaptation. Carbon sequestration is only one of many valuable services provided by aquatic ecosystems. There are multiple direct and indirect co-benefits, such as flood risk management, biodiversity recovery, sustainable communities and livelihoods, and water quality improvement that come with watershed-scale aquatic ecosystem management. These benefits need to be accounted for while integrating emissions reduction targets in the Nationally Determined Contributions.
- Net emissions reduction goals and opportunities need to be given greater emphasis within broad water resources management strategies. There is also a need for financing mechanisms and tools to monitor and reduce emissions from freshwater ecosystems and BCE management at the local, regional, and national levels. Regulatory reform, capacity building, and better data on aquatic environments are needed to further opportunities and materialize implementation.

## 5.1 Introduction

Freshwater ecosystems such as wetlands, rivers, and lakes are linked intimately with climate mitigation since aquatic environments can act as both greenhouse gas (GHG) sources and sinks based on their environmental conditions and management practices. However, the role of freshwater ecosystems in achieving climate mitigation targets has yet to be acknowledged to the extent reflecting their potential. Freshwater ecosystems can be sources of all three major GHGs (carbon dioxide or $CO_2$, methane, and nitrous oxide) and eliminating emissions entirely from these systems is unrealistic due to their natural processes. But their carbon storage capacity, for which they have high potential, can be enhanced and emissions from these sources can be reduced to achieve net emissions reduction. In reviewing the mitigation potential of different freshwater ecosystems, this chapter makes a clear case for the adoption of land- and watershed-scale policies across different aquatic environments for effective and sustainable strategies that support and enhance the role of freshwater ecosystems in mitigating climate change.

'Blue carbon' ecosystems (BCE), particularly mangrove swamps, are commonly acknowledged for their mitigation potential and have received much greater attention than inland freshwater ecosystems in this regard (IPCC 2014). Hence, in this chapter we focus on freshwater ecosystems (wetlands, lakes, reservoirs, and rivers) and freshwater-dependent coastal and marine systems. This chapter takes a 'problem-cause-solution' approach to addressing freshwater ecosystem-based climate change mitigation. It discusses under what circumstances the long-term carbon sinks, i.e., the freshwater ecosystems, become carbon sources and how to undo or minimize that shift to continue benefiting from the potential to sequester carbon. These mitigation measures come with substantial co-benefits and align with the Sustainable Development Goals, but their adoption might need to be tailored according to the local and regional context.

This chapter examines the mitigation potential and water-related risks of inland freshwater ecosystems and freshwater-dependent coastal and marine systems. Section 5.2 addresses relevant mitigation measures, which are categorized as wetlands, rivers, streams, lakes, and reservoirs. Section 5.3 examines trade-offs related to freshwater-based mitigation as well as co-benefits, more specifically the enhancement of ecosystem services through mitigation measures; climate change adaptation and resilience benefits from mitigation measures; and nature-based solutions associated with the mitigation measures. Current policy measures are explained in section 5.4. In 5.5, potential implications for governance are mapped, including inclusion in national policies, system-level approaches, and implications of future climate change and socio-economic change. Section 5.6 provides conclusions and an outlook for the future.

## 5.2 Mitigation potential of inland freshwater ecosystems and freshwater-dependent coastal and marine ecosystems

Depending on the management applied, wetlands can act as GHG sources or sinks (Hamdan and Wickland 2016). While emission, sink, and sequestration patterns are widely studied and understood for some wetlands, there is considerably less research on rivers and streams. Wetlands have high carbon sequestration potential, but when disturbed and drained they become sources of GHG emissions. While restoration can significantly reduce GHG emissions and may start carbon sequestration, restored wetlands might not return to the undisturbed natural conditions that allow high climate mitigation potential even within decades (Günther et al. 2020; Joosten 2015; Kreyling et al. 2021). Under the current climate change trajectory, wetlands require attention because they have high potential for mitigation when managed well and can contribute to additional emissions when managed poorly. This section elucidates the mitigation potential and measures based on existing knowledge (Table 5.1).

Table 5.1. Mitigation measures in inland ecosystems and freshwater-dependent coastal and marine systems addressed in this chapter.

| MITIGATION MEASURE | MITIGATION POTENTIAL (GT $CO_2$-E/YEAR) |
|---|---|
| Reduce conversion, draining, and burning of peatlands | 0.45–1.22 |
| Reduce conversion of coastal wetlands (mangroves, seagrass, and marshes | 0.11–2.25 |
| Peatland restoration | 0.15–0.81 |
| Mangrove restoration through rewetting | 0.07 |
| Coastal wetland restoration | 0.20–0.84 |
| Reduced degradation or conversion of river corridors | – |
| River corridor restoration | – |
| Improved management of lakes and reservoirs | – |

Note: includes data on climate mitigation potential when available in recent Intergovernmental Panel on Climate Change (IPCC) reports (IPCC 2019; IPCC 2022) in Gigatons of carbon dioxide equivalent per year (Gt $CO_2$-e/year)

### 5.2.1 Mitigation measures in wetlands

Conserving and restoring wetlands, including peatlands and coastal wetlands, is a critical climate mitigation strategy. Wetlands have among the highest stores of soil carbon in the biosphere, storing more than 30 per cent of the estimated global carbon emissions (Nahlik and Fennessy 2016). Despite covering about 7 per cent of the world's surface, wetlands are considered as the largest terrestrial carbon sinks due to their carbon sequestration capacity, both for a longer timescale in the past and their future potential (Mitsch and Gosselink 2015; Ramsar Convention on Wetlands 2018). The vegetation in marshes (minerotrophic wetlands dominated by herbaceous plants) and swamps (wetlands dominated by arboreal vegetation), through the process of photosynthesis, captures $CO_2$ and fixes it as organic matter in leaves, stems, and roots. Much of this organic matter eventually becomes incorporated into the soil. The saturated soils of wetlands have slower decomposition than those of dry soils. When plant productivity exceeds decomposition there is a net accumulation of carbon-rich soil. As a result, wetland soils sequester more carbon per unit volume than terrestrial soils (Bridgham et al. 2006; Kolka et al. 2018; Mazurczyk and Brooks 2018; Moomaw et al. 2018).

While natural wetlands are generally carbon sinks, drainage and other anthropogenic activities can make wetlands net sources of GHG instead. Moreover, although wetlands are considered as important sinks for $CO_2$, almost all freshwater wetlands emit methane, which has significantly higher global warming potential than $CO_2$. Since methane is split relatively quickly by oxidation in the atmosphere (while atmospheric $CO_2$ continues to be absorbed), the long-term carbon balance of intact peatlands is positive. In addition, there is a risk of large quantities of $CO_2$ and methane being released when temperatures are warming in frozen soils (permafrost) within Arctic and sub-Arctic regions, but the magnitude and timing of GHG emissions from these regions and their impact on climate change remain uncertain (Schuur et al. 2015).

Mitigating climate change can also have a positive impact on wetlands (Yuan at al. 2022). Altered hydrological regimes and more frequent or intense extreme weather events due to climate change will contribute to wetland degradation. Wetland loss and degradation increase GHG emissions to the atmosphere, leading to positive feedback on climate change. In fact, global GHG emissions from wetlands are projected to increase by up to 78 per cent under certain climatic conditions (with a doubling of atmospheric $CO_2$) (Gedney et al. 2019; Salimi et al. 2021). It is essential to address the climate change induced changes in wetland management to limit GHG emissions. When there is a higher rate of decomposition than of photosynthesis, wetlands emit $CO_2$ and decomposition depends mostly on thermal and hydrologic regimes. For example, drought resulting from higher temperatures might shift the role of peatland from a $CO_2$ sink to a source, although higher temperatures with more water availability (through precipitation or rewetting) can promote more production than respiration and maintain the carbon sink (Salimi et al. 2021; Vanselow-Algan et al. 2015). Shoreline erosion due to sea-level rise or frequent and extreme weather events (triggered by climate change) cause losses of salt marshes and mangrove forests.

***Reduce the conversion of wetlands for agriculture, urbanization, aquaculture, or coastal development***

As noted, wetlands have some of the highest stores of soil carbon in the biosphere, storing more than 30 per cent of the estimated global carbon emissions (Nahlik and Fennessy 2016). Hence, maintaining these existing carbon pools in wetlands is important as their loss could significantly increase the concentration of atmospheric $CO_2$, further contributing to the climate crisis (Anisha et al. 2020). Between 1970 and 2015, the area of the world's natural inland and coastal wetlands declined by around 35 per cent (Ramsar Convention on Wetlands 2018). About 15 per cent of the world's peatlands have been drained for agriculture, forestry, and grazing, leading to release of the carbon stored in their soils and resulting in at least 5 per cent of the total global anthropogenic emissions (Joosten et al. 2012; Tanneberger et al. 2017). Mangrove forests have also experienced a loss of around 4.3 per cent globally in the 20 years preceding 2016, due predominantly to direct human impacts (urbanization, aquaculture, and agriculture) (Global Mangrove Alliance 2021). Preventing human-induced degradation of wetlands that leads to GHG emissions is also important. A meta-analysis on GHG emissions from global wetlands due to conversion estimates that at least 0.96 ± 0.22 Gt $CO_2$-e of GHG is released to the atmosphere each year from natural wetlands being drained, accounting for 8.0–9.6 per cent of the annual global GHG emissions estimated by IPCC (2014). Drainage of all wetlands will result in increased emissions of $CO_2$ as the soil organic matter is allowed to decompose. To formulate a mitigation strategy, it is important to understand the context-specific wetland management required for emissions reduction (Anisha et al. 2020). The management of the landscape surrounding a wetland also plays an important role in reducing emissions, particularly regarding nutrient control. Vegetation structure and level of degradation, tree density, livestock grazing intensity, etc., can impact soil water content, groundwater tables, soil nutrients, soil salinity, and several other factors, and thus have a significant impact on annual GHG fluxes (Han et al. 2014; Herbst et al. 2013; Tan et al. 2020).

### *Restoration of wetlands to increase carbon sequestration capacity*

Different types of wetlands sequester carbon and emit GHGs in various ways. When restoring wetlands, it is essential to understand the sequestration mechanisms and carbon dynamics specific to each wetland type and region to increase the capacity of wetlands to actively sequester carbon over the long term (Mazurczyk and Brooks 2018). Hydrological regime, climate, wetland soil type, sediment deposition, decomposition rate, and vegetation usually play important roles in a wetland's carbon storage mechanism (Mazurczyk and Brooks 2018; Mitsch et al. 2010; Mitsch et al. 2013; Moomaw et al. 2018; Zhang et al. 2002; Zhao et al. 2019). The sequestration rate in temperate and tropical wetlands is four to five times greater than that found in boreal wetlands (Mitsch et al. 2013). Examining more specific examples, Zhao et al. (2019) studied the effects of water level and inundation duration on $CO_2$ uptake in the Everglades National Park in the USA and suggested that there was lower net $CO_2$ uptake during extended periods of high water, while a study on the impacts of drought conditions on wet soils suggests that decomposition rates and the subsequent carbon storage in peatlands and mineral soil wetlands differ during drought periods (Stirling et al. 2020). The effects of the hydrological regime vary widely for different types of wetlands based on their region, and is one of the many drivers of carbon sequestration and GHG release in those wetlands.

In addition to water quantity and the surrounding land use, water quality plays a vital role in the emissions pattern from freshwater ecosystems. To initiate greater carbon storage, one method would be to slow the rate of decomposition, which is directly related to the biochemical and physicochemical processes (e.g., lack of available oxygen, pH, nutrients, conductivity, etc.) in the wetland (Mazurczyk and Brooks 2018; Moomaw et al. 2018; Pinsonneault et al. 2016; Weil and Brady 2016). For example, low pH reduces microbial activity, which lowers the decomposition rates. Temperature changes affect the microbial and plant activity and influence the carbon storage capacity. Decomposition rates increase exponentially with temperature, resulting in more carbon release (Batson et al. 2015a; Mazurczyk and Brooks 2018; Moomaw et al. 2018). Plant productivity and species composition are important in this regard and another proposed strategy to increase carbon storage in a wetland is to increase native species and fungi-based processes by planting perennial species.

Wetlands include many different ecosystems, such as peatlands, mangroves, marshes, swamps, and bogs. The following sections highlight ecosystems with especially high impact on climate mitigation.

### *Restoration and reduced conversion of peatlands*

Peatlands are a kind of wetland where the organic matter from decomposing plants forms peat layers in the soil. Restoration and reduced conversion of peatlands have strong long-term mitigation potential. IPCC estimates a yearly emissions reduction potential of 0.45–1.22 and 0.15–0.81 Gt $CO_2$-e/year respectively for reduced peatland conversion by drainage and burning respectively (IPCC 2022). Peatlands occur in all climate zones, from boreal to tropical. Globally, peatlands cover about 3 per cent of the landmass (Gorham 1991), or approximately 4.2 million square km (Xu et al. 2018). The area of peatlands in temperate and boreal regions is around 3.7 million square km, storing a total carbon stock of 415 petagrams (GtC: $10^{15}$ grams of carbon) (Hugelius et al. 2020; Yu 2012). The extent of tropical peatlands is about 450,000 square km, occurring in regions of Africa, America, and Asia, storing about 105 GtC, about 20 per cent of the carbon stock in high latitudes (Dargie et al. 2017; Rieley and Page 2016). The extensive carbon sink capacity of peatlands plays an important role in the global climate system and these systems have exerted a cooling effect due to their sustained carbon sequestration over millennia despite their substantial methane emissions (Frolking et al. 2006; Kirpotin et al. 2021). It is estimated that investing in healthy and well-managed peatlands may achieve reductions of at least 5 per cent of global anthropogenic $CO_2$ emissions (Joosten 2016). The soils of peatlands at high latitudes generally contain >65 per cent organic matter (Kolka et al. 2016), while tropical peatland soils contain as much as 99 per cent (Anshari et al. 2010; Page et al. 2011b). The primary constituent of organic matter is elemental carbon, and the carbon stock in tropical peat might be larger than current estimates, as areas of these wetlands may be underestimated (Gumbricht et al. 2017; Murdiyarso et al. 2019).

However, like other wetlands, peatlands are being degraded worldwide, causing many peatlands to turn from carbon sinks to carbon sources. Anthropogenic disturbances such as peat harvesting, drainage, peat fires, and land use changes, are major drivers that cause peat to become a source of atmospheric $CO_2$ (Andersen et al. 2013; Conchedda and Tubiello 2020; Hooijer et al. 2015; Kolka, et al. 2016; Loisel and Bunsen 2020; Moore et al. 2013). The amount of GHG emissions originating from drained peat globally is about 6 per cent of the global $CO_2$ emissions (Joosten et al. 2012). Under present land use management regimes, Urák et al. (2017) predicted about 25 per cent of peatland areas would degrade by 2050 and contribute 8 per cent of global $CO_2$ emissions. Using model-based projections of future peatland dynamics, Humpenöder et al. (2020) demonstrates that conservation and restoration of about 60 per cent of currently degraded peatlands is required to return the land system to a net $CO_2$ sink within the 21st century. Peatland conservation and restoration therefore have a large climate mitigation potential and need to be at the heart of climate policies (Menichetti and Leifeld 2018).

For northern peatlands, prompt post-disturbance rewetting and revegetating has been shown to substantially reduce adverse climate impacts from degraded peatlands (Günther et al. 2020; Nugent et al. 2019) and to return the carbon sequestration function of peatlands within a decadal timeframe (Nugent et al. 2018). Restoring natural hydrology and water table depth in peatlands is an important factor for the successful restoration of peatland ecosystem services (e.g., Gaffney et al. 2020) and has been shown to substantially reduce GHG emissions from drained peatlands (Evans et al. 2021). However, climate warming is expected to increase northern peatland water losses to the atmosphere through enhanced evapotranspiration, putting peatland restoration success (and water security for human and economic purposes) at risk (Helbig et al. 2020). Long-term monitoring of GHG emissions from restored peatlands thus provides an important tool to quantify sustained climate benefits and to improve carbon credit schemes for peatland restoration projects (Günther et al. 2018).

For tropical peatlands, critical measures include restoration of degraded peat and development of sustainable peat management to mitigate and adapt to climate change (Humpenöder et al. 2020; Menichetti

Tropical peatland burning in south Thailand. Source: Shutterstock.

and Leifeld 2018), including rewetting. Tropical peat forests showed resilience to natural disturbances of past climate change in the mid Holocene and late Pleistocene (Cole et al. 2019; Hapsari et al. 2018; Ruwaimana et al. 2020). Sorensen (1993) estimated that rates of carbon sequestration in tropical peat swamp forests in Indonesia ranged from 0.01 to 0.03 Gt per year. Intact tropical peat forests are rich in biodiversity in both terrestrial and associated aquatic habitats, but these are not properly valued for their wider benefits (Thornton et al. 2020). When many peat forests in Indonesia were logged from 1970 to the 1990s, selected commercial timber species were removed and sold to earn foreign currency. This deforestation was then followed by conversion to agricultural land rather than allowing for peatland recovery. These anthropogenic disturbances caused long-lasting cultural and environmental damage that affected local livelihoods, reduced carbon stocks, and decreased biodiversity and ecosystem services (Anshari et al. 2022; Gandois et al. 2020; Hoyt et al. 2020).

The Ramsar Convention 2021 Global Wetland Outlook stated that "Rewetting does not reduce emissions to zero: emissions depend on the extent to which the peatland water-table can be raised and kept high", emphasizing the need for monitoring, long-term planning, and sustainable management. The report also notes that despite high methane emissions at the initial stage of rewetting, the amount decreases over time when peat accumulation restarts, and the contribution of restored peatlands to global warming is less than that when in a drained state (Ramsar Convention on Wetlands 2021).

### *Restoration and reduced conversion of tidal wetlands*

Tidal wetlands, often called coastal wetlands, include seagrass meadows, tidal swamps (freshwater and saline mangrove swamps), and marshes (tidal wetlands without trees). Coastal wetlands may extend to the landward extent of tidal inundation and seaward to the maximum depth of vascular plants (Mitsch and Gosselink 2015; Wolanski et al. 2009). Rates of carbon accumulation are estimated to be 31.2–34.4 teragrams (TgC: $10^{12}$ grams of carbon) per year for mangrove swamps, 4.8–87.2 TgC/year for salt marshes, and 41.4–12 TgC/year for seagrass meadows (Howard et al. 2017; Kennedy et al. 2013). The coastal wetlands most affected by freshwater inputs are located in deltas and estuaries, where rivers and streams mix with seawater. Today, all three types of tidal wetland habitats face threats that can affect them in different ways,

Elkhorn Slough tidal marsh restoration project, U.K., which aims to restore 147 acres of vegetated tidal salt marsh, and native grasslands. Source: Shutterstock.

including activities in watersheds such as agricultural intensification, urbanization, and nutrient pollution. For example, a lack of sediment supply threatens marshes and mangrove swamps, while reduced water clarity can threaten seagrass meadows. Sustainability of tidal forests and marshes is dependent upon continued vertical accretion of soil to maintain the surface elevation with respect to sea level (Kirwan and Megonigal 2013), which is expected to rise at increasing rates with global warming (IPCC 2021). Increased sediment supply enhances this process while increased nitrogen from watersheds can cause a decline in production of the roots that are key to soil accumulation and the storage of carbon below ground (Darby and Turner 2008; Deegan et al. 2012). Delivery of excess nitrogen affects the ability of the tidal wetland to mitigate climate warming as microbial activity can transform some of it to nitrous oxide, a greenhouse gas with 265 times the global warming potential of $CO_2$ (on a 100-year timescale) (Myhre et al. 2013; Roughan et al. 2018). Nutrients are supplied to coastal waters from watersheds where sources are agriculture, sewage, and run-off from urban land.

Upstream dams reduce the level of suspended sediment released from watersheds; even 'mini-dams' for hydropower, which are purported to have less environmental impact, can reduce sediment loads. With respect to coastal wetlands, mini-dams have little advantage as they still retain sediments and in multiple numbers would have a considerable cumulative impact akin to the situation of the small dams built to power mills in the northeastern USA. Even as old dams are being removed (e.g., in USA), new ones are being constructed and continue to be planned in other regions such as Mexico. Many environmental and social factors are addressed when assessing the impact of dams, but generally these assessments have not included impacts on tidal wetlands. Promoting awareness of the links between sediment retention and loss of tidal wetland carbon sinks, along with the potential for obtaining carbon credits as an alternative income source, may encourage more balanced judgements when selecting sites for new dams.

### *Restoration and reduced conversion of inland mineral-soil (IMS) wetlands*

IMS wetlands (or freshwater mineral-soil wetlands) include freshwater marshes and freshwater swamps. IMS wetlands account for approximately 39 per cent of the total wetland area globally (Badiou 2017). These freshwater wetlands have significant carbon stocks due to their high productivity and waterlogged condition (Bernal and Mitsch 2012; Mitra et al. 2005). Carbon sequestration in IMS wetlands occurs when in situ biomass production exceeds decomposition rates (Bridgham et al. 2006; Mazurczyk and Brooks 2018; Moomaw et al. 2018). Like peatlands, IMS wetlands play an important role in climate change mitigation. The rate of carbon sequestration in peatlands is low compared with that of IMS wetlands (Bernal and Mitsch 2012; IPCC 2014; Zhang et al. 2016). A study on the IMS wetlands in the Great Plains, USA suggests that most of these organic soil carbon stocks were held in herbaceous freshwater mineral soil wetlands and the rest was found in woody freshwater mineral soil wetlands (Byrd et al. 2015). Carbon stocks in IMS wetlands vary from 12 to 557 tons per hectare, depending on the type of wetland and climate (Ausseil et al. 2015; Bernal and Mitsch 2008; Page and Dalal 2011). $CO_2$ and methane fluxes from IMS wetlands vary depending on the hydrology, soil wetness, land use type (e.g., disturbed or restored), sediment texture, and vegetation (Batson et al. 2015b; Hondula et al. 2021; Pfeifer-Meister et al. 2018).

Research on seasonally inundated forested IMS wetlands reveals that inundated soils switch from methane sources to sinks depending on water level, soil moisture, and the direction of water-level change (rising or falling). In fact, it is reported that methane emissions are associated with inundation extent and duration, but not frequency or depth, and that emissions are increasing with droughts and decreasing water levels (Hondula et al. 2021). An increase in $CO_2$ emissions is also observed with soil drainage and emissions are reduced by 49 per cent under long-term waterlogging (Tete et al. 2015). Significant nitrous oxide emissions are also associated with frequent drying of wetlands (Badiou, 2017; Pennock et al. 2010). Frequent wetting and drying events in IMS wetlands result in increased methane emissions compared with static water-level conditions (Badiou 2017; Hondula et al. 2021; Malone et al. 2013; Tete et al. 2015).

It is common practice to drain IMS wetlands as part of the preparation of land for agriculture, grazing, and forestry. A lower water level due to drainage leads to higher rates of decomposition, resulting in reduced carbon stocks (Page and Dalal 2011). Land conversion results in loss of stored carbon in soil through mineralization, which was otherwise protected against due to the anaerobic conditions (Mitra et al. 2003).

Many other anthropogenic activities such as levee, dam, and dike construction; irrigation; flow manipulation for water supply; and wildlife management can significantly alter the hydrology of IMS wetlands within the landscape (IPCC 2014; Mitsch and Gosselink 2015). Several studies demonstrate an increase in methane and nitrous oxide emissions due to increased nutrient loading from anthropogenic activities and land use (Gonzalez-Valencia et al. 2014; Silva et al. 2016).

The soil carbon accumulation and sequestration rates are much higher in natural unaltered IMS wetlands compared with restored wetlands, but over the long term, restored IMS wetlands have potential to regain a carbon stock similar to that of natural wetlands depending on factors such as hydrology, vegetation, soils, and land use (Bruland and Richardson 2005; Tangen and Bansal 2020). Many studies suggest that $CO_2$ contributes the most to the total GHG emission profile from restored IMS wetlands, while methane and nitrous oxide contribute much less. Soil saturation has been identified as a key limiting factor in methane and nitrous oxide production in restored wetlands (Gleason et al. 2009; Nahlik and Mitsch 2010; Phillips and Beeri, 2008; Richards and Craft 2015). Studies suggest that restored and recreated IMS wetlands have higher carbon sequestration rates and shorter time periods in making the transition from a net source to a net sink than many other restored or created ecosystems (Badiou 2017; Euliss Jr et al. 2006).

### *Wetland mitigation measures relevant in future planning and implementation*

The following wetland mitigation measures can be considered in future climate mitigation planning and implementation.

- **Conserve existing wetlands:** It is crucial to conserve existing wetlands with their carbon pools and prevent further degradation, as their loss could significantly increase the concentration of atmospheric $CO_2$.

- **Restore wetlands:** Wetland restoration has a large climate mitigation potential and needs to be at the heart of climate policies. For example, for northern peatlands, it is important to initiate the rewetting and revegetating as soon after the disturbance as possible to substantially reduce adverse climate impacts and to return the carbon sequestration function. Restoring natural hydrology and water table depth in peatlands is an important factor for the successful restoration of peatland ecosystem services.

- **Context-specific management:** It is important to understand context-specific wetland management for emissions reduction when developing strategies and measures. The management of the landscape surrounding a wetland plays an important role in reducing emissions, particularly regarding nutrient control. Vegetation structure and level of degradation, tree density, and livestock grazing intensity, etc., can impact soil water content, groundwater tables, soil nutrients, soil salinity, and several other factors, and thus have a significant impact on annual GHG fluxes.

- **Measures for increased carbon storage:** It is possible to increase the carbon storage capacity of wetlands by implementing measures suited to specific wetlands. For example, water quality plays an essential role in the emissions pattern from wetlands. To initiate greater carbon storage, one method would be to slow the rate of decomposition, which is directly related to the biochemical and physicochemical processes. Also, plant productivity and species composition are important and another proposed strategy to increase carbon storage in a wetland is to increase native species and fungi-based processes by planting perennial species.

- **Understand specific wetland types:** Different types of wetlands sequester carbon and emit GHG in various ways. It is crucial to understand the sequestration mechanisms and carbon dynamics specific to each wetland type and region to increase the capacity of wetlands to actively sequester carbon over the long term.

- **Promote wetland awareness for selecting dam sites:** Upstream dams reduce the level of suspended sediment released from watersheds, which impacts tidal wetlands. Promoting awareness of the links between sediment retention and loss of tidal wetland carbon sinks along with the potential for obtaining carbon credits as an alternative income source may encourage more balanced judgements when selecting sites for new dams.

- **Monitoring of GHG emissions:** To make informed decisions regarding peatland restoration, long-term monitoring of GHG emissions from restored peatlands provides an important tool to quantify sustained climate benefits and to improve carbon credit schemes for peatland restoration projects.

### *Knowledge and data gaps in the mitigation potential of wetlands*

The following knowledge and data gaps should be filled to maximize the mitigation potential of wetlands.

- Many countries in the world either do not have a national wetland inventory or are still in an initial stage of developing one. For instance, there is substantial uncertainty regarding the spatial extent of tropical peatlands and associated carbon stocks. More field data is needed to reduce these uncertainties and protect these ecosystems.

- Conservation and restoration of wetlands can have socio-economic trade-offs (see section 5.3). There needs to be a framework that can be used to assess potential trade-off scenarios.

- There is limited knowledge on how to restore degraded peatlands. More research, monitoring, and evaluation of existing restoration interventions is needed to make informed decisions, for instance regarding the hydrological system, drainage conditions, types of peat soils, climate, land use, and long-term climate change impacts.

- Research and efforts should build on emerging findings on the impact of thawing permafrost regions and develop guidance on mitigating large-scale carbon and methane release.

## 5.2.2 Mitigation measures in rivers and streams

River systems can store a significant portion of terrestrial carbon, but due to lack of research and data the estimated mitigation potential is not known. Still, inland waters are increasingly recognized as a significant source of GHG emissions (Zhang et al. 2021), while riverine floodplains have been acknowledged for their carbon storage (Sutfin et al. 2016). Rivers and streams do not just connect the carbon stocks of land and sea (Ran et al. 2015), but are also biogeochemical integrators in landscapes, both receiving and processing carbon, nitrogen, and phosphorus, and other biologically active elements (Crawford et al. 2017).

### *Enhanced carbon storage in river systems*

River systems are often referred to as river corridors, which include the active channel and the riparian zone (floodplain and hyporheic zone beneath the stream or river) (Harvey and Gooseff 2015). In a river corridor, organic carbon is stored in six forms, among which three primary reservoirs are: i) fallen dead large wood in the channel and floodplain; ii) standing biomass of riparian vegetation; and iii) soil organic carbon (SOC), which is technically the organic carbon on and beneath the floodplain surface. Fallen large wood, with its long residence time in a river and floodplain, stores organic carbon and delivers particulate organic matter (POM) to the channel and the floodplain. Vegetation is also a significant reservoir of organic carbon. However, floodplains are critical since they do not just support the biomass growth that is a source of large wood, they facilitate the transport, accumulation, retention, and breakdown of organic matter received from the channel and the riparian vegetation (Sutfin et al. 2016; Robertson et al. 1999; Wohl et al. 2017). A recent evaluation of carbon sinks within Amazonian floodplain lakes estimates that the accumulation of carbon may exceed the rate of emission from the river system (Sanders et al. 2017).

Several factors determine the carbon storage potential of a river corridor, including geology, climate, channel complexity, valley geometry, hydraulic connectivity, microbial activity, and riparian vegetation. As a river moves through different landscapes, the above-mentioned factors influence the travel time and retention of water, sediment, and organic carbon. For example, a high degree of channel complexity increases the residence time of water, sediment, and POM; facilitates the breakdown of organic matter; and filters excess nutrients and dissolved organic carbon (DOC) from surface and shallow subsurface waters (Sutfin and Wohl 2017; Sutfin et al. 2016; Wohl et al. 2017).

The surface and shallow subsurface of the floodplain host a large reservoir of organic carbon as SOC. For both small and large rivers, carbon is stored predominantly in the floodplain soil. During overbank

Unchallenged spring overflow of the Pripyat River, Ukraine. Source: Shutterstock.

flooding, floodplains also act as sinks for inorganic, organic, dissolved, and particulate fractions of both nitrogen and phosphorus (Noe and Hupp 2005; Wohl et al. 2017). Long-term carbon storage in the floodplain is determined by the source and form of organic carbon as well as the residence time of the floodplain sediment. A longer residence time enables the retention of sediments and organic carbon. Once stored in the floodplain soil, even DOC and POM take many years to travel through the river network (Cierjacks et al. 2010; Sutfin et al. 2016). This function of floodplains has been observed in different ecoregions, such as mountainous floodplains and tropical semi-arid lowland floodplains (Omengo et al. 2016; Scott and Wohl 2018; Sutfin and Wohl 2017).

In addition, hydrologic connectivity impacts the carbon sequestration potential of floodplains. Hydrologic connectivity exists longitudinally within channels, laterally between floodplains and channels, and vertically between surface water, hyporheic flow, and groundwater. While lateral and longitudinal hydrologic connectivity facilitate the transport, accumulation, retention, and breakdown of organic matter, lateral and vertical connectivity, on the other hand, facilitate saturated conditions in floodplains which limit decomposition of organic matter, microbial metabolism, and mineralization of SOC. Transport of organic matter from catchments occurs longitudinally and then laterally between floodplains and river channels. Increased carbon accumulation and storage is facilitated by increased lateral and vertical hydrologic connectivity. When the lateral connectivity between stream and floodplain is interrupted, there is decreased retention of water and sediment, which results in reduced carbon sequestration (Sutfin et al. 2016).

Several anthropogenic activities affect the carbon storage capacity of floodplains, particularly the disconnection of floodplains from the active channel through various activities. Some common examples are constructing levees and embankments, bank stabilization, conversion of floodplains to agricultural land, and urban expansion (Noe and Hupp 2005; Robertson et al. 1999; Shen et al. 2021). Construction of levees and embankments confine the active channel and alienate the floodplain, limiting overbank flows and lowering the rate of carbon deposition and sequestration (Wohl et al. 2017). Flow regime changes through damming, dredging, straightening, and/or bank stabilization can alter the quality of in-channel organic matter and increase downstream fluxes (Robertson et al. 1999; Sutfin et al. 2016).

### *GHG emissions from rivers*

Recent studies on GHG emissions from inland waters reveal emission rates that are higher than previously estimated (Raymond et al. 2013; Saunois et al. 2020; Tian et al. 2020). The methane emissions from inland water systems are now estimated to range from 117 to 212 Tg per year, nearly an order of magnitude greater than the initial estimate of 1.5 Tg per year (DelSontro et al. 2018; Saunois et al. 2020). In the case of nitrous oxide, rivers and streams can be considered as a significant source, depending on the organic matter and nutrient availability and other water quality parameters such as temperature, dissolved oxygen, and pH (Quick et al. 2019; Stanley et al. 2016; Zhang et al. 2021). Although nitrous oxide emissions from rivers had started to decline between 2010 and 2016 (due to decreased use of nitrogen fertilizers), a four-fold increase was seen in 2016 compared with 1900, i.e., 291.3 ± 58.6 gigagrams of nitrous oxide nitrogen per year (Gg $N_2O$-N/year) versus 70.4 ± 15.4 Gg $N_2O$-N/year (Maavara et al. 2019; Seitzinger et al. 2000; Yao et al. 2020).

Although there is evidence that rivers are emitting GHGs, there is no comprehensive knowledge about the drivers of emissions, their pattern, or their variability. The understanding of emissions from rivers is still constrained by a relatively small number of observations scattered around the world. These observations vary in measurement and upscaling methods, and have significant spatial and temporal fluxes and uncertainties (Allen and Pavelsky 2018; Crawford et al. 2017; Maavara et al. 2019; Natchimuthu et al. 2017; Zhang et al. 2021). Table 5.2 below synthesizes these findings.

Table 5.2. Synthesis of studies on riverine emissions

| STUDY SITE | GHG | KEY FINDINGS | SOURCE | STUDY APPROACH |
|---|---|---|---|---|
| Chaohu Lake basin, China | $N_2O$<br>$CH_4$<br>$CO_2$ | Urban rivers are emission hotspots (compared with forested and agricultural rivers).<br>Large nutrient supply and low oxygen levels drive the relatively high emissions from urban rivers. | Zhang et al. 2021 | This study investigates spatial variability of $N_2O$, $CH_4$, and $CO_2$ emissions from river reaches that drain from different types of landscapes (i.e., urban, agricultural, mixed, and forest landscapes). |
| Sweden | $N_2O$ | Agricultural and forest streams have comparable $N_2O$ fluxes despite higher TN concentrations in agricultural streams.<br>The percentage saturation of $N_2O$ in the streams is positively correlated with stream concentration of TN and negatively correlated with pH. The different TN concentrations but similar $N_2O$ concentrations in both types of streams have been attributed to the low pH (<6) of forest soils and streams. | Audet et al. 2020 | This study analysed a data set comprising approximately 1,000 stream $N_2O$ concentration measurements from agricultural and forest streams in Sweden covering temperate to boreal zones, especially low-order streams. |
| USA | $CO_2$ | Streams and rivers in the USA are supersaturated with carbon dioxide when compared with the atmosphere, emitting 97±32 Tg carbon each year.<br>The correlation between precipitation and $CO_2$ evasion is stronger than that of discharge and evasion due to the expansion of the river surface area with greater delivery of water through precipitation and higher flushing and delivery of soil and riparian/wetland $CO_2$. | Butman and Raymond 2011 | The study included total conterminous US streams/rivers with a surface area of 40,600 $km^2$. |
| Meuse River, Belgium | $N_2O$<br>$CH_4$<br>$CO_2$ | Surface waters are oversaturated in $CO_2$, $CH_4$, $N_2O$, acting as source of GHG to the atmosphere.<br>Highest GHG fluxes were observed during low water.<br>Highest GHG fluxes were observed in agriculture-dominated catchments. | Borges et al. 2018 | The study includes four seasonal surveys covering 50 stations, from yearly cycles in four rivers of variable size and catchment land cover, and from 111 groundwater samples. |

| STUDY SITE | GHG | KEY FINDINGS | SOURCE | STUDY APPROACH |
|---|---|---|---|---|
| Tibetan Plateau | $N_2O$<br>$CH_4$<br>$CO_2$ | The correlation between the precipitation and $CO_2$ emissions is stronger than that with DOC concentrations and water temperature (due to greater flushing and delivery of soil and riparian/ wetland $CO_2$ to streams and rivers).<br>A positive trend in $CH_4$ concentrations with the increased DOC concentrations was observed, indicating that water temperature placed a certain influence on driving pressure of $CH_4$ increased in anaerobic decomposition .<br>Partial pressures of $N_2O$ were correlated with dissolved nitrogen and were higher in main streams of the Tibetan rivers than those in tributaries due to anthropogenic activities around the mainstream. | Qu et al. 2017 | The study undertook one-time sampling from 32 sites in rivers of the Tibetan Plateau during2014 and 2015. |
| Sub-Saharan Africa | $N_2O$<br>$CH_4$<br>$CO_2$ | Riverine carbon dioxide and methane emissions increase with wetland extent and upland biomass.<br>A positive relationship was found between $CO_2$ and $CH_4$ flux and precipitation across the region, with the exception of two Malagasy rivers. | Borges et al. 2015 | The study is based on 12 rivers in sub-Saharan Africa, including seasonally resolved sampling at 39 sites, acquired between 2006 and 2014. |
| Amazonian Basin | $CH_4$ | Biological oxidation in large Amazonian rivers is a significant sink of $CH_4$, representing up to 7 per cent of the global soil sink.<br>The capacity for MOX can vary widely across various river types and hydrologic regimes.<br>The future river MOX process might be sensitive to environmental change, adding to the list of important climate feedback on natural GHG emissions. | Sawakuchi et al. 2016 | The study examines the cycling and flux of $CH_4$ in six large rivers in the Amazon basin, including the Amazon River in the year 2012, during high water and low water seasons. MOX rate has been studied. MOX reduces the diffusive flux of $CH_4$ in the rivers. |
| Amazon and Congo | $CH_4$ and $CO_2$ | The pressure of $CO_2$ and $CH_4$ concentrations significantly increased from the main stream to the small tributaries in both the rivers.<br>The analysis indicated a stronger contribution of $CO_2$ production from anaerobic organic matter degradation compared with aerobic respiration, which is speculated to be related to carbon processing within the wetlands in the vicinity. | Borges et al. 2015 | This study compares the $CO_2$ and $CH_4$ distributions in lowland river channels of the two largest rivers in the world and in the tropics, the Amazon (n = 136) and the Congo (n = 280), using a dataset of concurrent $CO_2$ and $CH_4$ concentration measurements in river channels |

Note: $N_2O$ = nitrous oxide; $CH_4$ = methane; $CO_2$ = carbon dioxide; TN = total nitrogen; DOC = dissolved organic carbon; MOX = methane oxidation

Despite a lack of coherent and generalized knowledge available to explain emissions from rivers, and how to minimize these, some observations are common across several studies. Nutrient loading and organic matter delivery due either to anthropogenic activities (urbanization or agriculture) or to natural causes (vegetation or wetlands) are observed to increase river saturation with $CO_2$, methane, and nitrous oxide. However, a combined impact of multiple factors such as geomorphologic and hydrologic conditions, temperature, alternative electron acceptors, pH, etc. can influence the emission of GHGs. For example, Stanley et al. (2016) illustrates how the concerted impact of several factors influences methane emissions in rivers (Figure 5.1). Some studies found a strong correlation between precipitation and $CO_2$ emissions due to greater flushing and delivery of soil and riparian/wetland carbon to streams and rivers (Borges et al. 2015; Qu et al. 2017; Butman and Raymond 2011). Borges et al. (2015) attempted to draw parallels between two major rivers in the tropics and concluded that "dynamics of dissolved $CH_4$ [methane] in river channels are less straightforward to predict and are related to the way hydrology modulates the connectivity between wetlands and river channels." In fact, the main streams and tributaries of the same river tend to emit differently, and the emission rates tend to change based on the stream orders (Audet et al. 2020; Borges et al. 2015; Qu et al. 2017; Raymond et al. 2013; Zhang et al. 2021).

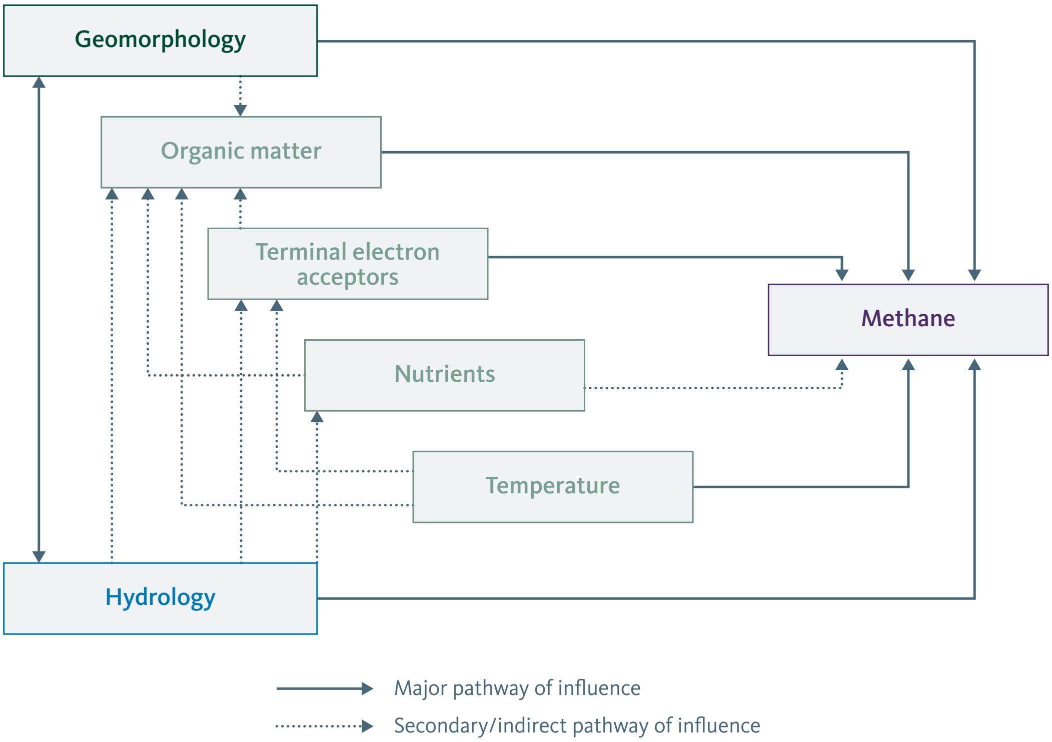



Figure 5.1. Conceptual framework of controls on methane production and persistence in rivers. Controls mentioned here are geomorphology, hydrology, organic matter, temperature, terminal electron acceptors, and nutrients. Source: adapted from Stanley et al. (2016).

### *River mitigation measures relevant in future planning and implementation*

The following river system mitigation measures, many of which align with general principles for managing the health of rivers, can be relevant to consider in future climate mitigation planning and implementation.

- **Connecting rivers with floodplains**: Construction of levees and embankments confines the active channel and alienates the floodplain as well as limiting overbank flows, which lowers the rate of carbon deposition and sequestration in floodplains. Maintaining lateral connectivity and ecosystem integrity in riparian areas can help increase the carbon pool in the floodplains. Floodplains work as buffers and reduce nutrient loading to the channels, which can help reduce emissions.

- **Limiting channel alterations**: It is important to protect and restore the physical complexity and flow regime of river corridors, which enable carbon storage. Channel alterations through dredging, straightening and/or bank stabilization can alter the quality of in-channel organic matter and increase downstream fluxes. Maintaining the lateral and vertical hydrologic connectivity of rivers enhances carbon sequestration potential to a greater extent than enhancing longitudinal connectivity.

- **Limiting nutrient and organic matter loading in rivers**: Nutrient loading and organic matter delivery, either due to anthropogenic activities (urbanization or agriculture) or due to natural causes (vegetation or wetlands), are observed to saturate rivers with $CO_2$, methane, and nitrous oxide. Monitoring, managing, and limiting nutrient and organic matter loading in rivers can reduce GHG emissions from rivers. Connecting rivers with floodplains also reduces nutrient loading in channels, which can help reduce emissions.

- **Context-specific monitoring**: The carbon sequestration potential of river corridors depends on regional and local controls, such as geology, climate, hydrology, geomorphic characteristics, etc. Also, for emissions, the main channel and tributaries of the same river tend to emit differently, and the emission rates tend to change based on the stream orders. Studies also suggest that the variation in emissions in different river reaches is related to their proximity to urban, agricultural, or forested landscapes. It is unlikely that there will be a generalized solution that fits all rivers, and management plans should be context specific.

- **Undertake watershed-scale management approaches**: Whether for enhanced carbon sequestration or emissions reduction, management approaches and decisions should be taken at the watershed scale. Carbon fluxes in rivers are affected by grazing, cropping on floodplains (nutrient source), or soil erosion due to removal of native species (POC loading). Rather than treating river systems as isolated segments, watershed-scale management that addresses the complex dynamics of the catchment can yield better outcomes.

***Knowledge gaps in the mitigation potential of rivers and streams***

Significant knowledge gaps remain, particularly the following, and it is critical to address these to realise the full mitigation potential of rivers and streams.

- Understanding of the spatial extent and magnitude of changes in riparian soil organic carbon content and biomass is currently based on only a handful of studies focused on limited regions. There is no global-scale comprehensive understanding of how historical and ongoing riparian modification impacts carbon dynamics in river systems.

- Carbon flux mechanisms and their transformations in the river corridors, as well as the impacts of future climate change on river corridors, must be better understood.

- Knowledge and understanding of the complex and nonlinear interactions among water, sediment yield, flow regime, biomass and primary productivity, soil moisture, and/or soil organic carbon must be developed.

- There is a need for more holistic studies to estimate the emissions potential of rivers by mapping emissions of all three major GHGs.

- In several river basins, the source of pollution (e.g., from industry) and the point of sequestration (e.g., the river corridor) may not be under the same jurisdiction. Policies need to consider such gaps and find a way to minimize them.

### 5.2.3 Mitigation measures in lakes and reservoirs

Lakes, either natural or reservoirs created behind dams, play a key role in global carbon cycling despite taking up less than 4 per cent of the earth's non-glaciated land area (Bastviken et al. 2011; Beaulieu et al. 2020; DelSontro et al. 2018; Raymond et al. 2013; Stanley et al. 2016; Verpoorter et al. 2014). Lakes and reservoirs can trap land-derived carbon (through carbon burial) in their sediments (Mendonça et al. 2017). Mendonça et al. (2017) recommended considering lakes and reservoirs as a 'new sink' for land-derived organic carbon, particularly because organic carbon is preserved more efficiently in inland water sediments than in other depositional environments (such as soils), and sediment delivery to the sea has decreased. Cole et al. (2007) also acknowledged the high carbon burial potential of reservoirs due to high sedimentation, but also warned about the unknown fate of reservoir sediment after dam removal.

However, lakes and reservoirs also produce high levels of methane (compared with $CO_2$) in nutrient-rich (eutrophic) sediments (Beaulieu et al. 2020; Berberich et al. 2020; DelSontro et al. 2018). Despite considerable rates of carbon burial, eutrophic freshwater with carbon-carrying sediments can become a greater net GHG source at a centennial time scale. This is a key concern, considering the global warming potential of methane is 28 times greater than that of $CO_2$ over a 100-year time horizon (Myhre et al. 2013). In fact, a study by DelSontro et al. (2018) showed GHG emissions from

Algal bloom in a Bavarian lake. Source: Shutterstock.

lakes and reservoirs are equivalent to 20 per cent of $CO_2$ emissions from global fossil fuels every year.

Lake size, depth, sedimentation rates, DOC concentration, and productivity rate (the lake's ability to support plant and animal life defines its level of productivity, or trophic state), alongside environmental factors such as temperature and precipitation, have been identified as the drivers of GHG emissions in reservoirs and lakes (Beaulieu et al. 2019; Berberich et al. 2020; DelSontro et al. 2018; Sanches et al. 2019; Waldo et al. 2021). Shallow and tropical lakes and reservoirs have high emission rates for GHGs, but methane is of most importance due to its link with lake and reservoir productivity and its high global warming potential (DelSontro et al. 2018; Gunkel 2009; Sanches et al. 2019). A higher ratio for the watershed area compared to the surface area of the reservoir usually results in high sediment and nutrient loading from the surrounding catchment compared to that for natural lakes, triggering greater production and carbon burial, and increasing methane generation in the system (Berberich et al. 2020). Nitrous oxide emission rates are also substantially lower for natural lakes than for reservoirs when measured per mean surface area (Lauerwald et al. 2019).

An important concern with lakes and reservoirs is the high aquatic productivity in response to nutrient increase, known as eutrophication. There is a significant relationship between freshwater eutrophication and GHG emissions (Berberich et al. 2020; DelSontro et al. 2018; Li et al. 2021; Mendonça et al. 2017; Sanches et al. 2019). In fact, there is a positive feedback loop between eutrophication in lakes and reservoirs and GHG emissions, meaning that freshwater eutrophication and GHG emissions are strengthened by each other. In simple words, when nutrient loading crosses a critical threshold, submerged plants are gradually replaced by other aquatic macrophytes or algae. Firstly, a shift in the dominant primary producer (from submerged plants to algae) affects GHG emissions since submerged plants reduce methane emissions more effectively. Secondly, algae become the dominant producer in the lake or reservoir system, and this plays an important role in the freshwater ecosystem emission dynamics. Algae have a higher $CO_2$ uptake rate (compared with other aquatic macrophytes) and can effectively reduce $CO_2$ emissions. On the other hand, harmful algal blooms cause a high production of methane and nitrous oxide. Warmer temperatures increase algal production, with a corresponding increase in emissions of methane and nitrous oxide (Burlacot et al. 2020; Plouviez et al. 2019; Su et al. 2019). These increased emissions contribute further to climate change and increased temperatures (Li et al. 2021). Li et al. (2021) illustrated the positive feedback loops between freshwater eutrophication and GHG emissions (Figure 5.2). The productivity of inland waters is projected to increase in the coming decades due to both increased mean temperature and increased nutrient loading, which makes the climatic impact of harmful algal blooms an important concern (Beaulieu et al. 2019). Watershed-scale soil erosion control and nutrient reductions may help reduce GHG emissions from lakes and reservoirs (Berberich et al. 2020).

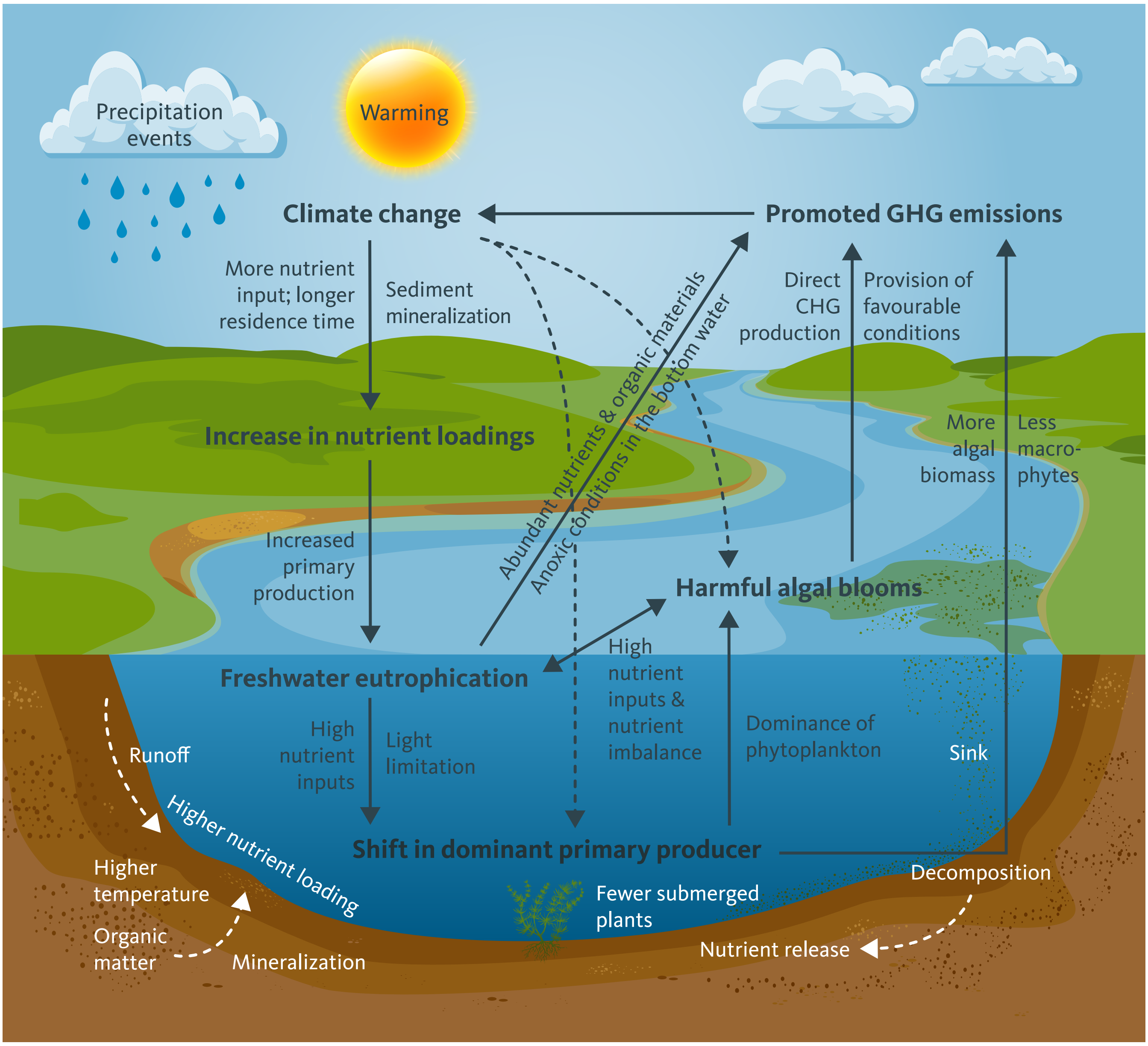



Figure 5.2. The positive feedback loops between freshwater eutrophication and GHG emissions. Source: SIWI, adopted from Li et al. 2021

High nutrient and organic matter loading are common factors influencing emissions from lakes and reservoirs, resulting in increased aquatic productivity. Lake and reservoir characteristics (depth, temperature, sediments, and rooted aquatic macrophytes) and catchment attributes (land use, terrestrial net primary production, and human activities) are also driving factors. Although reservoirs are increasingly recognized to emit significant amounts of GHGs, there are millions of small and large-scale dams, and more are being constructed all the time. It is important to discuss and implement the measures that can reduce emissions in existing reservoirs and how to reduce emissions in new reservoirs.

### *Lake and reservoir mitigation measures relevant to future planning and implementation*

The following mitigation measures in lakes and reservoirs can be considered in future climate mitigation planning and implementation.

- **Nutrient and organic matter control for eutrophication management**: As noted, reducing nutrients, primarily nitrogen and phosphorus, and organic matter loading can lower the rate of eutrophication. This can be done by reducing use of fertilizer, minimizing nutrient loads in the catchment, phosphate stripping at sewage treatment works, and installing vegetated buffer strips adjacent to water bodies that trap eroding soil particles (Berberich et al. 2020; McCrackin et al. 2017; Paerl et al. 2020). These measures bring the added benefit of improved water quality (Li et al. 2021; Yan et al. 2021). Nutrient loading control can be a longstanding measure for ecological restoration and emissions reduction.

- **Managing drawdown, operating levels, and downstream emissions in reservoirs**: Fluctuating water tables and shallow littoral areas between dry land and open water result in considerably more methane being produced by reservoirs than by natural lakes or other surface waters (Harrison et al. 2017). Water-level management should aim to minimize methane emissions from the sediments and the littoral zone. Downstream methane emissions from reservoirs can be reduced by selectively withdrawing water from near the reservoir surface, where methane concentration is less than at greater depths (Harrison et al. 2017; Harrison et al. 2021; Keller et al. 2021; Yan et al. 2021).

- **Technology for methane management:** Methane emissions can be reduced using a methane capture technology (which converts the captured methane into energy) and a technology to increase the dissolved oxygen (such as installing an aerating device) in the water (Fearnside 2007).

- **Management of older dams and dam removal processes**: Dam removal mobilizes sediments, nutrients, and organic carbon from the reservoir resulting in a high potential for emissions. Dam removal can also affect the downstream river channel by eroding the stream bed and the nutrient-rich sediments. On the other hand, deposited nutrients do not necessarily remain trapped in the reservoir when an old or out-of-operation dam is left in place. Due to decreased sediment and nutrient elimination efficiencies, the reservoir can become a nutrient source for the surrounding landscape (Maavara et al. 2019). Hence, management of old dams and dam removal needs to consider remobilization, mineralization, and subsequent emissions of deposited sediment, nutrients, and organic carbon.

- **Conception and planning of new hydropower dams**: The role of hydropower as a clean energy source is being revisited since dams affect river ecosystems, biodiversity, and society, with a potential impact on emissions from river systems (Box 5.1). As mentioned above, emissions can occur both during years of operation and when dams are old or removed, and this should be taken into consideration. During the decision-making process for new or rehabilitated dam development, there should be thorough accounting of the short- and long-term impacts and benefits of proposed projects at the conception and planning stage, so emissions can be minimized if the development proceeds (Fearnside 2007). It is necessary to consider the GHG exchanges before and after the impoundment. The difference between pre- and post-reservoir emissions from the whole river basin indicates the GHG status of the reservoir (UNESCO/IHP 2008).

### *Knowledge gaps in the mitigation potential of lakes and reservoirs*

Uncertainty and knowledge gaps regarding different aspects of GHG fluxes from lakes and reservoirs persist. Some of the key knowledge gaps and opportunities include the following.

- Although reservoirs emit all three major GHGs, few reservoirs have measurement records for all three, with the least number of data points for nitrous oxide (Deemer et al. 2016).

- There is noticeable variation in the estimation of GHG emissions from lakes and reservoirs. The global aerial coverage of reservoirs, including small reservoirs, is not well documented, which is why different studies used different areas and calculation periods, introducing variation in the estimation of GHG fluxes. In addition, GHG emissions from lakes and reservoirs show high spatial and temporal variability (Ion and Ene 2021; Yan et al. 2021).

- There is no standardized or widely accepted method for GHG emissions estimation in reservoirs. Until recently, emissions through ebullition and degassing pathways were not incorporated into the total GHG budget estimation. Downstream GHG emissions remain poorly studied although these could represent an important pathway of GHG release to the atmosphere (Keller et al. 2021; Yan et al. 2021).

- There is substantial uncertainty about how the impacts from climate change might affect GHG emissions from lakes and reservoirs in the future. GHG fluxes are likely to be impacted by potential changes in thae reservoirs (e.g., direct inputs, water management) and their watersheds (e.g., land use, microclimate) due to climate change (Yan et al. 2021).
- Only a handful of studies have examined the combined effects of land management change and climate change on nutrient loading, and these have been focused on individual watersheds. Socio-economic changes have an important bearing on how landscape management would be altered in the future. This uncertainty makes estimation of future GHG fluxes difficult (Sinha et al. 2019).

### Box 5.1. Hydropower dams: Friend or foe?

Hydropower dams have come under increasing scrutiny over the last decade regarding their function as a clean energy source. This is because the reservoirs created by these dams emit globally significant amounts of GHGs (Deemer et al. 2016; Fearnside 2006; Fearnside 2007; Prairie et al. 2021; Tremblay et al. 2005). The total annual GHG emissions from global reservoirs amounts to 2.3 per cent of total emissions from inland freshwaters (Yan et al. 2021). Until very recently, global estimates of GHG emissions from reservoirs were based on the assumption that reservoirs located in similar climates and regions would emit in a similar manner (Harrison et al. 2021; Prairie et al. 2021). Estimation of GHG fluxes in reservoirs has also been focused solely on diffusive gas fluxes until very recently, when ebullition fluxes have also been considered in the estimation (Deemer et al. 2016; DelSontro et al. 2018; Harrison et al. 2021).

Reservoirs emit all three major GHGs, but estimation of global nitrous oxide emissions have been limited due to a scarcity of data (Deemer et al. 2016; Yan et al. 2021). $CO_2$ and methane are emitted in four ways: by $CO_2$ diffusion, methane diffusion, ebullition, and degassing. Methane emission through degassing has been incorporated in the global GHG budget of reservoirs only recently. Recent findings suggest that methane that leaves the reservoir through ebullition is transported downstream from reservoirs (Harrison et al. 2021; Keller et al. 2021). Organic content and nutrient loading, reservoir sediments, primary productivity, and water temperature are the primary contributors to GHG emissions from reservoirs, but emissions can also be affected by the characteristics of reservoirs (temperature, depth, thermal stratification, trophic status, etc.) and their catchments (land use, terrestrial net primary production, and human activities) (Yan et al. 2021; Prairie et al. 2021). Reservoir drawdown areas are hotspots for $CO_2$ emissions (Keller et al. 2021).

Although Deemer et al. (2016) showed that some reservoirs can be $CO_2$ and nitrous oxide sinks, several other recent studies suggest that reservoirs are a net source of carbon emissions. In their first two to five years of construction, newly formed hydroelectric reservoirs emit almost three to ten times more GHG than natural lakes of the same size; and they continue to release $CO_2$ and methane during the plant operating lifetime (Fearnside 2006; Tremblay et al. 2005). Considering the additional GHG emissions in the drawdown areas, Keller et al (2021) suggests that hydroelectric reservoirs emit more carbon than they bury.

## 5.3 Co-benefits and trade-offs regarding freshwater-based mitigation

Freshwater ecosystems provide several important benefits for nature and human society, including provision of food and water, water quality improvement, disaster risk reduction, habitat protection, sediment retention and nutrient cycling, economic, and cultural and recreational benefits (Anisha et al. 2020; de Groot et al. 2008; Doswald and Osti 2011; Dybala et al. 2019). Mitigation measures based on freshwater ecosystems, for example conservation of wetlands or nutrient loading control, can offer some specific direct and indirect co-benefits. However, it is recognized that some socio-economic, socio-political, and development trade-offs would occur if freshwater ecosystems were managed for GHG reduction and increased carbon sequestration. This section highlights possible co-benefits and trade-offs regarding freshwater-based mitigation measures.

## 5.3.1 Enhancement of ecosystem services through mitigation measures

Burkhard and Maes (2017) define ecosystem services as the contributions of ecosystem structure and function to human well-being. In simple words, ecosystem services are the benefits humans obtain from the ecosystem. The Millennium Ecosystem Assessment (MEA 2005) identifies these services in four broad categories: a) Provisioning services; b) Regulating services; c) Cultural services; and d) Supporting services (see Chapter 3 and MEA 2005). Mitigation measures within freshwater ecosystems, such as pollution control, wetland conservation and restoration, hydrology, vegetation monitoring, etc., (outlined in section 5.2) can enhance the delivery of ecosystem services across all categories. Enhancement of ecosystem services refers to changes in the service that leads to greater benefits for people compared to existing scenarios (MEA 2005). Table 5.3 outlines some examples of how mitigation measures in freshwater ecosystems enhance ecosystem services in different service categories.

Table 5.3. Enhancement of ecosystem services through freshwater-based mitigation measures

| ECOSYSTEM SERVICE CATEGORY | FUNCTION | EXAMPLE |
|---|---|---|
| Provisioning | Water supply | Pollutant control in rivers and lakes improves the quality of water, which can be used by humans for drinking, swimming, fishing, or other activities (Dosskey 2001; Mitsch 1992). Flooded wetlands play a role in groundwater recharge (Gupta et al. 2020). |
| | Food | Protected and restored wetlands and well-managed floodplains foster edible plants, shrubs, herbs, and animals (Buckton 2018; Leaman 2018). |
| | Habitat | Protected and restored wetlands, lakes, and rivers provide a habitat, breeding ground, and refuge for different species of birds, mammals, amphibians, fish, and reptiles (Flores-Rios et al. 2020; Grizzetti et al. 2019). |
| Regulating | Pollutant control | Protected, restored, and/or constructed wetlands play a role in pathogen removal, and nutrient retention, removal, and breakdown (Vymazal 2018; Mackenzie 2018). |
| | Disaster risk reduction | Wetland and floodplain protection and expansion can reduce flood risk through enhanced hydraulic connectivity (McInnes 2018a; Tomscha et al. 2021). Coastal wetlands provide protection from storms and coastal erosion (MEA 2005). |
| | Water quality regulation | Protected and restored wetlands, with healthy vegetation cover, can trap sediments, remove pollutants, and protect rivers and lakes from nutrient overload (Mitsch 1992; Mitsch et al. 2005). |
| | Erosion regulation | Vegetated wetlands (swamps and marshes) trap sediments and regulate erosion (Fagorite et al. 2019; Ford et al. 2016). |
| | Microclimate regulation | Wetlands (protected, restored, and constructed) alongside rivers and lakes have a positive effect on the surrounding microclimate with a relative cooling impact (McInnes 2018b; Sun et al. 2012). |
| Supporting | Biogeochemical cycling | Restored wetlands can store elements such as nitrogen, phosphorus, and carbon for long periods in the soil and supply these elements to surrounding ecosystems; this is unlikely to occur in a drained condition (Everard 2018b; Tomscha et al. 2021). |
| | Water storage | Water moving through a protected or restored wetland is often slowed by vegetation and this can further promote water retention, infiltration, and storage (Carter 1996; Feng et al. 2021; MEA 2005). |
| | Hydric soil development | Wetland restoration promotes the development of saturated soil, which enables the growth and regeneration of vegetation adapted to saturated/inundated and low-oxygen conditions (Amon et al. 2005; MEA 2005; Mitsch et al. 2005). |
| | Biomass production | The nutrients and water retained by floodplains and wetlands aid the growth of vegetation and production of biomass. Wetland restoration supports native plant species diversity (MEA 2005; Tomscha et al. 2021). |

| ECOSYSTEM SERVICE CATEGORY | FUNCTION | EXAMPLE |
|---|---|---|
| Cultural | Recreation | Nutrient and sediment loading control in rivers and lakes can enhance water clarity, which contributes directly and indirectly to recreational benefits, including swimming, boating, fishing, etc. (Angradi et al. 2018). |
| | Aesthetic | Enhanced water clarity in rivers and lakes can increase visual appeal and improved water quality contributes to enhancement of biodiversity, which adds aesthetic value (Angradi et al. 2018; Papayannis and Pritchard 2018). |

## 5.3.2 Climate change adaptation and resilience benefits from mitigation measures

Ecosystem-based adaptation to climate change, i.e., the synergistic effects of integrating biodiversity and ecosystem services into climate adaptation, has received increasing acknowledgement as a cost-effective, proven, and sustainable solution to climate change adaptation. Freshwater ecosystems are commonly regarded as key components of this approach (Colls et al. 2009; UNEP and IUCN 2021; World Bank 2009). Freshwater-based climate change mitigation measures are based mostly around protecting and restoring water bodies to healthy states. The role of freshwater ecosystems in climate change adaptation has been emphasized due to their ability to persist through climate change effects and continue providing ecosystem services (Colloff et al. 2016; Colls et al. 2009; Lavorel et al. 2015; Morelli et al. 2016). Although climate change is predicted to affect freshwater ecosystems, floodplain ecosystems and well-managed wetlands, even if in a low-diversity state, are likely to persist under climate change and provide adaptation services (Lavorel et al. 2015). In fact, many areas with large water bodies have persisted through the climatic changes of the Holocene, proving their resilience (Morelli et al. 2016). However, there are concerns over whether this can be maintained under changing environmental conditions through the intersection of land-uses and the rapid progression of current climate change.

Climate change is predicted to increase the intensity of extreme precipitation events and the risk of flooding in some parts of the world and intensify drought events in others (Cook et al. 2018; Tabari 2020). Freshwater-based climate change mitigation measures, such as efforts to connect rivers with floodplains, and protect and restore wetlands, are recognized as adaptation measures against increased flood and drought risk (Endter-Wada et al. 2020; Lavorel et al. 2015; Opperman et al. 2009; Vigerstol et al. 2021). Protection or restoration of floodplains has the highest potential to mitigate riverine flood risk since it provides for natural storage and diversion in regularly flooded areas (Vigerstol et al. 2021; Opperman et al. 2009).

Seifollahi-Aghmiuni et al. (2019) highlighted the capacity of well-managed wetlands to retain run-off water and refill aquifers, both of which help minimize drought-induced stress on water reservoirs or stresses that occur due to increased temperatures. Endter-Wada et al. (2020) discussed how riparian wetlands associated with beaver dams can alleviate the impacts of wildfires by creating broad and diffused floodplain habitats that are more resistant to burning. As mean earth temperature rises, the cooling effects created by rivers, lakes, and wetlands provide adaptive services to both humans and animals (particularly in urban areas) (Chang et al. 2007; Costanza et al. 1997; Morelli et al. 2016; Sun et al. 2012).

In an urban setting, wetlands, reservoirs, lakes, and rivers create 'urban cooling islands', which maintain lower temperatures in an area compared with its surroundings. In fact, water bodies are relatively more efficient than other types of green spaces due to the higher rate of evapotranspiration (Gober et al. 2010; Hathway and Sharples 2012). Hence, protecting and restoring urban water bodies can bring both mitigation and adaptation benefits. The cooling effect of water bodies enables the creation of climate change refuges for local people, wildlife, and fisheries. In large water bodies and their surrounding areas (deep lakes and wetlands for instance), more solar energy is used in evaporation than in surface heating, which buffers regional warming (Morelli et al. 2016). Protection and restoration of riparian wetlands and forested wetlands can enhance the adaptive capacity of different terrestrial species in a warming climate. The hydrologic connectivity between river and floodplain is regarded as a key predictor of species richness of floodplain invertebrates (Tomscha et al. 2017). This hydrologic connectivity also enhances climate change resilience in many species by allowing movement to new areas when current habitats become unsuitable due to climate change (Cassin and Matthews 2021; Morelli et al. 2016).

### 5.3.3 Nature-based solutions associated with freshwater ecosystem mitigation measures

Nature-based solutions (NbS) are regarded as sustainable due to their ability to cope with different conditions without greatly altering structure or functionality (robustness). When an environmental condition exceeds a threshold, NbS can be adapted by altering their structure and operating conditions (Folke 2006; Mauroner et al. 2021). Such nature-centric solutions are applicable to different sectors, such as water resources management, disaster risk reduction, water quality control, agricultural technology, and climate change adaptation.

NbS involve advanced and deliberate applications of ecosystem services to meet climate mitigation objectives. Floodplain restoration and management, potentially a freshwater-based mitigation measure, is an effective NbS for flood mitigation, biodiversity protection, and surface water quality control (Acreman et al. 2021; Jakubínský et al. 2021; Keesstra et al. 2018; Perosa et al. 2021). Lo et al. (2021) evaluated the flood mitigation potential of floodplain expansion (called 'Room for the River') compared with three other grey/hard infrastructure solutions (levee extension in variable lengths) on the Nangang River in Taiwan. The authors considered 'Room for the River' to be the best suited flood mitigation measure due to its effectiveness associated with multiple co-benefits compared to grey solutions, which are a single-purpose infrastructure optimized to solve narrowly defined problems (Lo et al. 2021). Perosa et al. (2021) discussed floodplain restoration as NbS for flood protection in three locations of the Danube catchment in Europe and estimated the benefits in terms of monetized ecosystem services. The study estimated a total gain of ecosystem services worth approximately USD 5 million per year in all three locations combined (Perosa et al. 2021). Based on a comprehensive review of over 400 case studies on different NbS across the African continent, Acreman et al. (2021) concluded that floodplain wetlands are effective NbS for flood protection and sediment generation in Africa.

Restored and protected wetlands, even constructed wetlands, are commonly acknowledged as effective NbS for disaster risk reduction, flood management, water quality improvement, and climate change adaptation (Cabral et al. 2017; Keesstra et al. 2018; Liquete et al. 2016; UNEP 2014). In their discussion on the effect of NbS in land management for enhancing ecosystem services, Keesstra et al. (2018) included an example of vegetative sediment trapping measures in Ethiopia where wetlands, along with grassed waterways, were used to trap the sediment in its transport path. This provided solutions for widespread soil loss and sediment overload in the lakes and reservoirs downstream and was deemed superior to other options (Keesstra et al. 2018). Another study in the eastern Free State province of South Africa examined the role of wetlands in disaster risk reduction (such as drought, veld fires, and floods) and concluded that well-managed and protected wetlands are effective buffers and can effectively reduce the risk of veld fires, floods, and drought, whereas degraded wetlands substantially lack risk mitigation capacity. The authors emphasized that restoring degraded wetlands and monitoring the ecological state of protected sites can help to establish wetlands as efficient, cost-effective, community-driven NbS for disaster risk reduction (Belle et al. 2018).

NbS are usually multipurpose, able to address different issues, and aid other solutions or approaches while contributing to the safety, health, well-being, livelihoods, etc. of local populations (Cassin and Matthews 2021). UNEP (2014) outlined some NbS for water resource management and compared them against traditional grey solutions (Table 5.4). In this table, freshwater-based mitigation measures, such as reconnecting rivers to floodplains, wetland conservation/restoration, and constructing wetlands and riparian buffers, are observed as the NbS with the most co-benefits that can address issues regarding water quality regulation, water supply regulation, and extreme weather moderation.

### 5.3.4 Trade-offs in use of freshwater-based mitigation

The major drivers of wetland degradation and loss include urban expansion and infrastructure development, land conversion to agriculture and

Table 5.4 Nature-based solutions for water resource management

| WATER MANAGEMENT ISSUE (PRIMARY SERVICE TO BE PROVIDED) | | GREEN INFRASTRUCTURE SOLUTION | LOCATION | | | | CORRESPONDING GREY INFRASTRUCTURE SOLUTION (AT THE PRIMARY SERVICE LEVEL) |
|---|---|---|---|---|---|---|---|
| | | | WATERSHED | FLOODPLAIN | URBAN | COASTAL | |
| Water supply regulation (including drought mitigation) | | Re/afforestation and forest conservation | ■ | | | | Dams and groundwater pumping water distribution systems |
| | | Reconnecting rivers to floodplains | | ■ | | | |
| | | Wetlands restoration/conservation | ■ | ■ | ■ | | |
| | | Constructing wetlands | ■ | ■ | ■ | | |
| | | Water harvesting | ■ | ■ | ■ | | |
| | | Green spaces (bioretention and infiltration) | | | ■ | | |
| | | Permeable pavements | | | ■ | | |
| Water quality regulation | Water purification | Re/afforestation and forest conservation | ■ | | | | Water treatment plant |
| | | Riparian buffers | | ■ | | | |
| | | Reconnecting rivers to floodplains | | ■ | | | |
| | | Wetlands restoration/conservation | ■ | ■ | ■ | | |
| | | Constructing wetlands | ■ | ■ | ■ | | |
| | | Green spaces (bioretention and infiltration) | | | ■ | | |
| | | Permeable pavements | | | ■ | | |
| | Erosion control | Re/afforestation and forest conservation | ■ | | | | Reinforcement of slopes |
| | | Riparian buffers | | ■ | | | |
| | | Reconnecting rivers to floodplains | | ■ | | | |
| | Biological control | Re/afforestation and forest conservation | ■ | | | | Water treatment plant |
| | | Riparian buffers | | ■ | | | |
| | | Reconnecting rivers to floodplains | | ■ | | | |
| | | Wetlands restoration/conservation | ■ | ■ | ■ | | |
| | | Constructing wetlands | ■ | ■ | ■ | | |
| | Water temperature control | Re/afforestation and forest conservation | ■ | | | | Dams |
| | | Riparian buffers | | ■ | | | |
| | | Reconnecting rivers to floodplains | | ■ | | | |
| | | Wetlands restoration/conservation | ■ | ■ | ■ | | |
| | | Constructing wetlands | ■ | ■ | ■ | | |
| | | Green spaces (shading of waterways) | | | ■ | | |
| Moderation of extreme events (floods) | Riverine flood control | Re/afforestation and forest conservation | ■ | | | | Dams and levees |
| | | Riparian buffers | | ■ | | | |
| | | Reconnecting rivers to floodplains | | ■ | | | |
| | | Wetlands restoration/conservation | ■ | ■ | ■ | | |
| | | Constructing wetlands | ■ | ■ | ■ | | |
| | | Establishing flood bypasses | | ■ | | | |
| | Urban stormwater runoff | Green roofs | | | ■ | | Urban stormwater infrastructure |
| | | Green spaces (bioretention and infiltration) | | | ■ | | |
| | | Water harvesting | ■ | ■ | ■ | | |
| | | Permeable pavements | | | ■ | | |
| | Coastal flood (storm control) | Protecting/restoring mangroves, coastal marshes, and sand dunes | | | | ■ | Sea walls |
| | | Protecting/restoring reefs (coral/oyster) | | | | ■ | |

Source: UNEP (2014)

grazing, land-use change, water withdrawal, and pollutant overload (Galatowitsch 2018; Mitsch 2005). The conversion and restoration measures and pollutant control measures that are tied to climate change mitigation may require trade-offs with many of the aspects that have replaced and degraded the wetlands in the first place. In many countries, development is often centred on economic growth along with infrastructure development intended to facilitate growth, and other values are not given a similar priority especially if they are seen to be conflicting. Without the economic values of ecosystem services provided by mitigation measures being considered more commonly, implementing freshwater-based mitigation measures might be perceived as requiring major trade-offs with economic and infrastructural growth (Mauroner et al. 2021; Rozenberg and Fay 2019; World Bank 2012). For example, increasing water flow to a degraded wetland or floodplain for restoration purposes might compete with irrigation water for agriculture (de Groot et al. 2008). Some of the trade-offs and competing interests in implementing freshwater-based mitigation measures are listed below.

- **Trade-offs among the ecosystem services themselves**: As discussed in section 5.2, freshwater-based mitigation measures deliver a wide range of ecosystem services. But many wetlands in the world are valued and utilized mainly for their provisioning services, including food, water, timber, and other products useful to surrounding communities as opposed to the wider spectrum of benefits. The importance of supporting and regulating services can be overlooked by decision-makers, although these services are essential in strengthening the provisioning services received, not just from the wetlands but from the other elements in the ecosystem (such as forests and biodiversity). Mitigation measures, emphasizing the protection and restoration of a healthy ecological state for wetlands, should help support calls to minimize the overexploitation of wetlands, which might seem like a trade-off with how the wetland has been traditionally utilized (Mandishona and Knight, 2022).

- **Trade-offs between floodplain protection and agriculture:** Encroachment of agricultural land into riverine floodplains is common around the world (Pullanikkatil et al. 2020; Verhoeven and Setter, 2010). Protection, restoration, and expansion of floodplain wetlands for climate change mitigation, even with their benefits in sediment retention, water quality improvement, and pollutant control, stand as a trade-off with agricultural expansion, which is critical for present and future food security. Nonetheless, when floodplain wetlands are drained and degraded, their potential to deliver regulating and supporting ecosystem services becomes limited, which might

Migratory birds stop off at the Agamon Hula wetland in north Israel. Source: Shutterstock.

affect agricultural provisioning services. A study conducted on the Hula Wetland in Israel illustrates how degraded wetland conditions can result in declining agricultural production over time (Cohen-Shacham et al. 2011).

- **Trade-offs in urban floodplain restoration:** Floodplains in urban areas are often converted into human settlements, industrial settlements, and recreational facilities, especially since many floodplains have been disconnected from their rivers. Hence, mitigation measures that entail connecting rivers with floodplains and restoration of floodplains can be seen as having trade-offs with the interests of an urban population. Conflict of interest among stakeholders can be minimized if the NbS offered by the mitigation measures can be factored into the cost-benefit analysis and a multifunctional floodplain management approach can be adopted (Jakubínský et al. 2021; Sanon et al. 2012).

- **Trade-offs with community practices and local land-use:** Implementation of mitigation measures might conflict with cultural and social practices. If local communities and stakeholders are not involved fully in communication and collaboration, based upon the principles of free, prior and informed consent, implementation of mitigation measures is likely to meet resistance. Conservation can also limit access to the freshwater ecosystem and its services for indigenous peoples and local communities. This conflict of interests can be minimized by effective communication, education, inclusion, and multisectoral collaboration (Boughton et al. 2019; Dahlberg and Burlando 2009).

- **Trade-offs between wetland restoration and biodiversity:** Factors influencing freshwater-based mitigation measures include nutrient cycling and control, soil organic matter, biomass, decomposition rates, and potential denitrification (section 5.2). But restoring wetlands for carbon and nutrient storage and removal might not be favourable for biodiversity in all cases. In fact, it should not be expected that all ecosystem services would be maximized at a restoration site (Jessop et al. 2015; Peralta et al. 2017). A study conducted on a restored wetland in the USA suggested sites with less biodiversity had greater soil organic matter, biomass, decomposition rates, and denitrification potential (Jessop et al. 2015).

## 5.4 Policy status

Many countries in the world have policies to address the conservation, restoration, or management of wetlands, but less attention has been paid to other aquatic ecosystems. There are international agreements (e.g., treaties, conventions, and protocols) in place to ensure shared understanding of sustainable management of wetlands and to shape actions that can protect the wetlands and the ecosystems surrounding them. The Ramsar Convention on Wetlands of International Importance especially as Waterfowl Habitat, commonly known as the Ramsar Convention on Wetlands, is the longest established intergovernmental environmental agreement and the most relevant to wetlands internationally with 172 parties (nations or states) as signatories as of 2023 (Ramsar Convention 2016, Ramsar Convention 2023). According to the Ramsar Convention definition of wetlands, all freshwater ecosystems (including rivers, streams, lakes, reservoirs, etc.) are wetlands. This section discusses how freshwater-focused climate mitigation measures have been included in the Ramsar Convention and some countries' national policies.

### 5.4.1 Ramsar Convention on Wetlands of International Importance

As a multilateral environmental agreement, the Ramsar Convention provides a framework for national action and international cooperation on the conservation and wise use of wetlands and their resources (Finlayson 2012). Initially, the Ramsar Convention had its emphasis on the conservation and wise use of wetlands as a habitat for waterbirds (Ramsar Convention 2005). (Wise use of wetlands is the maintenance of their ecological character, achieved through the implementation of ecosystem approaches within the context of sustainable development.) The Convention has broadened its scope of implementation over the years, now addressing wise water use for enhanced ecosystem services, sustainable development, and biodiversity conservation, in addition to wetland conservation (Ramsar Convention 2016). While the ecosystem services provided by wetlands have been repeatedly addressed in the convention, the role of wetlands in climate regulation was highlighted much later in the process. Until 2008, the Ramsar Convention strategic plans did not address the importance of wetlands as carbon sinks (Ramsar Convention

1996). The Briefing Note 4 provided by the Ramsar Convention in 2012 acknowledged carbon sequestration as one of the key benefits of wetland restoration and the Ramsar Strategic Plan 2009–2015 emphasized the role of wetlands in climate change mitigation (Ramsar Convention 2008; Ramsar Convention 2012). Whether or not wetland-based climate mitigation was highlighted, the Ramsar Convention emphasis on wetland conservation and restoration throughout the years can be considered as an indirect but effective measure in supporting the role of wetlands in climate change mitigation.

In the latest strategic plan (Resolution XII.2: The Ramsar Strategic Plan 2016–2024), the Ramsar Convention mentioned restoration of wetlands for their role in climate change mitigation and adaptation as one of the targets to achieve the strategic goal of wise use of all wetlands (Ramsar Convention Secretariat, 2015). In Briefing Note 10, published in 2018, the wise use and restoration of wetlands is identified as "essential to protect stored carbon and reduce avoidable carbon emissions" (Ramsar Convention Secretariat, 2018). In the latest two Global Wetland Outlook reports (published in 2018 and 2021), the importance of wetland conservation and restoration for climate change mitigation, mostly in peatlands and coastal 'blue carbon' ecosystems, was highlighted. The Ramsar Convention provides detailed guidelines on the management and restoration of both peatlands and 'blue carbon' systems to enhance their climate mitigation potential (Ramsar Convention 2018; Ramsar Convention 2021).

Wetland conservation and restoration are essential to utilize their potential in climate change mitigation. For example, drained peatlands stop sequestering carbon and lose previously stored carbon through decomposition processes for a long period of time resulting in GHG emissions. Rewetting or restoring wetlands, particularly peatlands, can significantly reduce $CO_2$ emissions (also other GHGs) and may reinitiate carbon sequestration, but rewetted peatlands might not return to the undisturbed natural conditions that allow high climate mitigation potential even within decades. Hence, conservation of these wetlands is to be prioritized to avoid additional emissions, and restoration is to be prioritized to reduce emissions and enhance carbon sequestration (Kreyling et al. 2021; Günther et al. 2020; Joosten 2015). For years, the Ramsar Convention's efforts in global wetland conservation and restoration played a big role in protecting the carbon pools in wetlands. Although Ramsar identifies rivers, streams, lakes, and reservoirs as wetlands, there are no obvious guidelines to minimize emissions from these systems.

## 5.4.2 National policies

National-level policies on wetlands have the capacity to outline goals related to wetland management, timelines for achievement of those goals, roles and responsibilities of various actors, and budget commitments (Gardner 2018b). The Ramsar Convention recommends that parties develop national wetland policies to implement the Convention at national and regional levels (Ramsar Convention Secretariat 2015; Ramsar Convention Secretariat 2010; Bonells 2018). While some countries have wetland-specific national policies, others include wetland-related policies under broader environmental policies or land-use and water-use policies. Peimer et al. (2017) examined wetlands policies in 193 countries and found that only 9 per cent have an existing wetland-specific policy; 38 per cent have a broad environmental policy or law that includes wetlands; 18 per cent have a wetland policy in development; and 23 per cent have no national-level environmental policy or strategy to protect wetlands.

Wetland-specific national policies can be important in protecting and managing wetlands and ensuring they maintain their role in climate change mitigation (Peimer et al. 2017). For example, the adoption of a national wetlands policy in Uganda in the early 1990s paved the way for inclusion of wetlands in many other national policies and eventually included them in Uganda's updated Nationally Determined Contributions (NDC) for 2021–2030. The updated NDC includes wetlands under one of the key sectors of agriculture, forestry, and other land-use for mitigation (Mafabi 2018; Ministry of Water and Environment, Uganda, 2021; also see Chapter 3). This is one of the few examples of wetlands inclusion in the first round of NDCs. Chile also developed a national wetlands strategy in 2005; this enables coordinated and efficient protection of wetlands and aligns with the country's national biodiversity strategy. To achieve one of the objectives of the strategy, the country has created a national wetlands inventory (Suárez-Delucchi 2018). As per Chile's latest NDC updates, the country now considers wetlands in its mitigation strategy (See Box 5.2).


Wetlands restoration project at Libertyville, Illinois, USA. Source: Shutterstock.

In the USA, wetlands are included in several different broad environmental policies, management plans, acts, regulations, and even executive orders. The USA adopted the 'No net loss' policy (a policy also adopted by the European Union) for wetland preservation in 1989 with the goal to balance wetland loss with replacement wetlands, mainly through reclamation, mitigation, and restoration to maintain the total areal coverage of wetlands in the country (Everard 2018a). The policy showed promising results in the initial years, but 62,300 acres of wetland was reported lost from 2004 to 2009 (Smaczniak 2018). One of the key measures of 'No net loss' is wetland offsets, also called compensatory wetlands, which entails creation or restoration of wetlands of at least the same area as that lost (Fennessy and Dresser 2018). As these compensatory/replacement wetlands may be significantly different from the natural wetlands in character and function, their role in climate change mitigation also may vary (BenDor and Riggsbee 2011; Everard 2018b; Fennessy and Dresser 2018; Neubauer and Verhoeven 2019). Neubauer and Verhoeven (2019) maintain that GHG emissions from disturbed wetlands persist long after a wetland is restored or replaced by a mitigation wetland. Hence, from a climate change mitigation perspective, stronger priority should be given to protecting existing natural wetlands (Neubauer and Verhoeven 2019).

Wetland-specific national policies should emphasize wetland conservation, restoration, and wise use. But if nations are considering wetlands for climate change mitigation, this needs to be reflected in their NDCs as well as in national and local policies with quantitative emissions targets. Wetland-related measures should be considered as an integral part of an NDC (Anisha et al. 2020). Box 5.2 illustrates some examples of wetland-centric mitigation measures in NDCs. Inclusion of freshwater-related policies in national-level documents, such as National Adaption Plans, National Biodiversity Strategies and Action Plans, and Integrated Coastal Zone Management can lay the groundwork for NDCs and vice versa in the future.

## Box 5.2. Integration in NDCs

Freshwater and tidal wetlands were included in most of the enhanced NDCs that were prepared in the two years prior to January 2022. Within Annex 1 countries, references to wetlands are mainly noted through recognition within land use, land use change, and forestry category targets, although parties such as Canada and Iceland included actions to restore wetlands as part of their measures. Freshwater ecosystem measures, including protection, rehabilitation, and enhancement activities are more commonly found within updated NDCs from non-Annex 1 parties, including both adaptation and mitigation. In the first round of NDCs, only seven non-Annex 1 parties included measures relating to wetlands, most notably Uganda, and most of these were related to adaptation, although Uganda did include some measures within its mitigation section. Similarly, in the first round, only a few countries, most notably the Bahamas, noted the role of mangrove swamps as a carbon sink and their ecological functions.

In comparison, a total of 65 non-Annex 1 countries (57 per cent), out of 114 non-Annex 1 NDCs released between 2019 and 2022 have included wetland measures in their enhanced NDCs, with a further 4 including wetlands within their inventories. Most of these wetland measures are adaptation priorities, but recognition of the role of wetlands in mitigation or in integrated mitigation and adaptation increased significantly. Approximately 18 non-Annex 1 parties included specific wetlands mitigation measures (16 per cent of the total), and 25 countries included mangrove forests specifically in their mitigation priorities, noted mainly as 'blue carbon' priorities. Of note are measures by the Democratic Republic of the Congo with respect to the important role of peatlands nationally and globally, especially regarding emissions reductions. Measures for wetlands found in mitigation sections were much less detailed when compared with measures found in adaptation sections.

Acknowledgement of the role of mangrove ecosystems in both mitigation and adaptation was much greater in enhanced NDCs compared with previous versions, most notably from Belize and Colombia. Forty-nine countries included mangroves within their respective enhanced NDCs, including close to 62 per cent of those countries hosting mangrove ecosystems, but as above, a smaller number included mangrove measures within their mitigation sections.

The potential role of other water-related ecosystems such as rivers or lakes in mitigation was not directly found in any enhanced NDCs, despite recent research suggesting that overly degraded systems may be a strong source of emissions. However, water pollution through inadequate wastewater management, and its impact on freshwater ecosystems and their capacity to provide ecosystem services, was noted in many adaptation sections, and was much more prominent compared with the first round of NDCs.

Examples of mitigation measures include:

- **Belize:** Enhance the capacity of the country's mangrove and seagrass ecosystems to act as a carbon sink by 2030, through increased protection of mangroves and by removing a cumulative total of 381 kilotons of $CO_2$ equivalent (Kt $CO_2$-e) between 2021 and 2030 through mangrove restoration.

- **Sierra Leone:** Organic manure to reduce fertilizer use that has the tendency of depleting soil fertility and polluting wetlands.

- **South Sudan:** Conservation and sustainable use of wetlands for improved carbon sequestration. South Sudan will collaborate with international research institutes and agencies to conduct research on the release of methane emissions from the Sudd wetland and develop measures to sustainably manage and mitigate high emissions coming from the country's wetlands.

- **Uganda**: The measure aims to increase wetland coverage from 8.9 per cent in 2020 to 9.57 per cent in 2025, and approximately 12 per cent by 2030 through the implementation of wetland management practices such as demarcation, gazettement, and restoration of degraded wetlands. The mitigation reduction potential for this measure is expected to account for 0.4 Mt $CO_2$-e by 2030.

Background to the NDCs is found in Chapter 3.

Source: UNDP-SIWI Water Governance Facility (2023).

# 5.5 Potential implications for governance

## 5.5.1 Inclusion in national policies

Section 5.4.2 illustrates the importance of having national policies on wetlands to promote wetland-focused climate change mitigation measures. Uganda and Chile (cases mentioned previously in this chapter) demonstrate a clear example of this. Wetland-specific national policies should emphasize wetland conservation, restoration, and wise use. But whether or not nations are considering wetlands or other freshwater ecosystems for climate change mitigation is reflected in their NDCs. Freshwater-related mitigation measures should be considered as an integral part of NDCs (Anisha et al. 2020). However, inclusion of freshwater-related policies in national-level documents, such as National Adaption Plans, National Biodiversity Strategies and Action Plans, and Integrated Coastal Zone Management can lay the groundwork for NDCs.

## 5.5.2 Systems-level approach

Many of the mitigation measures outlined in section 5.2 are applicable to freshwater ecosystems. For example, nutrient control benefits rivers, lakes, reservoirs, and other wetlands for climate change mitigation, as GHG production in aquatic systems is fuelled mainly by inputs from the watershed. Effective emissions reduction strategies should entail coordinated approaches for land management, restricting nutrient loading, and maintaining and improving ecohydrological connections. Inland water bodies constantly interact with other components of the ecosystem (vegetation, landform, biodiversity, and humans) and among themselves through subsurface flow, groundwater flow, ecohydrological connectivity, and sediment and organic matter exchange. Hence, mitigation benefits cannot be sustainably materialized if the activities are undertaken in isolation. System-level approaches on a local, sub-regional, or regional level can minimize the potential trade-offs among different interests. This requires inter-sectoral coordination and policy synergies. Management and planning ought to consider the different scales at which socio-ecological systems might interact with freshwater ecosystems and make sure the dynamics are sustainable.

## 5.5.3 Implications of future climate change

Climate change is predicted to affect freshwater ecosystems, but floodplain ecosystems and well-managed wetlands, even those in a low-diversity state, are likely to persist under climate change and provide adaptation services (Lavorel et al. 2015). In fact, many areas with large water bodies have persisted through the climatic changes of the Holocene, proving their resilience (Morelli et al. 2016). It is uncertain though, whether the freshwater ecosystems would persist with the same characteristics that enable them to sequester carbon over long periods of time (Sutfin et al. 2016; Yan et al. 2021). For example, higher rainfall due to climate change will increase flushing and delivery of soil and riparian/wetland carbon to streams and rivers, resulting in higher GHG emissions. Peatlands will release more carbon if drought conditions prevail. Tidal wetlands will be affected by sea-level rise. Hence, planning should not be based on historic or present trends but should take future climate change scenarios into consideration. Developing an understanding of how ecosystems might transform under climate change can assist in adopting measures that can be adapted as conditions change.

## 5.5.4 Implication of socio-economic change

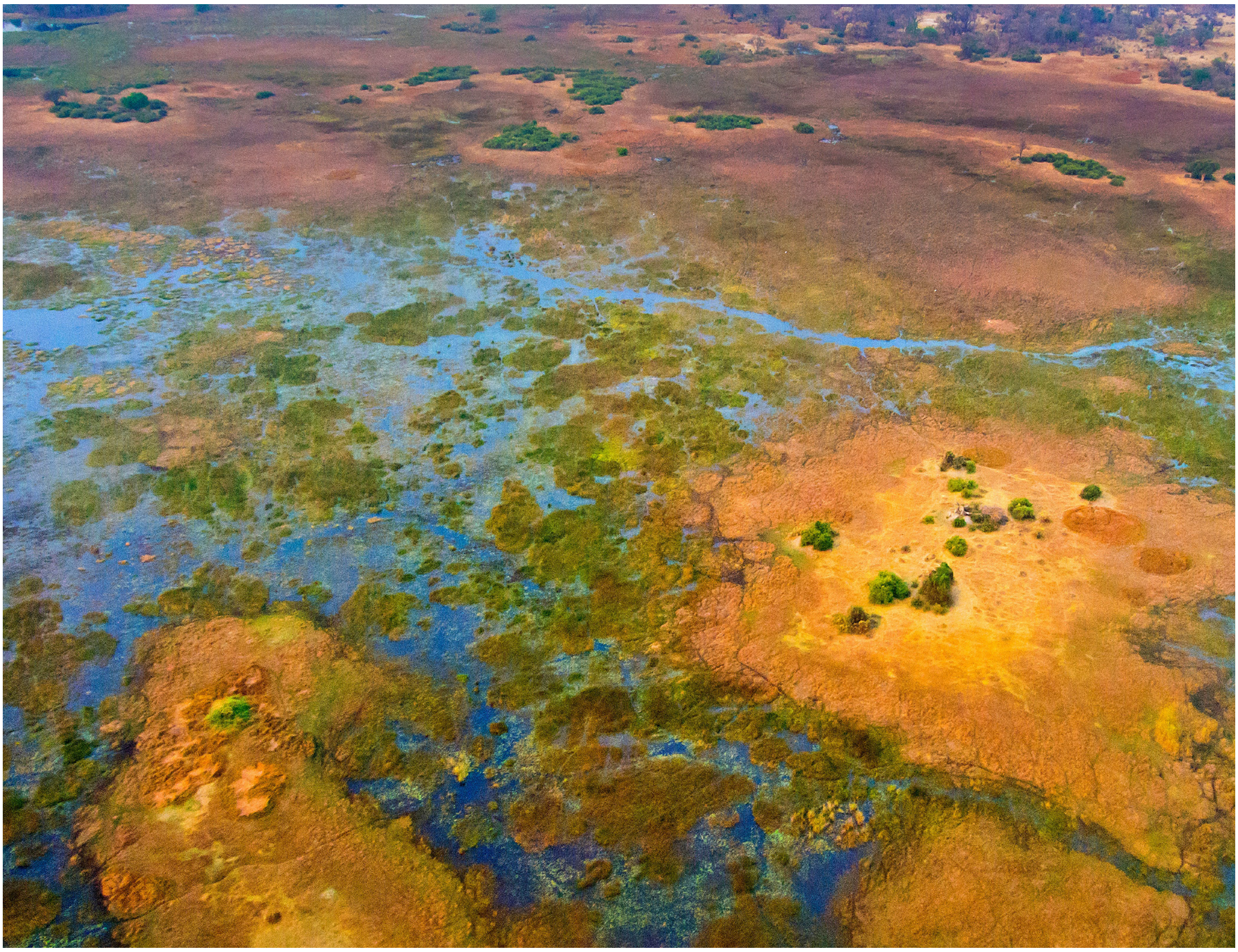
As discussed in section 5.2, anthropogenic activities have disturbed the carbon pool in freshwater ecosystems and increased GHG emissions, and probably will continue to do so. For example, societal choices will determine the future total nitrogen loading in a freshwater ecosystem. The future global population and its socio-economic choices will determine global demand for food and agriculture, bioenergy, assumptions about trade, and assumptions about agricultural management practices, which will eventually determine the total nitrogen loading in freshwater ecosystems, although practices might vary regionally (Sinha et al. 2019). The planning and management of freshwater-based mitigation measures should consider these socio-economic changes for successful implementation.

## 5.6 Conclusions and outlook

Historically, the climate change mitigation potential of freshwater ecosystems has been highly underrated. Although freshwater marshes, swamps, and peatlands have been included regularly in recent discussions (but not yet sufficiently), the management of rivers, lakes, and reservoirs is still not reflected in important national policies (e.g. NDCs). Freshwater ecosystems have generally been considered as carbon neutral or carbon sinks, which is true for most of these ecosystems before being exposed to anthropogenic disturbances. However, freshwater ecosystems in most parts of the world have been subjected to some kind of disturbance, which imposes a risk of those systems becoming net sources of GHG emissions. Every signatory party under the Paris Agreement has some potential to include freshwater-based mitigation targets in their NDCs and it is essential that inclusion of freshwater ecosystems is mainstreamed.

Freshwater ecosystems also need to be included within GHG inventories. To achieve this, global datasets and reporting methods for freshwater ecosystem health and coverage should be strengthened through both policies and financing mechanisms. In particular, countries need to be incentivized to develop robust inventories of aquatic ecosystems that can be used to safeguard biodiversity and ecosystem services, including the mitigation of GHG emissions. It is also critical to facilitate the development of measurement technologies, especially in contexts where conventional measurement techniques cannot be used, to acquire standardized global data sets targeting long-term, continuous, large-scale data that can be measured simply and at low cost.

For successful water-wise climate mitigation in freshwater ecosystems, governance across all levels needs to be strengthened. Possibilities to align the NDCs with other policies, such as National Adaption Plans, National Biodiversity Strategies and Action Plans, and Integrated Coastal Zone Management, should be explored.



Okavango Delta, a UNESCO World Heritage Site and Ramsar Site, Botswana, Africa. Source: Shutterstock.

## 5.7 References

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