8 Hydrology of Flooded and Wetland Forests

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Abstract
Flooded or wetland forests are commonly continuously inundated for many months. Trees that can survive this have specialized mechanisms for allowing roots to respire. The forests can be classified by the source of the water causing inundation – rainfall, groundwater, flow from an adjacent watercourse or tidal inundation. The latter may include specialized vegetation at the ocean salt/freshwater interface known as 'mangroves'. These seem to require some input of freshwater, although the mechanism of how this assists their survival is unclear. The hydroperiod is the usual annual period for which a forest is inundated. Flooded forests usually contain a range of vegetation aligned to the hydroperiod of specific sites. Flooding of the forests gives them an unusual, distinctive and highly valued character, both in the vegetation and the associated fauna. Often, these forests have large accumulations of carbon in anoxic soils. Many flooded forests are under some sort of threat relating to changes in their inundation due to the value of water for other uses. The resulting problems may be difficult to resolve and require compromise to achieve resolution. The advent of climate change and the impacts of this on rainfall in large catchments pose a particularly serious threat to the long-term survival of this group of forests around the world. Oxidation of dried-out 'wetland soils' can be a major source of greenhouse gases.

8.1 Introduction

In this chapter, we examine the hydrology of forested areas that are subject to prolonged soil saturation by precipitation, groundwater or surface flooding. These include flood-plain forests, estuarine tidal forests, mangrove forests, the forested portions of peatlands and the tree-dominated wetlands defined by the Ramsar Convention on Wetlands (www.ramsar.org, accessed 18 April 2025). A broad outline of the ecology of all wetlands has been described by Mitsch and Gosselink (2015). Forested wetlands are a subset of this all-embracing term and generally lack the flooding extremes of wetlands. Trees found in these regions commonly share with other wetland plants a metabolism that allows translocation of oxygen through stem tissues to the roots, thereby facilitating root respiration (Kozlowski, 2002). This may involve specialized tissue development. Fig. 8.1 gives a view of one such area in an Australian flooded river red gum (*Eucalyptus camaldulensis*) forest.

As most forest species (except certain mangroves) cannot regenerate under continuous flooding (Lugo, 1988), the wet limit of forested wetlands requires at least periodic drying of the

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Fig. 8.1. View of an Australian flooding forest. This shows young river red gum invading a 'grass plain' (although the ground species is mainly water milfoil, *Myriophyllum* spp.).

soil surface. How wet a soil has to be to be classed as a 'wetland' is ambiguous but is generally associated with soil saturation that is of sufficient duration to produce visible soil features (creating a 'hydric soil') and to limit the growth of plants not specially adapted to saturated soils. This is of importance in conservation because it restricts weed invasion, as many weeds cannot tolerate prolonged inundation. Around the world, the local definition of 'wetlands' commonly involves an interplay of science, economics, and local and national politics. The terminology can be context dependent, ambiguous and often unsatisfactory to apply to areas outside of where the definition was formulated. We have used the term 'flooded forests' or 'forested wetlands' interchangeably. Terms such as mires, fens, swamps, bogs or marshes are often ambiguous as to whether the presence of trees or forests is implied.

The most common model of a flooding (freshwater) forest is one of forest on a flood plain. The streams carry silt and, over time, this causes the river bed to rise above the adjoining plain. The river may also form natural 'levees' – walls that constrain flow in the channel; sometimes these are 'improved' by human activity to bring them to a constant river level. Periodically, an excess of water may flow down the channel and cause the water to overtop these levees or to pass through gaps ('crevasses') in them. This allows flooding from the river into the forest. Often, this leads to deep groundwater recharge on the flood plain. The origin of this water is from streamflow derived by storms upstream. Usually, once the water has left the river channel, it flows through the forest (sometimes designated a 'flowing wetland'). The water quality tends to reflect the water quality of the source river. Because forests

are hydraulically rough, the water slows down compared with its velocity in open channels. This causes deposition of sediment, and many flooded forests are 'rising' topographically because of this. Sooner or later, the source of water diminishes, and the water 'dries up' – this can be due to a reduction in river levels, water flowing offsite, perhaps infiltration to deeper aquifers and evapotranspiration. In some cases, the soil surface may be below saturation but at a matric potential close to that of free water. In such cases, it is common to find a 'water table' (phreatic surface) not far below the land surface. The term 'saturation' implies no air in the soil matrix, implying that the matric potential, Ψ, is below the 'air entry' value for that soil. Rawls *et al.* (1982) listed geometric values of Ψ from 7.3 cm (sand) to 36.5 cm (clay). The Rawls *et al.* (1982) criterion may be a reasonable methodology for defining 'saturated'.

The period of time for which the forests may reasonably be expected to be flooded (on a mean annual basis) is called the 'hydroperiod', and for most flooded forests might reasonably be expected to be in the 3–9 month range, given the usual annual seasonal behaviour. Forests at the low end of the range are sometimes called 'riparian forests' in which the trees can tolerate flooding but do not acquire special adaptations to cope with prolonged inundation (Meixner *et al.*, 2006). Flooded forests may also have a high 'frequency of flooding'. This term is vague but implies the number of times the forest might be expected to have separate flooding events (with a drying out period interposed between flooding) in each year. Such terminology is useful but can also be ambiguous (i.e.a forest may have a substantial number of flooding events in a given year, but if each is of a short duration, then the hydroperiod may not be long). A useful first task in any quantification of a flooded forest is to define the hydroperiod and the flooding frequency as best one can.

Flooding has a number of effects. First, it provides the forests with an inflow of water and nutrients (both dissolved and attached to sediment); in some cases (e.g.Australian red gum forests; see below), the water complements the inadequate local rainfall. Without this, the trees survive but have little growth; with flooding, there is an immediate flush of growth. Second, it gives plants with the ability of surviving long periods of inundation an advantage on such sites by excluding those less able. Third, it creates a diverse range of environments that foster 'life' – in terms of both flora and fauna. Flooded forests commonly have specialized flora and fauna occupying a diverse range of habitats. These are greatly valued on ecological and economic grounds.

8.2 the Origins of Flood Water

A useful (but not always easy) classification is based on the origin of the water causing inundation.

8.2.1 Precipitation-excess wetlands

Precipitation-excess wetlands are found in moist climatic regions and occur where precipitation is greater than transpiration. Annual precipitation is likely to equal or exceed annual evapotranspiration and precipitation must exceed evapotranspiration for a significant portion of the year for wetland conditions to occur. Restricted surface and/or subsurface drainage are commonly present. These wetlands generally have shallow surface drainage (if any). In many cases, these wetlands are found in relatively young geological formations where mature drainage patterns have not yet developed. Groundwater flows are restricted vertically by a confining layer or, in the horizontal plane, by a lack of slope and/or low hydraulic conductivity of the media. Brinson (1993) classed these wetlands as 'mineral' or 'organic' flats, while Semeniuk and Semeniuk (1995) called them 'damplands', and Tiner (2017) called them 'seasonally variable wetlands'. Emphasis should be put on their 'seasonal' nature because they may have (very) long periods of dry land between inundation. Because of their dependence on recent rainfall, they can be very ephemeral.

These are the only possible wetlands on topographic convex surfaces at watershed divides. In the bog–fen terminology, all bogs are rainwater wetlands. These wetlands must be convex enough and high enough in the landscape such that groundwater and surface water leave the site. Rainwater wetlands are most

sensitive to climate and management. Forest species, density and age all alter the transpiration component. Ditching draining, bedding, burning, road construction or any other soil alteration will alter the runoff component. This means that their hydrology can be inadvertently changed but also creates opportunities for hydrological modification to improve suitability for selected species (Amatya *et al.*, 2024).

Although examples of these can be found all over the world, the greatest extent is found in the northern hemisphere, including north-eastern and north-central USA, eastern and most of northern Canada, north-eastern Europe, Fennoscandia, and Russia in Eurasia. Common tree species are pines (*Pinus* spp.) or birch (*Betul*a spp.) in Eurasia, and spruce (*Picea mariana*), larch (*Larix laricina*) and birch in North America. Sometimes, these are called by the generic term 'mires', and a distinction is made between bogs (precipitation fed) and fens (groundwater fed). Among others, Payette and Delwaide (2003) showed that boreal forests at high latitudes are climate-sensitive ecosystems that respond directly to environmental forcing by changing their boundaries (retreating/advancing) and/or altering their abundance at local and regional scales. Fires and excessive inundation have caused events such as mass mortality of the forests and post-fire deforestation. They noted that 'future moisture changes … will result in important rearrangements of wetland ecosystems'.

In some glaciated landscapes, a distinction can be made in undisturbed peat bogs between the 'acrotelm' and the 'catotelm'; the former overlies the latter. The boundary between the two layers is defined by the transition from peat containing living plants (acrotelm) to peat consisting of dead plant material (catotelm). This typically coincides with the lowest level of the water table (i.e.the catotelm is the zone of permanent inundation). Trees may be a component of the acrotelm, with roots penetrating into the catotelm in forested peatlands – in such cases, the trees may have physiological adaptations to allow respiration of the roots.

The southern hemisphere lacks large areas of land at high (southern) latitudes, so there is very limited development of such forest on glaciated landscapes. It does, however, have large areas of precipitation-excess wetland forest developed on tropical peatland, particularly in Borneo and New Guinea. Wösten *et al.* (2008) found such an area with a 10 year average annual rainfall of 2570 mm and an estimated evapotranspiration of 1500 mm. They also found large variations in the rainfall range (1848–3749 mm); a practical consequence is that such forests may suffer substantially from annual drought and become fire prone during such times. Such tropical swamp forests are commonly sought after for competitive uses, particularly oil palm plantation development. This has been controversial.

8.2.2 Groundwater-fed forested wetlands

Occasionally, a substantial groundwater aquifer will pass water into an adjacent wetland area; commonly this would be where a permeable hillside adjoins a flood plain or a large old lake has filled with sediment and developed forest. In such a case, the contribution of the hillslope can be substantial and prolonged, and can keep the forest supplied with water in excess of its transpiration capacity for substantial periods. Waddington *et al.* (1993) gave a detailed description of one such area in Toronto, Canada. The 'swamp' consisted of fluvio-glacial wash overlaid by peat soils. The forest consisted of cedars (*Thuja occidentalis*) and hemlock (*Tsuga* spp). Groundwater entered the wetland through a series of springs at the margin of the wetland, creating many diffuse, saturated zones that joined together to form small streamlets. Chemical separation of groundwater contribution from the rainwater composition suggested that 70% of the runoff was 'pre-event' water (i.e.groundwater).

Groundwater outflows are stable for long periods, but such wetlands can be subject to offsite influences relating to groundwater drawdown (pumping), drainage or a change in recharge of the aquifer. Such change can occur many kilometres away from the wetland and can be hard to recognize. Simon *et al.* (2023) discussed such a case in Hungary in which a poplar wetland deteriorated. Similar issues were cited by van Deventer *et al.* (2021) in South Africa and by Durigan *et al.* (2022) in Brazil; in

both of these cases, the authors felt that existing environmental legislation was inadequate to recognize the threats to the forested wetlands and to counter the observed changes.

8.2.3 Forested wetlands due to surplus surface water flow

In these, the combination of rainfall plus water from adjacent sources (particularly rivers or lakes) exceeds (or in Australia, helps to meet) the evapotranspiration needs of the trees. These wetlands are sometimes called 'fringing forests' because they fringe a lake or river, although this 'fringe' may extend many tens of kilometres from the water source. Riverine forested wetlands are the 'prototype' forest described in Section 8.1, Often such forests are of great economic benefit and have large, ecosystem-dependent communities living in or near them. A common hydrological variation is that a major river receives flow from high rainfall mountains and passes through an incised channel to an alluvial plain of lower rainfall. On this plain, the incised channel may give way to a braided channel with complex branching and interconnections. Sometimes, the channel braiding is the outcome of a sediment-filled lake bed forming. This develops a forest cover with an intricate mosaic of waterways, giving a wide diversity of hydroperiods and vegetation types. Such areas can be greatly valued for their biological diversity (e.g. the Okavango Delta in north-western Botswana, and the Achafalyala Delta in the USA).

8.3 Three Continents and Three Examples of Flooded Forests

Flooded forests are found around the world. Three brief examples illustrating this are given here. In each case, management of the forests involves an interplay of state and federal politics involving considerations other than the hydrological well-being of the resource. Although differing in location and tree characteristics, the areas share the feeling of being in a flooded forest – with the smell of water-saturated landscapes and unusual species (of flora and fauna) never being far away. In each case, there can be long periods without flooding, in which case the forest becomes the more common 'dryland' variant – and this can go on for many months. Readers are encouraged to extend the examples here – there are many that have achieved international fame because of their uniqueness and/or distinctiveness in form or landscape. Other areas are hardly recognized as flooded forests because they are 'taken for granted'.

In each of the cases below, the forests have their own benefits in terms of forest products and biodiversity. They also serve as large, transient water storages. These reduce peak flows in the river and protect towns along the river from flooding. Readers are encouraged to view videos extolling how the biodiversity of these forests 'comes alive' on media such as YouTube. Although this is miraculous in itself, the really important factor is that of adding water. All else is a consequence of that.

8.3.1 The red gum forests of the River Murray in Australia

In economic terms, the River Murray is Australia's most important river. It starts in the well-watered hills and mountains of eastern Australia and flows west and then south to enter the sea near Adelaide (South Australia). A ubiquitous tree found close to the river is river red gum (*E. camaldulensis*). At many locations, it forms extensive forests, of which the Barmah-Millewa Forest (straddling the New South Wales/Victoria state border) is the best known.

In most of these flooded forests, river red gum is the only woody species; other vegetation comprises grasses or reeds. These forests have a hydroperiod of 4–6 months. Typically, annual rainfall in these areas is around 400 mm. The tree is thought to transpire about 1100 mm/year if the water is available. The annual flooding provides the balance of water between the annual rainfall and the trees' needs. If this does not occur, then the tree is reduced to a dryland state. When the forest floods, it 'comes alive' – the crowns dramatically expand and change colour from a greenish-yellow to a dark green, and the trees actively grow. This change is accompanied by major bird-breeding events and a vast

increase in faunal activity (tortoises, kangaroos and echidnas are commonly encountered).

The forests have a long history of sustaining indigenous people. More latterly, the forests sustained a substantial timber industry supplying heavy timber used in construction. The higher flood frequency areas have traditionally been too wet to sustain river red gum. However, changes in the last six decades associated with irrigation water use have made these areas flood less frequently. The result is that river red gum is 'invading' these grass plains, changing the 'character' of the area, as discussed by Bren (1992) and Colloff (2014), and is viewed by many as a major and undesirable floral change.

River red gum is Australia's most widespread eucalypt and is found in both dry and wet sites. It is also widely planted around the world in industrial plantations. These take advantage of the ability of the tree to survive both prolonged flooding and prolonged drought. Extensive genetic work using Australian red gum as a 'base' (e.g.Butcher *et al.*, 2009) have shown that there is a wide genetic variation in the species, reflecting its provenance.

8.3.2 The swamp cypress forests of the Lower Mississippi River, USA

Bald cypress (*Taxodium distichum*) forests once dominated the swamps of the Lower Mississippi River, but today only small areas remain, of which the Atchafalaya Delta is a major area. In general, the tree occurs on seasonally inundated wetlands with flat topography and humid climates. The tree is deciduous (in winter) and has 'knees' – roots that protrude out of the water. These were once thought to intake oxygen for the roots under anaerobic conditions, but this has been shown not to be the case. They are often found in association with 'tupelo' (*Nyssa* spp.). Even a brief Internet perusal will show the value of the forests for a diversity of food stuffs and the distinctive Cajun cooking style based on these. The misty forests with towering, shapely trees festooned with moss also attract artists and photographers.

The Atchafalaya Delta is an alternative course of the Mississippi River and includes large areas of flooded forest (see Piazza, 2014, for a full account). The area is a maze of forested wetlands (and other vegetation) growing on ever-changing deposition and erosion features. The main course of this river is of huge importance for navigation and water supply, and the high energy of this system combined with engineering projects to maintain non-forest values have created a huge diversity of habitats (and many management conundrums). Much effort has been put into stopping main river flows from passing down the Atchafalaya River to the sea; this makes a definition of the 'natural flow regime' a tenuous task. Threats include salinity from channel construction to the ocean, channel instability (and the possibility of the main river spontaneously 'jumping' to an alternative course to the ocean), diversions of river flow to ameliorate flooding, and penetration of sea water into freshwater environments associated with oil drilling.

The flooding serves to exclude invasive species and create a 'unique environment'. Unlike the red gum forests above, the rainfall is high enough for the trees to thrive without flooding. It is almost impossible to overstate the importance of these 'forests'.

8.3.3 The willow forests of the Danube River, Europe

The Danube River has a length of 800 km and crosses 15 countries from its origins in southern Germany to its confluence with the Black Sea (Hein *et al.*, 2016). The forests have a rich diversity, including willows, poplars, oak, ash, hornbeam, lime, elms and maple. The forests are well suited to the Danube's frequent flooding, with flexible branches and roots that help stabilize riverbanks and withstand strong winds and strong current. The flood plain of the Danube is dynamic, with sediment deposition establishing new areas. The stages of this development series lead from herbaceous vegetation on freshly created pioneer areas to a phase with willow bushes to the establishment of the first wetland forest trees and the so-called 'softwood riparian forest'.

Mölder and Schneider (2011) examined the composition of Danubian hardwood

flood-plain forests and found that the distribution of forest types was quite stable, but there was much greater diversity in the understorey herb-layer vegetation along the river. They concluded that there was a 'remarkable congruence between the results of their flood-plain vegetation analysis and the longitudinal river eutrophication patterns'. Thus, with increasing distance downstream, the river had higher nutrient concentrations, and this promoted the growth of taller forbs, which outcompeted other plant species. They concluded that anthropogenic eutrophication is a factor in the growth of the Danubian hardwood flood-plain forests.

As in the two previous examples, the ability of the channel to carry navigation is of national importance. Practically, this means many series of locks and dams, and the concept of a 'natural river' has not existed for centuries on this river. The meshing of forest-management needs with river-management needs across international boundaries is a fine balancing act with a strong emphasis on the ability to compromise.

8.4 Common Management Issues of Flooded Forests

8.4.1 Are flooded forests homogeneous ecosystems?

'Flooded forests' may be large areas (>1000 km^2) encompassing a wide range of flooding frequencies and durations. Many studies (e.g.Correa-Araneda *et al.*, 2012) have shown that, given time, the vegetation will order itself to adapt to the diverse environments offered. Thus, some areas may be permanently flooded wetlands; it is unlikely that these will be forested; rather, the flora will be specialized wetland plants (particularly reeds, rushes and some grasses). As the flooding frequency or duration decreases, there will be a range of habitats, which will be occupied by trees or forests. The higher end will be occupied by specialist flood-tolerant species. The lower flood frequencies (often higher in the topography) commonly have trees that can survive a few months of flooding. These may grade into species that can tolerate occasional flooding. Using the term 'flooded forest' usually glosses over many types of vegetation communities (not always forests) found within the forest. There will be a similar gradation of fauna within the forests. Shallow flooding allows animals to splash through the flood waters (e.g.kangaroos, deer), but deeper flooding favours specialized swimming animals (e.g.beavers, otters) or animals that can live in and move through the tree crowns.

8.4.2 River development and flood modification

Forested wetlands along rivers exist in an intimate relationship with the flow of the river. High flows have the energy to push freshwater to distant parts of the forest. In contrast, low flows can usually only inundate areas in direct contact with the river. Rivers are valuable state and national resources. Modifications include the construction of large dams and reservoirs for water supply (domestic and irrigation) and to maintain river flows to allow irrigation and river navigation, and the removal of high flow peaks to avoid flooding of towns and farms. In general, these reduce the peak flows of the river and increase the low flows (in particular, this is often a major aim of the structures). As well as this, the dams will often allow settlement of sediment entering them so that forests are no longer the recipient of the sediment and nutrients that they once were. In some such cases, the water entering the forests may pick up sediment rather than deposit it. The seasonality of river flows may be changed dramatically to meet irrigation requirements.

Such changes have been well documented in the scientific literature (e.g.Day *et al.*, 2012; King and Keim, 2019). Quantification of the changes is an excellent first step, but a more difficult issue is stopping or reversing such changes, as large economic and developmental forces may be at work. Often, large dams and water resource developments can be symbols of national pride and development, and the possibility of a future ecological change in a remote flood-plain forest will not stop the surge of national pride invoked by the developments. Usually, the change

involves collection of inter-related issues. Bargaining points may include the magnitude and timing of flows (within the limits set by the structures), the provision of pumping to get water to distant parts of the forest (expensive but sometimes used), occasional provision of additional water to 'peak' smaller flood freshets, and occasional lowering of river water levels to allow topographically lower forest areas to 'dry out'. In the last few decades, forest managers have become acquainted with the quantitative hydrology of their flooded forests and the economics of river management; this makes them much more potent forces in negotiating better outcomes.

The use of rivers as state or national boundaries gives rise to an unusual set of issues. In the Barmah–Millewa river red gum forests of Australia, the south bank of the River Murray is defined as the boundary between the states of Victoria and New South Wales, with the river flowing more or less through the middle of this large, semi-natural area. A practical consequence is that any 'diversion' of the river water to one side must be matched by a diversion to the other side to maintain parity between the states. The river flows through a (currently but not historically) stable channel in a braided stream network; a river avulsion in a large flow would presumably make a sudden, large change to the boundaries of the two states, with many issues (ecological, economic and social) possibly entailed.

8.4.3 Coming to grips with the hydrology of flooded forests

To deal properly with management needs and/or threats to a flooded forest ideally requires some years of quantifying the hydrology. This is a mixture of gaining experience, assembling available hydrographic data, collecting your own hydrographic and forest data, and somehow assembling the information to give a coherent 'model' of the forest. Each of these can be a difficult task.

The first task is quantifying the source of the water. An excellent first step is mapping the extent of flooding in the forest at a given date. In the past, this was done by observers and, over a period of years, a catalogue of flooding information can be built up (see Bren *et al.*, 1988, for an example of an analysis of 34 maps containing annual and intermediate flood levels). The forest maps should be tied to discrete annual hydrographs if they are to be used in statistical modelling.

Fig. 8.2 is derived from Bren *et al.* (1988) for the Barmah river red gum forests along the River Murray in Australia and shows the percentage of the forest flooded as a function of mean monthly flow in the river (expressed in daily units) during annual periods of active flooding. Among other things, this shows that the forest can be viewed as a 'finite container' – flows of about 90,000 ml/day effectively 'wet' the forest completely. Higher flows do not increase the areal extent of flooding but do increase the depth. This is effectively a 'static model' but was useful in quantifying what changes in river flow levels did mean in annual forest flooding. These showed that river regulation associated with irrigation had decreased the size of forest flooding overall but had also increased the month-to-month variability of flooding. The maintenance of summer-time irrigation flows at a time when the River Murray would have very little flow meant that some areas close to the river were not getting a 'drying period', thereby changing their ecology.

Multi-temporal satellite data and use of personal aerial observation devices has allowed improved mapping of flood dynamics and special distribution of vegetation more effectively (e.g.Martinez and Le Toan, 2007). By combining water level reports with maps of different flood stages, the flooding patterns can be discerned, along with the vegetation succession processes. Martinez and Le Toan (2007) concluded that 'the spatial distribution of vegetation communities is governed by flood stress and can be modelled as a function of the mean annual exposure to floods'.

Ideally, a dynamic model of forest flooding would involve quantification of the following:

1. The relationship between stage height in the water source and flow in the source.
2. The hydraulic properties of points of entry and exit of water into the forests. Most flooded forests have many of these. In some cases, there are 'water gates', levees or other

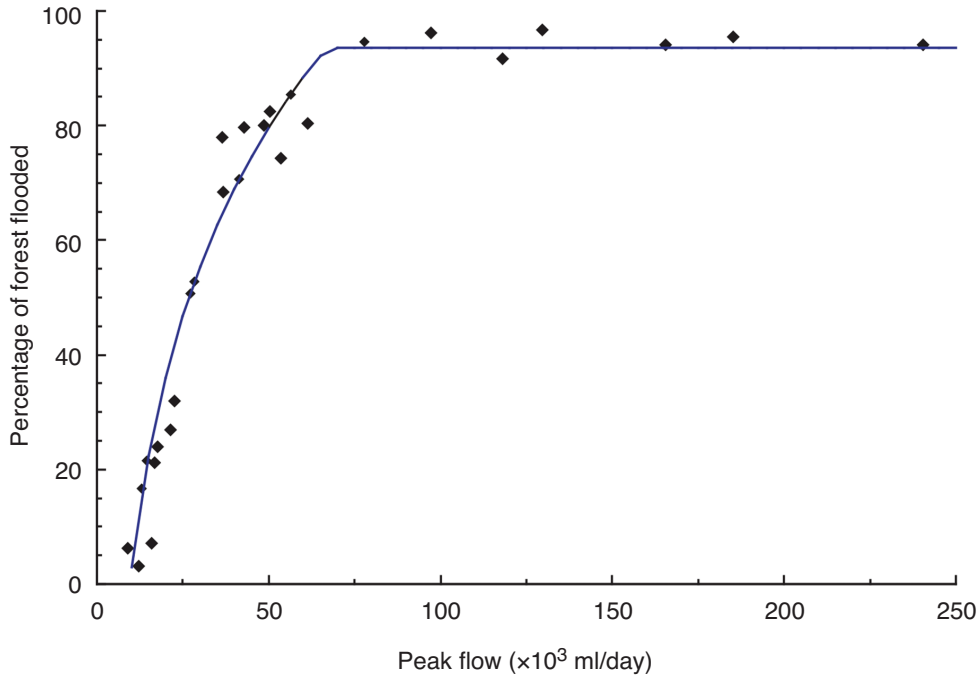

Fig. 8.2. Percentage of the Barmah Forest flooded as a function of the peak daily flow during the flooding period. Modified from Bren *et al*. (1988).

forms of flow control on water entry and exit. Having such water gates set correctly and controlling them (often against locals who 'know better') can be a formidable task.

3. The height of the forest floor relative to the source of water and its variation across the extent of the forest. Modern LiDAR (light detection and ranging) techniques (e.g.Chen *et al.*, 2020) have made this feasible.
4. Hydraulic roughness of flow paths and its variation with water levels at different points of the forest. This is particularly important as flooded forests are not homogeneous entities. For many wetland communities, the hydraulic roughness decreases with increasing depth. The flow paths can be a chaotic maze in a natural flooded forest (Fig. 8.3).
5. Agreement between flooding data and the model. Assessment of this is easier said than done – not the least is the difficulty of movement in a flooded forest.

Such data can provide parameters for a large, spatially based hydraulic model (commonly based on cellular divisions of the flooded area). Once such a model is developed, this can become a trusted tool, allowing examinations of 'what-ifs' and interpretation of the impact on the forest caused by changes in river flow over long periods, in terms of forest growth and biodiversity. Such modelling is good practice in dealing with urban flooding, so there is no reason why it should not be feasible in forest situations. It is, however, a long and expensive exercise in quantification, requires high levels of analytical and modelling skills (and excellent equipment), and dedicated (and long-serving) staff to bring to fruition. The first task is to quantify the impacts of management actions on the hydrological behaviour of the forest. The next step – assessing the impacts on the biological resource – is another demanding area.

At the time of writing, such an approach is feasible in that commercial software capable of modelling is available, LiDAR measurements of floodplains and vegetation is often a routine operation, and there is growing experience in complex flood modelling (particularly in dealing

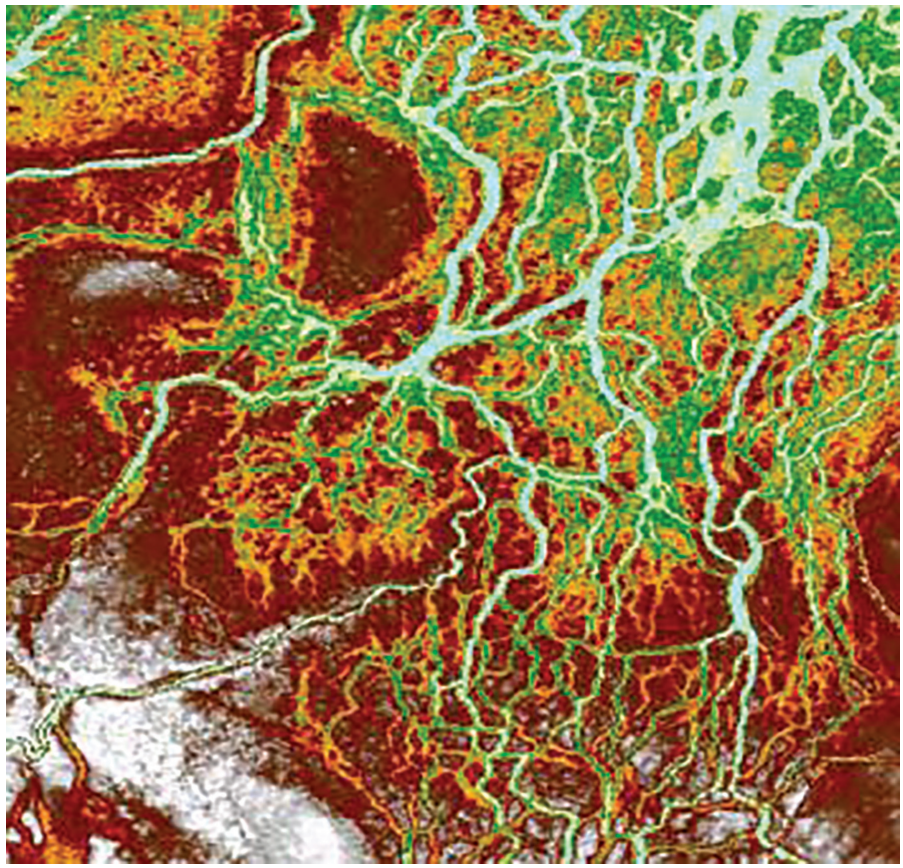

Fig. 8.3. A chaotic maze of flow paths is shown by a LiDAR image in a river red gum forest in Australia. The point of inflow to the forest is at the lower left-hand corner. Image courtesy of Ben Tate of Water Technology Pty Ltd and the Department of Environment and Primary Industry (Victoria, Australia).

with urban flooding). Putting these together could be done by a large, well-resourced forest management operation. This has been viewed as a desirable aim for many years.

The model being espoused here is one in which the forest manager can define the impact of given levels of river water in the associated flow system on their forest, in both the long and short term. As forest control and water control are not usually vested in one organization, the forest manager can approach the water manager with quantitative suggestions on water issues. Ideally, the two organizations would work together to overcome problems for the good of the public. Both will, of course, have many other constraints in achieving some sort of compromise.

8.4.4 Blackwater events

Blackwater is water with a high concentration of dissolved organic carbon (Kerr *et al.*, 2013); characteristically, this gives the water a black appearance, hence the name. A blackwater event is when this water is discharged from a flooded forest into the river mainstream. These commonly occur in lowland flood plains, during flood events. This water may become hypoxic, particularly when combined with high temperatures. This leads to lethal and sublethal effects on aquatic biota. A major tributary of the Amazon River flowing out of the Amazon forest is named the Rio Negro because of the blackness of its water.

The source of the organic carbon is leachate from surface plant litter. This represents an abundant food source for aquatic bacteria. When carbon loads are high, when flooding occurs during periods of high temperature or when floodwaters are pooled for extended periods, the metabolic activity of these bacteria may consume dissolved oxygen at a faster rate than it can be replenished. This results in hypoxia, which may be detrimental to aquatic species. Hypoxic blackwater events occur periodically in streams that are normally well oxygenated and have low to moderate concentrations of dissolved organic carbon (typically <10 mg/L). River regulation may limit forest flooding and lead to an accumulation of organic matter so that when blackwater events occur, they may be more serious than in a less regulated system.

Blackwater events have been well reported in the literature, including in the Atchafalaya River in Louisiana (Fontenot *et al.*, 2001), the Rio Grande catchment of New Mexico (Valett *et al.*, 2005) and Australia (Howitt *et al.*, 2007; Hladyz *et al.*, 2011; Baldwin, 2021). Each of these discharge events was associated with inundation of the forested floodplains. Between flood events, forest litter accumulated on the flood plain and in dry channels. When inundated, carbon compounds were leached from this decomposing litter, contributing dissolved organic carbon to the water column; Kerr *et al.* (2013) has given a fuller description of the various processes involved.

Ultimately, at least some of this water returns to the main channel, particularly in the initial flush of the flooding event. This can lead to death of species less able to tolerate low oxygen levels. In the Australian case, it is quite common for River Murray crayfish (*Euastacus armatus*) to emerge (typically by climbing trees) to avoid the water for substantial periods; this makes them vulnerable to desiccation, exploitation and predation (King *et al.*, 2012). In the the Atchafalaya Delta in the USA, Piazza (2014) showed red swamp crawfish using the same strategy (this time on water hyacinth) to escape anoxic water. A 2023 survey of River Murray crayfish populations (Raymond *et al.*, 2023) suggested a slow recovery from a blackwater episode in 2010. Such events often include difficult judgements as to whether it is a 'natural' event or, somehow, exacerbated by river management. Neville *et al.* (2021) looked at the dynamics of a blackwater stream in North Carolina and concluded that their results highlighted the potential for extreme flooding events to impact biogeochemical processes in large rivers long after flood waters subside. The association of blackwater events and higher temperatures does suggest some management pathways for avoiding these in well-regulated systems. In some forests with a prolonged 'dry period' (e.g.river red gum), this may include fuel-reduction burning to reduce the organic litter load.

8.5 Intertidal Forests

Tidal variation makes ocean levels fluctuate on a bi-diurnal basis, with the amplitude varying due to other variables. Low-lying forests are exposed to the flow of water, either directly by the tidal inflow and outflow, or by pressure changes in groundwater. Sometimes, in sandy areas such as islands, an increase in tidal levels will cause a rise in fresh groundwater levels due to its floating as a Ghyben–Herzberg lens on the underlying more saline (and denser) seawater (e.g.Tribble, 2008).

8.5.1 Intertidal freshwater forests

Figure 8.4 shows an example of such a forest from a low-lying area near Charleston, South Carolina (where such forests are common). Typically, they are low-lying areas close to the coast with a maze of waterways allowing flow in and out between the forest and coastal areas. A range of hardwood and softwood species more usually found in upland forests occur. These have some ability to tolerate salinity (for short periods at least). Williams *et al.* (2019) noted that these forests have been understudied. In general, these forests occur on areas where freshwater is passing to the sea. Commonly, high tides will restrict the outflow of freshwater to the sea (due to high sea levels), causing increased inundation by the freshwater outflow. However, occasional high tidal surges (particularly when accompanied by low freshwater outflow) allow

Fig. 8.4. Occasional flooding in the Francis Marion National Forest near Charleston, South Carolina. Usually, these areas are not flooded, but this was associated with cyclonic heavy rainfall in a coastal area. Photograph courtesy of Rick Wrenn (retired, USDA Forest Service).

the penetration of ocean water upstream. Thus, the forests must have some ability to tolerate saline ocean water if they are to survive. Odum (1988) showed that these forests occur at salinities below 0.5 parts per thousand but suggested that salinities of 2 parts per thousand may lead to vegetation change. Hydrology within these forests can be difficult to interpret because of river discharge, tidal stage and bidirectional flow, local precipitation, evapotranspiration, groundwater and prevailing winds (Anderson and Lockaby, 2011).

8.5.2 Freshwater hydrology of mangrove forests: a mystery?

Intertidal mangrove forests occur along tropical, subtropical and some temperate coasts, and often overlap with high and increasing densities of human populations. Friess (2024) noted AQ1 that mangrove forests show 'amazing diversity in structure and process' across scales ranging from local to global. This diversity includes the definition of 'What is a mangrove?' They provide important ecosystem services including fish, timber, fuelwood, coastal protection, pollution control and cultural values. In some cases, they are associated with peat formation, but more commonly they lead to land being reclaimed from the sea. Drivers such as aquaculture, agriculture and urban development have sometimes led to mangrove deforestation. Mangroves are further threatened by resource overextraction. Mangrove forests are particularly impacted by changes such as relative sea-level rise and fluctuations in sea level linked to climate oscillations (Friess *et al.*, 2019). Friess (2025) argued that research into mangrove forests has a geographical bias that avoids lower-income countries where these forests commonly occur, and argues that this distorts our 'science'. He also noted that high-ranking scientific journals sometimes reject papers on mangroves as 'too peculiar' (or other reasons unrelated to their scientific merit).

The term 'mangrove' encompasses about 80 different species of which *Avicennia* and *Rhizophora* spp. are the best known. There is a wide variation in tree size, salinity tolerance and requirements within this group (Gopal and Chauhan, 2018; Beniwal *et al.*, 2024). Mangroves grow in areas with low-oxygen soil

where slow-moving waters allow fine sediment to accumulate. The trees develop dense tangles of prop roots that sometimes make the trees appear to be standing on stilts above the water. The tangle of roots (sometimes called a 'mangal') allows the trees to handle the bi-diurnal rise and fall of tides. The roots slow the movement of tidal waters, causing sediment to settle out of the water and build up the muddy bottom, and providing habitat for fish and other organisms.

Radabaugh *et al.* (2021) showed that mangroves experience stress or mortality when gas exchange by aerial root structures is hindered by sediment burial or constant inundation. The resulting loss of belowground roots and increased decomposition can lead to a loss of surface elevation through peat collapse, furthering the degree of inundation. Signs of forest stress include pools of stagnant water (often with their own colour, distinctive biota and very low oxygen levels) and abundant adventitious root growth.

The role of freshwater hydrology in the survival of mangroves is not well understood but is known to be important in both mitigating salinity extremes and in providing nutrients to the growing plants. Particularly in estuarine environments, a reduction in freshwater inflow to the estuary may result in decline or death of 'freshwater' mangroves species less adopted to salinity. Wang *et al.* (2011) suggested that mangroves are obligate halophytes, basing this conclusion on the observations that most mangroves cannot survive indefinitely in freshwater. Studies such as that of Peng *et al.* (2023) have examined the role of both groundwater and surface mixing of fresh runoff with tidal water. This study did not support the model of the mangrove forest 'hanging on' by being dependent on a flow of freshwater in an otherwise saline environment, although there was some mixing in both the freshwater and the groundwater. A common hypothesis is that mangal roots are often located in (relatively) fresh, upwelling groundwater from the adjacent land, and that this mitigates extremes of salinity. This hypothesis appears hard to either prove or disprove.

Gopal (2014) noted the sensitivity of many mangroves to reductions in freshwater flowing from land into estuaries, but also noted the lack of detailed studies on the matter. Such results suggest that a chapter such as this can only make generalizations on the role of fresh water in the survival of mangroves. It may well be possible to manage onshore land uses in such a way that, for instance, groundwater flows from the land into the root zones of mangroves are optimized, but we do not have the ability to make refined predictions or to do the arithmetic of production to look for economic trade-offs. The area is ripe for research.

In the tropics a variety of mangrove species are able to grow along the gradient that is described for temperate tidal wetlands. Mangroves may be able to compensate for sea-level rises by capturing fine sediments by production of extensive aerial root systems (Stringer *et al.*, 2016). These root systems can also contribute to carbon assimilation.

Hydrology is probably the single most important determinant of ecological processes in wetlands (Gosselink and Turner, 1978). There are few quantitative water budgets for mangroves, which limits our understanding of how hydrology controls ecological processes of mangrove ecosystems (Twilley and Chen, 1998). In their study in Florida, these authors used a finite-difference hydrology model (HYMAN). They reported that the relative significance of tides and rainfall deficits (rainfall < evapotranspiration) on the seasonal patterns of soil saturation (water levels) and soil salinity, which at higher elevations in the intertidal zone, where tidal inundation frequency is reduced, is more sensitive to changes in rainfall deficit.

Similarly, Dai *et al.* (2018) highlighted the value of a tool to assess carbon dynamics in mangroves, especially for regional or large mangrove forests, and estimated their role in mitigating climate change because of their high carbon density, the threats to their integrity from land-use change and sea-level rises, and functional linkages of the many goods and services. Based on their modelling analysis, the authors reported that the responses of gross and net primary productivity and aboveground biomass to alterations of mean daily temperature were quadratic, or increasing or decreasing non-linearly with an increment or decrement in mean daily temperature, but leaf production was linear. Similarly, other mangrove carbon components, such as dissolved organic carbon, particulate organic carbon, dissolved inorganic carbon and black

carbon, respond substantially to variations of the ecological drivers.

8.6 Contribution of Forest Wetlands to Climate Change

8.6.1 Wetlands and stored carbon

Wetlands are a major repository of stored carbon representing one of world's largest carbon sinks (Poulter *et al.*, 2022). Wetlands are also the largest and most uncertain biological source of atmospheric methane, with hydrological fluctuations exacerbating this uncertainty (Cui *et al.*, 2024). Water-table level controls of biogeochemical cycles influence emissions of greenhouse gases such as methane (CH_4), carbon dioxide (CO_2) and nitrogen oxides (NOx), which can have an influence on regional and global climate (Paschalis *et al.*, 2017). Wetland hydrology (which reflects the local water balance) is directly affected by climatic change and variability (Zhu *et al.*, 2017).

Wetland forest hydrology can be an important driver of climate impacts. Zhang *et al.* (2019) aimed to improve the approach for quantifying the hydrological resilience of wetland ecosystems to climate variability and climate change by developing metrics including the variations of the groundwater table, overland flow and saltwater table.

Wetland soils below the water table have little aerobic decomposition so that even small productivity gains result in carbon sequestration for long periods. However, unless the soil is frozen, prolonged anaerobic decomposition depletes the soil of alternative electron acceptors and carbon is reduced to CH_4, a potent greenhouse gas. As drainage increases, the hydroperiod decreases, and the rates of productivity and decomposition increase (Fig. 8.5). However, as drainage increases, aerobic decomposition will spread to the older peat deposits, and decomposition can increase beyond productivity. Wetland management in the past has not considered climatic effects but has concentrated only on increased plant production. This focus is changing in the 21st century with recognition of the ecological values of wetlands and the challenges of climate change. In the future, the goal will be to maintain wetland hydroperiods in the zone

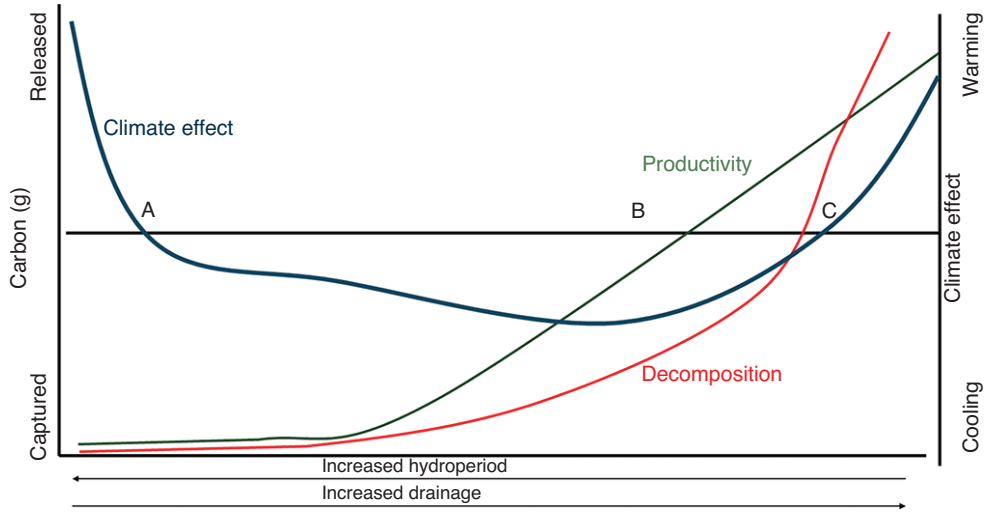

Fig. 8.5. Idealized reaction of forested wetland carbon sequestration and the climate warming effect of varying degrees of soil saturation. The horizontal line is carbon neutral. Point A is saturation to the extent that methanogenesis occurs. Point C is soils drained to the point to promote peat oxidation. Point B is an ideal wetland hydrology that promotes maximum growth but does not promote peat oxidation.

between A and C of Fig. 8.5. Points A, B and C are dependent on, at least, temperature, species, concentrations of alternative electron acceptors (e.g.oxygen, nitrogen, iron and manganese) and the many factors that determine the rate and quantity of these receptors, and the rate and quality of water flowing through the system. Northern-hemisphere peatlands and coastal wetlands both represent the systems facing the most critical climatic and land-use change challenges. Sea-level rises due to climatic change have added new stress to coastal wetlands (Aguilos *et al.*, 2021).

8.6.2 Northern bogs and fens

In the far northern regions of the planet, the interaction of climate warming, permafrost melt and methane production pose the threat of rapid global warming. In northern Canada, melting permafrost is creating a new landscape, by creating meltwater fens that can coalesce into drainage channels (Haynes *et al.*, 2023). The interplay of forest, snow accumulations, depth of the active layer, heat transfers in meltwater and degree of refreezing is an area of active and important research. In Canadian discontinuous permafrost areas, permafrost thaw and forest cover loss were found to be related to forest plateau edge area. As the perimeter:area ratio increased (i.e.areas became less circular and more irregular), the thaw of permafrost forest plateaus increased (Baltzer *et al.*, 2014). The decrease in bogs and increase in fen has resulted in enhanced CH_4 release (AminiTabrizi *et al.*, 2020).

South of the permafrost regions, vast areas of peatland forest exist across most of the northern hemisphere. Northern peatland forests are characterized by low evapotranspiration and extended periods of soil saturation with very wet conditions in the absence of adequate natural drainage (Skaggs *et al.*, 2016). During the 20th century, drainage of peatland for forestry was commonly practised. Although the practice was widespread, it was most extensive in Finland and Russia. The objectives of drainage were for accessibility and enhanced growth of merchantable timber. Paavilainen and Päivänen (1995) presented a detailed review of the history, methods and results of forest drainage of peatlands. Although preservation of soil organic matter was a goal of Nordic silviculture, excessive drainage has resulted in carbon release and soil subsidence, including decreased pH (Minkkinen *et al.*, 2008), decomposition rates of soil organic matter (Domisch *et al.*, 2000) and soil carbon stock (Minkkinen and Laine, 1998; Laiho, 2006). Peat oxidation and carbon release are more likely in peatlands cleared for agriculture due to a greater need for access to the fields with annual crops. Peatlands are also responsible for the majority of CH_4 emissions from wetlands globally (Wang *et al.*, 2021). Hydrological changes induced by climatic and anthropogenic disturbance may substantially alter CH_4 emission in peatlands. Wang *et al.* (2021) showed that restoration through a non-inundated rewetting would not stimulate CH_4 emission in drained/degraded low-latitude shrub bogs such as the pocosin wetlands (mainly *Pinus serotina*) found in the Carolinas area of the USA.

In the 21st century, new drainage initiatives are limited and there are efforts to restore peatlands by plugging drainage ditches. Climate-smart restoration could include controlled drainage to achieve conditions between point A and C of Fig. 8.5, with permanent sequestration favoured near point A and maximum carbon capture approaching point C.

8.6.3 Climate change and tidal freshwater forested wetlands

Alluvial rivers eventually lead to the coast where the river is subject to ocean tides. The tidal influence results in a progression of wetlands as hydroperiods and salinity vary along the gradient from river flood plain to estuary fringe. As sea-level rises due to changing climate, these wetlands will be subject to stress and migration (Morris and Sundberg, 2024).

The hydraulics of the tidal river creates various zones where river flow and tidal momentum interact. The vegetation and ecology of these zones are determined by river flows and the tide. These vegetation zones will change as climate change alters river flows and enhances sea-level rises (Williams *et al.*, 2019). Currently,

the zones reflect the slow rise of sea level since the early Holocene. Rising sea level will cause the zones of tidal influence in the river to move inland and shift species by mortality of the least flood-intolerant species, and later the least salt-tolerant species. In the upper reaches of this zone, the topography will become hummock and hammock with root mortality resulting in subsidence of the hammocks (Krauss *et al.*, 2023). As this zone advances, the hummocks will be filled as tidal sedimentation covers the alluvial river topography. While the forest species die from inundation and salt stress, the system will be a source of carbon to the atmosphere as both CO_2 and CH_4. Methane production will increase as the hydroperiod of the decomposing forest is prolonged by tidal subsidy. The site will cease to be a source of CO_2 and CH_4 as marsh grass productivity increases and seawater sulfate becomes available as an electron receptor for anaerobic decomposers (Helton *et al.*, 2019).

8.7 Conclusions

Forested wetlands are found throughout the world and in a variety of landscape positions. They are valued for their unique biology and their distinctive environments. As well as directly providing habitation, they provide various ecosystem services including water quality improvement, groundwater recharge to wildlife habitat and carbon sequestration.

Forested wetlands can be classified by the source of the water that causes a surplus of inflow over loss. Precipitation may be the only cause of water surplus for sites on nearly level slopes. These sites are characterized by poor nutrition and slow tree growth. Organic matter may accumulate on the surface due to slow decomposition. Drainage of these sites to improve plantation tree growth has been common around the world.

Sites where the inflow surplus is due to groundwater additions to precipitation are generally located on concave landscape positions. The length of flooding generally depends on the storage characteristics of the aquifer(s) feeding the site and ranges from small, short-lived contributions to aquifers with small storage to nearly constant saturation when fed by aquifers with large storage. The most common location occurs at the abrupt change in slope from hillside to valley bottom.

The third common source of water is from contributions ('subsidy') from adjacent rivers. In the common case, water overflows from the river into the flood-plain forest. This water than infiltrates, evaporates or makes its way back to the river at a lower topographical position. Such areas can be large and important. Because of the direct linkage between these areas and the adjacent river, they are heavily influenced by river-management projects, which commonly reduce inflows (decreasing the hydroperiod) but in some cases increase the hydroperiod.

An important but not fully understood class of forested wetlands is associated with forests found in direct association with the ocean – sometimes along coastlines or in the lower portions of estuaries. These are usually subjected to tidal forcing, as well as other hydrological inputs. It is well known that they depend to some extent on freshwater contributions from the land to ameliorate the ocean salinity, but the exact mechanism by which this is achieved is not fully understood.

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