CHAPTER 19

MANAGING FRESHWATER, RIVER, WETLAND AND ESTUARINE PROTECTED AREAS

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TITLE PAGE PHOTO

Ramsar and World Heritage-inscribed wetlands, Kakadu National Park, Australia
Source: Graeme L. Worboys

Introduction

Better practices for managing inland aquatic ecosystems in protected areas—including rivers, other brackish and freshwater ecosystems, and coastal estuaries—are the focus of this chapter. Most natural protected areas are designated as 'terrestrial' or 'marine', and the obvious question for most managers is 'why should I worry about the (usually) small portion of my protected area that involves freshwater habitat'.

On the contrary, in this chapter, we argue that freshwater and estuarine habitats are significant for conserving biodiversity in most land-based protected areas and that managers need to apply the freshwater-specific conservation tools outlined here to do a good job. Freshwater ecosystems have the greatest species diversity per unit area, a larger portion of freshwater and estuarine species are threatened, and the ecosystem services of these biomes are used unsustainably to a greater extent than any other biomes (MEA 2005; Dudgeon et al. 2006). Many terrestrial species depend on freshwater ecosystems. Rather than a marginal part of management, freshwater conservation is central to sustaining protected areas and their biodiversity.

We start by defining inland aquatic ecosystems. We then examine the principles and processes that are essential to conservation of freshwater ecosystems and aquatic species. Briefly, we introduce the threats to freshwater ecosystems and the flow-on implications for protected area design. A number of the counterintuitive implications for and conflicts between terrestrial versus freshwater protected area design and management are then detailed. Case studies are used to illustrate principles and practices applied around the world.

The next section of the chapter considers the specific management needs of rivers and swamps, lakes, peatlands, groundwater-dependent ecosystems and estuaries. Methods and options for providing environmental flows to conserve biodiversity and ecosystem services are summarised. We then turn to management of fresh waters in protected areas in the broader landscape, showing how natural resource governance processes can be harnessed to better manage freshwater biodiversity in protected areas. The final section is vital for all protected areas with freshwater components, addressing how we can adapt to climate change.

Freshwater ecosystems

Defining freshwater ecosystems

The terms (non-marine) wetlands and freshwater ecosystems are used interchangeably in this chapter. In the parlance of the Convention on Biological Diversity (CBD 2010), freshwater ecosystems are called 'inland waters'. Wetlands are places where water is the primary factor controlling plant and animal life and the wider environment, where the water table is at or near the land surface, or where water covers the land. The Ramsar Convention on Wetlands defines wetlands as 'areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres' (Ramsar 2009a:Art. 1, Clause 1).

Consequently, saline wetlands are included in this chapter. Marine wetlands are considered in Chapter 20. Riverine and 'marshy' wetlands along rivers are the focus of the section on environmental flows and wetland water regimes. Peatlands, groundwater-dependent ecosystems, lakes and estuarine wetlands are discussed in separate sections. Next we describe the diversity and distribution of freshwater ecosystems in greater detail.

Diversity and distribution of freshwater ecosystems

There is a tremendous diversity of freshwater ecosystems and many approaches for classifying them at different scales (Finlayson and van der Valk 1995; Higgins et al. 2005). At the global scale, freshwater ecosystems have been grouped into 426 freshwater ecoregions that largely follow watershed divides and capture the distributions of freshwater fish and ecological and evolutionary patterns (Abell et al. 2008). Lehner and Döll (2004) used remote sensing to map wetland occurrence to present a global map of wetland distribution (Figure 19.1). At a more granular level, many governments have mapped wetland systems within their borders—for example, the State of Queensland in Australia (Government of Queensland 2014). Despite such efforts, data for wetland distribution and extent vary considerably (Table 19.1) due to differences in definitions and approaches used for mapping (Finlayson et al. 1999).

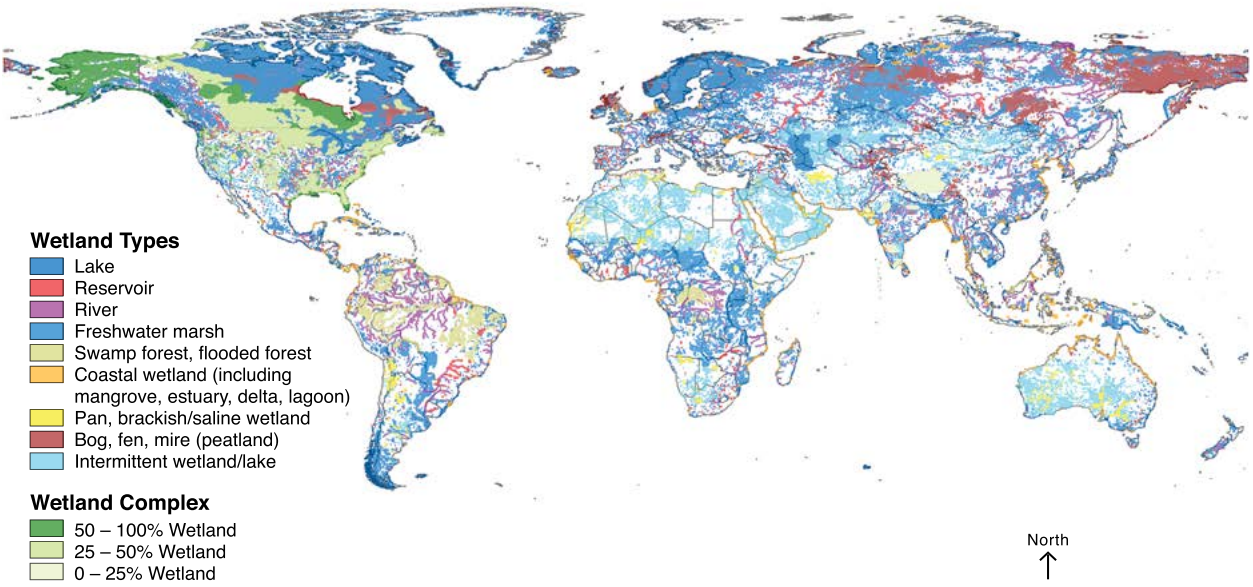


Figure 19.1 Global distribution of wetlands

Source: Modified from Lehner and Döll (2004)

Table 19.1 Estimates of inland wetland area (million hectares)

Region	Finlayson et al. (1999)	Lehner and Döll (2004)
Africa	121–4	136
Asia	204	286
Europe	258	26
Neotropics	415	159
North America	242	287
Oceania	36	28
Total	12.76–21.29	917

Note: The large differences in the figures for wetland area in Europe and the Neotropics have not been analysed in the literature.

The estimated percentage of wetlands included in protected areas is relatively high compared with many terrestrial ecosystems—around 30 per cent in Europe and North and South America (Chape et al. 2008)—but these areas have not been reserved systematically, and are rarely accorded priority in management.

Freshwater ecological principles

Freshwater ecosystems are expressions of the geophysical and ecological histories of the landscape through which water flows. The water present in any freshwater ecosystem forms part of the global water cycle—the movement of water throughout the Earth and its atmospheric system (Shiklomanov 1993). Freshwater and terrestrial ecosystems are intimately linked by the water flowing through them. Consequently, every land-use decision is effectively a water-use decision (Bossio et al. 2010).

The effect of reduced flows on terrestrial habitats and communities has been demonstrated very clearly in many parts of the world. For example, the excessive diversion of inflowing rivers for irrigated agriculture from the 1960s shrank the Aral Sea to 10 per cent of its former area by 2007, degrading the surrounding land with saline, polluted dust (Micklin and Aladin 2008). The importance of land cover, particularly forest cover, for hydrological flows is complex (Bruijnzeel 2004).

Effects from different upstream catchments are compounded as water moves downstream. This may be a challenge where multiple negative effects are compounded, or may provide solutions where the negative effects from one catchment are reduced by water flowing in from a non-impacted catchment (for example, the Olifants and Blyde rivers in South Africa; Kotze 2013). Freshwater flows carry carbon, nitrogen, oxygen and other substances that are essential for the

A black bear (*Ursus americanus*) in a river in Canada
Source: Rod Mast

functioning of downstream ecosystems, supporting a rich variety of life. These flows also carry sediments, washed in from upstream terrestrial habitats and eroding banks. The connectivity that exists across rivers, their tributaries and associated wetlands supports the diversity of species present, providing access to habitats for feeding and reproduction, and promoting population growth, community diversity and productivity (Bunn and Arthington 2002; Campbell-Grant et al. 2007).

In some cases, marine linkages are vital, such as when anadromous fish return to their natal river to spawn and, upon dying there, deposit many ocean-derived substances within freshwater systems. In the Pacific north-west of North America, for instance, there are some forests where much of the soil nitrogen is derived from marine sources via salmon migration (Helfield and Naiman 2006) (see photo above).

Freshwater ecosystems are dependent on the quantity, timing and quality of water flowing through them. Many changes in the natural flow regime can compromise the survival of species that are adapted to the historical regime (Laizé et al. 2014). Many wetland birds and terrestrial species undergo widespread migrations based on seasonal changes in the availability of water, habitat and food in rivers and wetlands. Disturbance of the flow regime in freshwater ecosystems can also promote the invasion of introduced and alien species that can tolerate the modified flow conditions (Bunn and Arthington 2002). An important application of the concept of the natural flow regime is in the definition of 'environmental flows', which is detailed in a later section.

Managing threats to freshwater systems

Freshwater and estuarine ecosystems are among the most threatened in the world, with the Millennium Ecosystem Assessment (MEA 2005) describing freshwater ecosystems as being overused, under-represented in protected areas and having the highest portion of species threatened with extinction. People are inextricably linked to freshwater ecosystems, and both people and nature benefit by managing risks to the health of these habitats (Dudgeon et al. 2006; Vörösmarty et al. 2010). Primary direct drivers of degradation and loss of riverine and other wetlands include infrastructure development, land conversion, water withdrawal, pollution, overharvesting and overexploitation of freshwater species, the introduction of invasive alien species, and global climate change (MEA 2005; Dudgeon et al. 2006). The World Commission on Protected Areas (WCPA) outlines how freshwater biodiversity is particularly threatened because its conservation depends on maintaining ground and

surface water flows, managing activities within the catchment and coordinating the activities of multiple management authorities (Dudley 2013).

Later sections provide advice on managing threats at the landscape scale, whereas management of threats to freshwater ecosystems within protected areas is briefly summarised here (see also Chapters 16 and 17).

Water infrastructure and diversions

Water diversions and infrastructure alter flows that are vital to maintaining freshwater biodiversity. Wherever possible, redundant water storages in protected areas should be decommissioned. There are a number of manuals available for removing dams (Bowman et al. 2002; Lindloff 2000). For example, in the United States, two large dams are being removed on the Elwha River to enable migratory salmon to recolonise habitat within Olympic National Park in Washington State (Howard 2012) (see Chapter 12).

Where infrastructure is retained, there are four key measures that will reduce but not fully compensate for the impact on freshwater ecosystems (Davies 2010; Pittock and Hartmann 2011): restoration of fish passage around dams; provision for release of environmental flows (see section below); building dam outlet structures that eliminate thermal pollution; and conservation of the river corridor below the dam—for example, by restoring riparian vegetation. Screening water diversion intakes to prevent loss of fish and other aquatic wildlife may also help (Baumgartner et al. 2009).

Invasive species

Alien animal and plant species, once introduced into water bodies, are particularly difficult to eliminate or control. To prevent introductions and control those that do occur:

- identify vectors for introduction of species (for example, aquaculture farms, ornamental gardens) and seek voluntary or regulatory measures to prevent pest releases
- monitor freshwater ecosystems to identify new problem species, drawing on information on pest species in your country or region
- eliminate newly observed populations of threat species (incursion management)
- prevent the spread of pest species (this may be a case where a barrier dam in a stream is used to protect upstream populations of indigenous species from exotic species spreading from downstream)
- institute control measures where this is feasible (Chatterjee et al. 2008).

Recreational use of water bodies

Freshwater ecosystems are a major focus of visitor activities in most protected areas, requiring trade-offs between visitor use and biodiversity conservation (Hadwen et al. 2012) (see also Chapter 23). Riparian areas often provide a biodiverse corridor of moisture-loving vegetation running through drier regions, creating moist microclimates and habitat for many species. Fragmentation and trampling of this vegetation can significantly impact on the freshwater ecosystem. Sediment-laden run-off from roads and tracks into water bodies can seriously harm aquatic biota, by reducing filter feeding and prey visibility and by smothering rocky substrates used for fish spawning and insect development. The smallest 'jump' up to or over a causeway or culvert across a water body may be a barrier to migration of aquatic species like fish and invertebrates.

Key management responses should include: zoning land access, siting visitor facilities away from water bodies, fencing visitors out of riparian areas, creating boardwalks and access points to water, and regulating use of motorised vehicles (Mosisch and Arthington 1998; Chatterjee et al. 2008). Roads and tracks should be located to drain run-off away from water bodies and onto land. Crossings should be built as bridges or broad culverts sunk into the stream bed so as to maintain passage for aquatic fauna. Regulating fishing activities is essential to conserve biodiversity (Ramsar 2005). Avoiding contaminated discharge and treating sewage are particularly important in preventing pollution of water bodies. Toilet facilities should be sited well away from water bodies.

Pollution spills

Protected area management requires use of chemicals such as fuels and herbicides that would have negative impacts if discharged into water bodies. Spills should be prevented wherever possible through good workplace health and safety practices, including siting chemicals away from water bodies, and securing and labelling stored chemicals. Potential pollutants should be stored and used on hard, internally draining surfaces that can contain accidental spills. Materials for soaking up any spills such as hay, sawdust or cat litter should be available on site, plus tools and bags for removing them for treatment. Spills into waterways require urgent advice to downstream authorities to close water diversions and prevent use of polluted water by people, wildlife and livestock wherever possible (see also Chapter 26).

Flood, drought and fire

Floods, droughts and fire are natural processes in many ecosystems and plants and animals can normally tolerate or recover from them. In particular, many freshwater species and ecosystems are adapted to variability in water volumes and timing of flows and require variability to thrive, such that regulated water bodies should not be managed with unnatural, permanent or stable flows (Postel and Richter 2003). Some freshwater ecosystems are adapted to fire, such as floodplain forests in southern Australia, whereas others are destroyed by and should be protected from fire—for example, peat swamp forests in Borneo. Riparian forests are often naturally fire resistant even among other, flammable vegetation types. The traditional practices of local and indigenous peoples of cool patch burns around these ecosystems may conserve them from hot wildfires.

While this brief section on threats cannot detail all mitigation measures, a particularly concise source of information for managing wetlands in protected areas to avoid or mitigate these threats is *Wetland Management Planning: A guide for site managers* (Chatterjee et al. 2008). The resolutions and guidelines of the Ramsar Convention and the *Ramsar Handbooks for the Wise Use of Wetlands* (Ramsar 2011) provide excellent advice on good international practices for almost any wetland management challenge. An adaptive management approach is important to facilitate the engagement and empowerment of stakeholders and rights-holders, inclusive and iterative learning, and purposeful action amid inherent complexities (Kingsford et al. 2011). We now turn to the conservation of freshwater species and protected area design options that involve mitigating threats and maximising biodiversity protection.

Conserving freshwater species

Freshwater species include 'real aquatic species' which accomplish all or part of their life cycle in or on water and 'water-dependent' (paraquatic) species which show close and specific dependence on aquatic habitats (for example, for food or habitat). The first global freshwater animal diversity assessment (Balian et al. 2008) found that there were 126 000 freshwater animal species, representing approximately 9.5 per cent of all recognised species.

Efficient investment of resources in protecting freshwater species within protected areas requires striking the right balance between actions targeted at the level of ecosystems and landscapes and those that target individual species. Actions at the landscape scale that address major threats to freshwater ecosystems can be effective in protecting a large proportion of freshwater species (for example, erosion control). Many significant threats to populations of freshwater species are not, however, reflected in the condition of surface water catchments—for example, downstream artificial barriers. Hence, there will often be a need for carefully planned actions to protect the populations of these species. This is particularly important where climate change is likely to lead to rapid expansion of invasive freshwater species, resulting in a decline in populations of native species (Rahel et al. 2008).

One of the first steps in developing action plans for managing freshwater species in protected areas is to access relevant data, which are often scattered among different custodians (for example, fisheries management agencies and university researchers). The Global Biodiversity Information Facility (GBIF 2014) and BioFresh data portal (BioFresh 2013) are two important sources of freshwater species data. Species observations made by volunteers (citizen scientists) and uploaded to databases using mobile phone apps, such as the Global Freshwater Fish BioBlitz (FFSG 2013), are increasingly important. Also there are a large number of national, regional and continental assessments—for example, for Africa (Darwall et al. 2011).

Prioritisation is then needed of species and interventions. Important factors to consider in this process include: International Union for Conservation of Nature (IUCN) Red List status (IUCN 2003); local threatened species legislation; community interest; species used in setting regional freshwater conservation targets (for example, Khoury et al. 2011); and species that are essential as sources of food or habitat for threatened species. Where occurrence data for a species of interest are limited, species distribution models can be used (Pearson 2007). These models can also assess the distribution of invasive species. These outputs can also be used in developing regional freshwater conservation plans (for example, Esselman and Allan 2011). Good protected area design is vital to conserving threatened species and biodiversity.

Freshwater protected area design

Freshwater conservation planning has traditionally lagged behind the systematic and quantitative planning for terrestrial and marine realms, mainly due to the spatial and temporal complexities characteristic of freshwater systems. Fortunately, conservation studies in recent years have provided the methods to plan better for freshwater systems (Collier 2011).

To be effective, protected areas must consider some particularities of freshwater ecosystems. Spatial–temporal connectivity plays a key role in maintaining important ecological processes (Ward 1989), such as dispersal, gene flow or transport of energy and matter essential for the persistence of populations and species. There are examples of how to effectively incorporate connectivity in all its dimensions—longitudinal (Hermoso et al. 2011), lateral (Hermoso et al. 2012a), vertical (Nel et al. 2011) and temporal (Hermoso et al. 2012b)—into systematic conservation planning frameworks, which help design protected areas that are ecologically functional from a freshwater point of view. There also have been advances in integrating threats and degradation processes into conservation planning, to avoid the allocation of conservation efforts in areas where the existence of threats or their propagation could compromise the persistence of biodiversity (for example, Moilanen et al. 2011; Linke et al. 2012).

Planning for persistence of biodiversity through maintenance of ecological resilience requires consideration of the political and socioeconomic factors that influence aquatic systems. Social (Knight et al. 2011) and political (Faleiro and Loyola 2013) aspects of conservation play an important role in the success or failure of a plan. This phenomenon is widely documented and is addressed in cross-governmental initiatives at national (Pittock and Finlayson 2011) and international scales (Haefner 2013) in river science.

The final key to effective conservation for fresh waters is embedding protection schemes in a wider environmental context—ideally at the whole catchment scale. This issue was identified as a critical point for the success of freshwater conservation by Abell et al. (2007), who called for multiple tiers in freshwater protection—from strict protected areas to catchment management zones. The patchy reservation of the Pantanal wetlands in South America (Case Study 19.1) highlights these issues.

Unique considerations

What is different from terrestrial systems?

An obvious question for land-based protected area managers is 'why do I need to do anything different to conserve freshwater biodiversity'. The differences are well detailed in the *Guidelines for Applying Protected Area Management Categories* (Dudley 2013), and can be summarised as follows.

- Flow regimes: Water is critical for maintaining freshwater biodiversity, including the volume, timing and quality of surface water flows as well as surface water–groundwater dynamics.
- Longitudinal and lateral connectivity: Protecting water flows along rivers and from channels onto floodplains is essential. This involves preventing or removing artificial physical and chemical barriers, and providing bypass facilities for aquatic wildlife.
- Groundwater–surface water interactions: Protection of groundwater flows is needed since most surface waters depend to some extent or at some times on aquifers (the water table).
- Relationship to the broader landscape: Wetland systems in a protected area cannot usually be 'fenced off' from impacts arising in the wider terrestrial landscape, and will normally require integrated threat management at the catchment scale.
- Multiple management authorities: Different government agencies usually have overlapping and often conflicting responsibilities concerning freshwater management. Conservation is complicated by the need to coordinate management activities among government agencies with diverse mandates.

Upcoming sections suggest ways to manage these differences. Unique types of freshwater protected areas are now outlined as well as conflicts between terrestrial and freshwater conservation, before considering conservation of specific types of wetland ecosystem.

Freshwater protected area types

The unique characteristics of freshwater ecosystems mean that there is sometimes confusion as to what constitutes a freshwater protected area and insufficient recognition of some unique types of protected areas. The IUCN states that a 'protected area is a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values' (Dudley 2013:8).

Areas managed for conservation of freshwater biodiversity are protected areas even if they occur on a variety of land tenures or are managed without specific legislation or by non-governmental managers, as long as these are 'effective'. In this context, sites designated under the Ramsar Convention are protected areas even if they are not recognised in national law (see the section below on Ramsar). Similarly, the 'Heritage Rivers' of Canada are protected areas. Freshwater areas conserved by the traditional laws of indigenous peoples and the wetland portions of the non-legislated Indigenous

Case Study 19.1 Pantanal, South America

The Pantanal is a large internal delta and, at 160 000 square kilometres, is one of the largest wetlands in the world. It is divided between Brazil, Bolivia and Paraguay (Figure 19.2). An annual flood pulse has led to a dynamic mosaic of permanent terrestrial through to permanent aquatic habitats (Nunes da Cunha and Junk 2011). The Pantanal supports a traditional pastoral industry and can be considered a managed cultural landscape with high aesthetic value and large species and habitat diversity (Junk et al. 2006). Only 5 per cent of the Brazilian Pantanal is fully protected in Ramsar sites and other kinds of protected areas.

Hydro-electric power plants have begun to modify the flood pulses. Occupation of the catchment by large agro-industries has led to increased soil erosion and sediment loads. Agricultural developments are encroaching on the Pantanal and have led to renewed consideration of the 'hidrovia' canalisation of the Paraguay River. The Pantanal case study highlights the need to: better define the borders of the wetland and protect key habitats; collaborate with local communities for wetland-friendly livelihoods; and maintain near-natural flood pulses by controlling water releases from dams (Junk and Nunes da Cunha 2012).

Figure 19.2 Pantanal wetlands, South America
Source: US National Park Service

Protected Areas (IPAs) in Australia are protected areas. Reserves under fisheries legislation are another example. The Cosumnes River Preserve in the United States (Case Study 19.2) is an example of a freshwater protected area involving coordinated management by different organisations across tenures. The *Guidelines for Applying Protected Area Management Categories* should be consulted to assist managers assign freshwater areas to categories for protected area inventories (Dudley 2013).

Conflicts between terrestrial and freshwater conservation

Regrettably, many terrestrial protected areas are created as a trade-off for damaging freshwater ecosystems, and many erstwhile positive conservation measures have perverse impacts on aquatic biota and ecosystems. Protected area establishment is often linked to hydro-electric or water-supply dam development. For example, the establishment of the Kosciuszko National Park in Australia was intended to reduce erosion in the catchments of the Snowy Mountains Hydro-Electric Scheme constructed within the park from 1949 to 1974. It was only in 2002 that agreement was reached to restore minimal environmental flows to these degraded rivers (Miller 2005). More recently, protected areas have been established in mountain catchments in developing countries as a trade-off for the impacts of hydro-electric development. The Nam Theun II hydro-power project in Laos is an example of improved management of protected forest areas agreed to as an offset for degrading internationally significant river ecosystems (Porter and Shivakumar 2010).

In many places, hydro-electric power generators or water consumers are paying fees for the conservation of the watersheds of dams, including as protected areas (Postel and Thompson 2005). While payment for watershed services may benefit terrestrial conservation and the conservation of headwater streams, the significant environmental damage caused by the dams that are the source of the revenue is rarely recognised. Richness and abundance of aquatic species are often lower in upland protected areas (Chessman 2013). In freshwater ecosystems, the large mid-slope and lowland rivers are usually the ones that have the greatest aquatic species diversity and provide vital corridors for migratory animals. Usually these are the parts of rivers targeted for water infrastructure development (Sheldon 1988; Tockner et al. 2008).

Under these circumstances, managers have an obligation to ensure that any resources provided by water infrastructure developers contribute to conservation of freshwater biodiversity downstream, as well as upstream of dams. There are four key interventions—namely: restoration of fish passage around dams; provision for release of environmental flows; building dam outlet structures that can eliminate downstream thermal pollution; and the conservation of the river corridor below the dam, for example, by restoring riparian vegetation (Davies 2010; Pittock and Hartmann 2011). These measures will

Case Study 19.2 Cosumnes River Preserve, USA

'Pre-wetting' the river bed aids conservation of fish in the Cosumnes River Preserve, USA

Source: Carson Jeffres

Water resources in California's Central Valley have been directed to drinking water and irrigated agriculture. Agricultural development has seen wetlands reduced to less than 6 per cent of the original 1.8 million hectares (Whipple 2012). The Cosumnes River Preserve conserves key remnants on 20 000 hectares of managed floodplain and river ecosystems distributed over 150 square kilometres, and is managed via a formal partnership (Figure 19.3; Kleinschmidt Associates 2008). The Nature Conservancy and federal Bureau of Land Management are the primary landowners, with other contributions from six federal, State and local government agencies, a non-governmental organisation (NGO) and private lands in conservation easements. Memoranda between these entities encourage both nature protection and sustainable use of some lands, particularly because some practices, such as forage and rice production, create seasonal habitat for focal bird species (Kleinschmidt Associates 2008). This form of management is akin to IUCN Category VI. This example illustrates how a freshwater protected area can comprise many different land tenures, owners and legal agreements.

The primary management challenge is countering the abstraction of groundwater to meet municipal and agricultural demands, as the Cosumnes River and the adjacent mosaic of wetlands (Type II groundwater-dependent ecosystems; see sections below) are now disconnected from the water table and seasonally dry. 'Pre-wetting' the river channel with managed water prior to winter precipitation could maximise the biodiversity benefits from natural inflows (Fleckenstein et al. 2004). Other forms of adaptive management include the breaching of dykes and levees to reconnect former farmland to floodwaters and promote rearing of juvenile fishes like Chinook salmon (*Oncorhynchus tshawytscha*) (Jeffres et al. 2008).

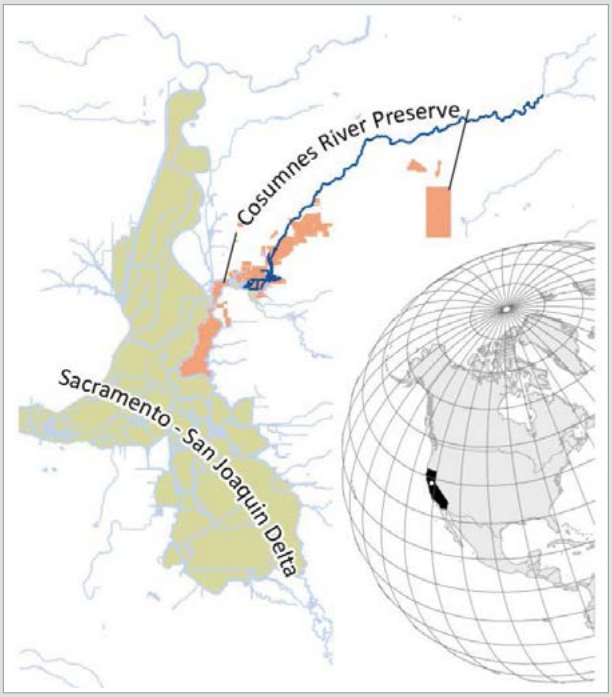


Figure 19.3 Cosumnes River Preserve, United States of America

Source: Modified from Josh Viers

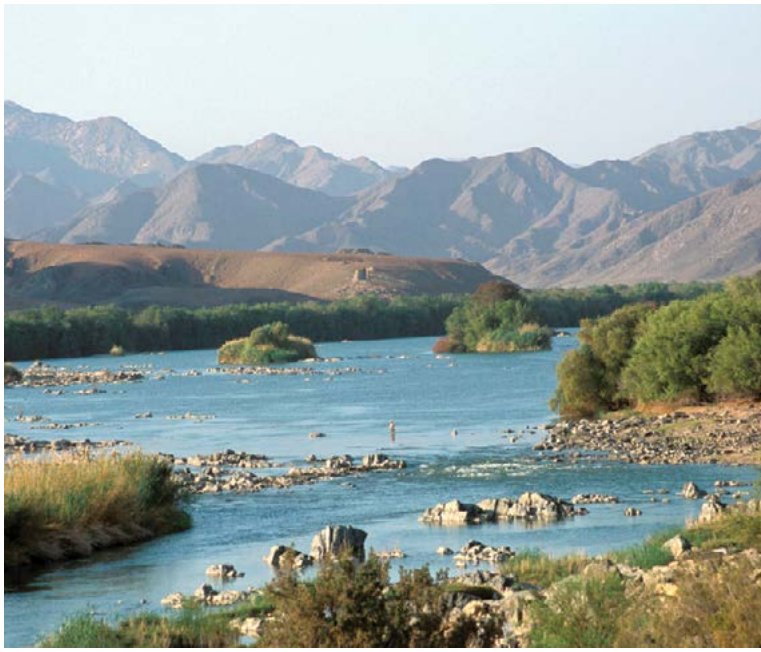
reduce but never fully compensate for the impact of water infrastructure on freshwater ecosystems. Hence, managers should resist the construction of water infrastructure impacting on protected areas. In an era of growing water scarcity, more proposals to exploit water resources within nature reserves are likely and should be resisted, but if imposed, the mitigation measures described above should be mandatory.

Many protected area managers have installed dams, either to supply staff and visitors or to enhance wildlife viewing. Establishing watering points for wildlife is a misguided notion that should only be considered in exceptional circumstances, such as part of a targeted threatened species recovery plan. Water should be accessed from groundwater, off-river storage tanks or small dams to reduce the ecological impacts of water supply infrastructure. Even small dams across streams can block the passage of aquatic wildlife. There are negative impacts on terrestrial and riparian ecosystems from concentrating grazing by herbivores. Generally, dams for wildlife and other redundant water storages in protected areas should be decommissioned, as is occurring in Kruger National Park (Brits et al. 2002).

New kinds of perverse impacts are emerging, often associated with climate change mitigation measures that consume a lot of water (Pittock et al. 2013). One example is planting trees to sequester carbon—an approach supported by many environmental managers as a way of funding biodiversity restoration. Planting forests, however, inevitably increases evapotranspiration and reduces inflows into freshwater ecosystems (Jackson et al. 2005; van Dijk and Keenan 2007). One projection for the overallocated Macquarie River in Australia suggested that reafforesting 10 per cent of the upper catchment would reduce river flows into the Macquarie Marshes Nature Reserve and Ramsar site by 17 per cent (Herron et al. 2002). There are ways of reconciling these conflicts—for example, by requiring acquisition of water entitlements for the environment to offset increased evapotranspiration by trees, or restoring vegetation in areas that contribute less water to rivers (Pittock et al. 2013). There may be acceptable trade-offs—for example, restoring riparian forests has many benefits for freshwater ecosystem conservation that may offset the consumption of water.

Dodgy borders: Managing divided freshwater systems

A great many of the world's land-based protected areas have boundaries defined in part by rivers. Obviously, the threats to freshwater biodiversity are greater where part of the water basin is outside the boundaries of a protected area. Among the likely threats are: diffuse pollutants and eroded sediments washing into water



Conserve lowland rivers as well as headwaters: Richtersveld National Park, South Africa

Source: Conservation International/Haroldo Castro

bodies, point-source pollution discharges, water extraction, introduction of alien species, extraction of aquatic plants and animals, mining riverbanks and beds, and clearing of riparian forests. In one respect, having a river as a border is just one manifestation of not having an entire watershed inside a protected area; however, where a sinuous river forms the boundary, the border is usually longer, exposing freshwater ecosystems to dispersed conservation threats and making management responses more challenging.

How, then, should protected area managers enhance conservation in circumstances where the river is the boundary? Key among the approaches is engaging stakeholders and rights-holders outside the protected area in cooperative management arrangements. In the section below on landscape management, a number of these opportunities are outlined. Managers of Kruger National Park in South Africa have applied these approaches (Case Study 19.3).

Managing specific freshwater ecosystems

In this section, we consider the specific management requirements of particular freshwater ecosystems before reviewing landscape-scale management options.

Dam removal restores river connectivity and fish passage, Veazie Dam, Penobscot River, USA
Source: Joshua Royte, The Nature Conservancy

Environmental flows and wetland water regimes

Environmental flows

To maintain freshwater biodiversity and ecological services inside protected areas, conservation reserve managers must try to ensure that the natural water regimes of lakes, wetlands and rivers are protected from overuse, diversion and impoundment. Freshwater management has been integrated into the broader scope of ecological sustainability through the provision of environmental flows, which are defined as 'the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and wellbeing that depend upon these ecosystems' (Brisbane Declaration 2007).

There is now wide recognition that a dynamic, variable water regime is required to maintain species phenology (seasonal timing of events in the life cycle) and the native biodiversity and ecological processes characteristic of every river and wetland ecosystem. The natural flow regime and diverse ecohydrological principles (for example, Bunn and Arthington 2002) flesh out the influence of flow volume, seasonal timing and variability on aquatic biodiversity, population recruitment and ecosystem productivity. These ecohydrological principles inform assessment of the environmental flow requirements of aquatic plants and animals.

The key challenge for managers whose protected areas receive water from unreserved upstream catchments is to engage water managers and users to agree on a process for assessing and deciding on environmental flows. More than 250 practical methods, models and frameworks are available to link water volumes and patterns of flow to biodiversity and ecological processes (Dyson et al. 2003; Tharme 2003). While environmental flow assessment may seem complex, even daunting, a simple guide to the technical options available for protected area managers to assess what is required is given in Table 19.2. These methods focus largely on rivers; however, they are applicable in concept and practice to water bodies that rarely flow but nevertheless experience natural spatial and seasonal patterns of water-level fluctuation, wetting and drying, and links to groundwater. Estuaries also need to receive freshwater inflows (see section below). Methods and applications for all aquatic ecosystem types can be found in Arthington (2012).

Setting limits to hydrologic alteration

Despite tremendous advances in methods, setting a limit on hydrologic alteration remains the most challenging aspect of environmental flow science and sustainable water management. Simple methods set this limit as a percentage of the natural flow, or define the river discharge that maintains fish habitat and connectivity through the channel network. In the holistic 'downstream response to imposed flow transformations' (DRIFT) and 'ecological limits of hydrologic alteration' (ELOHA) frameworks (Table 19.2), and several

Case Study 19.3 Kruger National Park rivers, South Africa

Five major rivers that traverse the breadth of Kruger National Park (KNP) (IUCN Category II) are crucial to conserving its biodiversity (Figure 19.4). Most of the rivers originate in or flow through highly developed, urbanised, industrialised, mining or agricultural areas, rendering the park particularly vulnerable to upstream impacts. South African National Parks (SANParks) initiated the multi-institutional KNP Rivers Research Programme (see Biggs and Rogers 2003) in response to the deteriorating quantity and quality of many of these rivers. SANParks sees the KNP as embedded in a wider socioecological system (the catchment) that needs to be managed adaptively and collaboratively with the surrounding communities. This approach has been strengthened through a number of initiatives, especially the work of the Association for Water and Rural Development, a research-based NGO, and the Inkomati Catchment Management Agency (Pollard and du Toit 2011).

Development pressure is resulting in a decline in the condition of all but one of the KNP rivers, including non-compliance with statutorily defined environmental flows for water quality and quantity. The advocacy by networks of competent actors, however, together with ongoing monitoring and adaptive responses, means the rivers are likely in a better shape than they would otherwise have been (Pollard and du Toit 2011). Moreover, the increasing mobilisation of opinion, effort and concerted action by catchment management agencies offers hope. SANParks' work highlights how park managers have an important watchdog role to play in the context of multi-scale catchment and water governance (Pollard and du Toit 2011).

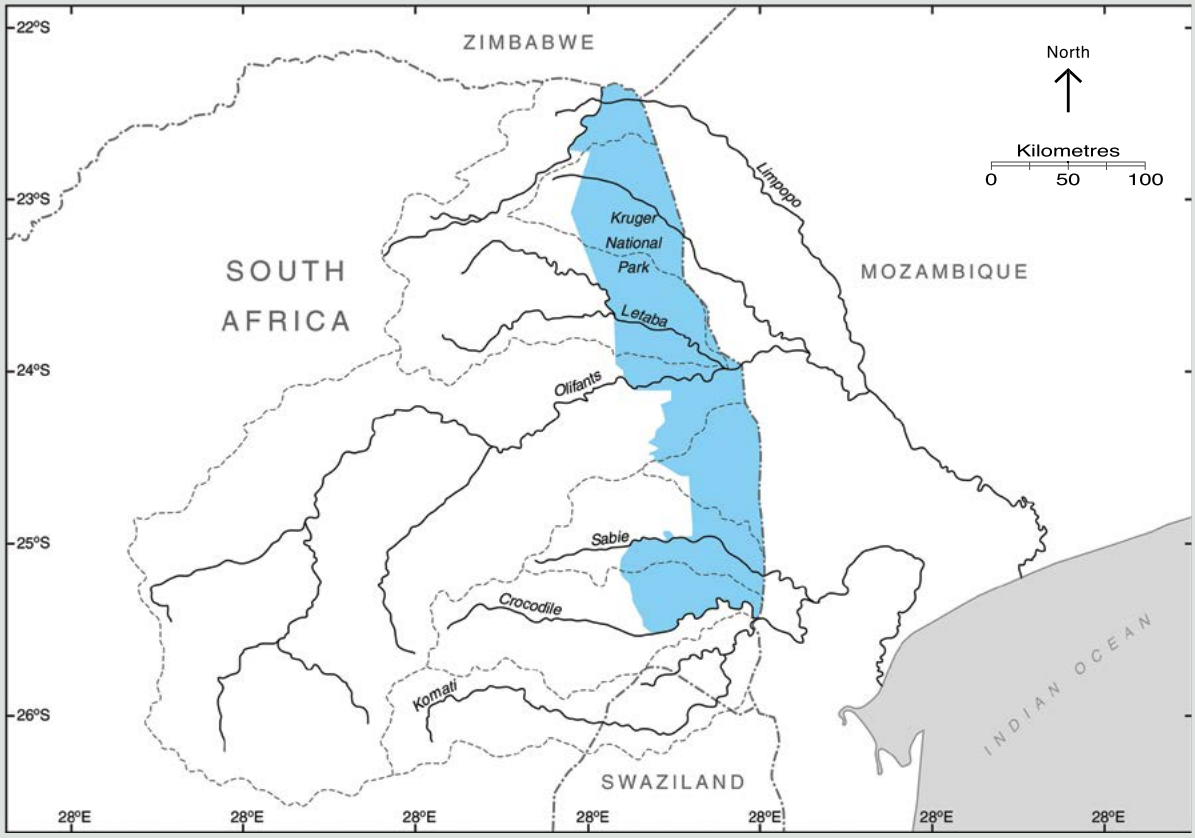


Figure 19.4 Kruger National Park, South Africa

Source: © Clive Hilliker, The Australian National University

restoration protocols (for example, Richter et al. 2006), scientists, stakeholders, rights-holders and managers give consideration to a suite of flow alteration–ecological response relationships for each system under study. An important concept is the idea of a threshold beyond which unacceptable ecological changes are likely to occur. Where there are clear threshold responses (for example, overbank flows needed to support riparian vegetation or provide fish access to backwater and floodplain habitats), a 'low-risk' environmental flow would be one that does not cross the threshold of hydrologic alteration for overbank flows. For a linear response where there is no clear threshold demarcating low from high risk, a consensus stakeholder process will be needed to determine 'acceptable risk' to a valued ecological asset, such as an estuarine fishery dependent on freshwater inflows (Loneragan and Bunn 1999). It is important to differentiate the scientific assessment of ecological limits to hydrologic alteration from the social process of finally deciding on the recommended flow (Arthington 2012).

Table 19.2 Environmental flow methods: comparison of the four main types of methods used worldwide to estimate environmental flows = environmental water allocations (EWA)

Type	River ecosystem components	Data requirements and resource intensity (time, cost and technical capacity)	Resolution of output (EWA)	Appropriate levels of application
Hydrological	Whole ecosystem, non-specific, or ecosystem components such as fish (Tennant 1976)	Low Primarily desktop Use virgin/naturalised historical flow records Some use historical ecological data	Low Expressed as percentage of monthly or annual flow (median or mean), or as limits to change in vital flow parameters—for example, range of variability approach (Richter et al. 1996, 2006)	Reconnaissance level of water resource developments, or as a tool within habitat simulation or holistic (ecosystem) methodologies *Used widely*
Hydraulic rating	Instream habitat for target biota	Low–medium Desktop, limited field Historical flow records Discharge linked to hydraulic variables—typically single river cross-section	Low–medium Hydraulic variables (for example, wetted perimeter) used as surrogate for habitat flow needs of target species or assemblages	Water resource developments where little negotiation is involved, or as a tool within habitat simulation or ecosystem methodologies *Used widely*
Habitat simulation	Primarily in-stream habitat for target biota Some consider channel form, sediment transport, water quality, riparian vegetation, wildlife, recreation and aesthetics—for example, the Physical Habitat Simulation computer modelling system (PHABSIM) developed by the US Fish and Wildlife Service (Bovee 1982)	Medium–high Desktop and field Historical flow records. Many hydraulic variables are modelled at range of discharge at multiple stream cross-sections Physical habitat suitability or preference data needed for target species	Medium–high Output in form of weighted usable area of habitat for target species (fish, invertebrates, plants). Can involve time-series of habitat availability	Water resource developments, often large scale, involving rivers of high strategic importance, often with complex, negotiated trade-offs among users, or as method within holistic (ecosystem) approaches *Primarily used in developed countries*
Holistic (ecosystem) frameworks	Whole ecosystem, all or several ecological components Most consider in-stream and riparian components, some also consider: groundwater, wetlands, floodplains, estuary and coastal waters May assess social and economic dependence on species/ecosystem (for example, downstream response to imposed flow transformations (DRIFT); King et al. 2003)	Medium–high Desktop and field Use virgin/naturalised historical flow records or rainfall records compared with current gauge records Many hydraulic variables—multiple cross-sections Biological data on flow and habitat-related requirements of biota and some/all ecological components	Medium–high Advanced fish methods use data on movement and migration, spawning, larval/juvenile requirements, water-quality tolerances; exotic species included (for example, downstream response to imposed flow transformations (DRIFT); Arthington et al. 2003) Ecological limits of hydrologic alteration (ELOHA) quantifies e-flow 'rules' for rivers of contrasting hydrological type at user-defined regional scale (Poff et al. 2010)	Water resource developments, typically large scale, involving rivers of high conservation and/or strategic importance, and/or with complex user trade-offs Simpler approaches (for example, expert panels) often used where flow ecology knowledge is limited, or there are limited trade-offs among users, and/or time constraints *Used in developing and developed countries*

Source: Adapted from Tharme (2003); for examples, see Arthington (2012)

Adapting to climate change

The natural environmental regimes that govern aquatic ecosystems, especially water regimes, have been replaced with altered regimes in many areas of the world under increasing human pressure for fresh water and in response to shifting climates. The combination of climate change and flow regulation is now driving structurally novel ecosystems that may require new concepts and a range of approaches to water management to cope with increasingly uncertain futures (Palmer et al. 2008). Research that identifies flow regime characteristics and associated ecological responses to variability is one of the best options for preparedness. The study of ecological responses along contemporary gradients of flow variability (wet to dry tropics, coastal to arid zone regions) may provide analogues for future climatic shifts (Arthington et al. 2006). Yet the surest way to advance understanding of the ecological roles of flow, and to improve water use for ecosystem and human benefit, is through well-designed monitoring of ecological outcomes over time (Arthington et al. 2010; Davies et al. 2014).

Conservation managers can take the lead in applying environmental flow concepts and methods to the diverse protected areas they manage. Common key steps in the different environmental flow methods outlined above include:

- consulting stakeholders and rights-holders to identify the different, flow-related elements of the environment that are valued, such as fish migrations
- identifying thresholds for the quality of water and volume and timing of flows needed to sustain those values—for example, the water required for waterbirds to successfully breed in a wetland
- considering the natural flow variability of their rivers and wetlands, and seeking to mimic important features as much as possible—for instance, with water releases from dams
- negotiating agreements with water agencies and other stakeholders and rights-holders, including water departments and utilities, to deliver the environmental flows
- monitoring the impact, and evaluating and adjusting the environmental flows to achieve the desired environmental and social objectives.

Environmental flows need to be applied to conserve lakes and estuaries, as described in the next subsections.

Lakes

Globally, there are an estimated 27 million natural lakes and half a million artificial lakes (reservoirs) greater than one hectare in area. The term 'lakes' is henceforth used to refer to both natural lakes and artificial reservoirs, noting that the biodiversity values of artificial lakes are generally much lower than those of natural ones. Lakes collectively contain more than 90 per cent of the liquid fresh water on the surface of our planet, and in addition to providing habitat for aquatic species, they provide extensive services to humanity. Lakes and reservoirs are easily polluted and degraded (Illueca and Rast 1996).

Managing these water bodies for their conservation is a complex undertaking involving a range of scientific, socioeconomic and governance elements. Lakes are hydrologically linked to upstream rivers or tributaries flowing into them, to downstream water systems into which they discharge, and sometimes also to subsurface groundwater aquifers (Figure 19.5). Downstream water needs can sometimes significantly dictate the management requirements of upstream lakes that supply water to them, an example being the Lake Biwa–Yodo River complex in Japan (Nakamura et al. 2012).

Lake conservation translates into managing lakes, their basins and their resources for sustainable ecosystem services (MEA 2005). The scientific considerations include the quantity and quality of surface and groundwater sources, drainage basin characteristics, flora and fauna, soils, topography, land use and climate—all of which collectively define the physical presence and condition of lake waters. Institutional aspects include the legal and institutional framework within a lake drainage basin, economic considerations, demography, cultural and social customs, stakeholder participation possibilities and political realities. The last arguably comprise the most important elements, in that they define the factors controlling how humans use their water resources (GWP 2000).

Effectively managing lakes for conservation and sustainability also requires recognition of three unique features: 1) an integrating nature; 2) long water retention time; and 3) complex response dynamics (ILEC 2005). Because of their location at the hub of a drainage basin, lakes are the flow regime integrators within the entire lake–river basin complex. The integrating nature of a lake refers to its function essentially as a 'mixing pot' for everything entering it from its surrounding drainage basin, and sometimes even from beyond its basin via the long-range transportation of airborne pollutants. The long water retention time refers to the average time water

Environmental flow from the Alamo Dam into the Bill Williams River, USA, a demonstration site in the Sustainable Rivers Project of the US Army Corps of Engineers and The Nature Conservancy

Source: US Army Corps of Engineers

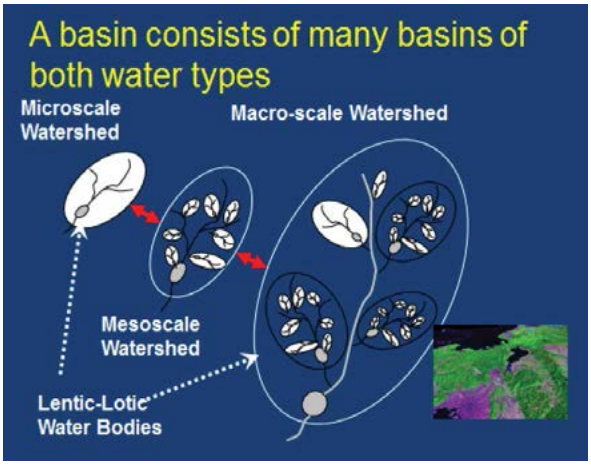


Figure 19.5 Links between water basins at different scales and of different types

Source: Nakamura and Rast (2011)

spends in a given lake. Lake problems often develop gradually, and may not become evident until they have become serious lake-wide problems that can significantly impact human water uses and ecosystem integrity. This same buffering trait also can produce a 'lag' phenomenon in response to remedial programs implemented to restore them. All lake problems are essentially lake-wide problems, with lakes experiencing serious degradation, including to the aquatic communities for which they provide habitats, typically not returning to the condition they exhibited prior to the degradation (Nakamura and Rast 2011).

The underlying cause of nearly all lake and other aquatic ecosystem degradation or overexploitation is inadequate governance. Based on examining lake management experiences around the world, the International Lake Environment Committee (ILEC 2005) has identified six major lake governance pillars requiring recognition and consideration:

1. policies, which essentially represent the 'rules of the game'
2. organisations, representing the entities responsible for carrying out the rules of the game
3. stakeholder participation—the meaningful involvement of all relevant stakeholders and rights-holders in implementing effective management plans
4. technology, involving selection of hard (constructions) versus soft (behavioural change) management approaches
5. knowledge and information, which can comprise both scientific studies and indigenous knowledge
6. finances, including identifying and ensuring sustainable sources of adequate financial support.

These six pillars make up the essential governance elements that collectively form the management regime for an integrated approach to managing lakes and their basins, as discussed in detail by Nakamura and Rast (2011). A practical lake management approach that considers both the scientific and the governance elements is encompassed within the concept of 'integrated lake basin management' (ILBM), as exemplified in the ILBM Platform Process developed by the International Lake Environment Committee (ILEC 2005; Figure 19.6).

Peatlands

Peatlands cover about 4 million square kilometres globally, although there is a degree of uncertainty about their extent (Joosten 2009; Figure 19.7). There are several definitions of peatlands, but they are generally considered to be areas of land with a naturally accumulated layer of peat, formed from carbon-rich dead and decaying plant material under waterlogged conditions, and comprising at least 30 per cent dry mass of dead organic material that is greater than 30 centimetres deep. They can develop under a range of vegetation including lowland or upland fens, reed beds, wet woodland, bogs and mangroves.

Peatlands occur in many countries and could represent more than one-third of global wetlands. The largest areas are found in the northern hemisphere, especially

in the boreal zone, with 1 375 690 square kilometres in Russia and 1 133 926 square kilometres in Canada (Joosten 2009). Estimates of peatlands from pre-1990 sources in tropical regions range from 275 424 to 570 609 square kilometres, although there has been extensive destruction in recent years (Hooijer et al. 2010).

Peatlands contain 10 per cent of the global freshwater volume and are significant for maintaining freshwater quality and the hydrological integrity of many rivers. They play an important role in maintaining permafrost and preventing desertification. In recent years, their importance as global carbon stores and sinks has come to the fore (Joosten 2009; Hooijer et al. 2010; Joosten et al. 2012). They support important biological diversity and are refugia for some of the rarest and most unusual species of wetland-dependent flora and fauna (Joosten and Clarke 2002). Under waterlogged conditions, they preserve a unique palaeoecological record, including valuable archaeological remains, and records of environmental contamination. They support human needs for food, fresh water, shelter, warmth and employment (Joosten and Clarke 2002).

Human pressures on peatlands are both direct—through drainage, land conversion (for example, for oil palms and oil sands), excavation and inundation—and indirect, as a result of air pollution, water contamination, water removal and infrastructure development. When they are destroyed, they release large amounts of carbon and are not easily restored. In response to the degradation of peatlands, the Ramsar Convention has adopted detailed *Guidelines for Global Action on Peatlands* (Ramsar 2002), including: establishing a global database of peatlands and detecting changes; developing and promoting awareness, education and training; reviewing national networks of peatland protected areas and implementing peatland management guidelines; and stimulating international cooperation on research and technology transfer.

More recently, guidance has been provided to limit the loss of carbon from peatlands and to encourage their retention and restoration as part of climate change mitigation measures (Joosten et al. 2012). This is particularly important given the past loss of peatlands globally and the more recent degradation of tropical peatlands (Joosten et al. 2012).

Groundwater-dependent ecosystems

Groundwater is often crucial to the maintenance of the hydrological regime supporting ecosystems: these are known as groundwater-dependent ecosystems (GDEs). The area of these ecosystems is often poorly defined.

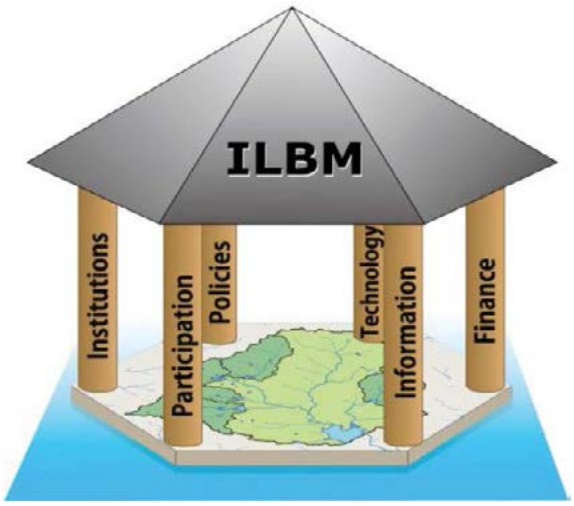


Figure 19.6 Integrated lake basin management
Source: Adapted from Nakamura and Rast (2012)

A change in the quantity or quality of groundwater, often associated with human activity, will impact on the state and condition of GDEs (Eamus and Froend 2006).

Richardson et al. (2011a) recognised three types of GDEs:

1. aquifer and cave ecosystems that provide unique habitats for organisms (for example, stygofauna and troglofauna—the animals which live underground), including karst aquifer systems, fractured rock and saturated sediments
2. ecosystems fully or partly dependent on the surface expression of groundwater, including wetlands, lakes, seeps, springs, river base flow, and some estuarine and marine ecosystems
3. ecosystems dependent on the subsurface presence of groundwater (via the capillary fringe), including terrestrial vegetation that depends on groundwater fully or on an irregular basis.

The degree of dependence on groundwater relative to other sources of water is important in differentiating these ecosystems and their response to changes in groundwater availability (Eamus et al. 2006). Of particular significance are the spatial and temporal variabilities in water tables and the nature of groundwater discharge into flowing or still surface water bodies. According to these interactions, different physico-chemical properties and species assemblages will develop (Horwitz et al. 2008).

Interest in GDEs has largely developed from a need to understand the consequences of direct use or pollution of aquifers. Both the quantity and the quality of groundwater are important as well as the spatial and temporary variability. These relationships can be disrupted by

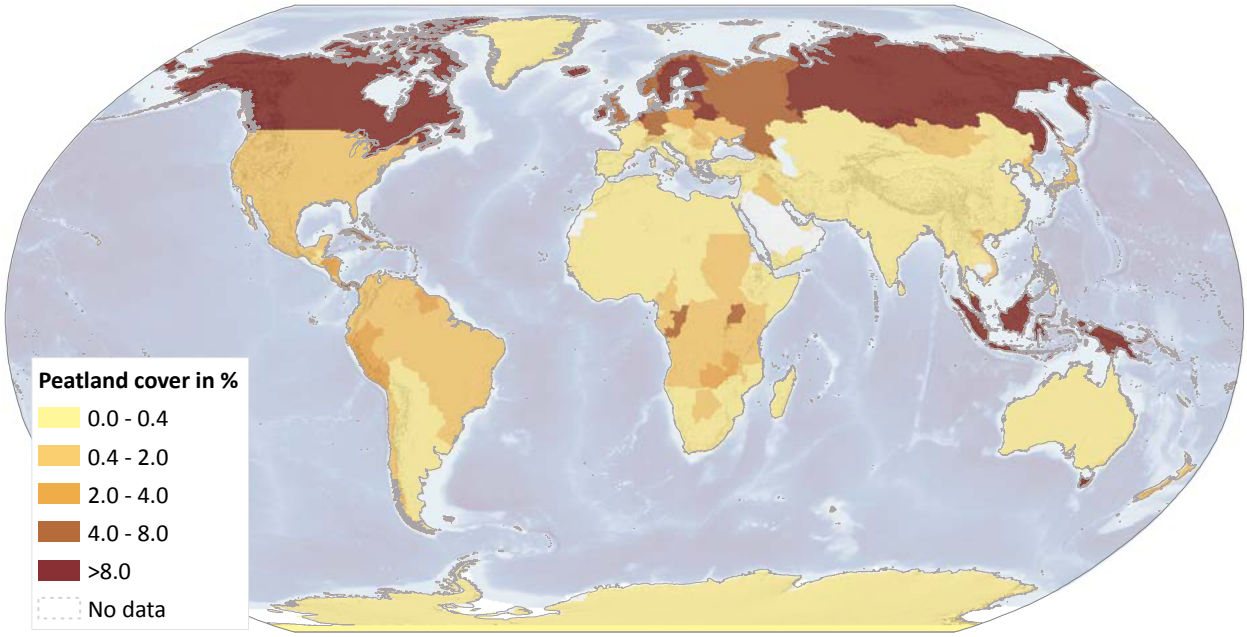


Figure 19.7 Global peatland distribution
Source: Adapted from IMCG Global Peatland Database 2014

changes to the groundwater through abstraction, pollution and reduction in rainfall recharge. Effective management of GDEs requires integration of associated surface and groundwater resources and necessitates an understanding of the origins, pathways and storages of water. For example, some GDEs are entirely maintained by continuous groundwater discharge while others are maintained by minor but critical groundwater inflows restricted to particular seasons or interannual episodes.

In general, processes that threaten GDEs are no different to those that threaten other ecosystems. Changes in groundwater can arise from reduced rainfall recharge, land clearing, forestry and agriculture, urbanisation and direct groundwater abstraction for water supply. The ecological changes brought about by these activities will vary between types of GDEs, depending on their hydrological requirements (Hatton and Evans 1998; Richardson et al. 2011a).

Identifying the importance of groundwater in ecosystems prior to development of groundwater resources (or other activities in a catchment) will inform resource planning and potential trade-offs. The array of current approaches to identifying groundwater requirements of GDEs is summarised by Richardson et al. (2011b), and ranges from measurement of groundwater transpiration by individual trees to hydrological water balances and remote sensing at the landscape scale. In most cases an integration of different approaches and associated disciplines and knowledge is required.

Management of GDEs can also be informed by understanding the potential for ecosystems to adapt to changes in groundwater availability. For example, some GDEs of the Swan Coastal Plain in Western Australia may have shifted to an alternative state (defined by biota and ecological processes) in accordance with changes in the groundwater regime (Froend and Sommer 2010; Sommer and Froend 2014). The potential of GDEs to adapt, however, can be limited under catastrophic (and largely irreversible) changes in the availability of groundwater, such as the widespread mortality of groundwater-dependent (phreatophytic) vegetation by groundwater abstraction in times of drought (Sommer and Froend 2011). In response, management agencies have assessed the threats to phreatophytic vegetation (Barron et al. 2013) and restricted groundwater pumping near vulnerable wetland ecosystems (McFarlane et al. 2012). In order to avoid such scenarios, integrating catchment management and balancing water demands with conservation are required.

Estuaries

The position of estuaries at the interface of the terrestrial and marine environment makes them vulnerable to the impacts of just about all human activities, whether land-based or marine, including the impacts of climate change. Estuaries are also a magnet for human activity. Thus, managing estuaries as protected areas can be particularly challenging, and its effectiveness often depends on managing external influences even more than on managing *in situ* activities. The successful

management of estuarine protected areas hinges on cooperative governance between a number of community and government stakeholders.

Estuarine functioning is primarily driven by the quantity and quality of freshwater inputs and their temporal distribution, plus inputs from the marine environment (Borja et al. 2011; Whitfield et al. 2012). Mediated by freshwater inflows and tides, fresh and salt waters mix in a nutrient-rich environment that supports a diversity of aquatic species. Freshwater abstraction decreases the overall quantity of freshwater entering estuaries. On the other hand, interbasin transfer schemes, wastewater treatment works and increased run-off from 'hardened' catchments (for example, road networks) increase freshwater inflow (Nirupama and Simonovic 2007).

Ideally, the freshwater flow into an estuary should be maintained in all its variability to support its overall habitat structure and dynamics (van Niekerk and Turpie 2012). Base flows are generally responsible for maintaining the salinity regime, and in the case of temporarily open systems, their connectivity to the sea (mouth state). In contrast, floods shape the geomorphological aspects such as the size and shape of an estuary and its characteristic sediment structure. These processes help to maintain the linkages between estuaries and their surrounding terrestrial, freshwater and marine systems. There are many species whose life history strategies depend on movement between these systems, for which the maintenance of open mouth conditions at the right time of year is essential. This includes many marine species of conservation and commercial value. Thus, estuaries should not be managed as isolated systems (van Niekerk and Turpie 2012).

In addition to the quantity of water entering estuaries, catchment activities and infrastructure also affect the quality of this water, in terms of the loads of sediments, nutrients and other pollutants (Turner et al. 2004). This can result in smothering of habitats, increased turbidity and eutrophication—all of which can result in significant changes in biotic communities and local extinctions. While some of the pollution entering estuaries arises from estuary users and adjacent settlements, these are largely problems that arise from the entire catchment area and require protected area managers to collaborate with relevant stakeholders.

The protection of an estuary therefore entails ensuring that the quantity and quality of freshwater inflows are maintained as close to natural as possible, in order to maintain ecological functioning and biodiversity in a relatively natural state. In reality, estuary managers have to deal with many changes that are difficult to reverse to the extent desired, if at all. Where this is the case, protection of estuaries can involve imposing artificial means such as flood-flow releases from dams and breaching the estuary artificially. These interventions are far more complex than trying to maintain natural processes, and require considerable investment in research and monitoring in order to devise strategies that achieve conservation goals. The Chilika Lagoon (Case Study 19.4) is such an example.

The endangered red-finned blue-eye (*Scaturiginichthys vermeilipinnis*) lives only in artesian springs, Edgbaston Reserve, Australia
Source: Adam Kerezsy

The main pressures that have to be managed within estuary systems are developments that encroach on estuary habitats, harvesting of resources such as fish and mangroves, aquaculture and the eradication or control of invasive alien species (Perissinotto et al. 2013). Managing the use of an estuary involves making trade-offs between the different types of values that it can generate (Turpie et al. 2007). For example, allowing subsistence fishing will impact on the provision of ecosystem services such as their functioning as nursery areas to support marine fisheries, and allowing excessive development and access will impact on the biodiversity of the system and its value as an ecotourism destination.

In order for the protection of estuaries to be successful, all of the following interventions at local to national scales are necessary:

- integrated conservation planning that takes landscape processes and socioeconomic trade-offs into account (Turpie and Clark 2007)

The restoration of Lake Chilika Ramsar site in India supports the livelihoods of fishers
Source: Ritesh Kumar

- catchment management and the setting of environmental flow requirements to assure provision of adequate quantity and quality of inflows to maintain the protected estuaries in a desired state of health (Adams 2013)
- management plans to control competing uses within estuaries
- restriction of consumptive use to prioritise conservation of biodiversity and the supply of regulating services such as nursery areas for crustaceans and fish, carbon sequestration and coastal protection
- delineation of development setback lines to protect landscape value as well as to accommodate estuary mouth migration, and water levels associated with changes in mouth state and sea-level rise.

EPA (2012) provides further information for good estuarine management.

Managing freshwater protected areas in the landscape

Ramsar Convention on Wetlands

The Convention on Wetlands of International Importance arose from concerns of governments and NGOs to conserve diminishing wetlands. It was the first modern environmental treaty and was agreed in the Iranian city of Ramsar in 1971. The Ramsar Convention also implements the inland waters program of work on behalf of the Convention on Biological Diversity (CBD) and complements the activities of the Convention on Migratory Species (and related treaties). While other treaties also cover specific sites or values, the Ramsar Convention is discussed in depth here due to its wetlands focus.

Contracting parties (countries) to Ramsar must designate at least one wetland for inclusion on the List of Wetlands of International Importance, known as the Ramsar List (Ramsar 2008). These sites are protected areas and are selected for designation using nine criteria (Table 19.3).

Case Study 19.4 Restoration of Lake Chilika, India

Chilika is an estuarine lagoon in Odisha State that seasonally covers an area of 906 to 1165 square kilometres, and is flanked by an ephemeral floodplain of 400 square kilometres (Figure 19.8). Chilika comprises shallow to very shallow marine, brackish and freshwater ecosystems with estuarine characteristics and is a hotspot of biodiversity, with more than one million overwintering migratory birds (Kumar and Pattnaik 2012). Chilika was designated as a Ramsar site in 1981 (IUCN Category VI).

The livelihoods of some 200 000 fishers and 400 000 farmers depend on the lagoon but were threatened when increased sediment from a degrading catchment reduced the connectivity of the lagoon to the sea, causing a rapid decline in fisheries (Mohapatra et al. 2007). The introduction of shrimp culture as well as the decline in fisheries led to resentment between traditional fishers and immigrants (Dujovny 2009). To restore the lake, in 1991 the Government of Odisha created the Chilika Development Authority, chaired by the chief minister and comprising senior representatives of all concerned departments as well as representatives of the fishing communities. It has programs for catchment restoration, hydrobiological monitoring, sustainable development of fisheries, wildlife conservation, community participation and development and capacity-building.

In 2000 a channel was created to reconnect the lagoon to the sea, and restoration of the hydrological and salinity regimes (Ghosh et al. 2006) led to the recovery of the fisheries and biodiversity. An integrated management planning process involving key stakeholders and rights-holders was initiated in 2008 to guide ongoing conservation of Chilika. A management planning framework was developed (Kumar and Pattnaik 2012), with a plan released in 2012.

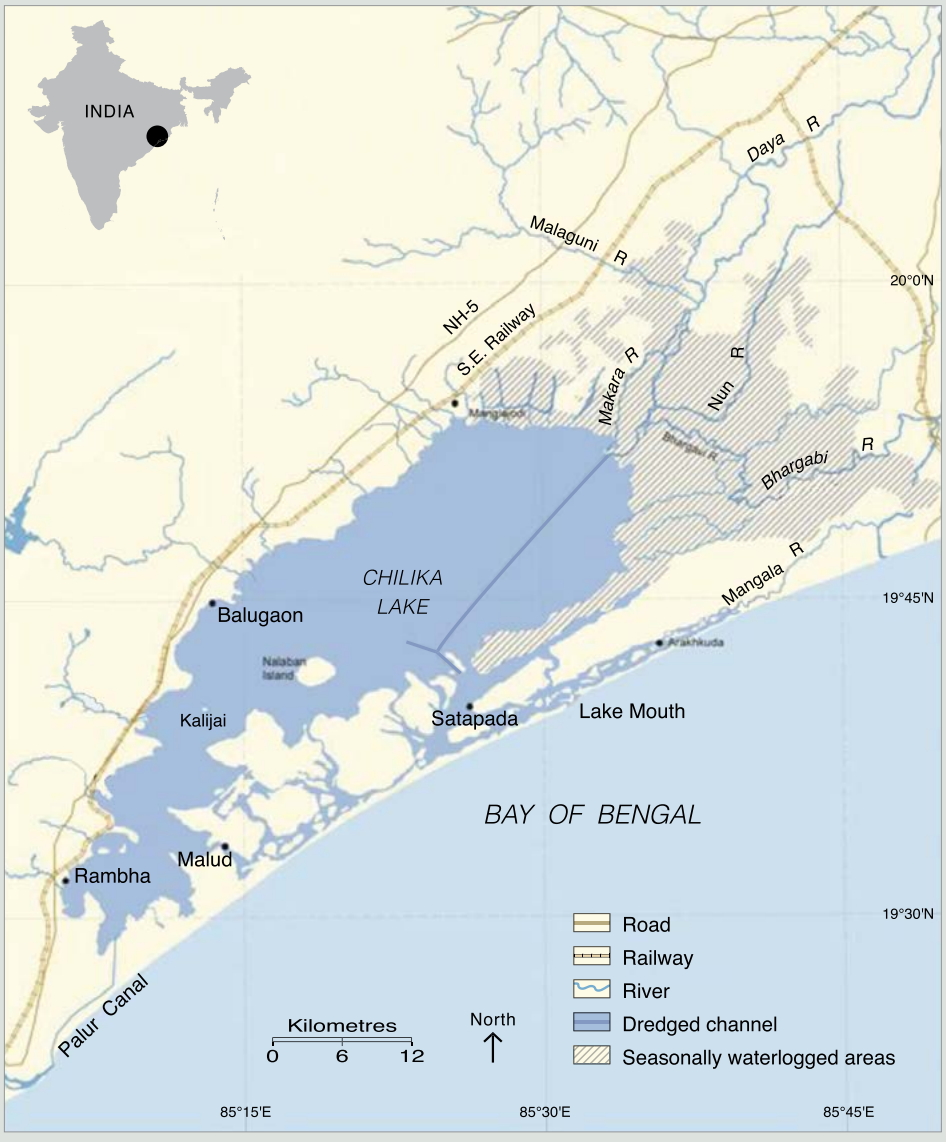


Figure 19.8 Chilika Lagoon, India

Source: Modified from Chilika Development Authority and Wetlands International

Table 19.3 Criteria for listing Wetlands of International Importance and long-term targets for the Ramsar List

Specific criterion	Long-term target
Contains a representative, rare or unique example of a natural or near-natural wetland type found within the appropriate biogeographical region	Include at least one suitable representative of each wetland type, according to the Ramsar classification system, which is found within each biogeographical region
Supports vulnerable, endangered or critically endangered species or threatened ecological communities	Include those wetlands that are believed to be important for the survival of vulnerable, endangered or critically endangered species or threatened ecological communities
Supports populations of plant and/or animal species important for maintaining the biological diversity of a particular biogeographical region	Include those wetlands that are believed to be of importance for maintaining the biological diversity within each biogeographical region
Supports plant and/or animal species at a critical stage in their life cycles, or provides refuge during adverse conditions	Include those wetlands that are the most important for providing habitat for plant or animal species during critical stages of their life cycle and/or when adverse conditions prevail
Regularly supports 20 000 or more waterbirds	Include all wetlands that regularly support 20 000 or more waterbirds
Regularly supports 1 per cent of the individuals in a population of one species or subspecies of waterbird	Include all wetlands that regularly support 1 per cent or more of a biogeographical population of a waterbird species or subspecies
Supports a significant proportion of indigenous fish subspecies, species or families, life history stages, species interactions and/or populations that are representative of wetland benefits and/or values and thereby contributes to global biological diversity	Include those wetlands that support a significant proportion of indigenous fish subspecies, species or families and populations
Important source of food for fishes, spawning ground, nursery and/or migration path on which fish stocks, either within the wetland or elsewhere, depend	Include those wetlands that provide important food sources for fishes, or are spawning grounds, nursery areas and/or on their migration path
Regularly supports 1 per cent of the individuals in a population of one species or subspecies of wetland-dependent non-avian animal species	Include all wetlands that regularly support 1 per cent or more of a biogeographical population of one non-avian animal species or subspecies

Source: Ramsar (2008)

The convention has a wide definition of wetlands that includes coastal, marine, artificial and inland ecosystems. A description of each designated wetland is provided by means of a Ramsar information sheet that includes data on scientific, conservation and management parameters and a map to delimit the boundaries of the site (Ramsar 2009b). Countries are encouraged to establish national wetland inventories as a basis for promoting the designation of the largest possible number of appropriate wetland sites. In 2012 only 43 per cent of countries had developed an inventory. A strategic framework provides a vision for the list to 'develop and maintain an international network of wetlands which are important for the conservation of global biological diversity and for sustaining human life through the maintenance of their ecosystem components, processes and benefits/services' (Ramsar 2008:Clause 6).

The strategic framework has objectives to:

- establish national networks of Ramsar sites that fully represent the diversity of wetlands and their key ecological and hydrological functions
- contribute to maintaining global biological diversity through the designation and management of appropriate wetland sites
- foster cooperation in the selection, designation and management of sites
- use the site network as a tool to promote national, supranational/regional and international cooperation over complementary environmental treaties (Ramsar 2008).

The list in 2014 contained 2177 sites covering 2.08 million square kilometres, which represents 16 per cent of the estimated 12.8 million square kilometres of global wetlands (Finlayson et al. 1999). There are 795 inland freshwater wetlands on the Ramsar List, covering a total area of 104.7 million square kilometres (Figure 19.9; Table 19.4).

A further requirement for countries under the Convention is to prepare and implement appropriate management plans for listed wetlands. Table 19.4 shows the regional extent of management planning instruments for inland

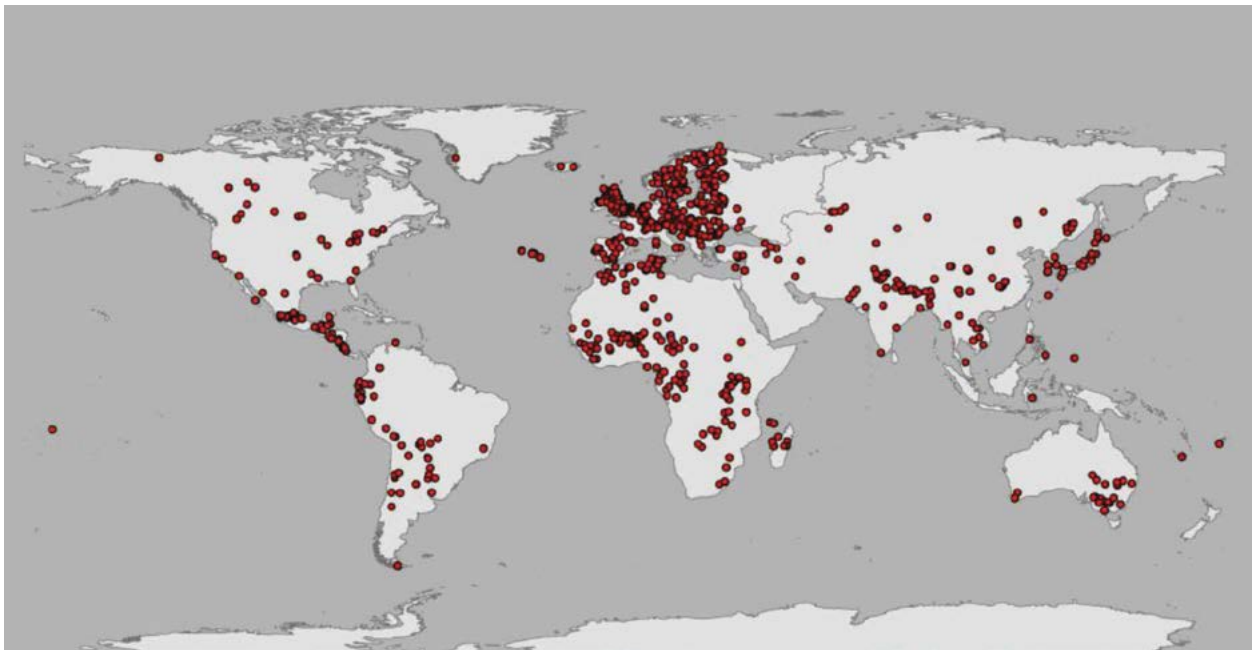


Figure 19.9 Distribution of inland freshwater Ramsar sites

Source: Adapted from Ramsar Sites Information Service

freshwater wetlands. The information provided does not indicate whether management plans are fully in place, regularly updated or effective in achieving the stated objective.

Countries undertake to make wise use of all wetlands and maintain their ecological character—the combination of the ecosystem components, processes and benefits/services that characterise the wetland. The convention also records reports of adverse change in the ecological character of Ramsar sites (Finlayson et al. 2011). These commitments are supported by an extensive suite of guidance for managers (Ramsar 2011). Reviews of the convention's implementation suggest Ramsar sites have stronger legal status and are better conserved than non-Ramsar protected areas (Bowman 2002). Kakadu National Park in Australia is an example of a prominent Ramsar site (Case Study 19.5).

Freshwater corridors

Rivers are nature's natural corridors. The flow of water, nutrients and sediments and the movement of species along streams generate consistent habitat in riparian corridors across terrestrial landscapes. These riparian and floodplain corridors are particularly biodiverse and often form key habitat for animals in the terrestrial landscape (Naiman et al. 1993). Tockner et al. (2008:51) conclude that 'far more species of plants and animals occur on floodplains than in any other landscape unit in most regions of the world'.

Consequently, the maintenance and restoration of riparian corridors are conservation priorities for both freshwater and terrestrial ecosystems.

Table 19.4 Number of inland freshwater wetlands included in the Ramsar List as of February 2014

Region	Number of wetlands	Area of wetlands (million sq km)	Number of wetlands with management plans
Africa	149 (19%)	71.2 (68%)	87 (58%)
Asia	105 (13%)	4.9 (5%)	74 (70%)
Europe	412 (52%)	5.5 (5%)	362 (85%)
Neotropics	55 (7%)	16.8 (16%)	44 (80%)
North America	51 (6%)	3.7 (4%)	47 (92%)
Oceania	23 (3%)	2.6 (2%)	23 (100%)
Total	795	104.7	637 (80%)

Source: Ramsar Sites Information Service

Case Study 19.5 Wetlands of Kakadu National Park, Australia

Kakadu National Park (IUCN Category II) is located to the east of Darwin in the north of Australia (Figure 19.10) and covers approximately 20 000 square kilometres, including most of the catchment of the South Alligator River. Wetlands include mangroves, salt flats, freshwater floodplains, small lakes (billabongs) as well as springs and pools (Finlayson and Woodroffe 1996). The importance of the wetlands has been recognised by the Ramsar Convention and the World Heritage Convention.

The park is a living cultural landscape and is jointly managed by Indigenous traditional landowners and the Federal Government. The management plan supports joint management and aims to maintain 'a strong and successful partnership between traditional owners, governments, the tourism industry and Park user groups, providing world's best practice in caring for country and sustainable tourism' (Kakadu Board of Management 2007:8).

The management plan and Ramsar ecological character description outline the major management issues (BMT WBM 2010). The park has active teams of rangers who control incursions of key weeds and introduced animals. Climate change and sea-level rise pose an increasing threat, with increased saltwater intrusion into freshwater wetlands and inland movement of mangroves. The mining and processing of uranium ore in an enclave surrounded by the park pose an ongoing threat to the wetlands.

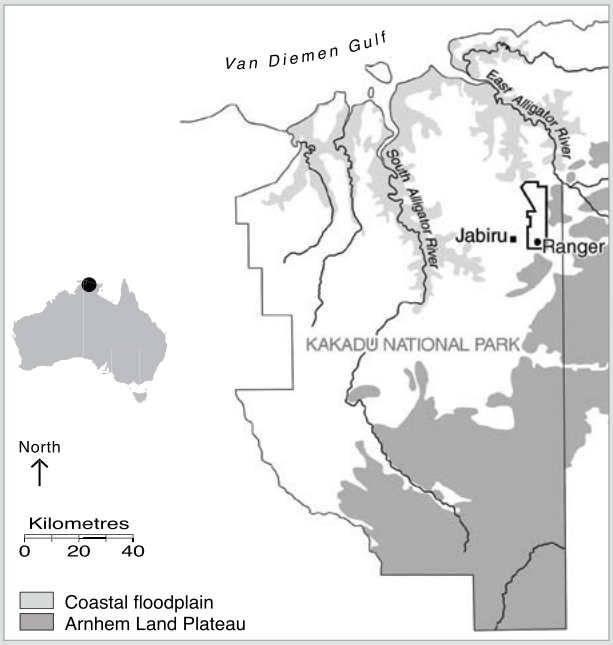


Figure 19.10 Kakadu National Park

Source: US NPS adapted from © Clive Hilliker Australian National University

There are considerable benefits to be gained from restoring riparian forests (Lukasiewicz et al. 2013). Riparian forests play key roles in providing organic matter that drives the aquatic food chain, forming physical habitat, filtering out pollutants and maintaining appropriate water temperatures. As a result of their geomorphic evolution, rivers provide the most gentle elevation gradients in the landscape and thus the ideal corridors for changes in distribution of many species under climate change.

A key question for managers restoring riparian corridors in areas where land use is contested is 'how wide is wide enough'. The simple answer is as wide as possible but specific assessment is required in each case (Spackman and Hughes 1995). The minimal answer could be wide enough to enable full development of the vegetation canopy to maximise shade across the relevant water body and form an adequate mesic (moist, humid) microclimate. Riparian vegetation is often thick and forms extensive shade and reduces air movement, forming a mesic microclimate that supports particular species and resists fire. A more ideal answer is that the full width of the regularly inundated riparian land should be restored—that is, the floodplain as distinguished by wetland vegetation and soils (DWAF 2008; Kotze et al. 1996).

In recent years landscape-scale linkage projects (see Chapter 27) have commenced in many regions of the world, including Australia, the United States and Europe (Wyborn 2011; Fitzsimons et al. 2013). Surprisingly, very few of these initiatives are centred on river corridors, unlike many linkage projects that are replete with biophysical barriers. Exceptions are the 'room for rivers' floodplain restoration programs along major rivers, such as those along the Danube (Ebert et al. 2009) and Rhine (Case Study 19.6). These combine habitat restoration, corridor establishment and ecosystem-based adaptation to climate change and reducing flood risk.

Catchment and water planning

Anthropogenic land use is a critical driver of terrestrial conditions that directly affect the structure, function and resilience of aquatic ecosystems (Dudgeon et al. 2006), including within protected areas. Different places within a catchment will support varied movement pathways for biotic and abiotic elements, which, in turn, drive different aquatic processes (Figure 19.12). River catchments generally do not coincide with lines of human ownership, including protected area boundaries (Figure 19.13), requiring managers to engage in catchment-wide land and water-use planning outside protected areas. These processes may include catchment visioning, scenarios and trade-offs around water use and allocation, and granting of water licences for new developments outside the protected area.

Unfortunately, conservation management has conventionally been separated from water resource management (Gilman et al. 2004). Protected area authorities, however, have a mandated responsibility to engage in planning for freshwater conservation. Where regional proactive development planning is absent, protected area authorities should catalyse these processes. Such proactive planning approaches will help to ensure that the water allocation and quality needed for freshwater conservation are met in downstream protected areas (Case Study 19.7). If the protected area is in a headwater catchment, protected area authorities may also wish to seek benefit-sharing opportunities for the water provided to downstream communities. Protected area authorities therefore act as powerful stakeholders and negotiators for freshwater conservation within integrated water resource management processes. Where water development (for example, the building of dams and other water schemes) upstream of a protected area is necessary, managers should insist on the establishment and enforcement of environmental flow requirements for sustaining ecosystems (Table 19.2; Hirji and Davis 2009).

Catchment management plans are a means of integrating the diverse land and water uses and owners, who, combined, may directly or indirectly influence the quality of a shared river system (Abell et al. 2007; Russi et al. 2013). They are opportunities for protected area managers to favourably influence stakeholders, rights-holders and neighbouring land users (Case Study 19.3). Successful examples of catchment management and planning usually involve collaboration between community, governmental and non-governmental stakeholders and rights-holders. Examples have been documented in the United States (Flitcroft et al. 2009), Australia (Curtis and Lockwood 2000), South Africa (King and Brown 2010) and Europe (Warner et al. 2013). More examples of what works and what does not are becoming available (Sadoff et al. 2008).

There are many names used globally for catchment management. The water sector often uses 'integrated water resources management' for management across water-using sectors and stakeholders/rights-holders (GWP 2000). To focus on ecological units, many organisations have focused on 'integrated river basin management' (WWF 2003) and 'integrated lake basin management' (as discussed above). In North America, the term 'watersheds' is often applied to catchments. The concept is also applied to groundwater basin management. Regardless of the jargon, good catchment management engages multiple stakeholders and rights-holders in applying a common vision for sustainably managing a shared basin. Defining and managing for sustainable levels of water withdrawal and water quality are common elements and will reinforce conservation efforts within protected areas.

The Ovens River is protected as a free-flowing 'heritage river', Australia

Source: Jamie Pittock

Learning forums help to build a common understanding, vision and policy around water use and protection, which are critical to stimulating the cooperation needed to support the sustainability of water resources (Ison and Watson 2007). To this end, protected area managers should convene or participate in cross-sectoral learning forums for effective integrated water resource management. At the grassroots level, protected area staff may focus mainly on building trusting relationships with other local stakeholders and rights-holders in the catchments, seeking a common agreement on how to collectively meet everyone's needs (Etienne et al. 2011). At the managerial level, engagement with water resource decision-makers is required to ensure their policy processes are aligned to the needs of the protected area (Collins et al. 2009). At the protected area systems level, these forums should seek a common vision and cross-sectoral cooperation between departments (Roux et al. 2008).

Case Study 19.6 Millingerwaard, the Netherlands

The Millingerwaard is an area of former farmland on the floodplain along the Rhine River (Figure 19.11). Alluvial forests, marshlands, natural grasslands, surface waters and river dunes have been restored over two decades for nature conservation, recreation and flood management (Bekhuis et al. 2005). The 800 hectares are a Natura 2000 site and IUCN Category II area managed by the State Forestry Commission.

An agreement with commercial clay and sand extraction companies saw extraction of historical clay deposits following the underlying geographical relief to uncover the natural structure of the riverine landscape (Bekhuis et al. 2005). In this way river safety is improved by giving room for the river to manage flood peaks. Species like beaver (*Castor fiber*), badger (*Meles meles*), black stork (*Ciconia nigra*) and the white-tailed eagle (*Haliaeetus albicilla*) have returned to the floodplains. Old breeds of cattle and horses that mimic extinct herbivores roam the area and, together with beavers, deer and geese, control vegetation to improve spatial variety and create habitats for other species. Millingerwaard is a demonstration site for the 'Living Rivers' vision developed by the World Wide Fund for Nature (WWF) in the Netherlands in the 1990s (Helmer et al. 1992). The approach has been replicated along other parts of the Rhine River to contribute to reduced flood risk, recreation and biodiversity conservation.

The restored Millingerwaard has become a very popular recreational area, and it is estimated there has been an increase of €6 million a year in the regional economy (Bekhuis et al. 2005). Success factors include cooperation between businesses and nature and water management agencies, and the economic benefits from recreation. Challenges include maintaining high natural values and flood safety—for example, inundation-free refuges for the wild herbivores may obstruct river flow.

Floodplain restoration, Rhine River, at the Millingerwaard, the Netherlands

Source: Dirk Oomen, Stroming Ltd.

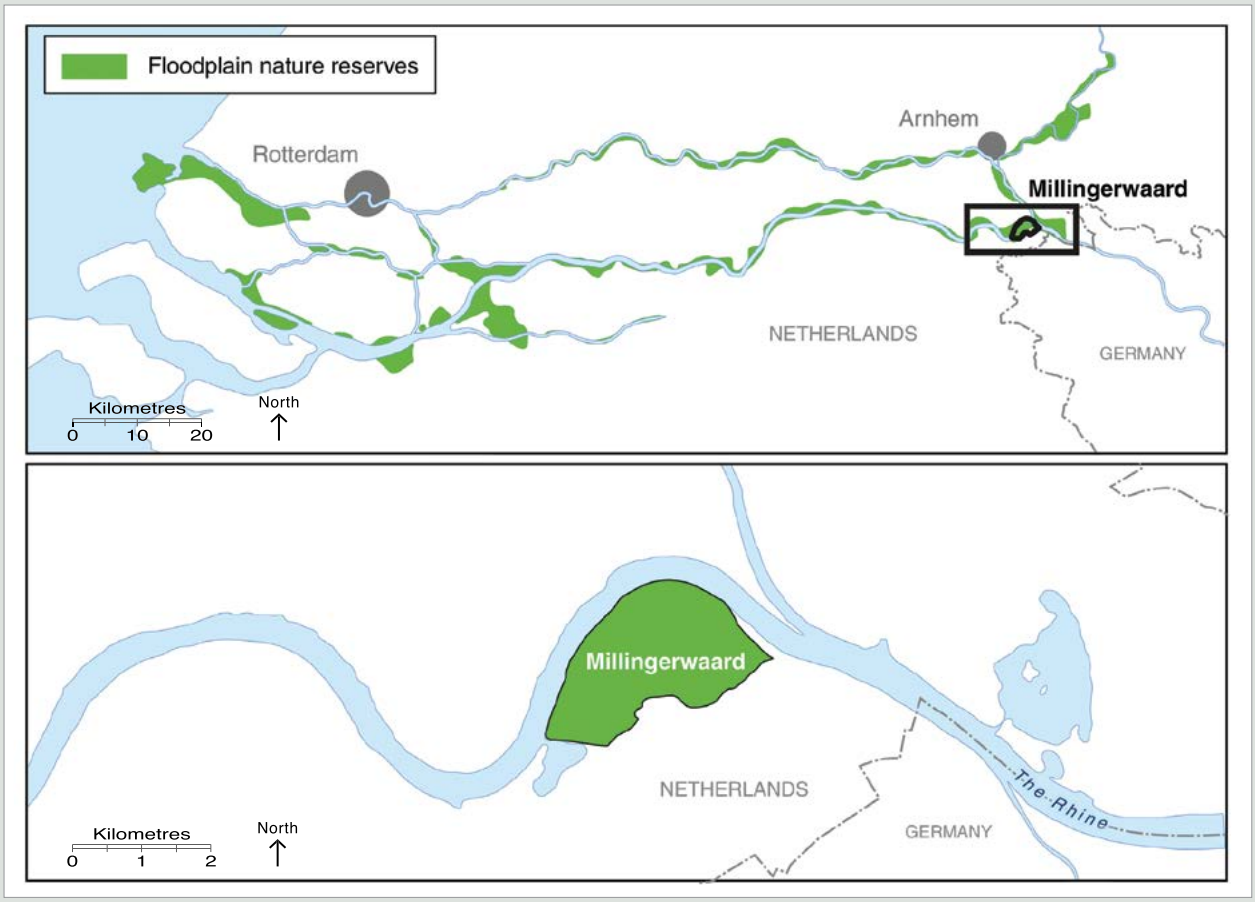


Figure 19.11 Millingerwaard, the Netherlands, showing nature reserves developed along the Rhine River
Source: © Clive Hilliker, The Australian National University

Climate change

Climate has primary, direct and indirect sets of influences on the location, phenology and phenotypic expression of a water body, and the interactions within populations and between species (Parmesan 2006). Water flows and dependant biota are intimately linked to the climate (Poff and Matthews 2013). Climate change will see the extension of the range of 'new' native species into protected areas, and this may signal effective autonomous adaptation rather than a species invasion that should be resisted. Likewise, declines in abundance may be evidence of a range shift. Species will need to be monitored and managed at a regional scale (Poff et al. 2010). More sessile or isolated species may require assistance to disperse to and establish in new habitats (Hannah 2010). Further, managing for a fixed ecological community definition may be counterproductive to effective climate-adaptive management (Matthews et al. 2011; Catford et al. 2012).

A range of climate change adaptation interventions has been proposed to better conserve freshwater biodiversity in wetland protected areas and river systems, including a set of options detailed in Australia (Arthington 2012; Lukasiewicz et al. 2013). These involve identifying and prioritising conservation of parts of the freshwater landscape that may be more resilient to climate change and which can provide refugia, such as river reaches shaded by mountains or those that form corridors that may enable species to move to more favourable habitats. Another option is to manage environmental flows to counter climate change impacts (Olden and Naiman 2010; Poff and Matthews 2013). Generally these flow measures are only possible on rivers with operable dams (Pittock and Hartmann 2011). These approaches require management institutions to maintain infrastructure and make timely decisions—for instance, to release water from dams. In contrast, free-flowing rivers do not require day-to-day management to provide the flows needed to conserve aquatic species, but they may be at risk from climate-induced changes that cannot be addressed without infrastructure (Pittock and Finlayson 2011).

Planning for freshwater conservation by national and provincial agencies in South Africa

Source: Dirk Roux

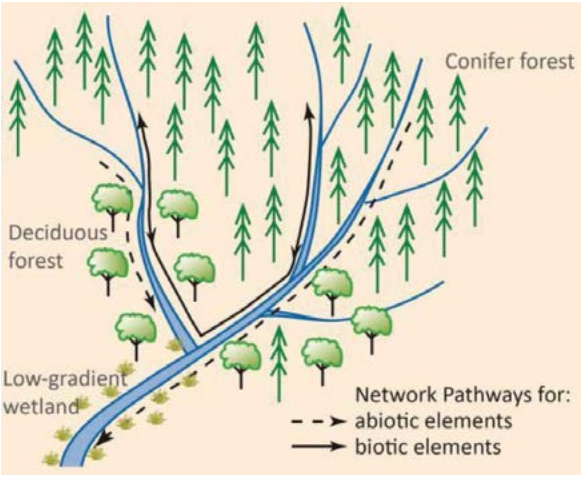


Figure 19.12 Ecological movement pathways: Movement pathways differ for biotic versus abiotic elements in a stream system; abiotic elements must move in the direction of water flow, compared with biotic elements that may also move against river flow

Source: US Department of Agriculture

Many adaptation measures are 'no regrets' measures that offer benefits for the environment and people regardless of climate change. The restoration of riparian forests to shade adjoining freshwater ecosystems and provide other conservation benefits is one example (Davies 2010). At Millingerwaard (Case Study 19.6), restoration of the Rhine River floodplain as a climate change adaptation measure reduces flood risk and conserves biodiversity. The co-benefits for different groups of people associated with these no-regrets adaptation measures provide opportunities to build greater support from stakeholders and rights-holders for conservation.

Upgrading the safety standards of existing water infrastructure for climate change provides opportunities for protected area managers to secure further changes to aid biodiversity adaptation, such as by installing fish passages on dams (Matthews et al. 2011; Pittock and Hartmann 2011). Proposed engineering interventions that use less water to conserve aquatic biodiversity, known as 'environmental water demand management' or 'environmental works and measures', are politically appealing but risk unforeseen environmental impacts and management failure, and should be considered with caution (Pittock et al. 2012; Case Study 19.7).

Infrastructure includes both built and 'natural' ecohydrological components of the landscape. Many institutions are promoting greater conservation of the environment to increase resilience to climate change impacts and aid adaptation. Jargon used to describe this approach includes 'green infrastructure', 'natural capital', 'ecosystem management', 'ecosystem-based adaptation' and 'ecosystem services' (IEMP 2011). These approaches often favour conservation of freshwater ecosystems.

Too often, decision-makers fix their attention on one intervention when each adaptation option has risks and costs as well as benefits that should be identified. The adoption of a suite of different but complementary interventions may spread risk, maximise benefits and avoid perverse outcomes. The use of environmental flows on regulated rivers linked to protection of free-flowing rivers is an example. With this in mind, Lukasiewicz et al. (2013) developed a catchment-scale framework for working with stakeholders and rights-holders to assess the risks, costs and benefits of options for climate change adaptation. As climate change will impact most if not all protected areas, these measures can help managers to assess priorities and achieve the best possible outcomes (see Chapter 17).

Conclusion

Although Earth's area supporting freshwater and estuarine ecosystems is relatively small, the biodiversity these systems support is particularly threatened at a global scale. We have outlined the characteristics of diverse types of ecosystems and how their conservation is critical to a core mission of protected area managers in conserving biodiversity.

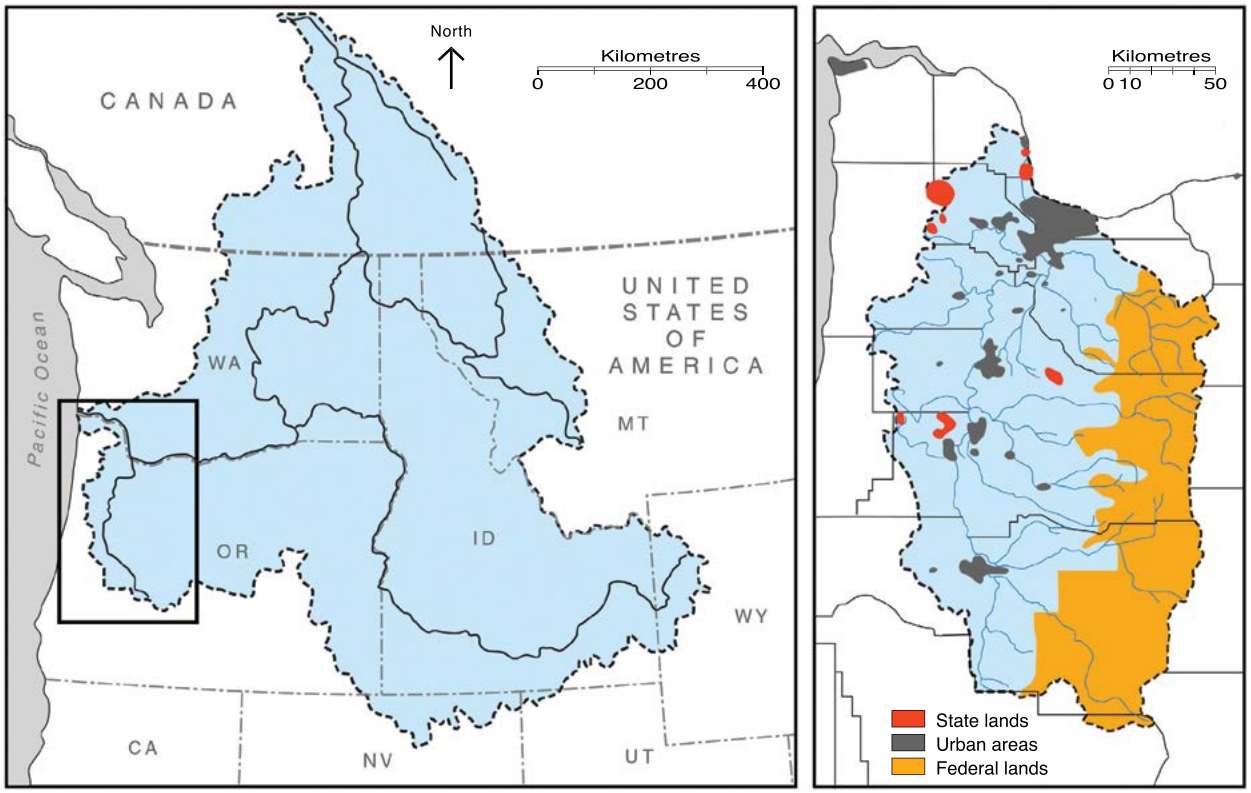


Figure 19.13 Catchments and jurisdictional boundaries: The Columbia River catchment crosses international and State/Provincial borders; the smaller Willamette River catchment crosses multiple local government borders and landownerships divided between the US Federal Government, the State of Oregon and private holdings

Source: © Clive Hilliker, The Australian National University

Freshwater ecosystems are challenging to conserve because the ecological processes that drive them, particularly water flows, are readily disrupted by people's demands for energy, food and water. People live by and irrevocably change freshwater systems, creating challenges but also opportunities for protected area managers to gain new audiences and supporters.

There are two golden rules for maintaining or restoring freshwater biodiversity. First, conserve the quality, timing and volume of water flows. Second, ensure connectivity is retained—along rivers, between water bodies and their floodplains, and vertically with natural variability in the depth of water bodies and connectivity with groundwater. This chapter has outlined why it is critical and how protected area managers can engage other stakeholders and rights-holders in landscape-scale water management. We urge managers to challenge development proponents and operators to ensure that existing and new water infrastructure are essential, and if so, that the structures and management regimes incorporate mitigation measures like environmental flows and fish passage facilities. Within protected areas, wildlife and visitor activities are usually focused on water bodies, making them a target and a challenge for managers.

Many terrestrially focused protected areas involve trade-offs and interventions that unwittingly degrade freshwater habitats. Hydropower and water-supply developments that establish or fund protected areas in catchments may do so at the expense of freshwater biodiversity. In these circumstances, managers have an obligation to ensure freshwater biodiversity is conserved as effectively as possible along the full length of rivers.

The reality of climate change will exacerbate competition between people and ecosystems for fresh water in many parts of the world. There are conflicts and positive synergies between different climate change mitigation and adaptation measures for water that protected area managers should engage. For example, planting trees to sequester carbon will normally diminish river flows, whereas strengthening dams to meet greater climatic extremes provides opportunities to mitigate ecological impacts, such as by adding fish passage facilities and providing environmental flows. Further, rivers are the

Case Study 19.7 Murray–Darling Basin Ramsar wetlands, Australia

The Murray–Darling Basin covers about 1 million square kilometres (or one-seventh) of Australia (Figure 19.14). Large floodplain forests and other wetlands cover more than 5.7 million hectares (5.6 per cent of the basin), with 636 300 hectares designated as 16 Ramsar sites (Pittock et al. 2010). The tenure of these site includes nature reserves (IUCN Category II) managed by state governments and NGOs, forestry and hunting reserves (IUCN Category VI) managed by state governments, and small areas of privately managed pastoral lands (IUCN Category VI). The waters of the basin are so exploited that median annual end-of-river flows have fallen to 29 per cent of pre-development levels. Vast areas of wetlands have suffered from changes in water flows, desiccation, salinity and acid sulphate generation (Pittock and Finlayson 2011).

In 2007–08 the national *Water Act* was adopted based on Australia's obligations to implement the Convention on Biological Diversity and the Ramsar Convention, and requires conservation of key environmental assets and ecosystem functions and services (Pittock et al. 2010). In 2012 a basin plan was adopted that could see up to 3200 gigalitres per annum (29 per cent of the water diverted for consumption) returned to the environment by 2024. The acquired water entitlements are owned and independently managed for conservation by the Federal Government's Commonwealth Environmental Water Holder (Connell 2011).

Engineering interventions known as 'environmental works and measures' are being deployed in an attempt to conserve wetland biodiversity with less water. They risk disrupting habitat connectivity and concentrating salt in wetlands, and rely on timely state government operations and maintenance (Pittock et al. 2012). While restoring adequate flows is important, other important actions have been overlooked, including restoring riparian forests, protecting remaining free-flowing rivers, re-engineering dams to eliminate cold-water pollution and restoring fish passage (Pittock and Finlayson 2011). As the basin plan is to be revised at least every 10 years, there is increased potential for further adaptive management of water allocations and other measures.

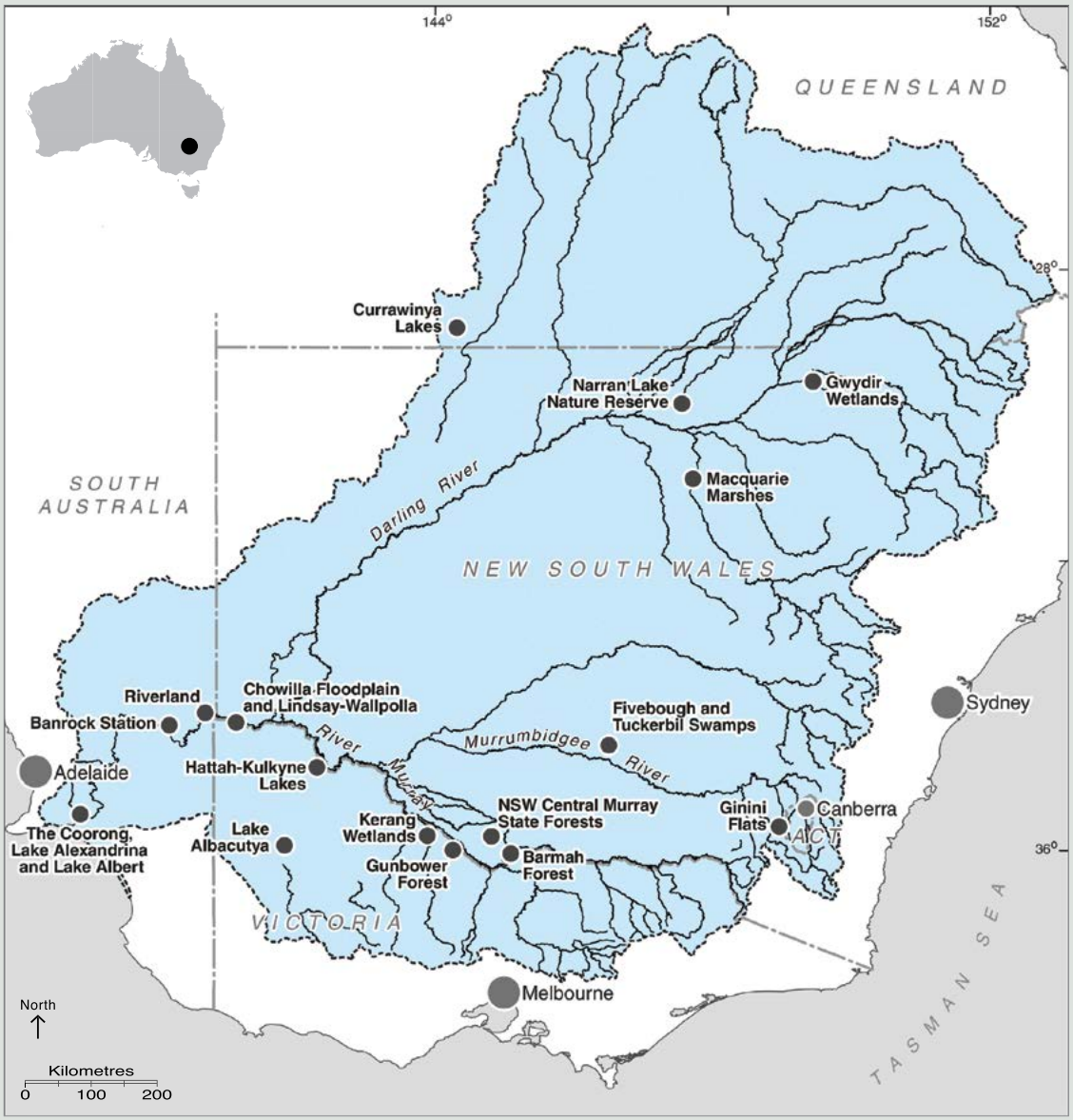


Figure 19.14 Murray–Darling Basin, showing the location of 16 designated Ramsar wetlands

Source: © Clive Hilliker, The Australian National University

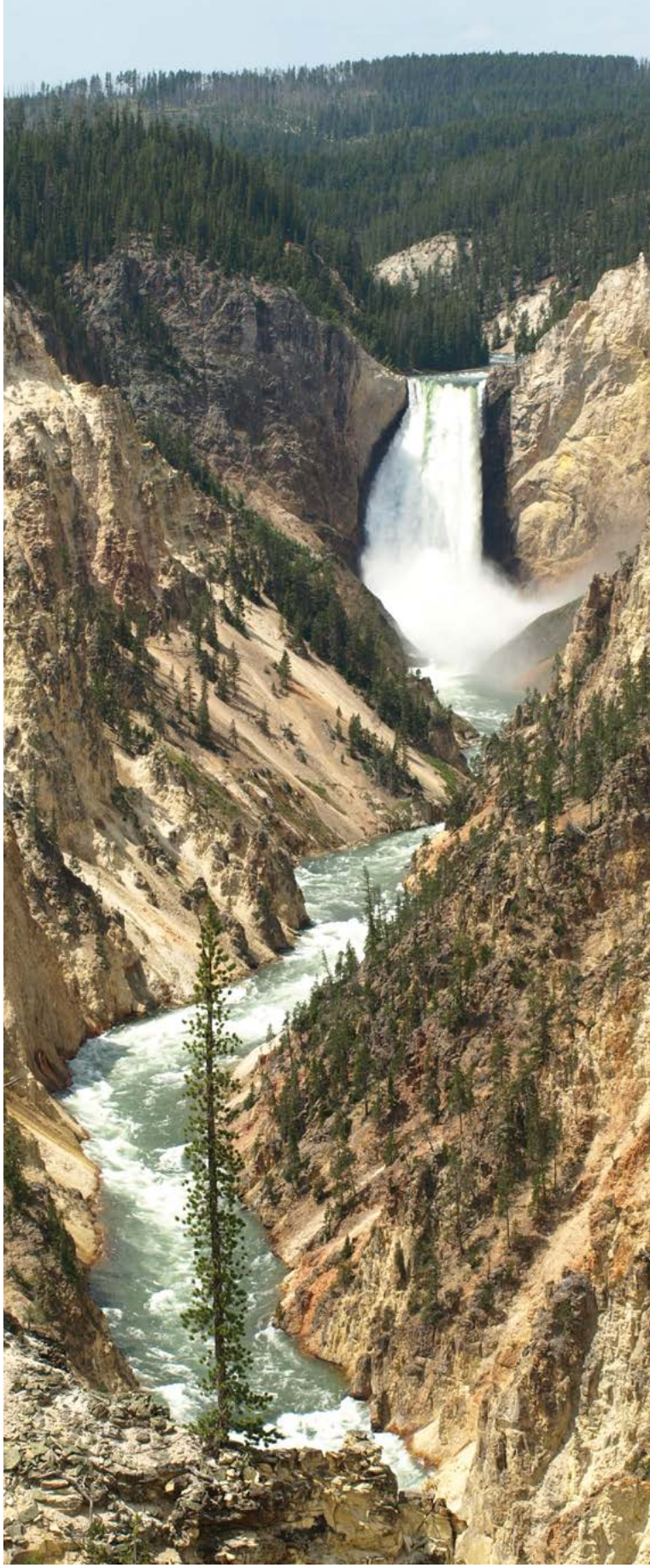
Needs water: the desiccated, acidified and salinised Bottle Bend floodplain, Murray River, Australia

Source: Jamie Pittock

natural landscape corridors with variable gradients, flows of water, nutrients and species for linking protected areas, including for climate change adaptation.

Conserving freshwater ecosystems also involves opportunities for securing the future of protected areas. People's interest in clean and secure water and in freshwater ecosystems is an opportunity to involve neighbours and the broader public in collaborative visioning and management activities.

Of course, conservation of each ecosystem is linked to outcomes for others, and none more so than in the case of freshwater and marine protected areas. Rivers and many aquifers discharge into the sea, bringing with them nutrients that stoke, or pollutants and silt that smother marine communities. Rivers and estuaries are critical breeding grounds for many largely marine species necessitating integrated management.



Yellowstone Falls and the Grand Canyon of the Yellowstone River, Yellowstone National Park, USA, a World Heritage property. This outstanding river is an undisturbed tributary of the Missouri River, which then flows to the Mississippi River before the waters reach the Gulf of Mexico.

Source: Graeme L. Worboys

References

Recommended reading

Abell, R., Allan, J. D. and Lehner, B. (2007) 'Unlocking the potential of protected areas for freshwaters', *Biological Conservation* 134: 48–63.

Abell, R., Thieme, M., Revenga, C., Bryer, M., Kottelat, M., Bogutskaya, N., Coad, B., Mandrak, N., Contreras-Balderas, S., Bussing, W., Stiassny, M. L. J., Skelton, P., Allen, G. R., Unmack, P., Naseka, A., Ng, R., Sindorf, N., Robertson, J., Armijo, E., Higgins, J., Heibel, T. J., Wikramanayake, E., Olson, D., Lopez, H. L., Reis, R. E., Lundberg, J. G., Sabaj Perez, M. H. and Petry, P. (2008) 'Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation', *Bioscience* 58: 403–14.

Adams, J. B. (2013) 'A review of methods and frameworks used to determine the environmental water requirements of estuaries', *Hydrological Sciences Journal* 59: 451–65.

Arthington, A. H. (2012) *Environmental Flows: Saving rivers in the third millennium*, University of California Press, Berkeley.

Arthington, A. H., Bunn, S. E., Poff, N. L. and Naiman, R. J. (2006) 'The challenge of providing environmental flow rules to sustain river ecosystems', *Ecological Applications* 16: 1311–18.

Arthington, A. H., Naiman, R. J., McClain, M. E. and Nilsson, C. (2010) 'Preserving the biodiversity and ecological services of rivers: new challenges and research opportunities', *Freshwater Biology* 55: 1–16.

Arthington, A. H., Rall, J. L., Kennard, M. J. and Pusey, B. J. (2003) 'Environmental flow requirements of fish in Lesotho rivers using the DRIFT methodology', *River Research and Applications* 19: 641–66.

Balian, E. V., Segers, H., Martens, K. and Lévéque, C. (2008) 'The freshwater animal diversity assessment: an overview of the results', in E. V. Balian, C. Lévêque, H. Segers and K. Martens (eds) *Freshwater Animal Diversity Assessment. Volume 198*, Springer, Netherlands.

Barron, O., Froend, R. H., Hodgson, G., Ali, R., Dawes, W., Davies, P. and McFarlane, D. (2013) 'Projected risks to groundwater-dependent terrestrial vegetation caused by changing climate and groundwater abstraction in the Central Perth Basin, Western Australia', *Hydrological Processes*, [online]. <doi:10.1002/hyp.10014>

Baumgartner, L. J., Reynoldson, N. K., Cameron, L. and Stanger, J. G. (2009) 'Effects of irrigation pumps on riverine fish', *Fisheries Management and Ecology* 16: 429–37.

Bekhuis, J., Litjens, G. and Braakhekke, W. (2005) *A Policy Field Guide to the Gelderse Poort: A new, sustainable economy under construction*, WWF-Netherlands, Zeist.

Biggs, H. and Rogers, K. H. (2003) 'An adaptive system to link science, monitoring and management in practice', in J. T. du Toit, K. H. Rogers and H. C. Biggs (eds) *The Kruger Experience: Ecology and management of savanna heterogeneity*, pp. 59–80, Island Press, Washington, DC.

BioFresh (2013) BioFresh data portal, BioFresh Project, Berlin. <data.freshwaterbiodiversity.eu/>

BMT WBM (2010) *Ecological Character Description for Kakadu National Park Ramsar Site*, Department of Sustainability, Environment, Water, Population and Communities, Canberra.

Borja, A., Basset, A., Bricker, S., Dauvin, J.-C., Elliott, M., Harrison, T. D., Marques, J.-C., Weisberg, S. B. and West, R. (2011) 'Classifying ecological quality and integrity of estuaries', in E. Wolanski and D. McLusky (eds) *Treatise on Estuarine and Coastal Science*, pp. 125–62, Academic Press, Waltham, MA.

Bossio, D., Geheb, K. and Critchley, W. (2010) 'Managing water by managing land: addressing land degradation to improve water productivity and rural livelihoods', *Agricultural Water Management* 97: 536–42.

Bovee, K. D. (1982) *A guide to stream habitat analysis using the IFIM*, US Fish and Wildlife Service Report FWS/OBS-82/26, Fort Collins, CO.

Bowman, M. (2002) 'The Ramsar Convention on Wetlands: has it made a difference?', in O. S. Stokke and Ø. B. Thommessen (eds) *Yearbook of International Co-Operation on Environment and Development 2002/2003*, pp. 61–8, Earthscan, London.

Bowman, B., Higgs, S., Maclin, E., McClain, S., Sicchio, M., Amy Souers, A., Johnson, S. and Brian Graber, B. (2002) *Exploring Dam Removal: A decision-making guide*, American Rivers and Trout Unlimited, Washington, DC, and Madison, WI.

Brisbane Declaration (2007) *The Brisbane Declaration*. <www.eflownet.org/>

Brits, J., van Rooyen, M. W. and van Rooyen, N. (2002) 'Ecological impact of large herbivores on the woody vegetation at selected watering points on the eastern basaltic soils in the Kruger National Park', *African Journal of Ecology* 40: 53–60.

Bruijnzeel, L. A. (2004) 'Hydrological functions of tropical forests: not seeing the soil for the trees?', *Agriculture, Ecosystems & Environment* 104: 185–228.

Bunn, S. E. and Arthington, A. H. (2002) 'Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity', *Environmental Management* 30: 492–507.

Campbell-Grant, E. H., Lowe, W. H. and Fagan, W. F. (2007) 'Living in the branches: population dynamics and ecological processes in dendritic networks', *Ecology Letters* 10: 165–75.

Catford, J., Naiman, R., Chambers, L., Roberts, J., Douglas, M. and Davies, P. (2012) 'Predicting novel riparian ecosystems in a changing climate', *Ecosystems* 16: 382–400.

Chape, S., Spalding, M. and Jenkins, M. D. (2008) *The World's Protected Areas*, Prepared by the UNEP-WCMC, University of California Press, Berkeley.

Chatterjee, A., Phillips, B. and Stroud, D. A. (2008) *Wetland Management Planning: A guide for site managers*, WWF, Wetlands International, IUCN and Ramsar Convention Secretariat, Gland.

Chessman, B. C. (2013) 'Do protected areas benefit freshwater species? A broad-scale assessment for fish in Australia's Murray–Darling Basin', *Journal of Applied Ecology* 50: 969–76.

Collier, K. J. (2011) 'The rapid rise of streams and rivers in conservation assessment', *Aquatic Conservation—Marine and Freshwater Ecosystems* 21: 397–400.

Collins, K., Colvin, J. and Ison, R. (2009) 'Building "learning catchments" for integrated catchment managing: designing learning systems based on experiences in the UK and South Africa', *Water Science and Technology* 59: 687–93.

Commonwealth of Australia (2012) *Basin Plan*, Commonwealth of Australia, Canberra.

Connell, D. (2011) 'The role of the Commonwealth Environmental Water Holder', in D. Connell and R. Q. Grafton (eds) *Basin Futures: Water reform in the Murray–Darling Basin*, pp. 327–38, ANU E Press, Canberra.

Convention on Biological Diversity (CBD) (2010) *X/28. Inland waters biodiversity*, UNEP/CBD/COP/DEC/X/28, Secretariat of the Convention on Biological Diversity, Montreal.

Curtis, A. and Lockwood, M. (2000) 'Landcare and catchment management in Australia: lessons for state-sponsored community participation', *Society and Natural Resources: An International Journal* 13: 61–73.

Darwall, W. R. T., Smith, K. G., Allen, D. J., Holland, R. A., Harrison, I. J. and Brooks, E. D. E. (2011) *The Diversity of Life in African Freshwaters: Underwater, under threat. An analysis of the distribution of freshwater species throughout mainland Africa*, Cambridge Publishers, Cambridge and Gland.

Davies, P. M. (2010) 'Climate change implications for river restoration in global biodiversity hotspots', *Restoration Ecology* 18: 261–8.

Davies, P. M., Naiman, R. J., Warfe, D. M., Pettit, N. E., Arthington, A. H. and Bunn, S. E. (2014) 'Flow–ecology relationships: closing the loop on effective environmental flows', *Marine and Freshwater Research* 65: 133–41.

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., Naiman, R. J., Prieur-Richard, A. H., Soto, D. and Stiassny, M. L. (2006) 'Freshwater biodiversity: importance, threats, status and conservation challenges', *Biological Reviews* 81: 163–82.

Dudley, N. (ed.) (2013) *Guidelines for Applying Protected Area Management Categories*, IUCN, Gland.

Dujovny, E. (2009) 'The deepest cut: political ecology in the dredging of a new sea mouth in Chilika Lake, Orissa, India', *Conservation & Society* 7: 192–204.

Department of Water Affairs and Forestry (DWAF) (2008) *Updated Manual for the Identification and Delineation of Wetlands and Riparian Areas*, Department of Water Affairs and Forestry, Pretoria.

Dyson, M., Bergkamp, G. and Scanlon, J. (eds) (2003) *Flow: The essentials of environmental flows*, IUCN, Gland.

Eamus, D. and Froend, R. (2006) 'Groundwater-dependent ecosystems: the where, what and why of GDEs', *Australian Journal of Botany* 54: 91–6.

Eamus, D., Froend, R., Loomes, R., Hose, G. and Murray, B. (2006) 'A functional methodology for determining the groundwater regime needed to maintain the health of groundwater-dependent vegetation', *Australian Journal of Botany* 54: 97–114.

Ebert, S., Hulea, O. and Strobel, D. (2009) 'Floodplain restoration along the Lower Danube: a climate change adaptation case study', *Climate and Development* 1: 212–19.

Environmental Protection Agency (EPA) (2012) *Estuaries and Coastal Watersheds*, United States Environmental Protection Agency, Washington, DC. <water.epa.gov/type/oceb/nep/index.cfm>

Esselman, P. and Allan, J. D. (2011) 'Application of species distribution models and conservation planning software to the design of a reserve network for the riverine fishes of northeastern Mesoamerica', *Freshwater Biology* 56: 71–88.

Etienne, M., du Toit, D. R. and Pollard, S. (2011) 'ARDI: a co-construction method for participatory modeling in natural resources management', *Ecology and Society* 16: 44.

Faleiro, F. V. and Loyola, R. D. (2013) 'Socioeconomic and political trade-offs in biodiversity conservation: a case study of the Cerrado Biodiversity Hotspot, Brazil', *Diversity and Distributions* 19: 977–87.

Finlayson, C. M. and van der Valk, A. G. (1995) 'Wetland classification and inventory: a summary', *Vegetation* 118: 185–92.

Finlayson, C. M. and Woodroffe, C. D. (1996) 'Wetland vegetation', in C. M. Finlayson and I. von Oertzen (eds) *Landscape and Vegetation Ecology of the Kakadu Region, Northern Australia*, pp. 81–112, Kluwer Academic Publishers, Dordrecht.

Finlayson, C. M., Davidson, N., Pritchard, D., Milton, G. R. and MacKay, H. (2011) 'The Ramsar Convention and ecosystem-based approaches to the wise use and sustainable development of wetlands', *Journal of International Wildlife Law & Policy* 14: 176–98.

Finlayson, C. M., Davidson, N. C., Spiers, A. G. and Stevenson, N. J. (1999) 'Global wetland inventory—current status and future priorities', *Marine and Freshwater Research* 50: 717–27.

Fitzsimons, J., Pulsford, I. and Wescott, G. (2013) 'Lessons from large-scale conservation networks in Australia', *Parks* 19: 115–25.

Fleckenstein, J., Anderson, M., Fogg, G. and Mount, J. (2004) 'Managing surface water–groundwater to restore fall flows in the Cosumnes River', *Journal of Water Resources Planning and Management* 130: 301–10.

Flitcroft, R. L., Dedrick, D. C., Smith, C. L., Thieman, C. A. and Bolte, J. P. (2009) 'Social infrastructure to integrate science and practice: the experience of the Long Tom Watershed Council', *Ecology and Society* 14(36). <www.ecologyandsociety.org/vol14/iss2/art36/>

Freshwater Fish Specialist Group (FFSG) (2013) *Global Freshwater Fish Bioblitz*, IUCN Freshwater Fish Specialist Group, Chester, UK.

Froend, R. and Sommer, B. (2010) 'Phreatophytic vegetation response to climatic and abstraction-induced groundwater drawdown: examples of long-term spatial and temporal variability in community response', *Ecological Engineering* 36: 1191–200.

Ghosh, A. K., Pattnaik, A. K. and Ballatore, T. J. (2006) 'Chilika Lagoon: restoring ecological balance and livelihoods through re-salinization', *Lakes & Reservoirs: Research & Management* 11: 239–55.

Gilman, R. T., Abell, R. A. and Williams, C. E. (2004) 'How can conservation biology inform the practice of integrated river basin management?', *International Journal of River Basin Management* 2: 135–48.

Global Biodiversity Information Facility (GBIF) (2014) Global Biodiversity Information Facility, GBIF Secretariat, Copenhagen. <www.gbif.org/>

Global Water Partnership (GWP) (2000) *Integrated Water Resources Management*, Global Water Partnership, Stockholm.

Government of Queensland (2014) 'WetlandInfo', *Queensland Wetlands Program*, Government of Queensland, Brisbane. <wetlandinfo.ehp.qld.gov.au/wetlands/>

Hadwen, W. L., Boon, P. J. and Arthington, A. H. (2012) 'Aquatic ecosystems in inland Australia: tourism and recreational significance, ecological impacts and imperatives for management', *Marine and Freshwater Research* 63: 325–40.

Haefner, A. (2013) 'Regional environmental security: cooperation and challenges in the Mekong subregion', *Global Change, Peace and Security* 25: 27–41.

Hannah, L. (2010) 'A global conservation system for climate-change adaptation', *Conservation Biology* 24(1): 70–7.

Hatton, T. and Evans, R. (1998) *Dependence of Ecosystems on Groundwater and its Significance to Australia*, Land and Water Research and Development Corporation, Canberra.

Helfield, J. M. and Naiman, R. J. (2006) 'Keystone interactions: salmon and bear in riparian forests of Alaska', *Ecosystems* 9: 167–80.

Helmer, W., Litjens, G., Overmars, W., Barneveld, H., Kink, A., Sterenburg, H. and Janssen, B. (1992) *Living Rivers*, WWF-Netherlands, Zeist.

Hermoso, V., Kennard, M. J. and Linke, S. (2012a) 'Integrating multidirectional connectivity requirements in systematic conservation planning for freshwater systems', *Diversity and Distributions* 18: 448–58.

Hermoso, V., Linke, S., Prenda, J. and Possingham, H. P. (2011) 'Addressing longitudinal connectivity in the systematic conservation planning of fresh waters', *Freshwater Biology* 56: 57–70.

Hermoso, V., Ward, D. P. and Kennard, M. J. (2012b) 'Using water residency time to enhance spatio-temporal connectivity for conservation planning in seasonally dynamic freshwater ecosystems', *Journal of Applied Ecology* 49: 1028–35.

Herron, N., Davis, R. and Jones, R. (2002) 'The effects of large-scale afforestation and climate change on water allocation in the Macquarie River catchment, NSW, Australia', *Journal of Environmental Management* 65: 369–81.

Higgins, J. V., Bryer, M. T., Khoury, M. L. and FitzHugh, T. W. (2005) 'A freshwater classification approach for biodiversity conservation planning', *Conservation Biology* 19: 432–45.

Hirji, R. and Davis, R. (2009) *Environmental Flows in Water Resources Policies, Plans, and Projects. Findings and recommendations*, The International Bank for Reconstruction and Development and The World Bank, Washington, DC.

Hooijer, A., Page, S., Canadell, J. G., Silvius, M., Kwadijk, J., Wösten, H. and Jauhiainen, J. (2010) 'Current and future CO_2 emissions from drained peatlands in Southeast Asia', *Biogeosciences* 7(5): 1505–14.

Horwitz, P., Bradshaw, D., Hopper, S., Davies, P., Froend, R. and Bradshaw, F. (2008) 'Hydrological change escalates risk of ecosystem stress in Australia's threatened biodiversity hotspot', *Journal of the Royal Society of Western Australia* 91: 1–12.

Howard, B. C. (2012) 'Salmon re-enter Olympic National Park river thanks to Elwha Dam removal', *National Geographic NewsWatch*, 21 August 2012. <newswatch.nationalgeographic.com/2012/08/21/salmon-enter-olympic-national-park-for-the-first-time-thanks-to-elwha-dam-removal/>

Illueca, J. and Rast, W. (1996) 'Precious, finite and irreplaceable', *Our Planet* 8. <www.ourplanet.com/imgversn/83/rast.html>

Intergovernmental Panel on Climate Change (IPCC) (2007) *Impacts, Adaptation and Vulnerability. Intergovernmental Panel on Climate Change. Climate Change 2007: Working Group II. Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report*, Intergovernmental Panel on Climate Change, Geneva.

International Ecosystem Management Partnership (IEMP) (2011) *Restoring the natural foundation to sustain a green economy*, UNEP Policy Series on Ecosystem Management No. 6, International Ecosystem Management Partnership, United Nations Environment Programme, Nairobi.

International Lake Environment Committee Foundation (ILEC) (2005) *Managing Lakes and their Basins for Sustainable Use: A report for lake basin managers and stakeholders*, International Lake Environment Committee Foundation, Kusatsu, Japan. <www.ilec.or.jp/en/pubs/p2/lbmi>

International Union for Conservation of Nature (IUCN) (2003) *Guidelines for Application of IUCN Red List Criteria at Regional Levels: Version 3.0*, IUCN Species Survival Commission, Gland and Cambridge.

Ison, R. and Watson, D. (2007) 'Illuminating the possibilities for social learning in the management of Scotland's water', *Ecology and Society* 12: 21. <www.ecologyandsociety.org/vol12/iss1/art21/>

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., le Maitre, D. C., McCarl, B. A. and Murray, B. C. (2005) 'Trading water for carbon with biological carbon sequestration', *Science* 310: 1944–7.

Jeffres, C. A., Opperman, J. J. and Moyle, P. B. (2008) 'Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river', *Environmental Biology of Fishes* 83: 449–58.

Joosten, H. (2009) *The Global Peatland CO_2 Picture: Peatland status and drainage related emissions in all countries of the world*, Greifswald University and Wetlands International, Waganingen, Netherlands.

Joosten, H. and Clarke, D. (2002) *Wise Use of Mires and Peatlands: Background and principles including a framework for decision-making*, International Mire Conservation Group and International Peat Society, Saarijärvi, Finland.

Joosten, H., Tapio-Biström, M. L. and Tol, S. (eds) (2012) *Peatlands: Guidance for climate change mitigation through conservation, rehabilitation and sustainable use*, FAO and Wetlands International, Rome and Ede, Netherlands.

Junk, W. J. and Nunes da Cunha, C. (2012) 'Wetland management challenges in the South-American Pantanal and the international experience', in A. A. R. Loris (ed.) *Tropical Wetland Management: The South-American Pantanal and the international experience*, pp. 315–32, Ashgate, Farnham, UK.

Junk, W. J., Nunes da Cunha, C., Wantzen, K. M., Petermann, P., Strüssmann, C., Marques, M. I. and Adis, J. (2006) 'Biodiversity and its conservation in the Pantanal of Mato Grosso, Brazil', *Aquatic Sciences* 68: 278–309.

Kakadu Board of Management (2007) *Kakadu National Park Management Plan 2007–2014*, Government of Australia, Canberra.

Khoury, M., Higgins, J. and Weitzell, R. (2011) 'A freshwater conservation assessment of the Upper Mississippi River basin using a coarse- and fine-filter approach', *Freshwater Biology* 56: 162–79.

King, J. and Brown, C. (2010) 'Integrated basin flow assessments: concepts and method development in Africa and South-East Asia', *Freshwater Biology* 55: 127–46.

King, J., Brown, C. and Sabet, H. (2003) 'A scenario-based holistic approach to environmental flow assessments for rivers', *River Research and Applications* 19(5–6): 619–39.

Kingsford, R. T., Biggs, H. C. and Pollard, S. R. (2011) 'Strategic adaptive management in freshwater protected areas and their rivers', *Biological Conservation* 144: 1194–203.

Kleinschmidt Associates (2008) *Cosumnes River Preserve Management Plan*, Cosumnes River Preserve, Galt, CA.

Knight, A. T., Grantham, H. S., Smith, R. J., McGregor, G. K., Possingham, H. P. and Cowling, R. M. (2011) 'Land managers' willingness-to-sell defines conservation opportunity for protected area expansion', *Biological Conservation* 144: 2623–30.

Kotze, D. C., Klug, J. R., Hughes, J. C. and Breen, C. M. (1996) 'Improved criteria for classifying hydric soils in South Africa', *South African Journal of Plant and Soil* 13(3): 67–73.

Kumar, R. and Pattnaik, A. K. (2012) *Chilika: An integrated management planning framework for conservation and wise use*, Wetlands International-South Asia and Chilika Development Authority, New Delhi and Bhubaneswar, India.

Laizé, C. L. R., Acreman, M. C., Schneider, C., Dunbar, M. J., Houghton-Carr, H. A., Flörke, M. and Hannah, D. M. (2014) 'Projected flow alteration and ecological risk for pan-European rivers', *River Research and Applications* 30: 299–314.

Lehner, B. and Döll, P. (2004) 'Development and validation of a global database of lakes, reservoirs and wetlands', *Journal of Hydrology* 296: 1–22.

Lindloff, S. (2000) *Dam Removal: A citizen's guide to restoring rivers*, River Alliance of Wisconsin and Trout Unlimited, Madison, WI, and Arlington, VA.

Linke, S., Kennard, M. J., Hermoso, V., Olden, J. D., Stein, J. and Pusey, B. J. (2012) 'Merging connectivity rules and large-scale condition assessment improves conservation adequacy in river systems', *Journal of Applied Ecology* 49: 1036–45.

Loneragan, N. R. and Bunn, S. E. (1999) 'River flows and estuarine ecosystems: implications for coastal fisheries from a review and a case study of the Logan River, southeast Queensland', *Australian Journal of Ecology* 24: 431–40.

 Lukasiewicz, A., Finlayson, C. M. and Pittock, J. (2013) *Incorporating Climate Change Adaptation into Catchment Management: A user guide*, Charles Sturt University, Albury, NSW.

McFarlane, D., Strawbridge, M., Stone, R. and Paton, A. (2012) 'Managing groundwater levels in the face of uncertainty and change: a case study from Gnangara', *Water Science and Technology: Water Supply* 12: 321–8.

Matthews, J. H., Wickel, B. A. and Freeman, S. (2011) 'Converging currents in climate-relevant conservation: water, infrastructure, and institutions', *PLoS Biology* 9: 1 001 159.

Micklin, P. and Aladin, N. V. (2008) 'Reclaiming the Aral Sea', *Scientific American* 298: 64–71.

Millennium Ecosystem Assessment (MEA) (2005) *Ecosystems and Human Well-Being: Wetlands and water synthesis*, World Resources Institute, Washington, DC.

Miller, C. (2005) *The Snowy River Story: The grassroots campaign to save a national icon*, ABC Books, Sydney.

Mohapatra, A., Mohanty, R. K., Mohanty, S. K., Bhatta, K. S. and Das, N. R. (2007) 'Fisheries enhancement and biodiversity assessment of fish, prawn and mud crab in Chilika lagoon through hydrological intervention', *Wetlands Ecology and Management* 15: 229–51.

Moilanen, A., Leathwick, J. R. and Quinn, J. M. (2011) 'Spatial prioritization of conservation management', *Conservation Letters* 4: 383–93.

Mosisch, T. D. and Arthington, A. H. (1998) 'A review of literature examining the effects of water-based, powered recreational activities on lakes and rivers', *Lakes and Reservoirs: Research and Management* 3: 1–17.

Naiman, R. J., Decamps, H. and Pollock, M. (1993) 'The role of riparian corridors in maintaining regional biodiversity', *Ecological Applications* 3: 209–12.

Nakamura, M. and Rast, W. (2011) *Development of ILBM Platform Process: Evolving guidelines through participatory improvement*, ILEC, Kusatsu, Japan.

Nakamura, M. and Rast, W. (2012) *Primer: Development of ILBM Platform Process – Evolving guidelines through participatory improvement*, International Lake Environment Committee, Kusatsu and Research Centre for Sustainability and Environment, Shiga University.

Nakamura, M., Yoshihiko, O., Michio, A. and Moriyasu, K. (2012) 'Evolving history of Lake Biwa and Yodo River basin management', in H. Kawanabi, M. Nishino and M. Maehata (eds) *Lake Biwa: Interactions between Nature and People*, pp. 371–417, Springer, Dordrecht.

Nel, J. L., Reyers, B., Roux, D. J., Impson, N. D. and Cowling, R. M. (2011) 'Designing a conservation area network that supports the representation and persistence of freshwater biodiversity', *Freshwater Biology* 56: 106–24.

Nirupama, N. and Simonovic, S. P. (2007) 'Increase of flood risk due to urbanisation: a Canadian example', *Natural Hazards* 40: 25–41.

Nunes da Cunha, C. and Junk, W. J. (2011) 'A preliminary classification of habitats of the Pantanal of Mato Grosso and Mato Grosso do Sul, and its relation to national and international classification systems', in W. J. Junk, C. J. da Silva, C. Nunes da Cunha and K. M. Wantzen (eds) *The Pantanal: Ecology, biodiversity and sustainable management of a large neotropical seasonal wetland*, pp. 127–41, Pensoft, Sofia.

Olden, J. D. and Naiman, R. J. (2009) 'Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity', *Freshwater Biology* 55: 86–107.

Olden, J. D. and Naiman, R. J. (2010) 'Incorporating thermal regimes into environmental flows assessments: modifying dam operations to restore freshwater ecosystem integrity', *Freshwater Biology* 55(1): 86–107.

Palmer, M. A., Reidy Liermann, C. A., Nilsson, C., Flörke, M., Alcamo, J., Lake, P. S. and Bond, N. (2008) 'Climate change and the world's river basins: anticipating management options', *Frontiers in Ecology and the Environment* 6: 81–9.

Parmesan, C. (2006) 'Ecological and evolutionary responses to recent climate change', *Annual Review of Ecology, Evolution, and Systematics*: 637–69.

Parmesan, C., Duarte, C., Poloczanska, E., Richardson, A. J. and Singer, M. C. (2011) 'Overstretching attribution', *Nature Climate Change* 1: 2–4.

Pearson, R. G. (2007) *Species Distribution Modelling for Conservation Educators and Practitioners: Synthesis*, American Museum of Natural History, New York. <ncep.amnh.org>

Perissinotto, R., Stretch, D. D. and Taylor, R. H. (eds) (2013) *Ecology and Conservation of Estuarine Ecosystems: Lake St Lucia as a global model*, Cambridge University Press, New York.

Pittock, J. and Finlayson, C. M. (2011) 'Australia's Murray–Darling Basin: freshwater ecosystem conservation options in an era of climate change', *Marine and Freshwater Research* 62: 232–43.

Pittock, J., Finlayson, C. M. and Howitt, J. A. (2012) 'Beguiling and risky: "environmental works and measures" for wetlands conservation under a changing climate', *Hydrobiologia* 708: 111–31.

Pittock, J., Finlayson, C. M., Gardner, A. and McKay, C. (2010) 'Changing character: the Ramsar Convention on Wetlands and climate change in the Murray Basin', *Environmental and Planning Law Journal* 27: 401–25.

Pittock, J. and Hartmann, J. (2011) 'Taking a second look: climate change, periodic re-licensing and better management of old dams', *Marine and Freshwater Research* 62: 312–20.

Pittock, J., Hussey, K. and McGlennon, S. (2013) 'Australian climate, energy and water policies: conflicts and synergies', *Australian Geographer* 44: 3–22.

Poff, N. L. and Matthews, J. H. (2013) 'Environmental flows in the Anthropocence: past progress and future prospects', *Current Opinion in Environmental Sustainability* 5: 667–75.

Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B. P., Freeman, M. C., Henriksen, J., Jacobson, R. B., Kennen, J. G., Merritt, D. M., O'Keeffe, J. H., Olden, J. D., Rogers, K., Tharme, R. E. and Warner, A. (2010) 'The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards', *Freshwater Biology* 55: 147–70.

Pollard, S. and du Toit, D. (2011) 'Towards adaptive integrated water resources management in southern Africa: the role of self-organisation and multi-scale feedbacks for learning and responsiveness in the Letaba and Crocodile catchments', *Water Resources Management* 25: 4019–35.

Porter, I. C. and Shivakumar, J. (2010) *Doing a Dam Better: The Lao People's Democratic Republic and the story of Nam Theun 2 (NT2)*, The World Bank, Washington, DC.

Postel, S. and Richter, B. (2003) *Rivers for Life: Managing water for people and nature*, Island Press, Washington, DC.

Postel, S. L. and Thompson, B. H. (2005) 'Watershed protection: capturing the benefits of nature's water supply services', *Natural Resources Forum* 29: 98–108.

Rahel, F. J., Bierwagen, B. and Taniguchi, Y. (2008) 'Managing aquatic species of conservation concern in the face of climate change and invasive species', *Conservation Biology* 22: 551–61.

Ramsar (2002) *Guidelines for Global Action on Peatlands (GAP)*, Ramsar Convention Secretariat, Gland.

Ramsar (2005) *Resolution IX.4: The Ramsar Convention and conservation, production and sustainable use of fisheries resources*, Ramsar Convention Secretariat, Gland.

Ramsar (2008) *Strategic Framework and Guidelines for the Future Development of the List of Wetlands of International Importance of the Convention on Wetlands*, Ramsar Convention Secretariat, Gland.

Ramsar (2009a) *Convention on Wetlands of International Importance Especially as Waterfowl Habitat. Ramsar (Iran), 2 February 1971. UN Treaty Series No. 14583. As amended by the Paris Protocol, 3 December 1982, and Regina Amendments, 28 May 1987*, Ramsar Convention Secretariat, Gland.

Ramsar (2009b) *Information sheet on Ramsar wetlands (RIS)*, Ramsar Convention Secretariat, Gland.

Ramsar (2011) *The Ramsar Handbooks for the Wise Use of Wetlands*, 4th edn, Ramsar Convention Secretariat, Gland.

Richardson, S., Irvine, E., Froend, R., Boon, P., Barber, S. and Bonneville, B. (2011a) *Australian groundwater-dependent ecosystems toolbox part 1: assessment framework*, Waterlines Report Series 69, National Water Commission, Canberra.

Richardson, S., Irvine, E., Froend, R., Boon, P., Barber, S. and Bonneville, B. (2011b) *Australian groundwater-dependent ecosystems toolbox part 2: assessment tools*, Waterlines Report Series 70, National Water Commission, Canberra.

Richter, B. D., Baumgartner, J. V., Powell, J. and Braun, D. P. (1996) 'A method for assessing hydrologic alteration within ecosystems', *Conservation Biology* 10: 1163–74.

Richter, B. D., Warner, A. T., Meyer, J. L. and Lutz, K. (2006) 'A collaborative and adaptive process for developing environmental flow recommendations', *River Research and Applications* 22: 297–318.

Roux, D. J., Ashton, P. J., Nel, J. L. and MacKay, H. M. (2008) 'Improving cross-sector policy integration and cooperation in support of freshwater conservation', *Conservation Biology* 22: 1382–7.

Russi, D., Ten Brink, P., Farmer, A., Badura, T., Coates, D., Förster, J., Kumar, R. and Davidson, N. (2013) *The Economics of Ecosystems and Biodiversity for Water and Wetlands*, IEEP, London and Brussels.

Sadoff, C., Greiber, T., Smith, M. and Bergkamp, G. (2008) *Share: Managing water across boundaries*, IUCN, Gland.

Sheldon, A. L. (1988) 'Conservation of stream fishes: patterns of diversity, rarity, and risk', *Conservation Biology* 2: 149–56.

Shiklomanov, I. A. (1993) 'World fresh water resources', in P. H. Gleick (ed.) *Water in Crisis*, pp. 13–24, Oxford University Press, Oxford.

Sommer, B. and Froend, R. (2011) 'Resilience of phreatophytic vegetation to groundwater drawdown: is recovery possible under a drying climate?', *Ecohydrology* 4: 67–82.

Sommer, B. and Froend R. H. (2014) 'Alternative states of phreatophytic vegetation in a drying Mediterranean-type landscape', *Journal of Vegetation Science* 25: 1045–55.

Spackman, S. C. and Hughes, J. W. (1995) 'Assessment of minimum stream corridor width for biological conservation: species richness and distribution along mid-order streams in Vermont, USA', *Biological Conservation* 71: 325–32.

Tennant, D. L. (1976) 'Instream flow regimens for fish, wildlife, recreation and related environmental resources', *Fisheries* 1: 6–10.

Tharme, R. E. (2003) 'A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers', *River Research and Applications* 19: 397–441.

Tockner, K., Bunn, S. E., Gordon, C., Naiman, R. J., Quinn, G. P., Standord, J. and Polunin, N. (2008) 'Flood plains: critically threatened ecosystems', in N. Polunin (ed.) *Aquatic Ecosystems: Trends and global prospects*, pp. 45–61, Cambridge University Press, Cambridge.

Turner, L., Tracey, D., Tilden, J. and Dennison, W. C. (2004) *Where River Meets Sea: Exploring Australia's estuaries*, Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Brisbane.

Turpie, J. K. and Clark, B. M. (2007) *The Health Status, Conservation Importance, and Economic Value of Temperate South African Estuaries and Development of a Regional Conservation Plan*, AEC/07/01, Anchor Environmental Consultants, Cape Town.

Turpie, J. K., Sihlope, N., Carter, A., Maswime, T. and Hosking, S. (2007) 'Maximising the socio-economic benefits of estuaries through integrated planning and management: a rationale and protocol for incorporating and enhancing estuary values in planning and management', in *Profiling estuary management in integrated development planning in South Africa with particular reference to the Eastern Cape Province*, Appendix 1, Water Research Commission Publication 1485/1/07, Water Research Commission, Pretoria.

van Dijk, A. I. J. M. and Keenan, R. J. (2007) 'Planted forests and water in perspective', *Forest Ecology and Management* 251: 1–9.

van Niekerk, L. and Turpie, J. K. (eds) (2012) *South African National Biodiversity Assessment 2011: Technical report. Volume 3: Estuary component*, Council for Scientific and Industrial Research, Stellenbosch, South Africa.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R. and Davies, P. M. (2010) 'Global threats to human water security and river biodiversity', *Nature* 467: 555–61.

Ward, J. V. (1989) 'The four-dimensional nature of lotic ecosystems', *Journal of the North American Benthological Society* 8: 2–8.

Warner, J. F., van Buuren, A. and Edelenbos, J. (eds) (2013) *Making Space for the River: Governance experiences with multifunctional river flood management in the US and Europe*, IWA Publishing, London.

Whipple, A. (2012) *Sacramento–San Joaquin Delta Historical Ecology Investigation: Exploring pattern and process*, San Francisco Estuary Institute, Richmond, CA.

Whitfield, A. K., Bate, G. C., Adams, J. B., Cowley, P. D., Froneman, P. W., Gama, P. T., Strydom, N. A., Taljaard, S., Theron, A. K., Turpie, J. K., van Niekerk, L. and Wooldridge, T. H. (2012) 'A review of the ecology and management of temporarily open/closed estuaries in South Africa, with particular emphasis on river flow and mouth state as primary drivers of these systems', *African Journal of Marine Science* 34: 163–80.

World Wide Fund for Nature (WWF) (2003) *Managing Rivers Wisely: Lessons from WWF's work for integrated river basin management*, WWF, Gland.

Wyborn, C. (2011) 'Landscape scale ecological connectivity: Australian survey and rehearsals', *Pacific Conservation Biology* 17: 121–31.

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