How effective is protected area designation for the conservation and restoration of freshwater biodiversity?

A systematic evidence review.

Sunset in Pantanal (Andre Dib/WWF-Brazil)

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Dr Manuel Angel Duenas-Lopez is a freshwater ecologist specialising in systematic reviews. He has worked as a visiting scientist at the NERC Centre for Ecology & Hydrology since 2004 undertaking research on wetlands and aquatic plant management. He has in-depth expertise in systematic reviews, particularly statistical analysis. He has also worked on extinction risk assessment from invasive species for the Centre for Agriculture and Bioscience International (CABI).

Executive summary

1. There is a wide consensus that freshwater biodiversity is continuing to decline rapidly at the global scale, with populations of freshwater species estimated to have declined by 83% since 1970. Many organisations, from governments to NGOs, have tried to reverse, halt or at least reduce the rate in this decline by designating protected areas within which laws restrict practices that adversely impact biodiversity and support practices that conserve or restore biodiversity. For example, there are 2,314 Wetlands of International Importance (Ramsar Sites) world-wide, covering 242,409,779 hectares, although many species within them are in decline. WWF is a science-based conservation organisation and needs to understand the evidence of whether protected areas have led to or supported conservation and restoration of freshwater species and why this has occurred.
2. WWF-UK set-up a quick scoping review (QSR) to provide an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to the specific question "How does freshwater biodiversity and habitat change with protected area designation, design and management?". Key principles of this work are that credible evidence reviews must be comprehensive, robust, objective, transparent and repeatable. Furthermore, the QSR should also provide results in an easily accessible manner that facilitates an audit trail from summary statements to underpinning knowledge.
3. The QSR followed recognised standards for conducting evidence reviews for ecological and environmental issues including guidance produced by UK Department of Environment, Food and Rural Affairs and process steps of the PRISMA 2009 checklist. The process included application of the PICO (population, intervention, comparator and outcome) framework. The study was independently peer-reviewed by Professor Angela Arthington.
4. Searches of the Web of Science database (including SciELO) and Google Scholar, requests to experts and institutions and scans of reference lists of review papers and books returned 2586 publications (after removing duplications). Application of strict selection criteria at either full text or title and abstract level identified 44 relevant publications containing 75 case studies. Many returned publications were rejected because they discussed concepts and inferred principles but contained no new data, some calculated protected area coverage as a percentage of the range of species but included nothing on the effectiveness of those protected areas, whilst others published results of species surveys within protected areas but no comparative data outside of the areas or before designation.
5. Key information was captured for each study from the selected publications and input to a searchable database. The only inferred information (*i.e*. not actually provided by the study authors) was the direction of change of biodiversity or habitat, specifically whether the protected area had been positive, neutral or negative for freshwater biodiversity. If, for example, the fish population within a protected area increased after designation compared to a reference non-designated area, this was considered a positive outcome. If the population was the same, it was considered neutral, whereas if the population was lower in the protected area after designation (compared to the reference area) it was considered a negative outcome. Additional information about each case study, such as the IUCN Protected Area category and the freshwater ecoregion, was found using available web-tools and guidance.
6. The majority of studies compared protected with un-protected areas, with only a few comparing the same area before and after designation. The most common metrics employed were species abundance and richness, followed by diversity (*e.g*. metrics that capture both species richness and the relative abundance of each species in a sample). Many papers did not specify the management measures employed following designation; of those that did, the most common were fishing restrictions and water management. The case studies were well-distributed across the globe and across ecosystem categories. The highest number of case

studies were from Asia, within tropical and subtropical floodplain rivers and wetland complexes, category II protected areas, and using fish metrics. The second highest numbers of studies were from the Neotropics, within temperate floodplain rivers and wetlands, category IV protected areas and for birds.

7. Of the 75 case studies, 39 reported positive outcomes, 25 were neutral and 11 were negative, so 52% of the studies showed protected areas to be effective in protecting freshwater biodiversity. Few studies recorded reasons why the protected area had been successful. There was no single cause of lack of success (negative or neutral direction of change); the wide range of causes recorded included fishing (often lack of law enforcement), dominance of environmental variables (such as climate, landscape, pH, river channel geometry), water management (abstraction and dams), invasive alien species and habitat degradation (e.g. from mining or agriculture).

8. Detailed analysis of the effectiveness categories did not highlight strong relationships with other information, such as taxa, basis of inference, IUCN protected area category or freshwater ecoregion. However, 73% of the case studies in tropical and subtropical coastal rivers show positive outcomes for protected areas, which exceeds the 52% overall figure. Negative changes in protected area fish biodiversity were recorded only in studies of rivers (i.e. there were none for lakes, ponds, wetlands or floodplains). The main causes were invasive species, variations in natural environmental variables (such as water pH and temperature) and local disturbances from dredging, mining and deforestation.

9. Several studies, including fish in Thai wetlands and birds on Finnish islands, reported that biodiversity increased with greater protected area size. Studies of fish in Canadian lakes and plants in Australian wetlands concluded that freshwater protected area design should include the entire ecosystem (lake or catchment). However, other studies, e.g. rivers of the southern Western Ghats, India, and Lake Tanganyika, Tanzania, concluded that although terrestrial-based protected areas did not adequately represent the habitat diversity of river systems, they were more effective in supporting higher endemic freshwater species richness than unprotected areas.

10. Conserving aquatic habitat, including the hydrological regime (surface and groundwater), water quality, and riparian terrestrial vegetation, was found to be vital for supporting freshwater biodiversity worldwide, including lizards in Brazil, fish in Mexico, birds in China and wetlands in Spain. One study selected in our review suggested that disconnection of the River Yangtze from its floodplain was a partial cause of reduced numbers of cranes in the Shengjin Lake National Nature Reserve, China. Another considered that lowering of groundwater contributed to degradation of vegetation in Mana Pools National Parks, Zambia. These studies demonstrate the importance of lateral (e.g. river-riparian and floodplain zones) and vertical (e.g. surface-groundwater) connectivity. No studies found lack of longitudinal connectivity (upstream-downstream) to be the main cause of negative outcomes for freshwater biodiversity in protected areas, though several authors infer this in discussion.

11. The need to reduce pressures in and around protected areas from grazing, inappropriate land and water management, pollution, tourism or general human disturbance was concluded from studies of wetlands in Tibet and USA, aquatic insects in India and birds in China. Catchment disturbances, *e.g.* dredging, mining, deforestation, were found to impact biodiversity in protected rivers in Venezuela, Kenya and Italy, and in wetlands across Africa, but protected areas were shown to be effective buffers from adverse external pressures for reptiles in Brazil and fish in India.

12. Invasive species pose threats to freshwater biodiversity within protected areas worldwide, such as fish escaping from farms in Mexico and Spain and invasive weeds in Australia.

13. Lack of law enforcement in protected areas has contributed to the decline of turtles in Hong Kong, birds in African wetlands and fish in India. In contrast, protection has reduced hunting of reptiles, birds, and mammals in the Amazon, Peru and over-fishing of shrimps in Costa Rica and of eels in France. In Brazil, community-based management approaches have succeeded in reducing poaching of turtle eggs, where formal law enforcement had previously failed.
14. Maintaining traditional management practices that are part of cultural heritage is a central objective of some protected areas, such as burning of upland blanket bog in the UK to maintain grouse shooting and cattle grazing.
15. There are many factors influencing freshwater biodiversity, including the natural distributions of species, variations in topography, river channel morphology, water quality and climate that are not within the control of protected area managers. Informative case studies include Australia's Murray–Darling Basin, streams in Singapore, karstic pools in Mexico and waterbird habitats in Morocco.
16. Many elected papers provided evidence to support principles of freshwater ecosystem management in protected areas formulated by Finlayson *et al.* (2018a) and Biggs *et al.* (2012). The evidence included: designating large landscape units, preferably the entire catchment; protecting areas that conserve biodiversity hotspots, species-rich habitats and threatened species; conserving the natural dynamics of river flows, lake and wetland water levels and water quality; maintaining ecological resilience; and promoting the participation of local people and enforcing laws. Some studies refer to the importance of connectivity between rivers and their riparian areas and floodplains and between surface and groundwater. There is no direct evidence that lack of longitudinal connectivity or fragmentation of habitats has been a factor in negative outcomes for any riverine protected area.
17. We distilled the evidence from the publications that met the inclusion criteria into ten lessons for protected area management to conserve freshwater biodiversity. These lessons concern the following issues: monitoring and research needs, waterscape connectivity and protected area size; effectiveness of terrestrial-based protected areas for freshwater species; habitat protection; managing internal pressures; managing external pressures; impacts of alien invasive species; law enforcement; involvement of local communities in protected area management; and continuation of traditional management practices.
18. We identified four potential areas for continuation of this work: meta-analysis of raw data from selected publications; a review of the importance of protecting connectivity between ecosystem components and protected areas; further review of rejected papers that include experiments undertaken in protected areas; and comparison of protected area effectiveness with alternative measures, such as global scale species protection or national/regional environmental flow and river health management programmes.

Contents

1. Background

Fresh water makes up only 0.01% of the World's water and covers only approximately 0.8% of the Earth's surface, yet freshwater ecosystems supports at least 100,000 species out of approximately 1.8 million – almost 6% of all described species (Dudgeon *et al*., 2006). The Ramsar Convention definition of wetlands covers all freshwater ecosystems (including rivers and lakes) and the total global wetland area has been estimated to cover between 15.2 and 16.2 million km^2. Some 77% of this total surface wetland extent is non-forested peatlands, marshes and swamps on alluvial soils, with peatlands forming 33% of natural inland wetlands. Ramsar's wetland definition also includes near-shore, marine and coastal areas, dominated by unvegetated tidal flats and saltmarshes, but these wetlands cover only 10% of total wetland global extent (Davidson & Finlayson, 2018). In addition to being home for numerous aquatic and wildlife species, wetlands provide important ecosystem services that support human welfare and livelihoods globally (Maltby & Acreman, 2011; Mitsch *et al*., 2015).

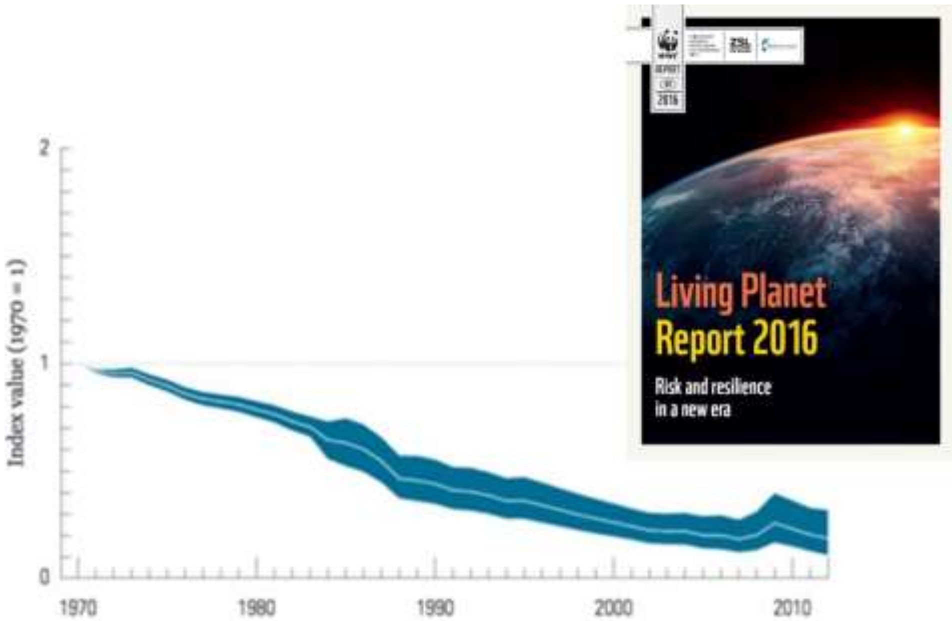


Figure 1 Decline in the index of freshwater wildlife populations by 83% since 1970 (WWF, 2018)

IPBES (2018) stated that degradation of the Earth's land surface through human activities is negatively impacting the well-being of at least 3.2 billion people, pushing the planet towards a sixth mass species extinction, and costing more than 10% of the annual global gross product in loss of biodiversity and ecosystem services. The Ramsar Convention (2018b) reported that overall available data suggest that wetland dependent species, such as fish, waterbirds and turtles are in serious decline, with one-quarter threatened with extinction particularly in the tropics. In 2018, 168 Ramsar Sites within the territories of 66 Contracting Parties were formally reported as being subject to negative human-induced change or likely change in the ecological character; an increased from the 2015 when there were 144 (Ramsar Convention, 2018c). WWF (2018) reported that freshwater biodiversity is continuing to decline rapidly at the global scale and that the index of freshwater wildlife populations has fallen by 83% since 1970 (Figure 1); this is more than double the rate of decline found in species populations in marine or terrestrial biomes (WWF, 2018). The Convention on Biological Diversity (2014) adds that pressures on biodiversity will continue to increase at least until 2020, and the status of biodiversity will continue to decline. The IUCN *Red List of Threatened*

Species– the global standard for measuring threats to species – is incomplete for freshwater species. For some species, such as the endangered Indus river dolphin, major investments have been made in monitoring (Braulik, 2006, Braulik *et al*., 2012; Braulik *et al*. 2015, Noureen, 2013, Aisha *et al.*, 2017), but for many other species little is known. For those species groups and regions where we have complete coverage, almost 30% of approximately 28,000 freshwater species that have been assessed for the IUCN Red List are categorised as being under immediate threat of extinction (IUCN, 2018). Furthermore, inland wetlands have declined in global extent by 64-71% during the 20th century (Davidson, 2014).

Many organisations, ranging from governments to NGOs have tried to help reverse, halt or at least reduce the rate in this decline by designating protected areas, defined by the Convention on Biological Diversity as 'a geographically defined area which is designated or regulated and managed to achieve specific conservation objectives'. Seasonal inland wetlands represent approximately 6% of the world's land surface, and about 89% of these are unprotected (Reis *et al*., 2017). As of 20 June 2018, there were 2,314 listed Wetlands of International Importance (Ramsar Sites) covering 242,409,779 hectares (Ramsar, 2018a). Freshwater biodiversity was the over-riding conservation priority during the International Decade for Action – 'Water for Life' – 2005 to 2015. Management of freshwater protected areas has been recognised as particularly important for achieving sustainable development goals by 2030 (Finlayson *et al*., 2018a). While designated primarily for nature conservation, protected areas supply a range of other ecosystem services to human society (Dudley *et al*., 2016). Nearly two-thirds of the global population living downstream of the world's protected areas are potential users of freshwater provisions (Harrison *et al*., 2016).

The Convention on Biological Diversity set 20 Aichi Targets to be met by 2020. There is an indication that WWF is meeting its 2020 ambition for the Target of 17% of the global area of inland water to be protected, although there is uncertainty that all inland waters are well represented (Abell *et al*., 2017). In 2010 there were already over 161,000 protected areas in the world covering 10-15% of the world's land surface (Soutullo, 2010) with, by 2015, over 2100 designated Ramsar Sites covering more than 2 million km^2 of rivers, lakes, marshes, floodplains, deltas and other wetland habitats across the world. However, the global increase in protected areas seems at odds with the continuing rapid decline in freshwater biodiversity, which has led conservationists to question the effectiveness of protected areas as a tool for freshwater species conservation and restoration (e.g., Pittock *et al*., 2015).

Many factors have been put forward to explain the apparent lack of effectiveness of protected areas for biodiversity conservation including:

- poor design and declaration of protected areas, for example where they fail to cover areas of highest biodiversity threat (Azevedo-Santos *et al.,* 2018)
- traditional notions of protected areas (often based on terrestrial or marine experience) translate imperfectly to protection of the freshwater realm because of the need for a whole catchment approach (Abell *et al*. 2007; Azevedo-Santos *et al*., 2018)
- most protected areas are residual leftover areas of the world pushed to the margins where they least interfere with extractive activities such as agriculture, mining, or forestry (Visconti, 2014)
- lack of protection beyond designated areas of habitats and movement corridors for highly mobile organisms, such as migratory fish (Bower *et al.,* 2014)
- lack of connectivity between protected areas (WWF, 2018)
- lack of understanding and protection of connectivity between freshwater ecosystems and the wider landscape (Finlayson *et al*., 2018b)
- lack of control of factors beyond the protected area, such as alterations to river flows or downstream flows of pollution into protected areas (Adams *et al*., 2015)

- lack of enforcement of laws, such that unsustainable exploitation or habitat destruction continue despite the protection status (Atkore *et al.,* 2011)
- lack of management due to understaffing and underfunding (Le Saout, 2013)
- lack of resources for freshwater management in protected areas (Thieme *et al*., 2012).

In global studies of terrestrial protected areas, only 20–50% of those assessed were found to be effectively managed (Laurance *et al*., 2012, Leverington *et al*., 2010; Bloom *et al*., 2004). Watson *et al.* (2014) stated that a step change involving increased recognition, funding, planning and enforcement is urgently needed if protected areas are to fulfil their potential. However, it could just be that better monitoring programmes are needed to assess more thoroughly the effectiveness of protected areas for freshwater biodiversity (Hermoso *et al.,* 2016). Monitoring outcomes in protected areas is expensive (Hockings *et al.,* 2006), but there remains an urgent need for improved assessment of the effectiveness of freshwater protected areas (Hermoso *et al*., 2018) and further work to define new performance metrics for measuring their effectiveness (Watson *et al.,* 2015).

A survey of all 22 Ramsar sites in the USA found that designation had increased funding opportunities, support for protection, tourism and scientific activity (Gardner & Connolly, 2007). Of 37 Ramsar site managers surveyed in Canada, 15 reported a change in ecological character of the wetland since designation, whilst 25 felt that designation helped to maintain ecological character, implying that change may have been greater in the absence of Ramsar status (Lynch-Stewart, 2008). A survey of African Ramsar sites from 18 countries collated a wide range of wetland benefits, with Lake Naivasha, Kenya, reporting that designation had assisted in poverty alleviation through increased tourist revenue (Gardner *et al*., 2009), although designation had also caused conflicts over resource use at Songor, Ghana, and Ichkeul, Tunisia. These results are extremely important and are based on cumulative knowledge of local experts, yet they often lack quantitative evidence.

A prerequisite to defining causes and solutions is the urgent need to systematically assess the quantitative information on the relationships between changes in biodiversity and changes in protection in different parts of the globe to verify or counter any assumptions about the effectiveness of protected areas. Such an assessment would also need to capture contextual information that will help elucidate reasons for success, or lack of it, and potential lessons for future biodiversity protection strategies. The review described in this report is based on these needs.

2. Objectives of this review

WWF is a science-based conservation organisation, so it needs to understand the available evidence being used in formulating policies and strategies. The objective of this review is to provide WWF with the available evidence on whether protected areas have led to or supported conservation and restoration of freshwater biodiversity and why this has occurred. This knowledge can feed into WWF's strategic planning for protected area creation and management.

Figure 2 outlines the major issues facing freshwater ecosystems, focusing on the drivers of change, resulting pressures, consequential state of freshwater ecosystems, the subsequent impacts and ensuing response. The DPSIR framework (European Environment Agency, 1995) has been used for analysis of risks to biodiversity (Maxim *et al.,* 2009). This review focuses on the decline in freshwater biodiversity and the designation of protected areas, which are intended to reduce pressures and alien species and increase habitat and indigenous species, leading to restoration and conservation of freshwater biodiversity (as depicted by the red box in Figure 2).

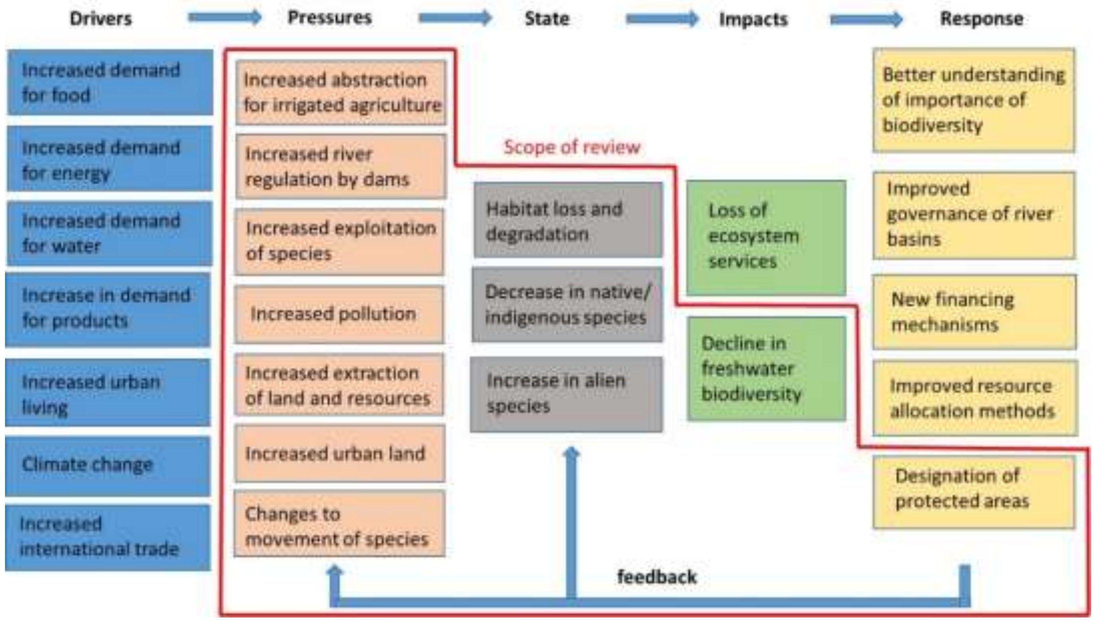


Figure 2. Major issues facing freshwater ecosystems and the scope of the review shown using the DPSIR framework (European Environment Agency, 1995)

The objective of this study was to describe the quantitative evidence that protected areas can support the conservation and restoration of freshwater biodiversity. We defined the primary question to be answered as:

"How do freshwater biodiversity and habitat change with protected area designation, design and management?".

A secondary question was defined as

"***What aspects of protected area designation, design and management are most significant in changing different aspects of freshwater biodiversity and habitat?".***

3. Finding evidence

3.1 Systematic evidence reviews

Achieving the objective of the study required collation of the quantitative evidence of change in biodiversity with the designation of protected area status (along with its implementation and enforcement). The word 'change' is used instead of 'impact' to avoid emotive terms and so as not to pre-empt a conclusion that biodiversity will necessarily be restored or conserved by designation (at least in the first instance). In the analysis of the evidence, the degree to which protected areas change biodiversity needs be considered along with contextual factors, such as geographical location, ecological type, form of protection and level of enforcement, to elucidate which factors have been most influential in the change. It also needs to compare changes within the protected area with changes in similar areas or reference non-protected areas because, for example, even where protected areas are still associated with biodiversity decline, the decline may be considerably worse in non-protected areas. Studying biodiversity change in unprotected areas alone is beyond the scope of this review.

Most studies start with a review, but they can vary enormously in quality and thoroughness. Reviews are often based on pre-existing knowledge of the authors (along with their preferences and biases), papers and book easily available on the authors' shelves or the first that come up from a hasty internet search. Key principles of this analysis are that credible evidence reviews must be comprehensive, robust, objective, transparent and repeatable. Reviews should also provide results in an easily accessible manner that facilitates an audit trail from summary statements to underpinning knowledge. Systematic evidence reviews were designed specifically to achieve these outcomes. They originated in medical research (Cook *et al.*, 1997) but have since been adapted to study environmental issues (Fazey, 2004; Pullin & Stewart, 2006; Norris *et al.*, 2012). Such systematic reviews follow very strict protocols to answer focused questions. The systematic review process we used follows the PRISMA 2009 checklist (Moher *et al*., 2009), a recognised standard for conducting Systematic Reviews adapted for ecological and environmental issues.

No review is ever fully complete and never covers all available literature; this is an open-ended task and, indeed, some academics spend their entire career amassing literature on very focused topics. The degree to which a review can be comprehensive depends on the resources available; all reviews are restricted by time and resources. Formal systematic reviews take many months and can cost up to £100,000. As part of its evidence-based policy-making, the UK Department for the Environment Food and Rural Affairs (Collins *et al.,* 2015) produced (in collaboration with the Centre for Ecology & Hydrology), a consistent set of evidence review methods. These included two less exhaustive methods than full systematic reviews (SR), namely quick scoping reviews (QSR) and rapid evidence assessments (REA). By using consistent processes, the three types of review use the same robust concepts and can be undertaken in sequence if necessary, with one building on another.

In this study, we undertake a QSR, which is usually based on scales of 3-5 months and funding of £10-30,000 (Collins *et al*., 2015). A QSR aims to provide an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to the question. It should be noted that this method does not include, for example, detailed statistical analysis of data extracted from sources.

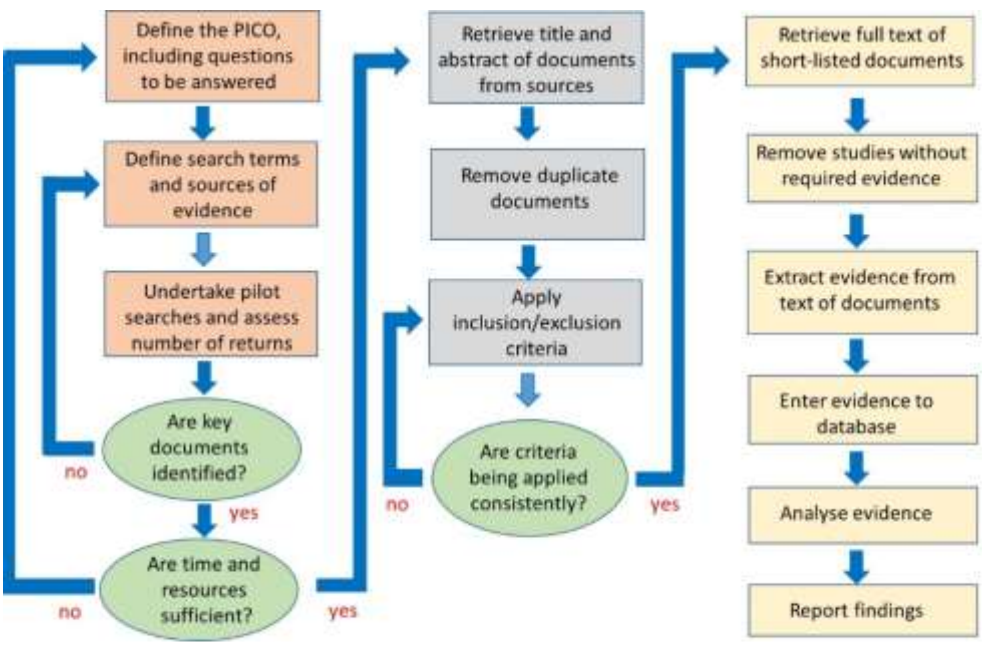


Figure 3. Steps in undertaking a systematic evidence review

Rather than striving to be completely comprehensive, the three review methods adhere to the principle of a conditional logic statement “if … then”. **If** I apply these terms to a search engine, include/exclude returned publications according to these rules and extract this information from the resulting sub-set, **then** I get this evidence. The search terms, inclusion/exclusion rules and the list of information to be extracted may be subjective, but this is minimised by peer-review and the process is replicable and conforms to quality assurance requirements.

The steps followed in the current QSR are described in the Figure 3 and the sections below.

3.2 Selection criteria

The PICO (population, intervention, comparator and outcome) framework for organising selection criteria is widely used in systematic evidence reviews. The elements of the PICO framework (Table 1) define the selection criteria (whether publications are included or excluded).

Table 1. PICO elements for this QSR

Primary question	How do freshwater biodiversity and habitat change with protected area designation, design and management?	
Secondary question	What aspects of protected area designation, design and management are most significant in changing different aspects of freshwater biodiversity and habitat?	
	Inclusion criteria	**Exclusion criteria**
Population	Freshwater ecosystems globally, including estuaries and deltas for which information is available from databases (e.g. Web of Science), search engines (e.g. Google scholar) or from experts contacted in the project.	Terrestrial, atmospheric, marine, coastal, near-shore ecosystems.
Intervention	Official/legal designation of protected areas e.g. Ramsar sites, Biosphere Reserves, national parks, local nature reserves.	General (national, regional or global) protection measures without specific geographical boundaries, e.g. environmental flows, species protection (CITIES); informal protection/exclusion zones; private land management; indigenous preferential use of different zones.
Comparator	Same area during protection vs. before protection or after protection removed, or reference area without protection or with different protection (e.g. buffer zone vs core area)	Studies without comparator, control or counterfactual (what could have happened to the area if it had not been designated by reference to an undesignated area).
Outcome	Quantitative measures of biodiversity, e.g. population size, richness, diversity, distribution, recruitment, migration path or other movement; measures of habitat, e.g. extent, diversity, condition.	Qualitative measures, personal views and perspectives, unquantified aesthetic qualities.

The scope of the study (the population) was defined as freshwater ecosystems worldwide. It was agreed that this should include brackish systems (estuaries and deltas) because these are normally integral parts of larger riverine (freshwater) systems. Truly saline systems (coastal and marine) were excluded. The population was further specified as including those ecosystems for which quantitative information was available, thus excluding anecdotal information or perceptions. It included formally published and grey literature (technical, research and project reports, working papers, issued by government or non-government organisations) from available sources.

The intervention we were assessing was the official establishment of protected areas; this included legally designated protected areas, e.g. Ramsar, national parks, reserves (national or regional). It excluded general protection measures that are not confined to specific geographical areas, e.g. environmental flows, species protection (such as CITIES). Informal protection/exclusion zones, private land management and indigenous preferential use of different zones were also excluded.

To test whether protected area designation had brought about change in biodiversity, we included studies that compared the same area before and after designation or after designation was removed. We also included studies that compared a designated area with a suitable undesignated reference area or a protected area with different type of protection (e.g. buffer zone v core area). We further included studies that as outcomes recorded changes in appropriate measures of biodiversity, such as species richness, population size. We excluded qualitative measures, personal impressions or inferences beyond the data collected. However, we agreed to include measures of habitat as a surrogate for biodiversity, since studies may record, for example, changes in forest cover after designation.

We included all publications from 1990 to the present and those in English language. We included publications from global databases, Web of Science and the Scientific Electronic Library Online (SciELO), plus the global search engine Google Scholar). In addition, we included publications recommended by experts and institutions and from reference lists of previous reviews and books (termed snow-balling).

3.3 Defining search terms for Web of Science

To retrieve information from global databases, such as Web of Science, the PICO elements must be translated into search terms using the database query language syntax that employs Boolean operators (e.g. AND, NOT, OR). We trialed different combinations of search terms and different syntax e.g. wildcards $ (one character) or * (any number of characters including spaces). Each returned different lists of publications from Web of Science.

We selected a set of search terms that returned key publications on the topic that were recommended by experts and the number of publications that could be reviewed within the time and resources of the project (i.e. around 2000 titles). Initial search terms were assessed by Professor Angela Arthington as part of the independent peer-review process. In particular, she recommended more emphasis on groundwater-dependent ecosystems. The final set of terms is presented in Box 1; this returned 2194 titles. To this we added publications recommended by experts that were not found on Web of Science (primarily grey literature) and reference lists from review papers and books (e.g. Finlayson *et al.,* 2018a). Review papers were excluded in their own right (unless they included new unpublished data) to avoid collating the reviewer's interpretations of other literature (see use of reviews and books below in section 3.4), so only primary sources were included. We also excluded journals that we considered would not yield required information, such as astronomy, petrology and applied mathematics. Applying these restrictions returned a total of 1871 titles on 24 September

2018. It is worth noting that the returns may be different if the same search terms are used on future dates.

Box 1. Search terms in Web of Science syntax

TS=(freshwater$ OR “aquatic ecosystem$” OR delta$ OR estuar* OR catchment$ OR wetland$ OR “peatbog$” OR peat* OR "groundwater-dependent ecosystem$" OR spring$ OR river$ OR stream$ OR riparian OR floodplain$ OR marsh* OR swamp$ OR lake$ OR pond$ OR reservoir$ OR canal$)

NOT
(TS=(salt*marsh* OR marin* OR aerial OR atmospher* OR land OR salin*))

AND
TS=(habitat$ OR biodiversity OR wildlife OR population$ OR “endangered species” OR “threatened species” OR "critically endangered species" OR "vulnerable species" OR species OR *bird* OR “water?fowl” OR fish* OR *invertebrate$ OR mammal$ OR amphibian$ OR frog$ OR reptile$ OR plant$ OR macrophyte$ OR “aquatic plant$” OR crustacean$ OR mollusc$ OR fung* OR insect$ OR dragonfl* OR damselfl* OR algae OR diatom$ OR phytoplankton OR zooplankton)

AND
TS=(“protected area$” OR Ramsar OR “national park$” OR “natur* park$” OR “nature reserve$” or “biosphere reserve$” or “wilderness area$” OR “protected landscape$” OR “world heritage site$” OR “Natura 2000” OR “wild scenic river$” OR “conservation area$” OR “natural monument” OR “management area”)

AND
TS=(compar* OR evaluat* OR effectiv* OR consequen* OR conserve* OR maintain* OR protect* OR enhance* OR sustain* OR trend* OR benefit$ OR restor* OR subsequent* OR assess* OR apprais* OR role OR influen* OR impact$ OR change$ OR performance$)

AND
TS=(previous* OR control$ OR baseline$ OR buffer OR un*protect* OR adjacent OR (before AND after) OR (inside AND out---side) OR (with AND without))

The Scientific Electronic Library Online (SciELO) database provides an additional means within Web of Science to search for open access journals from countries in the Neotropics (Latin America). The same search terms were used as for Web of Science (Box 1), which returned 56 papers.

3.4 Defining search terms for Google Scholar

Although the prime method of searching was via the Web of Science database (and its subsidiary database SciELO), it was decided that a search using Google Scholar would be undertaken to look for additional references. Google Scholar allow only simple search strings with a maximum of 256 characters. We employed the terms shown in Box 2. Google Scholar ranks the returns in order of their fit to the search terms. We selected the first 300 titles and only one was not already returned by the Web of Science search.

Box 2. Search terms in Google Scholar syntax

(freshwater$ OR “aquatic ecosystem$” OR wetland$ OR river$ OR lake$) AND (habitat$ OR biodiversity) AND (“protected area$” OR Ramsar OR “national park$”) AND (assess* OR impact$ OR change$ OR maintain OR protect* OR enhanc* OR compar* OR trend)

3.5 Defining searches from reviews and books

As indicated above, review papers and books were excluded in their own right (unless they included new, previously unpublished data) to avoid collating the reviewer’s interpretations of literature that we would most likely find in the original sources. However, we used the reference lists of these papers and books as an additional source, including Finlayson *et al*. (2018a) and Hermoso *et al.* (2016). In total, 333 papers were assessed on the basis of title (185 from Finlayson *et al*., 2018a; 84 from Geldmann *et al*., 2013; 64 from Hermoso *et al.,* 2016).

3.6 Asking organisations and experts

A further key part of the search strategy was to contact individual experts, such as academics who have published on the subject of protected areas and freshwater biodiversity, and organisations that include this topic within their mandate, including the Convention on Wetlands (Ramsar), the Convention on Biological Diversity, The International Union for Conservation of Nature - IUCN (World Commission on Protected Area, Freshwater Biodiversity Unit, Water Programme), Wetlands International, The Nature Conservancy and the Wildfowl and Wetlands Trust. Experts contacted are given in Box 3. Some institutions hold their own databases. IUCN for example has a catalogue of publications which includes the International Journal of Protected Areas and Conservation, PARKS. These databases were also searched. An additional 39 publications were identified.

Box 3. Organisations and experts consulted

Australian National University - Jamie Pittock
Carleton University - Steven Cooke
Center for Limnology, USA - Aaron Koning
Charles Darwin University - Michael Douglas
Charles Sturt University - Max Finlayson
Colorado State University - LeRoy Poff
Convention on Biological Diversity
Conservation International - Robin Abell, Ian Harrison
Frankfurt Zoological Society - Jessica Groenendijk
Freshwater Biological Association - Phil Boon
Griffith University - Angela Arthington, Mark Kennard
Hong Kong University - David Dudgeon
Independent - Nick Davidson (former Ramsar Convention), David Coates (former Convention on Biological Diversity), Rob McInnes (former Wildfowl and Wetlands Trust)
IUCN - Laura Máiz-Tomé
Queensland University - Nigel Dudley
Ramsar Convention
Stetson University - Roy Gardner
Sustainable Waters - Brian Richter
The Nature Conservancy - Eloise Kendy, Jonathan Higgins
Wetlands International – Ritesh Kumar
Wildfowl and Wetlands Trust
Wisconsin University - Pete McIntyre
WWF-US - Michele Thieme, Louise Glew
WWF-UK - Holly Pringle

4. Applying selection criteria

4.1 Short-listing returns from searches

The titles and abstractions of the 1927 publications returned from Web of Science (including SciELO) were added directly to an EndNote database.

Titles of the 300 publications returned from Google Scholar and 39 from experts and 333 from reviews were examined and 13 duplicates removed. Remaining publications were checked for relevance to the study. Those excluded at title stage were checked independently by the second co-author of this report. Where there was any doubt the abstract was retrieved. The PICO elements were applied as selection criteria to the titles and abstracts of the 2586 publications to screen for relevance to the study questions. The major criteria were that each paper must contain quantitative information on the effectiveness of protected areas for conserving freshwater biodiversity or habitat that would support biodiversity, both before and after designation of the protected area, or between the protected area and an un-protected or less protected control or reference area. A sub-set of abstracts was reviewed independently by the co-authors as a cross-check. Where there was any doubt from reading the abstract, the full paper was retrieved to make a final decision on relevance to the search criteria.

Papers describing the results of management actions taken at the time of designation were included. Those that reported later actions (sometime after designation) or changes due to actions outside the protected area were excluded. This is because there are many examples of adaptive management or management experiments undertaken in protected areas after designation and many on impacts of actions not influenced directly by the protected area authorities, such as removal of a dam downstream. Papers captured on these topics were considered out-of-scope of the current QSR. Clearly such knowledge could be extremely important to evaluating the success of protected areas, so could form the basis of a separate QSR (see section 12.2).

4.2 Numbers of papers and case studies

Figure 4 shows the number of publications at each stage of the selection process. A total of 2586 publications were identified by the searches. After screening and application of eligibility criteria, the number was reduced to 44 publications. Reasons for the high number of rejections include the following. Large numbers of publications contained conceptual ideas and inferences drawn from other studies but provide no new data. Many publications provided survey data for particular species in protected areas but no data before designation or outside the protected area with which to make comparisons. Some publications reported on the proportion of the range of a species covered by protected areas, but nothing defining how effective these areas are. Other publication contained the results of surveys of protected area managers containing their perspective but with no quantitative evidence.

Most selected papers contained information on a study of one site, on one taxonomic group and using one biodiversity metric, *e.g*. the Ramsar site contained a population of 1000 birds. However, some papers referred to several sites, more than one taxonomic group, and reported numerous metrics. Some metrics were divergent, *e.g*. abundance increased but diversity decreased. To take account of these varied reports in single publications, each set (one site, one taxon and one metric) was referred to as a 'case study'. The 44 publications contained 72 case studies.

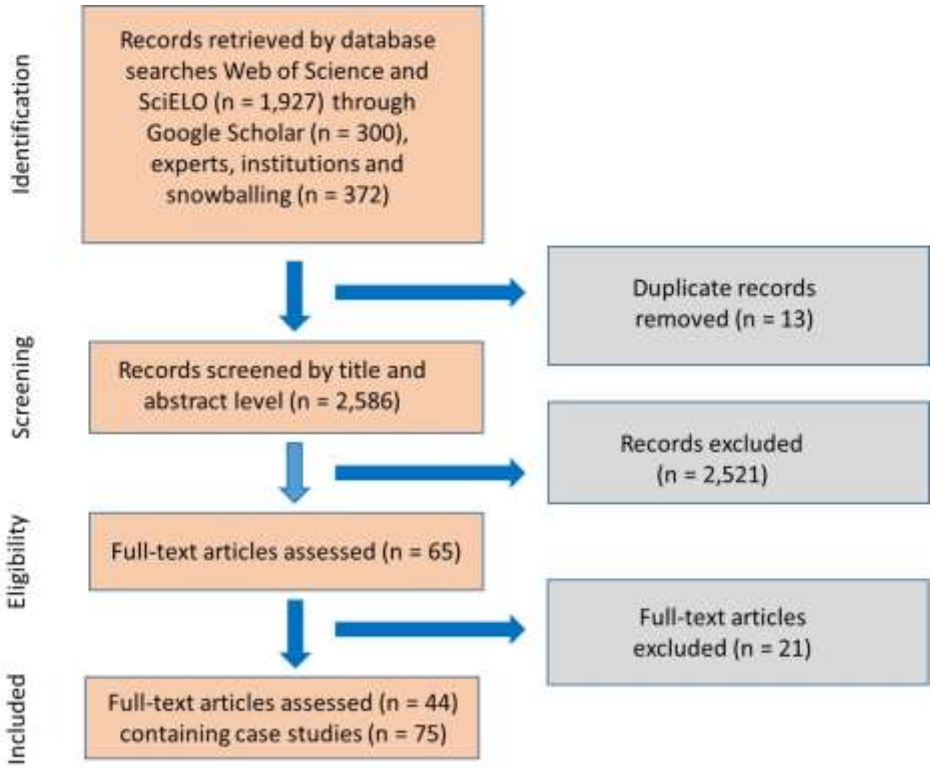


Figure 4. Numbers of papers and cases studies at each stage in the selection process

5. Extracting information from publications

A series of information types was defined and details for each were extracted consistently from every paper for each case study. The only inference made was in the case of the direction of change (see section 4.8 below), otherwise only information actually written in the publication was considered. The exception to this rule was that in a few cases factual information was found from other sources; for example, some papers did not indicate the date of designation of the protected area, so this was sought from the Internet. The following sections describe the information types recorded.

5.1 Publication details

Basic publication details were recorded, namely: authors, date, title of paper, name of publication (e.g. journal or report title), volume, DOI and source (e.g. Web of Science).

5.2 Summary statement

A short text was extracted from each paper that summarises the findings of the study. Normally this was taken from the abstract. Additional text was added where the abstract did not contain the quantitative results.

5.3 Geo-eco typology

Four measures of ecosystem type and geography were recorded. Country, Ramsar region (Figure 5), terrestrial ecoregion (from Olsen, 2001. Figure 6) and freshwater ecoregion (from Abel *et al.,* 2008. Figure 7).

Figure 5. Ramsar regions: Africa, Asia, Europe, North America, Neotropics, Oceania.

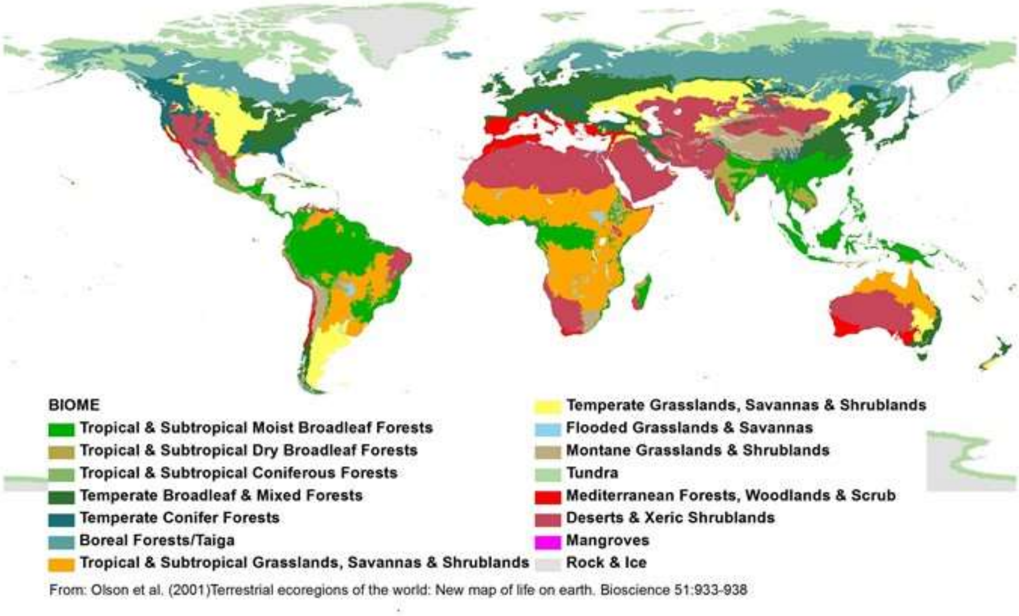


Figure 6. Terrestrial ecoregions (Olsen *et al.,* 2001)

Figure 7. Freshwater ecoregions (Abell *et al.,* 2008)

5.4 Protected area characteristics

Eight items of basic characteristic information concerning the protected area were extracted. These were: protected area name, protected area type (*e.g.* national park), date of designation, IUCN protected area category (Box 4), broad freshwater ecosystem type (*e.g.* river), purpose / objective of protection, protection measures and size of protected area (km^2) or length of river (km) and whether it is part of a network of protected areas.

Box 4. IUCN Protected Area categories (Dudley, 2008).

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"". There are six categories.

IUCN Protected Area Categories (Adapted from IUCN 2008)
Category Ia: Strict Nature Reserve. Human access is strictly controlled with the aim of conserving biodiversity and/or protecting landscape/seascape features.
Category Ib: Wilderness Area. Generally applied to areas with low to no anthropogenic impact. Human access is limited to preserve the natural condition.
Category II: National Park. Applied to large areas to preserve large-scale ecosystem processes and features. Human activity is permitted under regulatory guidance. May contain areas of strict protection resembling Categories 1a, 1b.
Category III: National Monument or Feature. Applied to specific locations that represent a natural or culturally significant feature or monument to preserve its state. Human traffic is regulated, but generally high volume.
Category IV: Habitat/Species Management Area. Applies to localized areas protected to promote restoration, conservation or maintenance of specific species or habitats. Human traffic is generally uncontrolled.
Category V: Protected Landscape/Seascape. Applies to areas of land and sea with distinct scenic and cultural features where traditional land-use has played a role in maintaining system integrity. Maintenance of current human use is a goal of this category.
Category VI: Protected Area with Sustainable Use of Resources. Applies generally to large, natural areas with the aim of maintaining sustainable natural resource use and low-level industrial use. Human traffic is usually uncontrolled. "No-take" zones are recommended.

5.5 Study-specific information

Six items of information were extracted concerning the study: taxonomic group studied, specific species recorded, status of species on the IUCN Red List (e.g. endangered), biodiversity metric employed (e.g. abundance), method of study (e.g. data comparison), source of data (e.g. field survey) and basis of inference of change in biodiversity or habitat (e.g. comparison of before and after designation).

5.6 Issues affecting the protect area

Information describing issues affecting the protected area were extracted. These were the catchment context (e.g. position of protected area within the river basin), internal pressures (e.g. fishing) and external pressures (e.g. alterations in flow due to upstream dams, pollution inflows).

5.7 Protected area management details

A few papers provided information on protect area management including staffing, additional resources (e.g. boats), financial investment, interaction with local community and the role of different institutions. These details were recorded where available.

5.8 Direction of change recorded

An important part of the study was to summarise the effectiveness of the protected area by recording the direction of change in metrics that had resulted from designation and factors underlying change. Effectiveness was recorded as positive, negative or neutral overall. In some cases, this assessment was straightforward. Where, for example, abundance of a rare species increased in a protected area designated for that species (compared with the area before designation or an unprotected reference area), the action was deemed positive. If the population remained constant after designation (in both the protected area and outside), then designation was considered to have a neutral outcome. If the population had declined in the protected (compared with before designation or in an unprotected reference area), then it was recorded as negative. It is noteworthy that if, for example, a paper reported a decrease in the total population, at first sight this might be considered a negative outcome. However, if this population decline was due to removal of alien invasive species, it was recoded as a positive outcome. In some cases, categorisation required closer review of the objectives of the protected area. Burning of vegetation is undertaken in some protected areas to support game birds for shooting and grazing for livestock. This might be considered negative for overall biodiversity, but positive if the purpose of the area is to conserve ecosystem services or cultural heritage.

6. Limitations of the study

Systematic reviews attempt to locate, collate, screen and assess available evidence on a topic in an objective, transparent, consistent, scientifically rigorous, unbiased, complete and repeatable manner. We have worked to achieve these aims but inevitably all reviews have limitations, which are discussed below.

6.1 Objectivity

This review had no pre-conditions. It did not seek to promote or denigrate protected areas. The focus of the study was to report evidence of effectiveness from available publications in an unbiased manner. We did not infer any results or give personal opinions but reported verbatim what was published. The exceptions to this were in defining 'direction of change' and 'IUCN category' which had to be inferred, but we have explained how this was achieved. Some factual information, such as date of designation, was sourced from Internet searches when not given in the publication.

The method, its application and results were reviewed internally by the WWF-UK project team and externally by Professor Arthington.

6.2 Transparency and repeatability

We have described each step in the process that we followed in the review. If anything is not clear, it is unintentional rather than an intention to conceal anything. This should enable any element of the review to be repeated. It is noteworthy that returns from databases, such as Web of Science vary over time (even when using the same search terms), for example as new publications are added. So repeating the exact review steps will not necessarily produce the same results.

6.3 Consistency

We established clear rules, such as the selection criteria, at the start of the review. There were two members of the review team and we undertook repeat split sample tests to ensure consistency and discussed any publications for which application of the criteria was uncertain.

6.4 Scientific rigour

Only studies reporting data in the form of ecological metrics or habitat change were included.

The basis of inference is an important element of scientific methodology. Before-after-control-impact (BACI) designs are a widely-used effective method to evaluate natural and human-induced perturbations of ecological variables (Eberhard, 1996; Conner *et al*., 2016). For this review the experimental design would be ecological data before and after designation as a protected area (the impact) and independent, but similar, area that had not been designated (the control). In the case studies collated, 20% compared ecological data before and after designation, but few had a control (or counterfactual) indicating what could have happened to the area if it had not been designated by reference to an undesignated area. The true effectiveness of designation depends on comparing the protected area with the situation outside. If, for example, bird abundance remained constant following designation of a protected area this would be a positive outcome relative to a decline in abundance outside, neutral if abundance stayed the same outside or negative if abundance outside increased.

Approximately 70% of studies compared data within and outside a protected area. Some compared time series or trends, but most compared data at a specific time. This approach may not always tell the full story. For example, even if fish abundance was lower within a protected area than outside, it could be recovering and higher than before designation. If fish abundance was higher inside, it may be declining rapidly.

Despite the above reservations, almost all case studies selected had good explanations of why the changes reported had occurred.

6.5 Publication bias

The citation index is a key performance indicator for scientific journals. So, journals strive to attract readers and achieve citations of their papers. Whilst editors try very hard to be unbiased, there has been a tendency to publish more ground-breaking and dramatic results that may be news-worthy and more likely to capture the readers' imagination. Studies that repeat previously published findings are therefore less likely to be submitted and accepted than those that make new discoveries. It is possible that the success of many protected areas, say in conserving wildlife populations, has not been considered worth reporting in the scientific press and so is under-represented.

6.6 Completeness

From the analysis of medical research, Green (2008) found that only 14% of proposed research ever makes it to research synthesis and guidance because of research agendas, funding limitations, proposal peer review, research success, publication peer review, or indexing to appear in systematic reviews. So there are likely to be many examples of the effectiveness of protected areas that do not appear in our study of publications.

All studies have limited resources. We agreed on search and selection criteria that would capture the maximum possible amount of evidence whilst being feasible to process within the project time and funding constraints.

Our selection criteria rejected many papers that may contain important lessons for protected area management. These include experiments undertaken separately from designation of the protected area, e.g. high flow releases from dams on the Colorado River, USA (Cross *et al*., 2011), and ongoing adaptations to management plans. Many papers were rejected because no control data are available. For example, Groenendijk *et al.* (2014) report recovery of the giant otter (*Pteronura brasiliensis*) within the protected floodplain of Manu National Park, south-eastern Peru, but the publication contains no data from outside the park for comparison, which meant it did not meet our inclusion criteria.

Assessing the true effectiveness of protected areas requires a comparison with the effectiveness of alternative measures, such as global scale species protection (e.g. CITIES) or catchment/national scale environmental flow and river health programmes. Assessing these measures was outside the scope of the review.

7. What the publications report

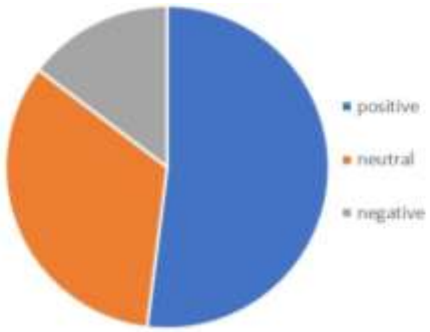
This section describes the characteristics of the information extracted from the publications.

7.1 The database

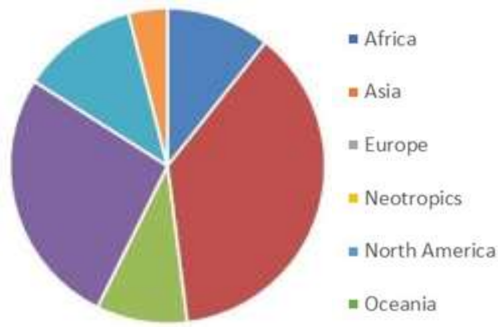
An Excel spreadsheet was established to hold the evidence base of information extracted from the selected publications. The spreadsheet has a column entry for each item of information described in Section 4 and a row for each of the 75 case studies found in the 44 publications. The spreadsheet facilitated easy analysis and production of summary diagrams (Figure 8a-l).

7.2 Characteristics of the database

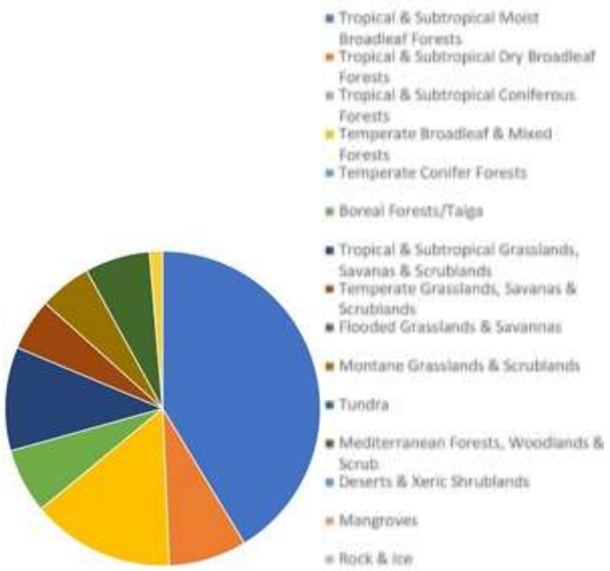
Figure 8a shows that of the 75 case studies, 39 reported positive outcomes, 25 neutral and 11 were negative, so just over half, 52%, of the studies show protected areas to be effective.



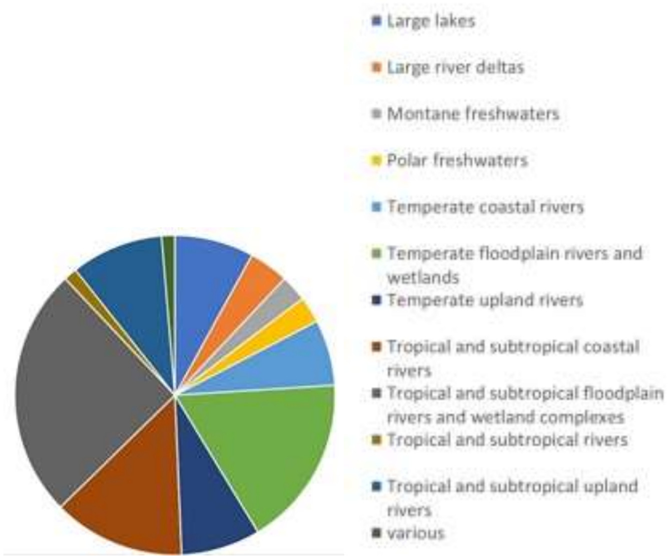
a. Direction of change



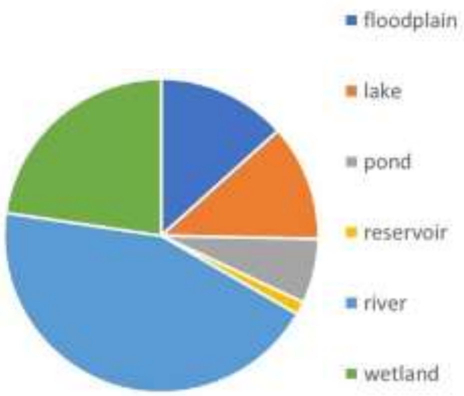
b. Ramsar region



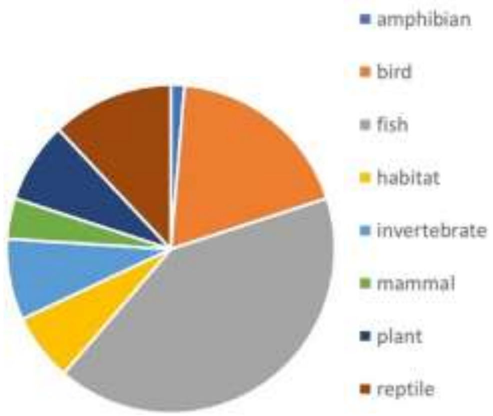
c. Ecoregion (Olsen, 2001)



d. Freshwater ecoregion (Abel *et al*., 2008)

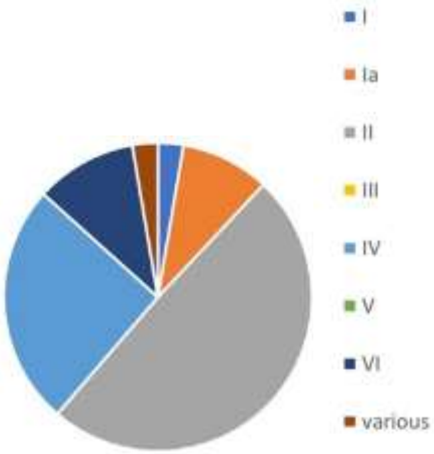


e. Freshwater ecosystem type

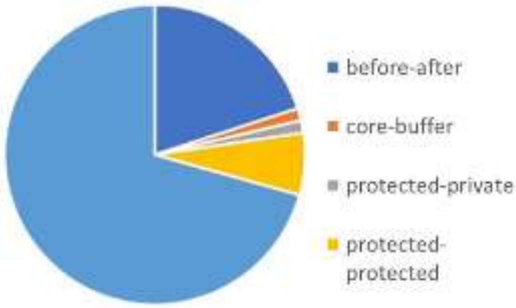


f. Taxa

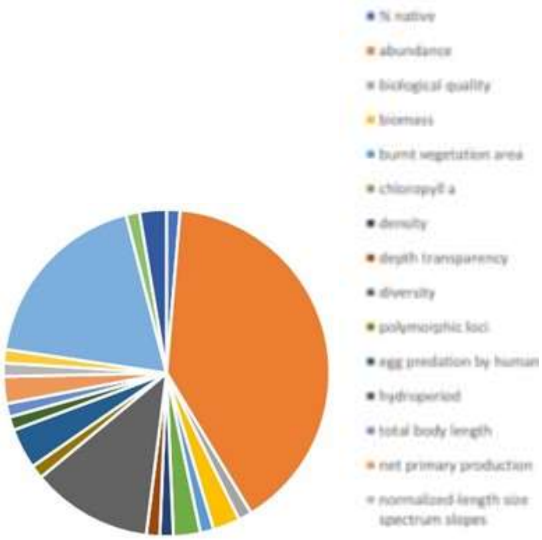
Figure 8. Characteristics of the database a-f



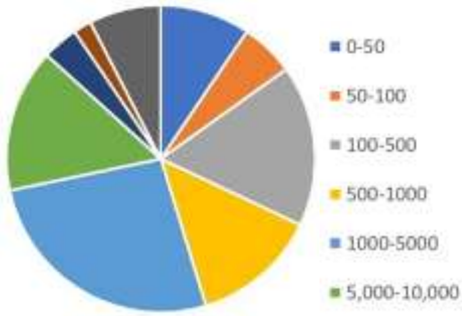
g. IUCN protected area category



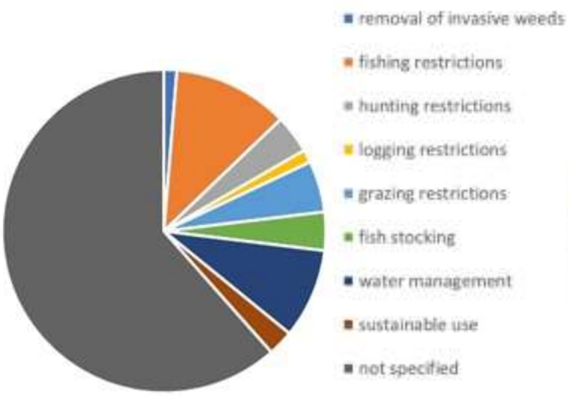
h. Basis of inference



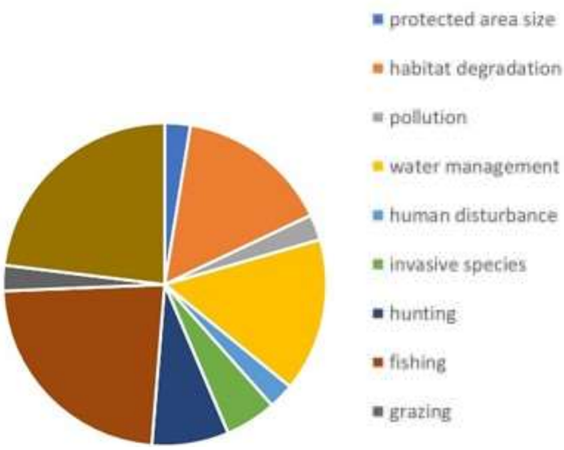
i. Metric



j. Protected area size (km^2)



k. Management measures



l. Causes of non-positive direction of change

Figure 8. Characteristics of the database g-l.

Di Marco *et al.* (2017) suggested a strong geographical bias persists in publications of conservation science, with 40% of studies carried out in USA, Australia or the UK, and only 10% and 6% respectively in Africa and South East Asia. However, Figure 8b shows a good spread across Ramsar regions of the world, but with a dominance of studies from Asia. Furthermore, Figures 8c-d display good spread in ecoregions with a dominance in the moist tropics and subtropics, subtropical floodplain rivers and wetland complexes. Studies from the Neotropics, within temperate floodplain rivers and wetlands are also well represented.

In terms of taxa, the case studies are dominated by fish and birds (Figure 8f). National Parks (large areas to preserve large-scale ecosystem processes and features) are by far the most common protected area category, *i.e*. type II (Figure 8g), with category IV Habitat/Species Management Areas (localized areas protected to promote restoration, conservation or maintenance of specific species or habitats. and birds) the second most well represented.

The majority of studies compared protected with un-protected areas, with only a few comparing the same area before and after designation (Figure 8h). The most common metrics employed were abundance and richness, followed by diversity (Figure 8i). Medium-sized protected areas 1,000-5,000 km^2 were most common amongst the case studies, although there were many of smaller size, 100-500 km^2 and a few were large 5,000-10,000 km^2 (Figure 8j). Many papers did not specify the management measures involved following designation; of those that did, the most common were fishing restrictions and water management (Figure 8k).

Figure 8l shows that the main causes of non-positive (negative or neutral) direction of change were fishing (often lack of law enforcement), the influence of environmental variables (such as climate, landscape, river channel geometry, pH), water management (abstraction and dams) and habitat degradation (*e.g*. from mining, agriculture).

7.3 Database element relationships

The obvious question that arises is whether the change of direction (negative, neutral or positive) is related to any characteristics of the protected areas, such as category, geographical location, ecological type or taxa evaluated. These issues are explored in Tables 1-6, which record the number of case studies with negative, neutral and positive outcomes related to different factors.

Table 1. Relationship between taxa evaluated and direction of change

	direction of change			
	negative	neutral	positive	total
amphibian	0	0	1	1
bird	4	3	7	14
fish	3	14	14	31
habitat	0	3	2	5
invertebrate	1	2	3	6
mammal	0	1	2	3
plant	1	1	4	6
reptile	2	1	6	9
total	11	25	39	75

Table 2. Relationship between basis of inference and direction of change

	direction of change			
	negative	neutral	positive	total
before-after	2	3	10	15
core-buffer	1	0	0	1
protected-private	1	0	0	1
protected-protected	1	1	3	5
protected-unprotected	6	21	26	53
total	11	25	39	75

Table 3. Relationship between Ramsar region and direction of change

	direction of change			
	negative	neutral	positive	total
Africa	1	3	4	8
Asia	6	6	16	28
Europe	1	2	4	7
Neotropics	3	7	10	20
North America	0	5	4	9
Oceania	0	2	1	3
total	11	25	39	75

Table 4. Relationship between IUCN category (Box 4, above) and direction of change

	direction of change			
	negative	neutral	positive	total
I	0	0	2	2
Ia	0	0	7	7
II	6	13	18	37
III	0	0	0	0
IV	4	9	6	19
V	0	0	0	0
VI	1	2	5	8
various	1	1	0	2
total	12	25	38	75

Table 5. Relationship between freshwater ecoregion category (Abel *et al*., 2008) and direction of change

	direction of change			
	negative	neutral	positive	total
large lakes	0	3	3	6
large river deltas	1	1	1	3
montane freshwaters	0	1	1	2
polar freshwaters	0	1	1	2
temperate coastal rivers	2	1	2	5
temperate floodplain rivers and wetlands	2	6	5	13
temperate upland rivers	1	1	4	6
tropical and subtropical coastal rivers	1	2	8	11
tropical and subtropical floodplain rivers and wetland complexes	4	6	9	19
tropical and subtropical upland rivers	0	2	5	7
various	0	1	0	1
total	11	25	39	75

When the 75 cases studies are divided amongst various factors in Tables 1-5, the numbers available for analysis of positive, neutral and negative outcomes of protected areas are quite small. In general, the sub-division of the effectiveness classes does not highlight very strong relationships with taxa, basis of inferences, IUCN category or freshwater ecoregion. For example, Table 1 shows that the figure of around 50% effectiveness remains, roughly, for all the taxa. So protected areas do not seem to favour conservation of one taxon over another. Studies based on before-after comparisons have two-thirds (66%) positive results, which is more than for protected-unprotected comparisons with 50% positive; these are the most common bases of inference (Table 2). Table 3 suggests there is tendency for protected area designation in Asia (57%) and the Neotropics (50%) to be more successful than in North America (44%), but these relationships are not massively different. Table 5 shows that 73% of the cases studies in tropical and subtropical coastal rivers show positive outcomes for protected areas, which exceeds the 52% overall figure.

The small number of case studies involved suggests that further breakdown of the classes (e.g. Asian protected areas studied with fish metrics) would not be worthwhile.

A particular issue highlighted in the general literature on protected areas for freshwater biodiversity (Finlayson *et al*., 2018a) is the lack of systematic protection of areas and habitats for different fish life stages and processes (e.g. spawning, larvae, juveniles, adults), particularly those that migrate. To explore this further, the selected papers reporting fish metrics were re-examined with a view to classifying the fish investigated into broad types – non-migratory and migratory (anadromous, catadromous) – and to assess effectiveness of protected areas for each type. However, many papers did not give species lists, whereas others gave long lists of fish some of which could not be classified due to lack of life-history information. So, we could not complete this analysis. Instead a simpler analysis was undertaken to determine if protection for fish was more effective in different broad water body types. It can be seen in Table 6 that only riverine case studies reported negative changes in fish metrics, with only 40% of case studies being positive. The three river studies of negative change in fish metrics reported the causes as invasive species (García-Marín *et al.,* 1998), environmental variables such as pH, temperature and habitat area (Kwik & Yeo, 2015) and local disturbances from dredging, mining and deforestation (Rodríguez-Olarte *et al.*, 2006). None of the fish case studies indicated habitat fragmentation or lack of connectivity as a cause of negative change.

Table 6. Relationship between broad water body type and direction of change (for studies involving fish metrics only).

	direction of change			
	negative	neutral	positive	total
river	3	3	4	10
lake	0	2	2	4
wetland	0	2	1	3
floodplain	0	4	0	4
pond	0	2	1	3
total	3	13	8	24

8. Key issues raised by the review

The following sections explore key issues concerning freshwater protected areas. In each section an introductory paragraph records some of the issues raised in general literature that was not selected according to the criteria of this study. We then present evidence from the selected literature on the topic, with the reference in bold text at the beginning and direction of change in bold at the end. It is noteworthy that the results of many case studies address more than one issue, so some appear in more than one section.

8.1 Protected area design, networks and connectivity

There has been long-term acknowledgment of the highly connected nature of freshwater ecosystems, longitudinally, laterally, vertically and temporally (Ward, 1989). The importance of lateral connectivity between rivers and their floodplains has been emphasised (Junk *et al.,* 1989; Kingsford, 2015) as well as longitudinal connectivity through the drainage network – often disrupted by dams (Cooper *et al*., 2017) - and vertical connectivity with groundwater (Pittock *et al*., 2015). Castello & Macedo (2016) contended that hydrological connectivity regulates the structure and function of Amazonian freshwater ecosystems and the provisioning of services that sustain local populations. Isolated freshwater protected areas are also vulnerable to pollution inputs from upstream unprotected zones. Freshwater areas are often protected because they happen to be within areas designated for terrestrial biodiversity. As such, the design of the protected area rarely reflects the need for connectivity between critical life-stage habitats for migratory species - such as spawning and nursery areas, migratory corridors, and feeding zones - that are essential for ensuring ecological and evolutionary processes (Bower *et al*. 2014). Azevedo-Santos *et al.* (2018) concluded that Brazil's protected areas are biased towards terrestrial ecosystems and have limited efficacy in the protection of freshwater biodiversity; new protected areas should better consider aquatic environments, covering entire basins, rivers and other freshwater habitats. Drainage network location and size also affect freshwater the conservation potential of protected areas (Thieme *et al.*, 2016). Protecting inter-connected elements of catchments with topographical diversity and habitat heterogeneity, incorporating low and high elevation sites, also makes freshwater reserves more resilient to climate change. Franks *et al*. (2016) suggest the UK's network of Special Protection Area (SPA) for birds will be resilient to climate change because of the degree of functional connectivity between areas at the regional level.

No studies selected in our review reported evidence that lack of connectivity or fragmentation of habitats for different life stages or for migration had been a factor in lack of effectiveness for any protected area. However, longitudinal connectivity is mentioned in discussion or inferred from results as a major issue. Some papers refer to the importance of connectivity between rivers and their riparian areas and floodplains and between surface and groundwater for habitat maintenance. The following seven studies provided contributions to the issue of connectivity.

Li *et al* (2015) found lower numbers of hooded cranes (*Grus monacha*) in the core areas of the Shengjin Lake National Nature Reserve, China, than in the buffer zones. By reference to other studies they suggested that the core areas had suffered degradation of natural habitats and a resulting decline in food resources due partly to dam-caused hydrological disconnection with the Yangtze River. **[negative]**

Sarkar *et al.* (2011) found that abundance and diversity of fishes was higher within than outside the protected area of the Katraniaghat Wildlife Sanctuary, India. Shading by dense riparian vegetation in the park was an important feature of the protected areas. This indicates the importance of connectivity between the river and riparian zone vegetation. **[positive]**

Ledo & Colli (2016) tested the effectiveness of the prescribed 30m buffer in maintaining lizard assemblages in riparian forests associated with narrow streams in central Brazil. They studied two preserved areas, and one deforested area, and recorded 11 lizard species. The reduced riparian forest had lower abundance, richness, evenness, and phylogenetic diversity compared to the preserved habitats and lacked forest specialist species. This shows the importance of connectivity with the riparian forest. **[positive]**

Vega-Cendejas *et al.* (2013) compared fish assemblage structure among 36 karstic pools located within protected areas of the Calakmul Biosphere Reserve, southern Mexico and unprotected adjacent areas outside the reserve. They found that the relative abundance of fish species was not influenced by protection, but for some was determined by natural water quality variable (K, NH_4, NO_3, and conductivity). This shows the importance of connectivity between the pools and karst groundwater system for water quality **[neutral].**

Mutusva *et al*. (2016) studied the *Faidherbia albida* vegetation community in the Lower Zambezi and Mana Pools National Parks, Zambia. They found lower tree density and regeneration capacity in Mana Pools National Park, which they attributed to several factors including lower water tables that followed river impoundment at Kariba Dam. This study demonstrates the importance of connectivity between the surface and groundwater systems for vegetation. **[negative]**

Penha *et al.* (2014) found no differences in fish abundance between the lagoons inside and outside reserves in the Pantanal, Brazil. They concluded that protection provided by the reserve not only protects the biota inside the reserve, but also acts as a source of fish to unprotected areas. **[neutral]**

Britton *et al.* (2017) found that although fish diversity was much higher within protected areas of Lake Tanganyika than outside of them, the reserves might be too isolated to act as a source of populations for colonisation of less diverse areas of the lake. **[positive]**

The following five studies provided contributions to the issue of protected area design.

Chu *et al*. (2017) studied fish populations in lakes in Ontario, Canada, some of which were national parks. Neither fish abundance nor diversity differed significantly across comparisons. However, normalized-length size spectrum slopes (NLSS - the slope of the line relating abundance to body size) were significantly steeper in lakes outside parks (i.e. there were comparatively fewer large fish). They suggested that lake ecosystems would benefit from freshwater protected area designs that include the entire lake rather than protecting part of the lake or shoreline. **[neutral] [positive]**

Koning (2018) found that reserves in Thailand had higher fish species richness than adjacent unprotected fished areas. This effect increased with reserve size as well as duration of protection, and proximity to the nearest village. **[positive]**

Yrjölä *et al*. (2017) studied the population growth and expansion of Barnacle Goose (*Branta leucopsis*) in Helsinki archipelago, Finland. Breeding densities in unprotected islands were higher than in protected islands as numbers were controlled by island size, the time each has been inhabited, and distance from the islands where breeding expansion started. **[neutral]**

Adams *et al.* (2015) reported that the declaration of Kakadu National Park in northern Australia was particularly significant because its boundaries encompassed almost all the catchment of the South Alligator River, the entire catchment of the smaller West Alligator River. The catchment approach facilitated park management, particularly reducing the nuisance invasive weed *Mimosa pigra*. However, they recognised strong interactions across the boundaries of protected areas or treatment areas that they called “spill-over effects”, which may be positive or negative and are likely to bias the evaluation of local impacts unless these connections are understood and controlled for. **[positive]**

Britton *et al.* (2017) found that fish diversity in Lake Tanganyika was up to 50% lower outside of protected areas than within them. Despite these protected areas being designed for terrestrial conservation (e.g. forests), they are clearly benefitting cichlid taxonomic and functional diversity within Lake Tanganyika, probably through local reduction in sediment deposition and/or pollution. **[positive]**

8.2 Representativeness of freshwater protected areas

There is considerable literature - not meeting the inclusion criteria of this review - on how well protected areas represent all existing habitats for particular species or ecosystems. For example, Hermoso *et al*. (2015) suggested that the Natura 2000 network in Europe lacks appropriate spatial design to make conservation for freshwater biodiversity effective. Meng *et al*. (2016) found that of 321 species of reptile studied in Tanzania, 116 had less than 20% of their distribution ranges protected. Carrizo *et al*. (2017) studied freshwater megafauna throughout the world and concluded that 58% of the 132 species included were threatened, with 84% of their collective range falling outside of protected areas. Using the inland waters of Michigan as a test case, Herbert *et al.* (2010) quantified the coverage of four key freshwater features (wetlands, riparian zones, groundwater recharge, rare species) within conservation areas and compared these with representation of terrestrial features. They found that wetlands were included within protected areas more often than expected by chance, but riparian zones were underrepresented across all protected lands, particularly for headwater streams and large rivers.

The following four studies selected in our review referred to the representativeness issue directly.

Abraham & Kelkar (2012) investigated the importance of existing terrestrial protected areas for conservation of stream fishes within and across three dammed and two undammed rivers in the global biodiversity hotspot of the southern Western Ghats, India. Protected areas had consistently higher endemic fish species richness than unprotected areas. However, they concluded that terrestrial protected areas did not adequately represent the habitat diversity of river systems. **[positive]**

Cui *et al.* (2014) studied waterbirds in China. The average numbers of species supported by internationally important sites were higher (lakes), the same (rivers) or lower (reservoirs) for well-protected sites than for partially-protected sites. They concluded that increased designation of wintering sites of waterbirds should be a priority and more wetland sites, especially coastal wetland sites, should be protected. **[positive] [neutral] [negative]**

Britton *et al.* (2017) found that fish diversity in Lake Tanganyika was up to 50% lower outside of protected areas than within, but they suggested that reserves might be too isolated to act as a source for less diverse areas of the lake. **[positive]**

Cucherousset *et al.* (2007) reported that protected areas potentially produce 8.4% of the total silver eel production in Grande Brière Mottière marsh, France, whereas they only account for 2.4% of the aquatic habitat area. They estimated that increasing the size of the protected areas to 31.1% would produce 50% of the potential silver eel of a fully protected marsh. **[positive]**

8.3 Ecological site management

Designation of a site or area is an important step in its protection, but success often depends on how the site is managed ecologically. Many species need a range of specific habitats for different life stages. Maintaining or restoring habitat conditions is critical to biodiversity conservation. A key issue is to define the objectives of the protected area and associated controls on activities therein and management. The IUCN categories (Box 4) show that protected areas can have a wide range of objectives from strict nature protection in which human access is not allowed or strictly controlled and the aim is to conserve biodiversity or natural conditions. In contrast other sites seek to preserve culturally important features, traditional land-use or sustainable natural resource use. Many wetlands require continued human management to prevent them transitioning or returning to woodlands and terrestrial habitats by natural succession (Mitsch & Gosselink, 1993). For example, the wet grasslands of the Somerset Levels and Moors Ramsar site, UK, require cattle grazing and woody vegetation is removed manually from reedbeds to maintain their characteristic flora and fauna and ecosystem services (Acreman *et al*., 2011).

The following seven studies selected in our review addressed the issue of ecological management.

Douglas *et al.* (2015) studied protected and unprotected areas of upland heath and blanket bog in the UK in which burning is a traditional but sometimes controversial, form of habitat management to maintain game birds for shooting and grazing for livestock. The proportion of moorland burned was significantly higher inside sites than on comparable areas outside protected areas. **[positive]**

Ledo & Colli (2016) tested the effectiveness of the prescribed 30m buffer in maintaining lizard assemblages in riparian forests associated with narrow streams in central Brazil. They studied two preserved areas, and one deforested area, and recorded 11 lizard species. The reduced riparian forest had lower abundance, richness, evenness, and phylogenetic diversity compared to the preserved habitats and lacked forest specialist species. **[positive]**

Sarkar *et al.* (2011) found that abundance and diversity of fishes was higher within than outside the protected area of the Katraniaghat Wildlife Sanctuary, India. Shading by dense riparian vegetation maintained in the park was an important feature of the protected areas. Conservation of large river fishes also required erosional and depositional channel habitats with specific substrate types, water depths and current speeds. **[positive]**

Vega-Cendejas *et al.* (2013) compared fish assemblage structure among 36 karstic pools located within protected areas of the Calakmul Biosphere Reserve, southern Mexico and unprotected adjacent areas outside the reserve. They found that the relative abundance of fish species was not influenced by protection *per se*, but for some was determined by water quality variables (K, NH_4, NO_3, and conductivity), whilst others were influenced by habitat created by aquatic vegetation, roots and arboreal cover. **[neutral]**

Zhang *et al*. (2015) found that the population abundances of waterbird species (family Anatidae) generally declined in wetlands along the Yangtze River floodplain over time, with a steeper decline in wetlands with a lower protection status. The area of grassland that is exposed when water levels fall, and hence available to grazing birds for foraging, determines the density of these birds. Impacts such as sand mining were found to decrease food availability for waterbirds. **[positive]**

Zhang *et al*. (2016) measured grassland net primary production (PP) on the Tibetan Plateau. After the establishment of nature reserves, the annual rate of PP increased inside the (wetland) nature reserve and was higher than that of the corresponding samples outside the wetland reserve, with reduced grazing pressure being the key determinant. **[positive]**

Jiang *et al*. (2016) assessed the stopover habitat for Siberian cranes (*Grus leucogeranus*) in a wetland in China restored as part of an area designated as a national nature reserve. The crane population increased initially when the daily water levels ranged from approximately −20cm to 20cm, which was ideal for growth of *Scirpus planiculmis,* the crane's primary food. However, previous ecological studies had concluded that Siberian cranes prefer daily water levels between 0cm and 50cm, so additional water was provided to the site. As a result, bird numbers sharply decreased to only 10–40% of the values prior to restoration as high water levels reduced growth of their food plant. **[positive] [negative]**

8.4 Fish and fishing

Fish are important biodiversity components and essential to maintain the natural structure and function of most freshwater ecosystems. Fish assemblages on the Mississippi River floodplain lakes vary with the degree of connectivity (Andrews *et al.,* 2014). Fish can also provide an important food source for many people. For example, Mekong fishes and fisheries provide the majority of the animal protein consumed by >50 million people in the river basin (Hortle, 2007) and ~2 million Cambodians are directly involved in the Tonle Sap Lake fishery (Nam & Song, 2011). However, if fishing is permitted in protected areas (such as Ramsar sites that allow 'wise use') it is vital to maintain effort at sustainable levels. Cooperman *et al.* (2012) found that intensive fishing of the Tonle Sap had resulted in the nearly complete removal of fish from approximately 20% of the lake, so 38 fishing lots were closed. Experience from marine protected areas shows that no-harvest reserves are most effective when coupled with active management of fished areas (Hilborn *et al.*, 2006). Curtailing the use of poisons, explosives and ultra-effective gear that catch entire schools of migrating fishes is essential.

Six selected publications addressed the issue of fisheries and fishing.

Britton *et al.* (2017) studied fish diversity in Lake Tanganyika and found it was up to 50% lower outside of protected areas, and herbivores appeared most affected. They suggested that reserves might be too isolated to act as a source for less diverse areas of the lake. **[positive]**

Atkore *et al.* (2011) measured fish abundance in Himalayan rivers but found no significant difference between protected and unprotected areas. Protected areas were under the same level of pressure of fishing as the unprotected areas, with dynamiting, poisoning and diverting water flows to collect fish being the major threats. Creating awareness, controlling illegal fishing and protecting the breeding grounds of fishes are some of the measures recommended to counter these threats. **[neutral]**

Cucherousset *et al.* (2007) found differences in the size-class structures and mortality rates of eels (*Anguilla anguilla*) between protected and fished areas in the Grande Brière Mottière marsh, France. They calculated that mean production of eels in a protected area would be 3.6 times higher than in the fished area, and the proportion of potentially migrating eels in the total population was found to be higher in the protected areas than in fished areas. The main pressure in unprotected areas was harvesting by fishers. **[positive]**

Penha *et al.* (2014) found no differences in fish abundance between the lagoons inside and outside reserves in the Pantanal, Brazil. However, there was a slight tendency of abundance reduction among the species used as baits in unprotected lagoons. They concluded that protection provided by the reserve is very efficient in river-floodplain systems, because it not only protects the biota inside the reserve, but also acts as a source of fish to unprotected areas. **[neutral]**

Snyder *et al.* (2013) measured shrimp abundance in two streams within the forest protected area of La Selva, Costa Rica and found it was relatively constant yearly and between recent post-disturbance (2008–2011) and historical pre-disturbance (1988–89) time periods. In contrast, a stream reach bordered by pasture accessible to fishers showed an 87% decrease in relative abundance between recent and historical time periods, suggesting site-level disturbance, possibly from fishing. **[positive]**

Srinoparatwatana & Hyndes (2011) found densities and biomass of fish in the Beung Borapet freshwater swamp, Thailand, did not differ or patterns were inconsistent between fishery protection areas and fished area due to non-selective fishing practices and low level of compliance and enforcement in the fishery. **[neutral]**

8.5 Hunting

Many animals are hunted both inside and outside of protected areas, primarily for food (Castilho *et al*., 2017). In freshwaters, hunting of water birds (ducks) and reptile eggs (*e.g*. turtles) occurs to provide food for people, hunting of large mammals provides trophies and traditional medicines, hunting of species that create a risk to humans also occurs (*e.g*. crocodiles). Hunting has always been part of local culture and at sustainable levels can be part of wise use of wetlands. However, poverty and lack of alternative livelihoods have led to significant pressure on wildlife due to hunting in many protected areas, emphasising the need to enforce hunting laws (Tanalgo, 2017). It has been argued that controlled hunting can be beneficial to conservation by motivating acquisition and protection of habitats and generation of revenue, when for example sport hunting fees are used for conservation of biodiversity (Loveridge *et al.,* 2006).

Four selected publications address the issue of hunting in protected areas.

Pitman *et al*. (2014) recorded 31 reptile, bird, and mammal species along a 47km stretch of river in the upper Amazon, Peru. For most taxa, sightings increased over the 4 years of monitoring following the establishment of the protected area, possibly as a result of reduced hunting. **[positive]**

Sung *et al.* (2013) compared demographic characteristics of big-headed turtles (*Platysternon megacephalum*) between four sites in national parks and one site in a private refuge in Hong Kong. The park sites had a history of illegal turtle harvesting and were characterized by the absence of large adults. The private refuge was fenced and frequently patrolled both day and night, which ensured that no unpermitted entry occurred, verified by lack of traps found. Adult density in the unharvested site was higher than at all harvested sites, and, on average male and female turtles were 23% and 10% larger in the unharvested site than in harvested sites. **[negative]**

Norris *et al.* (2018) assessed hunting of eggs of the yellow-spotted river turtles (*Podocnemis unifilis*) along 33km of river that runs between two sustainable use reserves in the Brazilian Amazon. Patrols to enforce lawful protection regulations had no effect on nest harvesting. In contrast, when community-based management approaches were enacted harvest levels dropped nearly threefold to a rate (26%) that is likely sufficient for river turtle population recovery. **[negative] [positive]**

Arraes *et al.* (2014) studied the yellow-spotted river turtle (*Podocnemis unifilis*) in the Araguari River basin, Brazil. They found that approximately 80% of the nests had suffered predation, mainly by humans for consumption, in both the protected areas of the reserves and the urban area of the Porto Grande city. **[neutral]**

8.6 Catchment water management

The catchment is a fundamental unit for surface water management (Ward & Robinson, 2008) and for ecosystem management (Maltby *et al*., 1989). Kingsford *et al.* (2005) include within their principles for a protective framework the need to recognise that rivers and their ecosystems require catchment-based management: a river reach, floodplain wetland, dependent aquifer or estuary cannot be managed or protected in isolation from its catchment. Many freshwaters are protected because they are part of terrestrial parks for which catchment management is not considered. Abell *et al*. (2017) reported that around the world, about 70% of river reaches (by length) have no protected areas in their upstream catchments, and only 11.1% (by length) achieve fully integrated protection. Given that all freshwater ecosystems are within catchments, there is a need to move from protecting specific areas to 'wholescape' management (Acreman *et al*., 2018). Concepts, such as environmental flows (Arthington, 2012) or, more broadly, environmental water (Horne *et al*., 2017) that define the water regime required for freshwater ecosystems, are now being applied across all water bodies within catchments (Arthington et al., 2018).

Four selected publications address the issue of catchment management.

Bustamante *et al.* (2016) compared the ecology of temporary ponds in the aeolian sands inside and outside the Doñana's National Park in Spain. They found that protected areas hold a better-preserved system of temporary ponds, with a flooding dynamic that fluctuates with precipitation. The unprotected area shows an increase in mean hydroperiod duration (the seasonal changes in water levels and surface area flooded), and a decline in hydroperiod variability due to the use of water for irrigation. **[positive]**

Abraham & Kelkar (2012) investigated the importance of protected areas for conservation of fishes within and across three dammed and two undammed rivers in the Western Ghats of India. They found that species in comparable stream orders across dammed and undammed river reaches were similar. For dammed rivers of comparable stream orders, endemic and total species richness was significantly higher in protected areas than in unprotected areas. This was attributed to greater threats in unprotected areas from sand mining, dynamite fishing, pollution and invasive fishes, suggesting these threats are more significant than the presence of dams. **[positive]**

Mutusva *et al*. (2016) studied the *Faidherbia albida* vegetation community in the Lower Zambezi and Mana Pools National Parks, Zambia. They found lower tree density and regeneration capacity in Mana Pools National Park, which they attributed to increased herbivore pressure, changes in river flooding regime and lower water tables that followed river impoundment at Kariba Dam, and also to variations in soil composition. **[negative]**

Adams *et al*. (2015) reported that the declaration of Kakadu National Park in northern Australia was particularly significant because its boundaries were located to ensure that they encompassed almost all the catchment of the South Alligator River, the entire catchment of the smaller West Alligator River, and significant parts of the catchments of the Wildman River and the East Alligator River. Kakadu floodplains differ from neighbouring floodplains in that they have not been exposed to extractive land uses, particularly grazing and mining. The catchment approach facilitated park management, such as preventing the nuisance invasive weed *Mimosa pigra* recolonising the area once cleared. However, they recognised strong interactions across the boundaries of protected areas or treatment areas that they called "spill-over effects", which may be positive or negative and are likely to bias the evaluation of local impacts unless these connections are understood and controlled. **[positive]**

8.7 Water quality

Water quality has a direct influence on freshwater ecosystems and biodiversity. Indeed, the assemblages of macro-invertebrates present in a river compared to those expected under natural conditions is a frequently used indicator of water quality (Clarke *et al.,* 2003). Important natural water quality determinands include nutrients (phosphorus and nitrogen) and pH (acidity or alkalinity), whilst other determinands can degrade water quality such as pesticides, heavy metals (Stafford *et al.,* 2016) and pharmaceuticals (Bjorklund *et al.*, 2016). Water quality within protected areas can be affected by upstream land use or within-reserve developments, such as agriculture and tourism (Pickering *et al*., 2003). Dudley *et al*. (2106) recognised that while designated primarily for nature conservation, protected areas supply a range of other ecosystem services to human society, such as water quality improvement by removing pollutants.

Four selected publications address the subject of water quality.

Christensen & Maki (2015) compiled Secchi depth, total phosphorus and chlorophyll-a data (which are important measures of ecosystem health) from lakes within Voyageurs National Park, Canada and compared datasets before and after a new water-level management plan was implemented in January 2000. Sand Point, Namakan, and Rainy Lakes remained oligotrophic, whereas eutrophication has decreased in Kabetogama Lake and Black Bay. Although nutrient inputs from inflows and internal sources are still sufficient to produce annual cyanobacterial blooms and may inhibit designated water uses in Kabetogama Lake and Black Bay, there had been no decline in lake ecosystem health since the implementation of the revised water-level management plan. **[neutral] [positive]**

González & Fariña (2013) studied populations of black-necked swan (*Cygnus melancoryphus*) in the Carlos Anwandter Nature Sanctuary and adjacent wetlands in Chile. They found that densities inside the sanctuary were lower (0.1 individuals/ha) than outside the sanctuary (0.5 individuals/ha) during 2005-2010. The environmental changes recorded in the protected wetland were related to human activities, specifically a pulp mill, which has caused the disappearance of Brazilian waterweed and triggered massive black-necked swan migration out of the area, and mortality due to starvation (as this plant – Brazilian waterweed - is a key food source) and high levels of iron and other chemicals in the water. **[negative]**

Kwik & Yeo (2015) sampled fish communities and environmental factors in 38 protected and non-protected streams in Singapore. They recorded 33 species with native fishes comprising 70.5%. Protected streams were defined by lower pH, temperature, and conductivity, higher cross-sectional areas and water velocity, and fishing permit requirements. Overall abundance of fish was higher in non-protected streams, but the proportions of non-native species was lower in protected areas. **[negative] [positive]**

Vega-Cendejas *et al.* (2013) compared fish assemblage structure among 36 karstic pools located within protected areas of the Calakmul Biosphere Reserve, southern Mexico and unprotected adjacent areas outside the Reserve. They found that the relative abundance of fish species was not influenced by protection, but for some was determined by natural water quality variables (K, NH_4, NO_3, and conductivity), whilst others were influenced by habitat created by aquatic vegetation, roots and arboreal cover. **[positive] [neutral]**

8.8 Catchment land-use change

Land use within a catchment can have significant impacts on receiving waters including flows of water (altering the flow regime, floods and droughts), water quality (including sediment, nutrients and pesticides) and, adjacent to water course, reduced shading and exchange of organisms between the river and riparian areas.

Five selected publications address the subject of land use change and protected areas.

Madella-Auricchio *et al.* (2017) studied reptile diversity in Caatinga-Cerrado ecotone areas the Parnaíba Basin, Brazil, where rapid expansion of agriculture threatens biodiversity and hastens its loss. They recorded 40 species on average within National Parks and Ecological Reserves, whereas the mean in other areas sampled was 23 species. **[positive]**

Mancini *et al.* (2005) measured biological quality in Italian rivers based on the composition of the benthic macroinvertebrate community. They found on average, the 18 study sites inside protected areas had biological quality similar to external control sites. In the protected areas, the biological quality of streams was higher than for the same streams in the surrounding territory provided that anthropogenic changes, particularly urbanisation, were fewer. These data indicate that the creation of protected areas *per se* did not increase freshwater biodiversity and that land use has a major impact on the biological quality of the stream in a protected area. **[neutral]**

Pryke *et al*. (2015) studied the Maputaland–Pondoland–Albany global biodiversity hotspot of South Africa, using dragonfly adults as bioindicators. Equal numbers of range restricted species were recorded from the World Heritage site protected area and remnant vegetation within forestry plantations. Pond size, habitat heterogeneity, elevation and dissolved oxygen were important determinants for species richness and diversity. Proximity of plantation trees had only a minor effect, and then only on species composition. **[neutral]**

Thiollay (2006) analysed data on African fish eagles (*Haliaeetus vocifer*) from Burkina Faso, Benin and Niger. Historically (period 1969-73), the populations in the unprotected areas were 50% higher than in the protected areas. In contrast 30 years later, the populations inside the PAs had remained the same whereas in the unprotected areas numbers had declined. The deterioration outside the parks was put down to human population growth and development, widespread habitat degradation and ecosystem impoverishment (woodcutting, agricultural intensification, overgrazing, desertification). **[positive]**

Rodríguez-Olarte *et al.* (2006) examined physical habitat and fish assemblages in rivers of the Aroa Mountains, Venezuela with different levels of environmental protection including the Yurubí National Park. Overall species richness was higher in protected areas, but abundance was higher in unprotected rivers. Populations of fish were controlled by the level of local disturbances (e.g. dredging, mining, deforestation). **[positive] [negative]**

Kleijn *et al.* (2011) reviewed bird population data in African wetlands. Averaged across all species, trends did not differ significantly between Ramsar sites and non-designated sites nor between IBAs and non-designated sites. It was recognised that across all wetlands in Africa, increasing areas of arable land, livestock numbers and deforestation were resulting in degradation of habitats and there was a lack of penalties for violations in protected areas. **[neutral]**

8.9 Invasive species

Invasive species are a feature of most ecosystems. As elsewhere, invasive alien species within protected areas can alter ecosystem structure and function at the level of habitats, communities, species and genetic characteristics. De Poorter *et al*. (2007) found that 277 Ramsar sites (17% of all Ramsar sites) were threatened by invasive alien species from within the site or from within the catchment. The problem is likely to worsen as species ranges alter under climate change, but Gallardo *et al*. (2017) predicted that protected areas will provide some refuge for native species.

Three selected publications address the subject of invasive species.

Adams *et al.* (2015) reported that one of the key management objectives following designation of the Kakadu National Park world heritage area (the largest national park in Australia) was to control invasive plants. Protected area management resulted in $58km^2$ of avoided infestation (compared to control areas) of *Mimosa pigra*. **[positive]**

García-Marín *et al.* (1998) detected hybridisation between native and non-native species of brown trout (*Salmo trutta*) in Spanish rivers. In some protected areas there was almost complete loss of native brown trout due to their replacement by alien species, whilst this species predominated in unprotected areas. They concluded that different strategies may be needed for protection of native populations in fished and protected areas and that more intense measures may be required in the latter instance. **[negative]**

Vega-Cendejas *et al.* (2013) compared fish assemblage structure among 36 karstic pools located within protected areas of the Calakmul Biosphere Reserve, southern Mexico and unprotected adjacent areas outside the Reserve. Fish abundance was higher in protected areas, but richness and diversity were similar in protected and unprotected areas. A major factor was that flooding during the rainy season allowed tilapia to escape from farms, endangering endemic and other native species. Water extraction and other uses by local people may have contributed to the deterioration of aquatic conditions, as they can affect biological patterns and ecosystem-level processes. **[positive] [neutral]**

8.10 Other variables influencing protected areas

There are many factors that influence protected (and unprotected) areas. These include the natural occurrence of competing species, environmental factors that vary naturally (such as geology, climate, soils) and others that are induced by human activity such as over-grazing, poor habitat management or pressure from fishing and tourism.

Eight selected publications address other influential issues.

Ng *et al.* (2015) found that the critically endangered Singapore freshwater crab *Johora singaporensis* was absent from the Bukit Timah Nature Reserve but was present in two unprotected areas. This resulted, in part, from the natural predation by a fish, *Betta pugnax*, and competition pressure from a prawn, *Macrobrachium malayanum*, which were absent where the crab was found. **[negative]**

Chessman (2013) analysed monitoring data from Australia's Murray–Darling Basin to compare fish assemblages between rivers inside and outside of protected areas. When analysis was confined to a subset of geographically and environmentally matched river sites, the richness and abundance of native species did not differ significantly between protected and unprotected areas, and only two native species were significantly more abundant within protected areas, whereas another two were significantly more abundant outside. Lower richness and abundance of native species were found in protected areas with steeper terrain and colder climates, suggesting these were over-riding controls on fish assemblage patterns. **[neutral]**

Vega-Cendejas *et al.* (2013) compared fish assemblage structure among 36 karstic pools located within protected areas of the Calakmul Biosphere Reserve, southern Mexico and unprotected adjacent areas outside the reserve. They found that the relative abundance of fish species was not influenced by protection, but for some was determined by water quality variable (K, NH_4, NO_3, and conductivity), whilst others were influenced by habitat created by aquatic vegetation, roots and arboreal cover. **[positive] [neutral]**

Dinakaran & Anbalagan (2007) studied the diversity patterns of aquatic insects in the Western Ghats of India. They found that unprotected areas had a lower diversity of aquatic insects due to tourism, pollution, channelization and the presence of embankments. **[positive]**

Hossack *et al* (2005) analysed data from wetlands in North Dakota, USA. Reptile and amphibian richness in the National Park remained unchanged over at least the last half-century and likely since 1920-1922. This area was buffered from the effects of extensive loss or modification of prairie wetlands that had caused declines in more disturbed areas. **[positive]**

Kanga *et al.* (2011) studied the population trends of common hippopotamus (*Hippopotamus amphibius*) in the Mara Region of Kenya. Populations increased both inside the Masai Mara National Reserve and outside on the pastoral ranches (earlier more so in the reserve, but later equally). These increases probably reflected population growth but could also have been due to exclusion of hippopotamus from parts of their former range in the adjacent pastoral areas because of progressive habitat loss and declining water levels in the Mara River. **[positive] [neutral]**

Li *et al* (2015) studied the hooded crane (*Grus monacha*) in the Shengjin Lake National Nature Reserve, China. Greater bird numbers were recorded in the rice paddy fields found in the buffer zone than the core area. By reference to other studies they suggested that the core area had suffered degradation of natural habitats and a resulting decline in food resources due to aquaculture-induced collapse of the submerged macrophyte-dominated vegetation community and dam-caused hydrological disconnection with the Yangtze River. Differences in the behavior of the cranes when foraging was noted in the highly disturbed buffer zone. **[negative]**

8.11 Interaction with local communities

Controversy exists over the best way to ensure that protected areas meet their objectives in the face of pressures for resource use from local communities. Fischer (2008) argued that strict protection by law enforcement is the most promising way, even if this means that benefits of individual human beings have to be compromised at times. Others suggest that the institutions and rules governing protected areas should ensure that they are better embedded in society and that governance should be adaptive to changing challenges (Borrini-Feyerabend *et al*., 2013). In a global meta-analysis on 165 protected areas, Oldekop *et al.* (2016) found that protected areas associated with positive socioeconomic outcomes were more likely to report positive conservation outcomes. Successful outcomes resulted from co-management regimes, empowered local people, reduced economic inequalities, and maintained cultural and livelihood benefits. Castro *et al.* (2002) assessed the prospects for conservation in over 660 Ramsar sites worldwide and concluded that the success of site designation improved with increased participation by local stakeholders in conservation and wise use.

Five selected publications address interactions with local communities.

Gupta *et al.* (2015) studied rivers in tiger reserves in India. They found greater numbers of threatened fish species within terrestrial protected areas and managed areas. Among all sites, lower levels of habitat degradation were found inside protected areas. Non-protected sites showed higher impacts of water quality, illegal fishing, diversion of water flows, clearing of riparian vegetation and sand and boulder mining than in protected sites. The lack of legislative, religious or socio-economic driven protection at unprotected sites could have resulted in increased anthropogenic threats and reduction in fish species richness. **[positive]**

Kleijn *et al.* (2011) analysed data from many bird species in African wetlands. They reported that trends did not differ significantly between Ramsar sites and non-designated sites nor between IBAs and non-designated sites. Across wetlands in Africa the increasing area of arable land, livestock numbers and deforestation resulted in increasing degradation of habitats. A key factor was the lack of penalties for violations in protected areas. **[neutral]**

Norris *et al.* (2018) assessed populations of yellow-spotted river turtles (*Podocnemis unifilis*) that were suffering from nest harvesting by humans along a 33km of river that runs between two sustainable use reserves in Brazil. Two years of patrols by park officials to enforce lawful protection regulations had no effect on nest harvesting. In contrast, for one year when community-based management approaches were enacted, harvest levels dropped nearly threefold to a rate (26%) that is likely sufficient for river turtle population recovery. **[negative] [positive]**

Atkore *et al.* (2011) measured fish abundance in Himalayan rivers of India. They found no significant difference between protected and unprotected areas. Protected areas were under the same level of pressure of fishing as the unprotected areas, with dynamiting, poisoning and diverting water flows to collect fish being the major threats. Creating awareness, controlling illegal fishing and protecting the breeding grounds of fishes are some of the measures recommended to counter these threats. **[neutral]**

Srinoparatwatana & Hyndes (2011) found densities and biomass of fish in a large freshwater swamp (Beung Borapet) in Thailand did not differ or were inconsistent between fishery protection areas and fished areas. This was due to non-selective fishing practices and low level of compliance and enforcement in the fishery protection area. **[neutral]**

8.12 Climate change

Global environmental changes drive large-scale shifts in the distributions of species and in the composition of biological communities. The development of ecosystems that differ in species composition and ecological functions from past and present systems is increasingly recognised (Hobbs *et al*., 2006) often in relation to changing climates including 'emerging', 'hybrid', 'no-analogue', and 'novel' ecosystems (Palmer *et al*., 2008, Hobbs *et al*., 2009; Acreman *et al*., 2014). The value of protected areas has been questioned given that they typically remain static, whereas species move, and they are predicted to continue to move under future climate scenarios. Protected areas may fail legally if they no longer contain the entities that they were gazetted to protect (Mascia & Pailler, 2011). However, Thomas & Gillingham (2015) found evidence that terrestrial protected areas are likely to continue to have high conservation value in the future, given their performance over the past 40 years of anthropogenic climate change. Furthermore, they are likely to gain protected entities (new species, or increased abundances of some species that are already present), even if they lose others that were previously present (Johnston *et al*., 2013). There is evidence that richness of invaders is significantly lower inside protected areas than outside them (Gallardo *et al*., 2017) and that protected areas have a greater impact on stemming extinctions than promoting colonisations of fishes (Frederico *et al*., 2016). Peach *et al*. (2018) found that increasing amounts of land protection benefitted species at range margins.

Four selected publications address interactions between protected areas and climate change.

Kleijn *et al.* (2014) found that after designation, waterbird species richness and abundance of birds in Morocco increased more rapidly in Ramsar wetlands than in non-designated wetlands. Compared to control sites, Ramsar sites had significantly higher cover of habitat types favoured by most waterbird species. The overall positive population trends in this study are therefore most likely the result of spatiotemporal changes in the migratory routes used by birds, caused by changes in precipitation levels in the Sahel, and not indicative of actual changes in population numbers. **[positive]**

Virkkala *et al.* (2014) examined the recent range shifts in 90 forest, mire, marshland, and Arctic mountain heath bird species of conservation concern in Finland, as well as the changes in their species richness in protected versus unprotected areas. Results suggest that the observed changes in bird distributions are in the same direction as the predictions for future bioclimatic envelopes, resulting in a decrease in species richness of mire and Arctic mountain heath species and an increase in marshland species. The patterns of changes in species richness between the two time slices are in general parallel in protected and unprotected areas. However, importantly, protected areas maintained a higher level of species richness than unprotected areas. **[positive]**

Zhang *et al*. (2015) found that the population abundances of the waterbird species (Anatidae) generally declined in wetlands along the Yangtze River floodplain, China, over time, with a steeper decline in wetlands with a lower protection status. Wintering birds tend to select warmer sites to reduce the cost of thermoregulation; climate warming was a good predictor for northward shifts noted for several bird species. **[positive]**

Zhang *et al*. (2016) measured grassland net primary production on the Tibetan Plateau. After the establishment of the nature reserves, the annual rate of increase inside the (wetland) nature reserve was higher than that of the corresponding samples outside the nature reserve, with reduced grazing pressure being the key determinant. Some samples did not show any obvious effectiveness of protection due to the dominance of other factors, such as a worsening climate over the same period. Current research indicates that the climate in the northwest of Tibet has become warmer and dryer over the period from 1970 to 2010. **[positive] [neutral]**

9. Relating the evidence to principles of protected area management

Several publications assimilate broad findings from many individual studies into principles, frameworks and guidance for the management of protected areas. For example, Kingsford and Biggs (2012) provide a generic Strategic Adaptive Management framework, with four essential steps, to assist rigorous implementation of adaptive management in aquatic protected areas and for management of environmental flows. Hocking *et al.* (2006) developed a framework that provides a consistent basis for designing assessment systems, gives guidance about what to assess and provides broad criteria for assessment. Saunders *et al.* (2002) provided strategies based on three primary threats to fresh waters: land-use disturbances, altered hydrology, and introduction of non-native species.

In their synthesis of issues, Finlayson *et al.* (2018b, chapter 14) evaluated five ecological principles for freshwater ecosystem management in protected areas. In addition, they quote seven principles for building resilience in socio-ecological systems formulated by Biggs *et al.* (2012), some of which overlap with those of Finlayson *et al*. (2018b), but two (numbers 6 and 7) focus on participation and governance and are complementary. In the sections below, we classify the evidence from the review according to the five principles from Finlayson *et al*. (2018b) and two from Biggs *et al.* (2012). We do not attempt to amend or further develop these principles.

9.1 Protected area scale

Principle 1 Finlayson *et al.* (2018b): The entire catchment with its land, water and biogeochemical resources is the ideal unit to be protected and managed.

Here we interpret 'entire catchment' more broadly to include issues of scale such as the size of protected areas and whole ecosystems, such as the 'entire lake' or river basin. Several studies provided evidence of the importance of large-scale protected areas including size and inclusivity of ecosystem diversity and extent.

Adams *et al*. (2015) reported that the declaration of Kakadu National Park in Australia was particularly significant because its boundaries were located to ensure that they encompassed almost all the catchment of the South Alligator River, the entire catchment of the smaller West Alligator, and significant parts of the catchments of the Wildman River and the East Alligator River. The catchment approach facilitated effective park management, such as reducing the nuisance invasive weed *Mimosa pigra*. However, they recognised that strong interactions across the boundaries of protected areas (called "spill-over effects") can still exist, perpetuating the vulnerability of the protected areas to external pressures, although at a reduced level.

Chu *et al*. (2017) found that neither fish abundance nor diversity differed significantly across comparisons of lakes in Ontario, Canada, some of which were national parks. However, normalized-length size spectrum slopes (NLSS) were significantly steeper in lakes outside parks. They suggested that lake ecosystems would benefit from freshwater protected area designs that include the entire lake rather than protecting only part of the lake or shoreline.

Koning (2018) found that reserves in Thailand increased fish species richness relative to adjacent fished areas. The effectiveness of protected increased with greater reserve size (as well as duration of protection and increasing distance from the nearest village).

Yrjölä *et al*. (2017) studied the population growth and expansion of Barnacle Goose (*Branta leucopsis*) in the Helsinki archipelago, Finland. Breeding densities in unprotected islands were higher than in protected islands as bird numbers were controlled by island size, the time each island has been inhabited, and distance from the islands where breeding expansion started.

Cucherousset *et al.* (2007) reported that protected areas of the Grande Brière Mottière marsh, France, only account for 2.4% of the aquatic habitat area for the silver eel. They estimated that increasing the size of the protected areas to 31.1% would produce 50% of the potential silver eel of a fully protected marsh.

9.2 Water dynamics and quality

Principle 2: Finlayson *et al.* (2018b). The flow of water is one of five dynamic environmental regimes that regulate much of the structure and functioning of every running water ecosystem and many aspects of lentic and groundwater systems.

We interpret the 'flow of water' broadly to include river flows, water level dynamics in lakes and wetlands and the quality of water (Horne *et al*., 2017). Several case studies addressed the importance of an appropriate hydrological regime.

Zhang *et al*. (2015) found that the population abundances of the waterbird species (*Anatidae*) had generally declined in wetlands along the Yangtze River floodplain over time, with a steeper decline in wetlands with a lower protection status. The area of grassland that is exposed when water levels fall, and hence available to grazing birds for foraging, determines the density of these birds.

Bustamante *et al.* (2016) compared the ecology of temporary ponds in the aeolian sands inside and outside the Doñana's National Park in Spain. They found that protected areas hold a better-preserved system of temporary ponds, with a flooding dynamic that fluctuates with precipitation. The unprotected area shows an increase in mean hydroperiod duration, and surface area flooded, and a decline in hydroperiod variability due to the use of water for irrigation.

Jiang *et al*. (2016) assessed the stopover habitat for Siberian cranes in a wetland in China restored as part of designation as a national nature reserve. The crane population increased initially when the daily water levels ranged from approximately −20 cm to 20 cm, which was ideal for growth of *Scirpus planiculmis,* the crane's primary food. However, previous ecological studies had concluded that Siberian cranes prefer daily water levels between 0 cm and 50 cm, so additional water was provided to the site. As a result, bird numbers sharply decreased to only 10–40% of the values prior to instigation as high water levels reduced growth of their food plant.

Mutusva *et al*. (2016) studied the *Faidherbia albida* vegetation community in the Lower Zambezi and Mana Pools National Parks, Zambia. They found lower tree density and regeneration capacity in Mana Pools National Park, which they attributed partly to changes in river flooding regime and lower water tables that followed river impoundment at Kariba Dam.

Christensen & Maki (2015) compiled Secchi depth, total phosphorus, and chlorophyll-a data from lakes within Voyageurs National Park and compared datasets before and after a new water-level management plan was implemented. Sand Point, Namakan, and Rainy Lakes remained oligotrophic, whereas eutrophication has decreased in Kabetogama Lake and Black Bay. Although nutrient inputs from inflows and internal sources are still sufficient to produce annual cyanobacterial blooms and may inhibit designated water uses in these two latter lakes, there had been no decline in lake ecosystem health since the implementation of the revised water-level management plan.

González & Fariña (2013) studied populations of black-necked swan (*Cygnus melancoryphus*) in the Carlos Anwandter Nature Sanctuary and adjacent wetlands in Chile. They found that densities inside the sanctuary were lower than outside the sanctuary. The environmental changes recorded in this wetland were related to discharges from a pulp mill, which has caused the disappearance of Brazilian waterweed and triggered massive black-necked swan migration out of the area and mortality due to starvation and high levels of iron and other chemicals in the water.

9.3 Hydrological, biogeochemical and ecological connectivity

Principle 3. Finlayson *et al.* (2018b). The spatial and temporal connectivity patterns and processes of aquatic ecosystems in their natural state are important elements for consideration in protected area design and management.

No case studies included in the review explicitly assessed the effectiveness of longitudinal connectivity (upstream-downstream along a river system) or connectivity of habitats needed for different life-stages. However, there was evidence of importance of connectivity between rivers and riparian areas, between rivers and their floodplains, between surface and groundwater and between different parts of lagoons and lakes.

Sarkar *et al.* (2011) found that abundance and diversity of fishes was higher within than outside the protected area of the Katraniaghat Wildlife Sanctuary, India. Shading by dense riparian vegetation maintained in the park was an important feature of the protected areas.

Ledo & Colli (2016) tested the effectiveness of the prescribed 30m buffer in maintaining lizard assemblages in riparian forests associated with narrow streams in central Brazil. They studied two preserved areas, and one deforested area, and recorded 11 lizard species. The reduced riparian forest had lower abundance, richness, evenness, and phylogenetic diversity compared to the preserved habitats and lacked forest specialist species.

Li *et al* (2015) found lower numbers of hooded cranes (*Grus monacha*) in the core areas of the Shengjin Lake National Nature Reserve, China, than in the buffer zones. By reference to other studies they suggested that the core areas had suffered degradation of natural habitats and a resulting decline in food resources due partly to dam-caused hydrological disconnection with the Yangtze River. These three studies show the importance of connectivity between rivers, riparian zones and floodplains.

Vega-Cendejas *et al.* (2013) compared fish assemblage structure among 36 karstic pools located within protected areas of the Calakmul Biosphere Reserve, southern Mexico and unprotected adjacent areas outside the reserve. They found that the relative abundance of fish species was not influenced by protection, but for some was determined by water quality variable (K, NH_4, NO_3, and conductivity).

Mutusva *et al*. (2016) studied the *Faidherbia albida* vegetation community in the Lower Zambezi and Mana Pools National Parks, Zambia. They found lower tree density and regeneration capacity in Mana Pools National Park, which they attributed to several factors including lower water tables that followed river impoundment at Kariba Dam. These two studies demonstrate the importance of connectivity between the surface and groundwater systems.

Penha *et al.* (2014) found no differences in fish abundance between the lagoons inside and outside reserves in the Pantanal, Brazil. They concluded that protection provided by the reserve not only protects the biota inside the reserve, but also acts as a source of fish to unprotected areas. However, **Britton *et al.* (2017)** found that although fish diversity was much higher within protected areas of Lake Tanganyika than outside of them, the reserves might be too isolated to act as a source of populations for colonisation of less diverse areas of the lake.

9.4 Species-rich habitats, radiations and vital resources

Principle 4. Finlayson *et al.* (2018b). A primary goal of biodiversity conservation is to delineate protected areas that conserve species-rich habitats and vital resources, important species radiations and the greatest number of threatened endemic species.

Most of the case studies did not specify the objectives of the protected area and supplementary searches, such as park web sites, only suggested the purpose was general wildlife conservation. The following case studies took place in areas designated specifically for freshwater biodiversity conservation.

Kleijn *et al.* (2014) found that after designation for waterbird species, their richness and abundance increased more rapidly in Ramsar wetlands in Morocco than in non-designated wetlands. Less positive results were reported by **Penha *et al.* (2014)** who found no differences in fish abundance between the lagoons inside and outside reserves in the Pantanal, Brazil, designated for fish protection. However, there was a slight tendency of abundance reduction among the species used as baits in unprotected lagoons. Mixed results were reported by **Cui *et al.* (2014)** who studied internationally important waterbird protection areas in China. The average numbers of species were higher (lakes), the same (rivers) or lower (reservoirs) for well-protected sites than for partially-protected sites. In their study of black-necked swan (*Cygnus melancoryphus*) in the Carlos Anwandter Nature Sanctuary and adjacent wetlands in Chile, **González & Fariña (2013)** found that densities inside the sanctuary, which had been established for waterbird conservation, were lower than outside the sanctuary. This was due to polluted discharges from a pulp mill, which has caused the disappearance of Brazilian waterweed and triggered massive swan migration out of the area and mortality due to starvation and high levels of iron and other chemicals in the water.

Several studies reported that some sites were effective for freshwater biodiversity conservation even though the areas had been designated for terrestrial species.

Gupta *et al.* (2015) found greater numbers of threatened fish species in the rivers of terrestrially-based Tiger reserves in India than outside, suggesting these did provide some protection for freshwater ecosystems and biodiversity. **Abraham & Kelkar (2012)** concluded that although terrestrial-based protected areas of the southern Western Ghats, India did not adequately represent the habitat diversity of river systems, they had consistently higher endemic freshwater species richness than unprotected areas. **Britton *et al.* (2017)** found that despite being designed for terrestrial species, fish diversity was much higher within protected areas of Lake Tanganyika than outside of them but suggested that reserves might be too isolated to act as a source of populations to effect re-colonisation of less diverse areas of the lake.

9.5 Ecological resilience

Principle 5. Finlayson *et al.* (2018b). Maintaining catchment integrity, natural flow and standing water regimes, the spatial and temporal dimensions of connectivity and native biodiversity hotspots will help to maintain the ecological resilience of aquatic systems in protected areas and support societal adaptations to shifting environmental and climatic regimes.

Case studies referred to in this section focus on those providing evidence of whether protected areas maintain resilience to climatic and other environmental changes.

Adams *et al.* (2015) reported that one of the key management objectives following designation of the Kakadu National Park world heritage area (the largest national park in Australia) was to control invasive plants. Designating entire catchments as protected areas helped control *Mimosa pigra.* However, they recognised that strong interactions across the boundaries of protected areas or treatment areas (that they called “spill-over effects”), can still exist, meaning that the protected areas remain somewhat vulnerable to external pressures. **Abraham & Kelkar (2012)** investigated the importance of protected areas for conservation of fishes within and across three dammed and two undammed rivers in the Western Ghats of India. They found that species composition found in comparable stream orders across dammed and undammed midland river reaches were similar. For dammed rivers of comparable stream orders, endemic and total species richness was significantly higher in protected areas than in unprotected areas. They found that threats from sand mining, dynamite fishing, pollution and introduced invasive fishes were lower in protected areas than unprotected areas.

Ng *et al.* (2015) found that the critically endangered Singapore freshwater crab was absent from the Bukit Timah nature reserve but was present in two unprotected areas. This resulted, in part, from natural predation by a fish, *Betta pugnax*, and natural competition pressure from a prawn, *Macrobrachium malayanum*, which were absent where the crab was found. Protection did not eliminate these pressures on the crab. **Vega-Cendejas *et al.* (2013)** compared fish assemblage structure among 36 karstic pools located within protected areas of the Calakmul Biosphere Reserve, southern Mexico and unprotected adjacent areas outside the reserve. Fish abundance was higher in protected areas, but richness and diversity were similar in protected and unprotected areas. A major factor was that flooding during the rainy season allowed tilapia to escape from farms endangering native and endemic species. Thus, designation did not make the area resilient to invasive species.

Virkkala *et al.* (2014) who observed that changes in bird distributions in wetlands in Finland are consistent with the predictions for future bioclimatic envelopes, but protected areas maintained a higher level of species richness than unprotected areas. Overall, they suggested that landscapes with significant amounts of protected areas alleviate the negative effects of climate warming on biodiversity. **Zhang *et al*. (2015)** found that the population abundances of the waterbird species (Anatidae) generally declined in wetlands along the Yangtze River floodplain, China, over time, with a steeper decline in wetlands with a lower protection status. Wintering birds tend to select warmer sites to reduce the cost of thermoregulation; climate warming was a good predictor for northward shifts noted for several bird species.

9.6 Broaden participation

Principle 6. Biggs *et al.* (2012). Participation is considered fundamental to promoting the collective action required to respond to disturbance and changes in socio-ecological systems. The participation of a diversity of stakeholders improves legitimacy, facilitates monitoring and enforcement, promotes understanding of system dynamics, improves the capacity to detect and interpret shocks and disturbances and builds trust and a shared understanding for cooperation.

Two case studies included in this section focus on interactions with local communities.

Norris *et al.* (2018) assessed populations of yellow-spotted river turtles that were suffering from nest harvesting by human along a 33 km of river that runs between two sustainable use reserves in Brazil. Two years of patrols by park officials to enforce lawful protection regulations had no effect on nest harvesting. In contrast, for one year when community-based management approaches were enacted, harvest levels dropped nearly threefold to a rate (26%) that is likely to be sufficient for river turtle population recovery. **Gupta *et al.* (2015)** studied rivers in Tiger reserves in India. They found greater numbers of threatened fish species within terrestrial protected areas and managed areas. Among all sites, lower levels of habitat degradation were found inside protected areas. Non-protected sites showed higher impacts from local community activities such as pollution, illegal fishing, diversion of water flows, clearing of riparian vegetation and sand and boulder mining than in protected sites. Designation protected the reserves from the anthropogenic threats experienced outside that had reduced fish species richness.

9.7 Promote polycentric governance

Principle 7. Biggs *et al.* (2012). In polycentric governance, multiple governing bodies interact and have the power to make and enforce rules within a specific policy arena and geography. This form of decentralised governance is believed to promote local self-organisation where more centralised formal procedures seem to fail.

There were no case studies examining polycentric governance *per se*. However, three case studies that focus on enforcement of laws are included in this section.

Kleijn *et al.* (2011) analysed data from many bird species in African wetlands. They reported that differences in trends did not differ significantly between Ramsar sites and non-designated sites nor between IBAs and non-designated sites. Across wetlands in Africa the increasing area of arable land, livestock numbers and deforestation resulted in increasing degradation of habitats. A key factor was the lack of penalties for violations in protected areas. **Atkore *et al.* (2011)** measured fish abundance in Himalayan rivers of India. They found no significant differences between protected and unprotected areas. Protected areas were under the same level of pressure of fishing as the unprotected areas, with dynamiting, poisoning and diverting water flows to collect fish being the major threats. Creating awareness, controlling illegal fishing and protecting the breeding grounds of fishes are some of the measures recommended to counter these threats. **Srinoparatwatana & Hyndes (2011)** found densities and biomass of fish in a large freshwater swamp (Beung Borapet) in Thailand did not differ or were inconsistent between fishery protection areas and fished area. This was due to non-selective fishing practices and low levels of compliance and enforcement in the fishery.

10. Lessons for successful freshwater protected areas

In each of the sections below we provide a lesson drawn from the review and record the evidence that supports it.

10.1 Evidence of the effectiveness of protected areas for freshwater biodiversity conservation

Lesson 1: More monitoring and research is required to quantify the effectiveness of protected areas for freshwater biodiversity conservation and to elucidate the factors that are important for their design, designation and management.

There are large numbers of freshwater protected areas in place around the world, including 2,314 Wetlands of International Importance (Ramsar Sites) covering 242,409,779 hectares, on which a wealth of scientific research has been undertaken resulting in the 2586 publications found in our searches relating broadly to their effectiveness. Despite this only 44 publications, containing 75 case studies, actually report data that provide quantitative evidence of the effectiveness of protected areas, based on comparison of protected areas and reference non-protected areas, or the same area before and after designation. Many surveys of species have been undertaken in protected areas, but these are rarely complemented by similar surveys outside or before-after designation. There is a pressing need to undertake more monitoring and to improve the design of surveys and research in and around protected areas to measure their effectiveness and to provide guidance for others by recording the reasons for success or lack of it.

10.2 Waterscape connectivity, diversity and protected area size

Lesson 2: Protected areas need to be of sufficient size and to incorporate various connected diverse elements of the waterscape to enable species to breed and migrate.

We use the term waterscape to include catchment or river basin and also entire lakes, wetlands or island archipelagos that are not strictly catchments. All examples come from selected papers in the database with references in bold.

Koning (2018) concluded from wetlands in Thailand that fish species richness increased with larger reserve size. **Yrjölä *et al*. (2017)** discovered that larger islands were more effective for the expansion of Barnacle Goose in the Helsinki archipelago, Finland. From their studies of fish populations in lakes in Ontario, Canada, **Chu *et al*. (2017)** found that lake ecosystems would benefit from freshwater protected area design that include the entire lake rather than protecting part of the lake or shoreline. **Abraham & Kelkar (2012)** concluded that although protected areas of the southern Western Ghats, India, had consistently higher endemic species richness than unprotected areas, these terrestrial-based protected areas did not adequately represent the habitat diversity of river systems. **Adams *et al.* (2015)** showed that designation of entire catchments was very beneficial in controlling invasive plant species but recognised that strong interactions across the boundaries of protected areas (that they called "spill-over effects") may still exist, which may be positive or negative for management. **Britton *et al.* (2017)** suggested that protected areas can be a source of recruitment (e.g. for fish) for unprotected areas if they are not isolated from each other. **Penha *et al.* (2014)** concluded that protected areas in the Pantanal, Brazil, not only protect the biota inside the reserve, but also act as a source of fish to unprotected areas. **Pryke *et al*. (2015)** found that pond size and habitat heterogeneity were major determinants of the richness and diversity of dragonfly adults in the Maputaland–Pondoland–Albany global biodiversity hotspot of South Africa. **Cucherousset *et al.* (2007)** reported increasing the size of the protected areas in the Grande Brière Mottière marsh, France, would significantly increase eel production.

Overall, there are important synergies between terrestrial and freshwater systems that need to be integrated in protected area design. **Ledo & Colli (2016)** found that maintaining riparian forests along narrow streams in central Brazil supported the abundance, richness, evenness, and phylogenetic diversity of lizard species. **Vega-Cendejas *et al.* (2013)** found that habitat created by aquatic vegetation, roots and arboreal cover maintained high fish abundance in the karstic pools of the Calakmul Biosphere Reserve, southern Mexico. **Sarkar *et al.* (2011)** found that abundance and diversity of fishes were higher within than outside the protected area of the Katraniaghat Wildlife Sanctuary, India, and that shading by dense riparian vegetation maintained in the park was an important feature.

Connectivity between surface and groundwaters is important for functioning of freshwater ecosystems. **Vega-Cendejas *et al.* (2013)** found that in some of the karstic pools of the Calakmul Biosphere Reserve, southern Mexico, fish assemblage structure was determined by water quality variable (K, NH_4, NO_3, and conductivity). **Mutusva *et al*. (2016)** found lower tree density and regeneration capacity in Mana Pools National Park, Zambia which they attributed to several factors including lower water tables that followed river impoundment at Kariba Dam. **Li *et al* (2015)** found lower numbers of hooded cranes (*Grus monacha*) in the core areas of the Shengjin Lake National Nature Reserve, China, than in the buffer zones. By reference to other studies they suggested that the core areas had suffered degradation due to hydrological disconnection with the Yangtze River.

10.3 Freshwater ecosystems within terrestrial protected areas

Lesson 3: Areas designated to protect terrestrial ecosystems can be effective for freshwater biodiversity conservation but may not always adequately integrate issues pertinent to freshwater ecosystem protection.

Britton *et al.* (2017) found that despite being designed for terrestrial species, fish diversity was much higher within protected areas of Lake Tanganyika than outside of them. **Abraham & Kelkar (2012)** concluded that although terrestrial-based protected areas of the southern Western Ghats, India did not adequately represent the habitat diversity of river systems, they had consistently higher endemic freshwater species richness than unprotected areas. From their studies of fish populations in lakes of Ontario, Canada, **Chu *et al*. (2017)** found that lake ecosystems would benefit from freshwater protected area designs that include the entire lake rather than protecting part of the lake or shoreline. However, in the rivers in Tiger reserves in India, **Gupta *et al.* (2015)** found greater numbers of threatened fish species within terrestrial protected areas and managed areas, suggesting these did provide some safety for freshwater species.

10.4 Habitat maintenance

Lesson 4: Conserving aquatic habitat, including hydrological regime, water quality, waterbody morphology and riparian terrestrial vegetation is vital to supporting freshwater biodiversity.

Ledo & Colli (2016) found that maintaining riparian forests along narrow streams in central Brazil supported abundance, richness, evenness, and phylogenetic diversity of lizard species. **Sarkar *et al.* (2011)** concluded that conserving erosional and depositional channel habitats with specific substrate types, water depths and current speeds, plus shading by dense riparian vegetation, were important factors in the Katraniaghat Wildlife Sanctuary, India, which maintained higher abundance and diversity of fishes than outside the protected area. **Vega-Cendejas *et al.* (2013)** found that habitat created by aquatic vegetation, roots and arboreal cover maintained high fish abundance in the karstic pools of the Calakmul Biosphere Reserve, southern Mexico. **Jiang *et al*. (2016)** discovered that numbers of Siberian cranes, in China, increased when the daily water levels ranged from approximately −20 cm to 20 cm, which was ideal for growth of *Scirpus planiculmis,* the crane's primary food. **Zhang *et al*. (2015)** found that the area of grassland exposed when water levels fall, and hence available to grazing birds for foraging determines the population abundances of the waterbird species (family Anatidae) along the Yangtze River floodplains, China. **Bustamante *et al.* (2016)** concluded that the natural hydrological dynamics of temporary ponds in the aeolian sands inside and outside the Doñana's National Park in Spain was essential to maintain these ecosystems.

10.5 Managing internal pressures

Lesson 5: Protected areas should reduce pressures from grazing, inappropriate land and water management, pollution, tourism or general human disturbance.

Zhang *et al*. (2016) found that reduced grazing pressure was the key determinant in achieving higher grassland net primary production inside a (wetland) nature reserve on the Tibetan Plateau. In their studies of aquatic insects in the Western Ghats of India, **Dinakaran & Anbalagan (2007)** found that unprotected areas had a lower diversity of aquatic insects due to tourism, pollution, channelization and the presence of embankments. **Hossack *et al* (2005)** reported that reptile richness had been sustained in national park wetlands in North Dakota, USA, since the 1920s as they had been buffered from the effects of habitat loss, and that declines have occurred in more disturbed areas.

Li *et al* (2015) reported lower numbers of the hooded crane foraging in the highly disturbed rice paddy fields in the Shengjin Lake National Nature Reserve, China, than in the core area due to habitat degradation in the core. **González & Fariña (2013)** recorded lower populations of black-necked swan (*Cygnus melancoryphus*) in the Carlos Anwandter Nature Sanctuary than in adjacent wetlands in Chile due to pollution from a pulp mill. **Christensen & Maki (2015)** concluded that eutrophication and cyanobacterial blooms in lakes within Voyageurs National Park still occurred due to high nutrient levels from effluent discharges.

10.6 Managing external pressures

Lesson 6: External pressures in the surrounding landscape can have major control over freshwater biodiversity that may over-ride protection measures. However, in some cases protected areas can provide a defense against human pressures.

Rodríguez-Olarte *et al.* (2006) found that populations of fish were controlled by the level of local disturbances (e.g. dredging, mining, deforestation) in rivers of the Aroa Mountains, Venezuela with overall species richness higher in protected areas. Similarly, **Mancini *et al.* (2005)** concluded that biological quality of Italian rivers (based on the composition of the benthic macroinvertebrate community) was controlled by land use indicating that the creation of protected areas *per se* did not increase freshwater biodiversity. **Kleijn *et al.* (2011)** found that bird populations African wetlands did not differ significantly between Ramsar sites and non-designated sites nor between IBAs and non-designated sites, since there was a general increase in areas of arable land, livestock numbers and deforestation resulting in degradation of habitats.

Protected areas can be very effective buffers from adverse external pressures. **Madella-Auricchio *et al.* (2017)** recorded greater reptile diversity in Caatinga-Cerrado ecotone areas the Parnaíba Basin, Brazil, where rapid expansion of agriculture in surrounding areas threatens biodiversity and hastens its loss. **Kanga *et al.* (2011)** recorded upward population trends of common hippopotamus in the Mara Region of Kenya, due partly to habitat loss in their former range in the adjacent pastoral areas. **Thiollay (2006)** reported that whilst numbers of African Fish Eagles in parks in Burkina Faso, Benin and Niger remained constant, outside of parks numbers had declined due to woodcutting, agricultural intensification, overgrazing and desertification. **Abraham & Kelkar (2012)** concluded that endemic and total fish species richness in rivers of the Western Ghats of India was significantly higher in protected areas than in unprotected areas due partly to lower threats from sand mining, dynamite fishing and pollution. **Bustamante *et al.* (2016)** found that protected areas within the aeolian sands of the Doñana's National Park, Spain with natural water regimes held a better-preserved system of temporary ponds and ecosystems.

10.7 Managing invasive species

Lesson 7: Invasive species pose a major threat to freshwater biodiversity both within and outside protected areas and connectivity may enhance vulnerability. Managing pathways for invasive species can reduce their spread and protection can provide a buffer.

Vega-Cendejas *et al.* (2013) found that tilapia escaping from farms into karstic pools within protected areas of the Calakmul Biosphere Reserve, southern Mexico, were endangering endemic and other native species. **García-Marín *et al.* (1998)** detected hybridisation between native and non-native species of brown trout in protected Spanish rivers. **Abraham & Kelkar (2012)** concluded that endemic and total fish species richness in rivers of the Western Ghats of India was significantly higher in protected areas than in unprotected areas due partly to lower numbers of invasive fishes. **Adams *et al.* (2015)** reported that reduction in the invasive weed *Mimosa pigra* in Kakadu National Park, Australia, was a successful major objective of the protected area management plan.

10.8 Law enforcement and working with local communities

Lesson 8. Laws associated with designation and management of protected areas need to be enforced, but regulation activities should involve engagement with and support for local community initiatives.

Sung *et al.* (2013) found more big-headed turtles in a private refuge in Hong Kong than in national parks as a result of fencing and frequent patrols both day and night. Likewise, **Gupta *et al.* (2015)** found greater numbers of threatened fish species in rivers within tiger reserves in India because illegal fishing, diversion of water, clearing of riparian vegetation and sand and boulder mining were all lower than in areas that lacked legislative, religious or socio-economic drivers of protection. **Pitman *et al*. (2014)** recorded more reptiles, birds, and mammal species following the establishment of the protected area in the upper Amazonian river, Peru, possibly a result of reduced hunting. **Snyder *et al.* (2013)** found that the protected area of La Selva, Costa Rica, had constant shrimp abundance, whereas in a stream reach bordered by pasture accessible to fishers, abundance had decreased by 87%. **Cucherousset *et al.* (2007)** found more migrating eels (*Anguilla anguilla*) in protected areas than in fished areas in France.

Kleijn *et al.* (2011) concluded that lack of penalties for violations had contributed to there being no difference between bird numbers in Ramsar sites and non-designated sites on wetlands in Africa Likewise, **Atkore *et al.* (2011)** measured no significant difference fish abundance in Himalayan rivers of India between protected and unprotected areas, because of the similar levels of fishing (including dynamiting, poisoning and diverting water flows) in both areas. Controlling illegal fishing and protecting the breeding grounds of fishes were recommended. Further, **Srinoparatwatana & Hyndes (2011)** found densities and biomass of fish in a large freshwater swamp in Thailand did not differ or were inconsistent between fishery protection areas and fished areas, due to non-selective fishing practices and low levels of compliance and enforcement in the fishery.

Atkore *et al.* (2011) suggested that creating awareness would be important for reducing fishing pressures in Himalayan rivers of India, where dynamiting, poisoning and diverting water flows were common techniques. Similarly, **Norris *et al.* (2018)** found that community-based management approaches were much more successful for protecting the yellow-spotted river turtles (*Podocnemis unifilis*) in Brazil than patrols by park officials to enforce lawful protection regulations. This might be a useful strategy in the Araguari River basin, Brazil, where **Arraes *et al.* (2014)** discovered predation of yellow-spotted river turtle eggs by human both within protected areas and urban areas.

10.9 Traditional management

Lesson 9: Maintaining traditional management practices that support cultural heritage is a central objective of many protected areas.

Douglas *et al.* (2015) found that burning as a traditional form of habitat management occurred more in protected areas of upland heath and blanket bog in the UK to meet of objectives of the park that included maintenance of historical resource management practices such as grouse shooting and cattle grazing.

10.10 Forces beyond the control of protected area managers

Lesson 10: There are many factors, including variations in natural drivers and human pressures, acting on the environment (Figure 2) that determine biography and are not within the control of protected area managers, such as climate, natural water quality and river channel morphology. However, protected areas may help mitigate the influence of changes in some of these factors.

Ng *et al.* (2015) found that the critically endangered Singapore freshwater crab was absent from nature reserves where there was natural predation by a fish and competition from a prawn but was present in two unprotected areas where the fish and prawn were absent. **Chessman (2013)** found that richness and abundance of native fish species was controlled by terrain steepness and climatic variations in Australia's Murray–Darling Basin, so there were no significant differences in these metrics between protected and unprotected areas. **Kwik & Yeo (2015)** concluded that fish communities in streams in Singapore were controlled largely by environmental factors such as pH, temperature, conductivity, cross-sectional channel characteristics and water velocity. **Vega-Cendejas *et al.* (2013)** found that fish assemblage structure in karstic pools in the Calakmul Biosphere Reserve, southern Mexico was for some species determined by water quality variables (K, NH_4, NO_3, and conductivity), whilst others were influenced by habitat structure created by aquatic vegetation, roots and arboreal cover. When studying grassland net primary production on the Tibetan Plateau, **Zhang *et al*. (2016)** found no obvious effectiveness of protection at some sites due to the dominance of other factors, such as a changing climate (the climate in the northwest of Tibet has become warmer and dryer over the period from 1970 to 2010). **Kleijn *et al.* (2014)** found that increases in waterbird species in protected wetlands in Morocco were most likely the result of spatiotemporal changes in the migratory routes used by birds, caused by changes in precipitation levels in the Sahel, and not indicative of actual changes in population numbers within the protected wetlands.

From studying Yangtze River floodplain, China, **Zhang *et al*. (2015)** found a northward shift in several bird species, but protection helped as there was a steeper decline in birds in wetlands with a lower protection status. Similar results were reported by **Virkkala *et al.* (2014)** who observed that changes in bird distributions in wetlands in Finland are consistent with the predictions for future bioclimatic envelopes, but protected areas maintained a higher level of species richness than unprotected areas. Further, they suggested that landscapes with significant amounts of protected areas alleviate the negative effects of climate warming on biodiversity.

11. Broad conclusions

The search for evidence of the effectiveness of protected areas for conservation of freshwater biodiversity returned 75 case studies in the 44 publications. Searching for, retrieving and extracting evidence from these publications was refined to a set of systematic and unbiased steps. The studies were well distributed around the world, covered many types of freshwater ecosystem and taxonomic groups, employing a variety of biodiversity metrics. Some inference was required to conclude that protected areas are effective in conserving freshwater biodiversity and habitats required to support biodiversity; 39 case studies (52%) were considered to demonstrate positive outcomes, 25 were rated neutral and 11 presented negative outcomes for conserving freshwater biodiversity.

There were no obvious strong relationships between effectiveness and ecosystem type or global location. A few studies concluded that effectiveness was due to protected area design, the area protected or connectivity of diverse freshwater ecosystem elements (*e.g*. connectivity along fish migration corridors or between elements of protected area networks). More studies determined that success was due to control (or lack of control) over internal pressures (such as fishing, hunting and grazing) and external pressures (such as land use change, water abstraction and pollution), or outcomes were over-ridden by variations in natural environmental variables (such as species biogeographic patterns and distribution, landscape location, pH, temperature and water body morphology). Some studies indicated the effectiveness of enforcement of laws, such as fencing and guard patrols, whilst others highlighted the advantages of a participatory approach involving local people to raise awareness of issues and work towards self-regulation by the community.

The evidence from the studies supported the five ecological principles proposed by Finlayson *et al*. (2018b) concerned with catchment scale protection, connectivity patterns and processes, natural hydrological and water quality processes, protection of species-rich habitats, radiations and threatened species, and maintaining ecological resilience under shifting climatic and environmental regimes. It also supported the two complementary principles of Biggs *et al.* (2012) related to stakeholder participation and law enforcement. Finally, ten lessons for protected area management to conserve freshwater biodiversity were formulated from this review of case studies. These include: enhanced monitoring and research to assess effectiveness; more emphasis on waterscape connectivity, diversity and protected area size**;** effectiveness of terrestrial-based protected areas**;** habitat maintenance; managing internal and external pressures; managing invasive species**;** law enforcement and working with local communities; traditional management, and last but not least, appreciation of forces beyond the control of protected area managers.

12. Recommendations for continuing research

The review has provided significant evidence of the effectiveness of protected areas for the conservation of freshwater biodiversity; over half of the 75 case studies demonstrate positive outcomes from protected area designation and management. It has also highlighted knowledge gaps and opportunities for additional related work that could be undertaken to complement the findings. This section does not cover wider recommendations such as additional long-term monitoring or research needed in a range of protected areas to define their effectiveness.

12.1 Analysis of raw data from selected publications

We have reported the results of analysis of raw data as presented by authors of the selected papers. However, authors have used different methods and provided different types of outputs. The next logic step in the systematic review would be to extract raw data from the publications and to undertake meta-analysis. This is a robust method frequently applied in medical sciences to reveal broad statistical relationships. It could bring-out relationships between effectiveness of protected areas and their characteristics. Poff and Zimmerman (2010) analysed raw data from numerous papers to develop flow-ecology relationships and revealed the challenges of trying to do so for aquatic ecosystems across diverse climatic and geographical realms.

12.2 Review of literature on experiments or trials undertaken in protected areas

Our selection criteria rejected many papers that may contain important lessons for protected area management, including experiments undertaken separately from designation of the protected area and adaptations to management plans. A follow-up review could seek to find evidence of management actions that have supported protected area effectiveness.

Three examples are:

Vilizzi *et al.* (2013) describe an experimental wetland wetting regime to rejuvenate fish assemblages. From 2005 to 2011, a series of managed inundation events involving pumping of river water followed by natural inundation allowed assessment and comparison of the fish assemblage developing in Hattah Lakes, a semi-arid wetland system of the regulated Murray River (Victoria, Australia). One-way pumping from the main channel to Hattah Lakes created a ‘filtered’ fish assemblage consisting mainly of small-bodied native species and very low numbers of non-native species within two years. After disconnection from the main river channel in the absence of pumping, within-system recruitment also occurred, but later drying of all water bodies caused the entire fish assemblage to perish. Flooding by natural inundation enabled a more diverse fish assemblage to develop.

Hitt *et al.* (2012) explain that American eel (*Anguilla rostrata*) abundances have undergone significant declines over the last 50 years, and migration barriers have been recognized as a contributing cause. They evaluated eel abundances in headwater streams of Shenandoah National Park, Virginia, to compare sites before and after the removal of a large downstream dam in 2004. Mann–Kendall analyses revealed consistent increases in eel abundances from 2004 to 2010 but inconsistent temporal trends before dam removal. Dam removal was associated with decreasing minimum eel lengths in headwater streams, suggesting that the dam previously impeded migration of many small-bodied individuals.

Cross *et al.* (2011) report on the outcomes of experimental high-flow dam releases, i.e. controlled floods, implemented on the Colorado River, USA (2008) in an effort to reestablish pulsed flood events, redistribute sediments, improve conditions for native fishes, and increase understanding of how dam operations affect physical and biological processes. Invertebrate biomass and secondary production declined significantly following the flood with most of the decline driven by reductions in two non-native invertebrate taxa. Production of rainbow trout increased substantially due to post-flood increase in production and drift concentrations of select invertebrate prey.

12.3 Importance of protecting connectivity between ecosystem components

There has been long-term acknowledgment of the highly connected nature of freshwater ecosystems, longitudinally, laterally, vertically and temporally (Ward, 1989). However, only one study selected in our review found evidence that lack of connectivity contributed to degradation of a protected area (in this case lowering of groundwater led to degraded vegetation). None of the case studies considered lack of connectivity was the main cause of negative outcomes for faunal biodiversity in protected areas. However, several papers refer to the importance of connectivity between rivers and riparian areas and between surface and groundwater. In most instances, the mention of longitudinal connectivity was restricted to discussion sections frequently quoting other studies. A follow-up study could explore the wider evidence for the importance of connectivity by, for example, searching for and assessing primary sources quoted by other publications.

12.4 Comparison of protected area effectiveness with other measures

Assessing the wider effectiveness of protected area could be achieved by comparison of this review with an additional review of the effectiveness of alternative measures, such as global scale species protection (e.g. CITIES) or catchment/national scale environmental flow and river health programmes.

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