Protected areas and freshwater biodiversity: a novel systematic review distils eight lessons for effective conservation

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\textbf{Abstract}

Protected areas are a global cornerstone of biodiversity conservation and restoration. Yet freshwater biodiversity is continuing to decline rapidly. To date there has been no formal review of the effectiveness of protected areas for conserving or restoring biodiversity in rivers, lakes, and wetlands. We present the first assessment using a systematic review of the published scientific evidence of the effectiveness of freshwater protected areas. Systematic searches returned 2,586 separate publications, of which 44 provided quantitative evidence comprising 75 case studies. Of these, 38 reported positive, 25 neutral, and 12 negative outcomes for freshwater biodiversity conservation. Analysis revealed variable relationships between conservation effectiveness and factors such as taxa assessed, protected area size and characteristics, International Union for Conservation of Nature (IUCN) protected area category, and ecoregion. Lack of effectiveness was attributed to many anthropogenic factors, including fishing (often with a lack of law enforcement), water management (abstraction, dams, and flow regulation), habitat degradation, and invasive non-native species. Drawing on the review and wider literature we distil eight lessons to enhance the effectiveness of protected areas for freshwater biodiversity conservation. We urge policymakers, protected area managers, and those who fund them to invest in well-designed research and monitoring programs and publication of evidence of protected area effectiveness.

\textbf{KEYWORDS}

conservation evidence, lakes, national parks, nature reserves, protected areas, Ramsar, rivers, systematic review, wetlands

\section{INTRODUCTION}

Freshwaters cover only approximately 0.8\% of the Earth’s surface, yet freshwater ecosystems are essential for at least 126,000 species out of approximately 1.8 million, which equates to almost 10\% of all described species on Earth, including one-third of all vertebrate species (Strayer & Dudgeon, 2010) and more than half of all fish species (Fricke, Eschmeyer, & van der Laan, 2019). Freshwaters also provide important ecosystem services that support human welfare and livelihoods globally (Maltby & Acreman, 2011). These freshwater ecosystems are embraced within the Ramsar
Despite its importance, freshwater biodiversity is continuing to decline rapidly at the global scale and the index of freshwater wildlife populations has fallen by 83% since 1970, more than double the rate of species decline found in marine and terrestrial ecosystems (WWF, 2018). More than 85% of wetlands present in 1700 had been lost by 2000; current wetland loss is three times faster than forest loss (Díaz, Settele, & Brondízio, 2019). The Ramsar Convention (2018a) reported that wetland-dependent species, such as fish, waterbirds, and turtles, are in serious decline, with one-quarter threatened with extinction, particularly in the tropics. The Convention on Biological Diversity (2014) concluded that pressures on biodiversity will increase at least until 2020, and the status of biodiversity is likely to continue to decline beyond that date.

The designating of protected areas, such as national parks and nature reserves, is undertaken globally to help conserve and restore biodiversity (Finlayson, Arthington, & Pittock, 2018) and supply ecosystem services to human societies (Dudley, Harrison, Kettunen, Madgewick, & Mauerhofer, 2016) as depicted in Figure 1. The Convention on Biological Diversity sets 20 Aichi Targets (https://www.cbd.int/sp/targets/) to be met by 2020 including Target 11, whereby at least 17% of global inland water areas are conserved through effectively and equitably managed, ecologically representative, and well-connected systems of protected areas. There are presently 39 wetland World Heritage Sites, 96 river Biosphere Reserves, and 2,314 listed Wetlands of International Importance (Ramsar Sites) covering 2.42 million km² (Ramsar, 2018b), an increase since 1992 when there were just 575 Ramsar sites. The continuing rapid decline in freshwater biodiversity globally seems at odds with this increase in protected areas, which might at least have aided reduction in the rate of biodiversity decline. This impasse has led to questions about the effectiveness of protected areas for freshwater species conservation and ecosystem restoration (e.g., Pittock et al., 2015).

Many reasons have been suggested for the apparent lack of effectiveness of protected areas for freshwater biodiversity conservation. Not all inland water types are well-represented; in fact only 10% of large rivers (Abell, Lehner, Thieme, & Linke, 2017) and just 11% of seasonal wetlands are protected globally (Reis et al., 2017). Published explanations for weak effectiveness include: absence of whole catchment approach (Abell, Allan, & Lehner, 2007); limited connectivity within freshwater ecosystems and with the wider landscape (Finlayson et al., 2018); lack of protection for migratory species beyond designated areas (Bower, Lennox, & Cooke, 2014); absence of control of threats beyond the protected area, such as inflows of pollution (Adams, Setterfield, Douglas, Kennard, & Ferdinands, 2015); insufficient law enforcement (Atkore, Sivakumar, & Johnsingh, 2011); and poor management due to understaffing and underfunding (Le Saout, 2013). In global studies of terrestrial protected areas, only 20-50% of those assessed were found to be managed effectively (Laurance et al., 2012). Furthermore, some 168
Table 1: Search terms and inclusion/exclusion criteria applied to capture published evidence of protected area effectiveness and to address specific questions

| Ecosystems included:                                                                 |
|------------------------------------------------------------------------------------------------------------------------------------------|
| Freshwater, aquatic ecosystems, deltas, estuaries, catchments, wetlands, peatbogs, peatlands, groundwater-dependent ecosystem, springs, rivers, |
| streams, riparian zones, floodplains, marshes, swamps, lakes, ponds, reservoirs, and canals                                              |
| Ecosystem excluded:                                                                        |
| Salt marshes, marine, saline, atmospheric, and land                                       |
| Species/habitat included:                                                                 |
| Habitat, biodiversity, wildlife, populations, endangered species, threatened species, critically endangered species, vulnerable species, birds, |
| waterfowl, fish, invertebrates, mammals, amphibians, frogs, reptiles, plants, macrophytes, aquatic plants, crustaceans, molluscs, fungi, insects, |
| dragonflies, damselflies, algae, diatoms, phytoplankton, and zooplankton                                                                 |
| Protected areas included:                                                                 |
| Protected areas, Ramsar sites, national parks, nature parks, nature reserves, biosphere reserves, wilderness areas, protected landscapes, world |
| heritage sites, Natura 2000 sites, wild scenic rivers, conservation areas, natural monuments, and management areas                          |
| Effectiveness measures included:                                                           |
| Comparisons, evaluations, effectiveness, consequences, conservation, maintenance, protection, enhancement, sustain, trend, benefits, restoration, |
| subsequent, assessment, appraisals, roles, influence, impacts, changes and performance                                                           |
| Inference measures included:                                                                |
| Previous, controls, baselines, buffers, unprotected areas, adjacent areas, before and after, inside and outside, and with and without |

Precise format of search terms in Web of Science syntax is provided in Box 1, Supporting Information

Ramsar Sites within 66 countries have been formally reported as subject to negative human-induced change or likely change in their ecological character, an increase from 2015 when there were 144 (Ramsar Convention, 2018c).

Although numerous factors may contribute to lack of effectiveness of protected areas for freshwater biodiversity, there has been no systematic global review of science-based evidence on this issue (Hermoso, Abell, Linke, & Boon, 2016). This paper is the first to use a systematic review process to address this deficiency. It explores constraints on the effectiveness of existing freshwater protected areas, and those incidentally protected by association with terrestrial reserves. From this review, we define eight lessons and recommendations to enhance the conservation of freshwater biodiversity.

2 | METHODS

Reviews are commonplace in scientific studies to establish the state of knowledge and to define future research needs. However, reviews are often incomplete in coverage of the literature, subjective, and biased, and the methods employed opaque. To counter this, systematic evidence reviews were designed specifically to be comprehensive, objective, transparent, and repeatable. They have been widely used and accepted as best practice in medical science to develop health policies from multiple studies and are now applied to environmental issues, including assessment of terrestrial protected areas (Geldmann et al., 2013). We undertook a systematic evidence review to answer focused questions (Table 1), by applying the Preferred Reporting Items of Systematic reviews and Meta-Analyses (PRISMA) (Moher et al., 2009) and guidance produced by the UK government’s Department for Environment, Food, and Rural Affairs (Collins, Coughlin, Miller, & Kirk, 2015). Our review included search and selection protocols based on the PICO (Population, Intervention, Comparator, and Outcome) framework (see Supporting Information). The search strategy, search terms, and inclusion/exclusion criteria were internationally peer-reviewed and amended before searches.

We searched the Web of Science database (including SciELO) and Google Scholar, made requests to experts and institutions, and scanned reference lists of review papers and books. The search terms are summarized in Table 1. These searches returned a range of information including published papers from journals and unpublished reports from conservation organizations. Some documents referred to more than one species, metric, or protected area; these were recorded as separate case studies. Only those containing quantitative evidence of the effectiveness of protected areas for freshwater biodiversity or habitat quality were retained. We rejected documents recording results of species surveys within protected areas but lacking comparative data outside of the area or before designation. Documents that discussed concepts and inferred principles but contained no new data were discarded, as were documents that calculated protected area coverage as percentages of geographical ranges of species but lacked information on the effectiveness of those protected areas.
Key information, including purpose of designation, species protected, and broad waterbody type, was recorded for each case study. We used the available data in each document to define the direction of change in biodiversity or habitat and classified each case study as positive, neutral, or negative for freshwater biodiversity. Positive change was recorded where freshwater biodiversity metrics in protected areas exceeded those in comparable control areas (either the same area before designation or in similar undesignated areas selected by study authors). Negative change was recorded where freshwater biodiversity metrics in comparable control areas exceed those in protected areas. Neutral change was recorded where metrics were similar in control and protected areas, or before and after their designation. Additional information about each case study, such as the International Union for Conservation of Nature (IUCN) Protected Area category, and the freshwater ecoregion was collated using available websites and web-tools, such as Freshwater Ecoregions of the World (Abell et al., 2008).

3 | RESULTS

After removing duplications, 2,586 potentially relevant documents were retrieved. Application of selection criteria described above identified 44 relevant documents containing 75 case studies. Of the 75 case studies, 38 reported positive outcomes, 25 were neutral, and 12 were negative, so 51% showed protected areas to be effective in protecting freshwater biodiversity. Few studies recorded reasons for positive outcomes. Many papers did not specify the management measures employed following designation; of those that did, the most common were fishing restrictions and water management. Furthermore, there was no single causal factor for lack of effectiveness (negative or neutral direction of change); factors presented included fishing (often with lack of law enforcement), water flow management (by abstraction and dams), invasive non-native species (e.g., from fish farms), and habitat degradation (e.g., from mining or agriculture).

No case studies undertook full before–after control-impact (BACI) monitoring. Most (70%) compared protected with unprotected areas, with only 20% comparing the same area before and after designation. The case studies included several taxonomic groups, but there was a bias toward vertebrates (birds 41% and fish 19%) with fewer studies of invertebrates (8%) and plants (8%). The case studies were well-distributed across the globe and across ecoregion categories. The highest numbers were from Asia, within tropical and subtropical floodplain rivers and wetland complexes, IUCN category II protected areas, and for fish (Table 2). The second highest numbers were from the Neotropics, within temperate floodplain rivers and wetlands, category IV protected areas, and for birds. The most common metrics employed were species abundance and richness, followed by diversity.

Detailed analysis of the effectiveness categories did not highlight strong relationships with other information, such as the purpose of designation (e.g., for terrestrial or freshwater conservation—Figure 2), taxa, IUCN protected area category, or freshwater ecoregion. Success or failure depended largely on the influence of internal (e.g., poaching) and external (e.g., catchment deforestation) pressures. Some regional variations were evident. For example, 73% of the case studies in tropical and subtropical coastal rivers showed positive outcomes for protected areas, which exceeds the 51% overall figure. Negative changes in protected area fish diversity were recorded only in studies of rivers (i.e., none for lakes, ponds, wetlands, or floodplains), with only 40% of case studies being positive for fish diversity (Table 3). These numbers are small and not tested for statistical significance. The main causes of negative changes were invasive non-native species, and disturbances from pollution and catchment degradation.

3.1 | Reasons given for positive and negative biodiversity outcomes

Several studies, including fish in Thai wetlands (reference 15 in Table 2) and birds on Finnish islands (26), reported that biodiversity increased with greater protected area size. Studies of fish in Canadian lakes (41) and plants in Australian wetlands (43) recommended that freshwater protected area design should include the entire ecosystem (lake or catchment). Other studies, for example, rivers of the southern Western Ghats, India (9) and Lake Tanganyika, Tanzania (1), concluded that although terrestrial-based protected areas did not adequately cover the habitat diversity of associated river systems, they had higher endemic freshwater species richness than similar unprotected areas.

Conserving aquatic habitat, including the hydrological regime (surface and groundwater), water quality, and riparian vegetation, was found to be vital for supporting freshwater biodiversity worldwide, including lizards in Brazilian rivers.
| Region | Change  | Abell et al., 2008 Freshwater ecoregion | Protected area name | No. | Authors | Metric |
|--------|---------|----------------------------------------|---------------------|-----|---------|--------|
| Africa | Positive| Large lakes                            | Gombe & Mahale       | 1   | Britton et al. (2017) | Fish diversity |
|        |         | Large lakes                            | Masai Mara           | 2   | Kanga, Ogutu, Olff, and Santema (2011) | Mammal abundance |
|        |         | Tropical and subtropical floodplain rivers and wetland complexes | Various             | 3   | Thiollay (2006) | Bird abundance |
|        |         | Temperate coastal rivers                | Various              | 4   | Kleijn, Cherkaoui, Goedhart, van der Hout, and Lammertsma (2014) | Bird abundance |
| Africa | Neutral | Large lakes                            | Masai Mara           | 3   | Kanga et al. (2011) | Mammal abundance |
|        |         | Various                                | Various              | 5   | Kleijn et al. (2011) | Bird abundance |
|        |         | Temperate upland rivers                | Maputaland–Pondoland–Albany | 6   | Pryke et al., 2015 | Invertebrate abundance |
| Africa | Negative| Tropical and subtropical floodplain rivers and wetland complexes | Chongwe & Mana Pools | 7   | Mutusva, Kativu, Mapaure, and Gandiwa (2016) | Plant density |
| Asia   | Positive| Tropical and subtropical coastal rivers | Neyyar, Peppara, Shendurney, Kulathapuzha & Palode | 8   | Abraham and Kelkar (2012) | Fish richness |
|        |         |                                      | South Western Ghats  | 9   | Dinakaran and Anbalagan (2007) | Invertebrate richness |
|        |         | Temperate floodplain rivers and wetlands | Various             | 10  | Cui et al. (2014) | Bird abundance |
|        |         |                                      | Various              | 11  | Zhang, Jia, Prins, Cao, and de Boer (2015) | Bird abundance |
|        |         | Montane freshwaters                    | Zoige                | 12  | Zhang et al. (2016) | Net primary production |
|        |         | Tropical and subtropical floodplain rivers and wetland complexes | Katraniaghat        | 13  | Sarkar et al. (2013) | Fish diversity |
|        |         |                                       | Central Catchment    | 14  | Kwik and Yeo (2015) | % Native fish |
|        |         |                                       | Various              | 15  | Koning (2018) | Fish biomass |
|        |         | Tropical and subtropical upland rivers | Corbett & Rajaji     | 16  | Gupta et al., 2015 | Fish diversity |

(Continues)
| Region | Change | Abell et al., 2008 Freshwater ecoregion | Protected area name | No. | Authors | Metric |
|--------|--------|----------------------------------------|-------------------|-----|---------|--------|
|        |        | Temperate upland rivers                | Momoge            | 17  | Jiang et al., 2016 | Bird abundance |
| Neutral|        | Tropical and subtropical upland rivers | Corbett           | 18  | Atkore et al. (2011) | Vegetation coverage |
|        |        | Montane freshwaters                    | Zoige             | 12  | Zhang et al. (2016) | Fish richness |
|        |        | Temperate floodplain rivers and wetlands | various          | 10  | Cui et al. (2014) | Net primary production |
|        |        | Tropical and subtropical floodplain rivers and wetland complexes | Bueng Boraphet | 19  | Srinoparatwatana and Hyndes (2011) | Fish diversity |
| Negative|        | Temperate floodplain rivers and wetlands | Shengjin Lake     | 20  | Li et al. (2015) | Bird abundance |
|        |        | Temperate upland rivers                | various           | 10  | Cui et al. (2014) | Bird abundance |
|        |        | Tropical and subtropical floodplain rivers and wetland complexes | Central Catchment | 14  | Kwik and Yeo, 2015 | Fish abundance |
|        |        | Bukit Timah                            | Various           | 21  | Ng, Yeo, Sivasothi, and Ng (2015) | Fish richness |
|        |        | Various                                | Various           | 22  | Sung et al. (2013) | Invertebrate abundance |
| Europe | Positive| Temperate coastal rivers               | Doñana            | 23  | Bustamante, Aragones, and Afan (2016) | Hydroperiod |
| 3 + 2 0 |        | Temperate floodplain rivers and wetlands | Grande Brière Mottière | 24  | Cucherousset et al. (2007) | Fish production |
| 2 –    |        | Polar freshwaters                      | Various           | 25  | Virkkala, Poyry, Heikkinen, Lehikoinen, and Valkama (2014) | Bird richness |
| Neutral|        | Polar freshwaters                      | Various           | 26  | Yrjola et al. (2017) | Bird abundance |
|        |        | Temperate coastal rivers               | Various           | 27  | Mancini et al. (2005) | Invertebrate biological quality |
| Negative|        | Temperate floodplain rivers and wetlands | Various           | 28  | Douglas et al. (2015) | Burnt vegetation area |
|        |        | Temperate coastal rivers               | Aiguis Tortas & Lago de San Mauricio | 29  | García-Marín, Sanz, and Pla (1998) | Fish frequency |
| Neotropics | Positive| Tropical and subtropical upland rivers | Gama–Cabeça de Veados | 30  | Ledo and Colli (2016) | Reptile abundance |
| 10 + 7 0 |        | Tropical and subtropical coastal rivers | Sete Cidades, Serra da Capivara, Uruçu-Uma & Serra das Confusões | 31  | Madella-Auricchio, Auricchio, and Soares (2017) | Reptile richness |
| 3 –    |        | Yurubi                                | Rodriguez-Olarte et al. (2006) | 32  | Rodriguez-Olarte | Fish richness |

(Continues)
| Region                        | Change   | Abell et al., 2008 Freshwater ecoregion | Protected area name | No. | Authors                                           | Metric                                                                 |
|-------------------------------|----------|----------------------------------------|---------------------|-----|--------------------------------------------------|------------------------------------------------------------------------|
| North America                 | Positive | Temperate floodplain rivers and wetlands | Voyageurs lakes     | 40  | Christensen and Maki (2015)                      | Chlorophyll a                                                          |
|                               |          | Large lakes                            | Various             | 41  | Chu et al. (2018)                               | Fish length                                                            |
|                               |          | Temperate upland rivers                 | Theodore Roosevelt  | 42  | Hossack, Corn, and Pilliod (2005)                | Amphibian richness                                                    |
|                               | Neutral  | Temperate floodplain rivers and wetlands | Voyageurs National Park lakes | 40  | Christensen and Maki (2015)                      | Reptile richness                                                      |
|                               |          | Large lakes                            | Various             | 41  | Chu et al. (2018)                               | Depth transparency                                                    |
|                               |          |                                      |                     |     |                                                  | Total phosphorus                                                       |
|                               |          |                                      |                     |     |                                                  | Chlorophyll a                                                          |
|                               |          |                                      |                     |     |                                                  | Fish abundance                                                         |
|                               |          |                                      |                     |     |                                                  | Fish diversity                                                         |
| Oceania                       | Positive | Tropical and subtropical coastal rivers | Kakadu Park         | 43  | Adams et al. (2015)                             | Vegetation coverage                                                   |
|                               |          |                                      | Various             | 44  | Chessman (2013)                                 | Fish abundance                                                         |
|                               | Neutral  | Temperate floodplain rivers and wetlands | Various             | 44  | Chessman (2013)                                 | Fish richness                                                         |
Relationship between broad water body type and direction of change (for studies involving fish metrics only)

| Direction of change | River | Lake | Wetland | Floodplain | Pond | Total |
|---------------------|-------|------|---------|------------|------|-------|
| Negative            | 3     | 0    | 0       | 0          | 2    | 3     |
| Neutral             | 3     | 2    | 2       | 4          | 0    | 8     |
| Positive            | 4     | 2    | 1       | 0          | 0    | 3     |
| Total               | 10    | 4    | 3       | 4          | 3    | 24    |

(30), fish in karstic pools in Mexico (34), birds in Chinese rivers (17), and wetlands in Spain (23). Disconnection of the River Yangtze from its floodplain was a partial cause of reduced numbers of cranes in a reserve in China (20). Lowering of the groundwater table contributed to degradation of vegetation in National Parks in Zambia (7). These studies demonstrate the importance of lateral (e.g., river-riparian and floodplain zones) and vertical (e.g., surface–groundwater) connectivity. The lack of systematic protection of different habitats and pathways for migratory fish (e.g., for spawning, larvae, juveniles, and adults) is highlighted in the general literature (Mcintyre et al., 2016). However, no studies directly observed lack of longitudinal connectivity (upstream–downstream) as the main cause of negative outcomes for freshwater biodiversity in protected areas, although several authors inferred the possibility in discussion.

The need to reduce pressures in and around protected areas from grazing, inappropriate land and water management, pollution, tourism, or general human disturbance was emphasized in studies of wetlands in Tibet (12) and the United States (42), aquatic insects in India (9), and birds in China (20). Catchment disturbances (dredging, mining, and deforestation) were found to impact biodiversity in protected rivers in Venezuela (32), Kenya (2), and Italy (27), and in wetlands across Africa (5), but protected areas were shown to be effective buffers from adverse external pressures for reptiles in Brazilian rivers (30) and fish in Indian rivers (16).

Three river studies reported reductions in endemic and other native species within protected areas caused by invasive non-native species. In Mexico (34), flooding during the rainy season allowed tilapia to escape from fish farms. In Spain (29), non-native fish species had a greater impact on protected areas than in fished areas, suggesting the need for different management strategies in the two. An Australian case study (43) reported that control of invasive plants was a major objective.

Lack of law enforcement in protected areas contributed to the decline of turtles in Hong Kong streams (22), birds in African wetlands (5), and fish in Indian rivers (16). In contrast, protection had reduced hunting of reptiles, birds, and mammals in the Amazon, Peru (35) and over-fishing of shrimps in Costa Rica (33) and of eels in France (24). In Brazil, community-based management approaches have succeeded in reducing poaching of turtle eggs, where formal law enforcement had previously failed (36).

Many factors influenced the natural distributions of species, their abundance, and freshwater biodiversity, including ecoregion, variations in the landscape, river channel morphology, water quality, flow regime, and climate. In some cases, these factors had more influence on biodiversity than protected area status and management, including Australia’s Murray–Darling Basin (43), streams in Italy (27) and Singapore (21), karstic pools in Mexico (34), and waterbird habitats in Morocco (4).

4 | LESSONS TO ENHANCE PROTECTED AREA EFFECTIVENESS

Although the information base is limited, our novel application of the systematic review process has produced evidence that protected areas can be effective for conservation and restoration of freshwater biodiversity. However, almost half of the 75 case studies were not effective. We distilled the evidence into eight lessons for improving protected area assessment, design, and management to enhance freshwater conservation effectiveness. Our lessons build on many previous works (e.g., Adams et al., 2015; Fiedler & Karieva, 1997; Hermoso et al., 2016, 2018; Strayer & Dudgeon 2010) and strengthen their essential messages by providing empirical evidence from the systematic literature search.

4.1 | Lesson 1: Monitoring and research to understand effectiveness should be built into management of protected areas

This review selected 44 papers (from 2,586 retrieved) containing only 75 case studies (of the many thousands of protected areas worldwide) based on quantitative evidence of changes in freshwater biodiversity that stem from protected area designation. The limited evidence base means there is possibly weak understanding of the conditions under which protected area succeed or fail to deliver freshwater conservation (Geldmann et al., 2013). Factors influencing the scarcity of evidence include constraints on study design, in particular the difficulty of finding comparable unprotected areas (i.e., control or reference aquatic systems), and the challenges of conducting before–after studies, especially BACI designs, which arguably require longer timeframes to detect biodiversity outcomes in freshwater systems with high natural temporal variability (Adams et al., 2015). Monitoring outcomes in protected areas can be expensive (Hockings, Stolton, Leverington, Dudley, & Courrau, 2006) and demands rigor to capture biodiversity responses.
Although invertebrates make up the bulk of freshwater animal diversity, in both taxonomic and functional contributions, they are poorly represented in assessments of protected area effectiveness, with a strong bias toward monitoring vertebrates. We recommend monitoring a wider range of faunal groups as well as plants and algae. Further work is also necessary to define new metrics for measuring freshwater protected area effectiveness that capture spatial and temporal variations in ecological processes and responses to common stressors, as well as typical metrics of change in biodiversity or the abundance of particular taxa (Hermoso et al., 2016, 2018). Greater recognition of variability and time lags in population and community responses could help us understand why some protected area assessments reveal positive biodiversity outcomes and others do not (Adams et al., 2015; Geist, 2015). It is also essential to monitor the many environmental factors that vary naturally, such as climate, geology, soils, vegetation, and water flows, as these influence biodiversity in both protected and unprotected areas. We reiterate calls for a step change involving increased monitoring and research in protected areas.

4.2 | Lesson 2: Protected areas need to be of sufficient size and configuration to connect diverse elements of the waterscape and maintain their biodiversity

This study records evidence that greater protected area size and habitat heterogeneity enhance biodiversity outcomes for invertebrates in ponds and fish in wetlands (Pryke, Samways, & De Saedeleer, 2015; Koning, 2018). In riverine systems, many fish species use different habitats and parts of the basin at different life stages, often migrating significant distances to maximize population potential (Mcintyre et al., 2016). Protection of each habitat and connecting pathways is essential for their survival and recruitment (Hermoso, Filipe, Segurado, & Beja, 2018). Lack of multi-direction connectivity, including longitudinal, lateral (river to riparian and floodplain habitats), vertical (surface-groundwater), and temporal connectivity, may compromise biodiversity protection (Linke, Turak, & Nel, 2011). We recommend application of systematic conservation planning principles and modelling techniques (e.g., Grantham et al., 2016; Howard et al., 2018) during the placement, design, and gazettal of freshwater protected areas.

4.3 | Lesson 3: Areas designated to protect terrestrial ecosystems can contribute to freshwater biodiversity protection if they are located, designed, and managed appropriately

Large areas set aside to protect terrestrial biodiversity, such as national parks, often do not protect freshwater biodiversity (Grantham et al., 2016). However, our review found new evidence of positive outcomes for freshwater biodiversity, such as higher fish diversity in areas of Lake Tanganyika designated for conservation of terrestrial species (Britton et al., 2017) and greater numbers of threatened fish species in rivers within Indian tiger reserves than in areas outside of terrestrial reserves (Gupta, Sivakumar, Mathur, & Chadwick, 2015). In another study, three of four pollution-intolerant fish species were more abundant in lakes with partially protected shorelines (Chu, Ellis, & de Kerckhove, 2018); here, fish populations would benefit from protected areas that include the entire lake rather than protecting just part of the shoreline. Likewise, extending the scope of terrestrial protected areas to incorporate freshwater ecosystems would benefit narrow-range endemic fishes in the Western Ghats, India (Abraham & Kelkar, 2012). These studies indicate the potential to derive biodiversity benefits for freshwater systems within or bordered by terrestrial protected areas by extending design features to include more aquatic habitat diversity, and by reducing threats (e.g., sand mining, dynamite fishing, pollution, and introduced invasive fishes) that affect aquatic biota. We suggest that such opportunities merit more attention in regions where declaration of dedicated freshwater protected areas may be unlikely or beyond resource capacity, yet beneficial adjustments and more sensitive management of terrestrial protected areas may help to conserve freshwater biodiversity.

4.4 | Lesson 4: Incorporating conservation of aquatic habitats, including hydrological regime, water quality, and riparian vegetation, into protected area strategies is vital to maintaining freshwater biodiversity

Freshwater habitats vary widely in character, spatial patterns, and temporal dynamics and many physical, chemical, and biological factors govern their potential to support freshwater biodiversity. The hydrological regime is a defining feature, governing channel structure and connectivity, substrate characteristics, and aquatic habitat features important to invertebrates and fish as shelter, sources of food, and spawning sites. The need for integrated management of water resources to sustain flowing, standing, and groundwater-dependent ecosystems is recognized in frameworks such as environmental flow management (Arthington et al., 2018), Integrated Lake Basin Management (ILBM), and Integrated Water Resources Management (IWRM). Aquatic habitats typically interface with a riparian or littoral zone where stands of semi-aquatic and terrestrial vegetation regulate shading and water temperature, channel stability, and supplies of nutrients and organic matter to aquatic food webs (Naiman et al., 2005). These habitat features contributed to positive fish diversity outcomes in protected areas of Indian rivers (Sarkar et al., 2013) and lizard diversity in Brazilian riparian forests (Ledo & Colli, 2016). Maintaining the heterogeneity...
of aquatic habitat structure and the natural factors that influence spatial scales and temporal dynamics of habitat within protected areas is essential to protect freshwater biodiversity.

### 4.5 Lesson 5: Protected areas should be free of external and internal pressures from inappropriate, illegal, or unregulated land and water management

Most freshwater ecosystems are influenced, usually adversely, by human disturbance of the natural characteristics of the catchment in which they are situated, including changes to water flow regimes and basin-scale connectivity, production of excess sediment, nutrients and toxic pollutants (Linke et al., 2011), and landscape modifications, such as deforestation and logging, livestock grazing, cropping, salinization, and urbanization (Dudgeon et al., 2006, Rodríguez-Olarte, Amaro, Coronel, & Taphorn, 2006). The overriding detrimental influence of catchment land use meant that creation of protected areas per se did not increase macroinvertebrate diversity in Italian rivers (Mancini et al., 2005). In African wetlands, bird populations did not differ significantly between Ramsar sites and non-designated sites, due to habitat degradation associated with increasing arable areas, livestock numbers, and deforestation in surrounding lands (Kleijn et al., 2011). For these reasons, management needs to extend beyond the limits of the freshwater ecosystem and to include at least some of the upstream catchment and drainage network, the riparian zone, and downstream reaches, and maintain habitat patchiness, connectivity pathways, and associated ecological processes (Dudgeon et al., 2006). Where protection of large portions of a multi-use catchment is not practical, we recommend riparian and catchment zoning (Abell et al., 2017; Sheldon et al., 2012) prescribing different management regimes consistent with conservation.

Human activities within protected areas can also generate disturbances that constrain biodiversity outcomes. This review recorded negative changes in river fish metrics within protected areas due to local disturbances from dredging, mining, and deforestation (Rodríguez-Olarte et al., 2006). Chemical contamination from a pulp mill that triggered the disappearance of Brazilian waterweed, the food plant of black-necked swan (Cygnus melancoryphus), caused high mortalities due to starvation as well as massive migration out of the protected area (González & Fariña, 2013). Illegal fishing and harvesting of turtle eggs and adults within protected areas has reduced biodiversity in Amazon rivers (Norris, Michalski, & Gibb, 2018). We recommend prohibitions or limitations on external and internal threatening processes, coupled with monitoring and research to quantify how much disturbance from particular forms of catchment land-use change and internal threats can be tolerated without compromising biodiversity and ecosystem resilience in freshwater protected areas.

### 4.6 Lesson 6: Well-managed protected areas can provide a refuge for native species against invasive non-native species

Introductions of aquatic fauna occur through, for example, bait-bucket releases by anglers, deliberate introduction of favored game fish, and escapes from the ornamental fish trade, fish farms, and ornamental ponds. de Poorter, Pagad, and Irfan Ullah (2007) found that 277 Ramsar sites (17% of all Ramsar sites) were threatened by invasive non-native species. Invasive species can alter habitat structure, the demography of native plants, fish and invertebrates, community composition, and the genetic characteristics of species through hybridization. Although the problem may worsen as species ranges alter in response to climatic shifts, Gallardo et al. (2017) predicted that protected areas will provide some refuge for native species, particularly in remote and pristine regions with very low human accessibility and density. Protected areas with high human accessibility and density are more likely to experience new invasive species and expanding invasion fronts. We recommend preventing, removing, or controlling invasive non-native species (particularly those that cause detriment or loss of native species), maintaining aquatic conditions that favor native species (e.g., “natural” flow regimes and habitat connectivity) and manipulating conditions that suppress invasive non-native species (e.g., water level and temperature fluctuations during fish spawning). We also recommend more effort to recognize, disrupt, and monitor pathways by which non-native flora and fauna can enter protected areas, and strategies to limit new introductions and control populations within, connected to, or near to protected freshwater systems (Genovesi & Monaco, 2013), such as prohibition of live fish transport, barriers to movement, and selective fish traps (e.g., Asian Carp Regional Coordinating Committee 2019).

### 4.7 Lesson 7: Meeting socioeconomic protected areas objectives, such as grazing, tourism, and recreation, may result in a tradeoff against biodiversity

The effectiveness of many freshwater protected areas is compromised by explicitly aiming to meet diverse human expectations other than biodiversity conservation and supporting activities such as recreational hunting, fishing, boating, and livestock grazing. Freshwater ecosystems are a major focus of visitor activities and most protected areas require management of the trade-offs between freedoms of visitor use, benefits in terms of revenue for park management, the health and cultural benefits for visitors, and biodiversity conservation. Burning carbon-rich upland heath and blanket bogs (moorland) in the UK to promote gamebird shooting, and to a lesser extent livestock grazing, is likely to be detrimental for soil carbon storage, water quality, and habitat condition
in conservation areas, as well as having implications for climate change and wider biodiversity (Douglas et al., 2015). Wetland losses and habitat degradation associated with aquaculture within important protected areas on Yangtze River floodplains have led to decline of the hooded crane (Grus monacha), listed as Vulnerable on the IUCN Red List (Li, Zhou, Xu, Zhao, & Beauchamp, 2015). Surrounding paddy fields provide alternative feeding grounds but even within this buffer zone the feeding behaviors and energetic benefits for cranes and other migratory waterbirds are compromised by human disturbances. We recommend more effort to ensure that any socioeconomic objectives of protected areas are consistent with maintenance or restoration of ecosystem resilience and conservation of freshwater biodiversity.

4.8 Lesson 8: Laws and regulations associated with protected areas need to be enforced, but regulation activities should involve engagement of 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. Many argue that strict protection by law enforcement is the most promising approach, whereas Borrini-Feyerabend et al. (2013) suggest that the institutions and rules governing protected areas should be embedded in societal norms and adaptive to changing challenges. Protected areas producing positive socioeconomic outcomes are more likely to report positive conservation outcomes (Oldekop et al., 2016) and the success of Ramsar sites improved with increased participation of local stakeholders (Castro, Chomitz, & Thomas, 2002). Big-headed turtles (Platysternon megacephalum) were more numerous in a private refuge in Hong Kong than in national parks as a result of fencing and frequent patrols both day and night (Sung, Karraker, & Hau, 2013). Greater numbers of threatened fish species occurred in rivers within tiger reserves in India because illegal fishing, diversion of water, clearing of riparian vegetation, and sand mining were all lower than in areas that lacked legislative, religious, or socioeconomic drivers of protection (Gupta et al., 2015). In Brazil, community-based management approaches have succeeded in reducing poaching of turtle eggs, where formal law enforcement had previously failed (Norris et al., 2018). We recommend participation of scientists, NGOs, decision-makers, and stakeholders in protected area design, management, and monitoring.

5 CONCLUSIONS

Protected areas have been cornerstones of biodiversity protection for decades. Yet, research on the effectiveness of protected areas for freshwater biodiversity has been sparse (Hermoso et al., 2016), limiting our ability to define principles and practices to enhance freshwater conservation. Our novel application of the systematic review process has produced results that build on many previous works (e.g., Abell et al., 2017; Dudgeon et al., 2006; Fiedler & Karieva, 1997; Finlayson et al., 2018; Reis et al., 2017; Strayer & Dudgeon 2010) and our eight lessons reiterate and reinforce their essential messages. They complement the findings of a similar review of terrestrial protected area effectiveness, in particular the influence of human activities on biodiversity and governance issues (Blanco et al., 2019). The review has revealed evidence from quantitative case studies that not all protected areas have been effective for freshwater biodiversity conservation. Nevertheless, there is great potential to improve effectiveness and to enhance its contribution to the conservation and restoration of freshwater biodiversity. We urge policymakers, protected area managers, and those who fund them to invest in well-designed research and monitoring programs, collection of relevant spatial and temporal data on a wider range of taxonomic groups and ecological processes, and publication of evidence of protected area effectiveness, or the lack thereof. The eight lessons and recommendations arising from this systematic review offer many opportunities to strengthen the conservation effectiveness of freshwater protected area designs, management, and socio-ecological trade-offs, but only if we have the resolve to support and implement them rigorously, collaboratively, and much more widely.

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REFERENCES MEETING REVIEW SELECTION CRITERIA

Abraham, R. K., & Kelkar, N. (2012). Do terrestrial protected areas conserve freshwater fish diversity? Results from the Western Ghats of India. Oryx, 46(4), 544–553. https://doi.org/10.1017/S0030605311000937

Adams, V. M., Setterfield, S. A., Douglas, M. M., Kennard, M. J., & Ferdinands, K. (2015). Measuring benefits of protected area management: Trends across realms and research gaps for freshwater systems. Philosophical Transactions of the Royal Society B, 370(1681). https://doi.org/10.1098/rstb.2014.0274

Arreas, D. R. D., & Taveiras-Dias, M. (2014). Nesting and neonates of the yellow-spotted river turtle (Podocnemis unifilis, Podocnemididae) in the Araguari River basin, eastern Amazon, Brazil. Acta Amazonica, 44(3), 387–391. https://doi.org/10.1590/1809-4392201302864

Atkore, V. M., Sivakumar, K., & Johnsingh, A. J. T. (2011). Patterns of diversity and conservation status of freshwater fishes in the tributaries of River Ramganga in the Shiwaliks of the Western Himalaya. Current Science, 1005, 731–736.
Britton, A. W., Day, J. J., Doble, C. J., Ngatunga, B. P., Kemp, K. M., Carbone, C., & Murrell, D. J. (2017). Terrestrial-focused protected areas are effective for conservation of freshwater fish diversity in Lake Tanganyika. Biological Conservation, 212, 120–129. https://doi.org/10.1016/j.biocon.2017.06.001

Bustamante, J., Aragones, D., & Afan, I. (2016). Effect of protection level in the hydropower level of water bodies on Donana’s Aeolian sands. Remote Sensing, 8(10), 867. https://doi.org/10.3390/rs8100867

Chessman, B. C. (2013). Do protected areas benefit freshwater species? A broad-scale assessment for fish in Australia’s murray-darling basin. Journal of Applied Ecology, 50(4), 969–976. https://doi.org/10.1111/1365-2664.12104

Christensen, V. G., & Maki, R. P. (2015). Trophic state in Voyageurs National Park lakes before and after implementation of a revised water-level management plan. Journal of the American Water Resources Association, 51(1), 99–111. https://doi.org/10.1111/jawr.12234

Chu, C., Ellis, L., & de Kerckhove, D. T. (2018). Effectiveness of terrestrial protected areas for conservation of lake fish communities. Conservation Biology, 32(3), 607–618. https://doi.org/10.1111/cobi.13034

Cucherousset, J., Paillisson, J. M., Carpentier, A., Thoby, V., Damien, J. P., Eybert, M. C., … Robinet, T. (2007). Freshwater protected areas: An effective measure to reconcile conservation and exploitation of the threatened European eels (Anguilla anguilla)? Ecology of Freshwater Fish, 16(4), 528–538.

Cui, P., Wu, Y., Ding, H., Wu, J., Cao, M., Chen, L., … Xu, H. (2014). Status of wintering waterbirds at selected locations in China. Waterbirds, 37(4), 402–409. https://doi.org/10.1675/063.037.0407

Dinakaran, S., & Anbalagan, S. (2007). Anthropogenic impacts on aquatic insects in six streams of south Western Ghats. Journal of Insect Science, 7, 37.

Douglas, D. J. T., Buchanan, G. M., Thompson, P., Amar, A., Fielding, D. A., Redpath, S. M., & Wilson, J. D. (2015). Vegetation burning for game management in the UK uplands is increasing and overlaps spatially with soil carbon and protected areas. Biological Conservation, 191, 243–250. https://doi.org/10.1016/j.biocon.2015.06.014

García-Marín, J. L., Sanz, N., & Pla, C. (1998). Proportions of native and introduced brown trout in adjacent fished and unfished Spanish Rivers. Conservation Biology, 12(2), 313–319. https://doi.org/10.1046/j.1523-1739.1998.96133.x

Gonzalez, A. L., & Farina, J. M. (2013). Changes in the abundance and distribution of black-necked swans (Cygnus melancoryphus) in the Carlos Amwander Nature Sanctuary and Adjacent Wetlands, Valdivia, Chile. Waterbirds, 36(4), 507–514. https://doi.org/10.1675/063.036.0408

Gupta, N., Sivakumar, K., Mathur, V. B., & Chadwick, M. A. (2015). Terrestrial protected areas and managed reaches conserve threatened freshwater fish in Uttarakhand, India. PARKS, 21(1), 89–101.

Hossack, B. R., Corn, P. S., & Pilliod, D. S. (2005). Lack of significant changes in the herpetofauna of Theodore Roosevelt National Park, North Dakota, since the 1920s. American Midland Naturalist, 154(2), 423–432. https://doi.org/10.1674/0003-0031

Jiang, H. B., Wen, Y., Zou, L. F., Wang, Z. Q., He, C. G., & Zou, C. L. (2016). The effects of a wetland restoration project on the Siberian crane (Grus leucogeranus) population and stopover habitat in Momoge National Nature Reserve, China. Ecological Engineering, 96, 170–177. https://doi.org/10.1016/j.ecoleng.2016.01.016

Kanga, E. M., Ogotu, J. O., Olff, H., & Santema, P. (2011). Population trend and distribution of the Vulnerable common hippopotamus Hippopotamus amphibius in the Mara Region of Kenya. Oryx, 45(1), 20–27.

Kleijn, D., Cherkouki, I., Goedhart, P. W., van der Hout, J., & Lammertsma, D. (2014). Waterbirds increase more rapidly in Ramsar-designated wetlands than in unprotected wetlands. Journal of Applied Ecology, 51(2), 289–298. https://doi.org/10.1111/1365-2664.12193

Kleijn, D., Nagy, S., Delany, S., Nasiriwa, O., Dodman, T., & Goedhart, P. (2011). African winter population trends of European waterbirds: The identification of critical sites and the effectiveness of Ramsar and IBA site designation for the conservation of migratory waterbirds (1566-7197). Fauna & Flora International, Oryx, 45(1), 22–27.

Koning, A. A. (2018). Riverine reserves: The conservation benefits of spatial protection for rivers in the context of environmental change. Madison, WI: The University of Wisconsin-Madison.

Kwik, J. T., & Yeo, D. C. (2015). Differences in fish assemblages in protected and non-protected freshwater streams in a tropical urbanized country. Hydrobiologia, 762(1), 143–156.

Ledo, R. M. D., & Colli, G. R. (2016). Silent death: The new Brazilian forest code does not protect lizard assemblages in cerrado riparian forests. South American Journal of Herpetology, 11(2), 98–109. https://doi.org/10.2994/sajh-d-16-00025.1

Li, C. L., Zhou, L. Z., Xu, L., Zhao, N. N., & Beauchamp, G. (2015). Vigilance and activity time-budget adjustments of wintering hooded cranes, Grus monacha, in human-dominated foraging habitats. Plos One, 10(3), e0118928. https://doi.org/10.1371/journal.pone.0118928

Madella-Auricchio, C. R., Auricchio, P., & Soares, E. S. (2017). Reptile species composition in the middle Gurguêia and comparison with inventories in the Eastern Parnaiba river basin, state of Piauí, Brazil. Papéis Avulsos de Zoologia, 57(28), 375–386. https://doi.org/10.11606/0031-1049.2017.57.28

Mancini, L., Formichetti, P., Anselmo, A., Tancioni, L., Marchini, S., & Sorace, A. (2005). Biological quality of running waters in protected areas: The influence of size and land use. Biodiversity & Conservation, 14(2), 351–364.

Mutasva, T., Kativu, S., Mapaure, I., & Gandiwa, E. (2016). Diversity, population structure and regeneration patterns of Faidherbia albida vegetation community in the Zambezi Heartland area. Tropical Ecology, 57(4), 839–847.

Ng, D. J. J., Yeo, D. C. J., Sivasothi, N., & Ng, P. K. L. (2015). Conservation challenges and action for the critically endangered Singapore freshwater crab johora singaporensis. Oryx, 49(2), 345–351. https://doi.org/10.1017/s0030605313000707

Norris, D., Michalski, F., & Gibbs, J. P. (2018). Community involvement works where enforcement fails: Conservation success through community-based management of Amazon river turtle nests. Peerj, 6, e4856. https://doi.org/10.7717/peerj.4856

Penha, J., Fernandes, I. M., Sáarez, Y. R., Silveira, R. M. L., Florentino, A. C., & Mateus, L. (2014). Assessing the potential of a protected area for fish conservation in a neotropical wetland. Biodiversity and conservation, 23(13), 3185–3198.

Pitman, N. C. A., Norris, D., Gonzalez, J. M., Torres, E., Pinto, F., Collado, H., & del Castillo, J. C. F. (2011). Four years of vertebrate monitoring on an upper Amazonian river. Biodiversity and conservation, 20(4), 827–849. https://doi.org/10.1007/s10531-010-9982-y

Pryke, J. S., Samways, M. J., & De Saedeleer, K. (2015). An ecological network is as good as a major protected area for conserving dragonflies. Biological Conservation, 191, 537–545.
Rodríguez-Olarte, D., Amaro, A., Coronel, J., & Taphorn, B. D. C. (2006). Integrity of fluvial fish communities is subject to environmental gradients in mountain streams, Sierra de Aroa, north Caribbean coast, Venezuela. Neotropical Ichthyology, 4(3), 319–328. https://doi.org/10.1590/s1679-62252006000300003

Sarkar, U. K., Pathak, A. K., Tyagi, L. K., Srivastava, S. M., Singh, P., & Dubey, V. K. (2013). Biodiversity of freshwater fish of a protected river in India: Comparison with unprotected habitat. Revista De Biología Tropical, 61(1), 161–172.

Snyder, M. N., Pringle, C. M., & Tiffer-Sotomayor, R. (2013). Landscape-scale disturbance and protected areas: Long-term dynamics of populations of the shrimp, Macrobachirium olfersii in lowland Neotropical streams, Costa Rica. Journal of Tropical Ecology, 29(1), 81–85.

Srinoparatwatana, C., & Hyndes, G. (2011). Inconsistent benefits of a freshwater protected area for artisanal fisheries and biodiversity in a South-east Asian wetland. Marine and Freshwater Research, 62(5), 462–470.

Sung, Y. H., Karraker, N. E., & Hau, B. C. H. (2013). Demographic evidence of illegal harvesting of an endangered Asian turtle. Conservation Biology, 27(6), 1421–1428. https://doi.org/10.1111/cobi.12102

Thiollay, J. M. (2006). The decline of raptors in West Africa: Long-term assessment and the role of protected areas. Ibis, 148(2), 240–254. https://doi.org/10.1111/j.1474-919X.2006.00531.x

Vega-Cendejas, M. E., Santillana, M. H., & Norris, S. (2013). Habitat characteristics and environmental parameters influencing fish assemblages of karstic pools in southern Mexico. Neotropical Ichthyology, 11(4), 859–870. https://doi.org/10.1590/s1679-62252013000400014

Virkkala, R., Poyry, J., Heikkinen, R. K., Leihköinen, A., & 7 Valkama, J. (2014). Protected areas alleviate climate change effects on northern bird species of conservation concern. Ecology and Evolution, 4(15), 2991–3003. https://doi.org/10.1002/ece3.1162

Yrjola, R. A., Holopainen, S., Pakarinen, R., Tuoriniemi, S., Luostarinen, M., Mikkola-Roos, M., & Vaananen, V. M. (2017). The Barnacle Goose (Branta leucopsis) in the archipelago of southern Finland: population growth and nesting dispersal. Ornis Fennica, 94(4), 161–171.

Zhang, Y., Jia, Q., Prins, H. H., Cao, L., & de Boer, W. F. (2015). Effect of conservation efforts and ecological variables on waterbird population sizes in wetlands of the Yangtze River. Scientific Reports, 5, 17136.

Zhang, Y. L., Hu, Z. J., Qi, W., Wu, X., Bai, W. Q., Li, L. H., & Zheng, D. (2016). Assessment of effectiveness of nature reserves on the Tibetan Plateau based on net primary production and the large sample comparison method. Journal of Geographical Sciences, 26(1), 27–44. https://doi.org/10.1007/s11442-016-1252-9

**GENERAL REFERENCES**

Abell, R., Allan, J. D., & Lehner, B. (2007). Unlocking the potential of protected areas for freshwater. Biological Conservation, 16, 1435–1437

Abell, R., Thieme, M. L., Revenga, C., Bryer, M., Kottelat, M., Bogutskaya, N., ... Petry, P. (2008). Freshwater ecoregions of the world: A new map of biogeographic units for freshwater biodiversity conservation. Bioscience, 58(5), 403–414

Abell, R., Lehner, B., Thieme, M., & Linke, S. (2017). Looking beyond the fenceline: Assessing protection gaps for the world’s rivers. Conservation Letters, 10(4), 384–394. https://doi.org/10.1111/conl.12312

Arthington, A. H., Bhaduri, A., Bunn, S. E., Jackson, S., Tharme, R. E., Tickner, D., ... Ward, S. (2018). The Brisbane declaration and global action agenda on environmental flows 2018. Frontiers in Environmental Science, Section Freshwater Science, 6, 45. https://doi.org/10.3389/fenvs.2018.00045

Asian Carp Regional Coordinating Committee. (2019). Asian Carp Action Plan for Fiscal Year 2019. Retrieved from https://www.asiancarp.us/Documents/2019ActionPlan.pdf

Blanco, J., Bellón, B., Fabricius, C., de O., Roque, F., Pays, O., ... Renau, P.-C. (2019). Interface processes between protected and unprotected areas: A global review and ways forward. Global Change Biology. https://doi.org/10.1111/gcb.14865

Borrini-Feyerabend, G., Dudley, N., Jaeger, T., Lassen, B., Pathak Broome, N., Phillips, A., & Sandwith, T. (2013). Governance of Protected Areas: From understanding to action. Best Practice Protected Area Guidelines Series No. 20. Gland, Switzerland: IUCN.

Bower, S. D., Lennox, R. J., & Cooke, S. J. (2014). Is there a role for freshwater protected areas in the conservation of migratory fish? Inland Waters, 5, 1–6. https://doi.org/10.5268/IW-5.1.779

Castro, G. K., Chomitz, K., & Thomas, T. S. (2002). The Ramsar convention: Measuring its effectiveness for conserving wetlands of international importance. Ramsar COP8 DOC, 37. Retrieved from www.ramsar.org/pdf/cop8/cop8.doc_37_e.pdf

Collins, A. M., Coughlin, D., Miller, J., & Kirk, S. (2015). The production of quick scooping reviews and rapid evidence assessments: A how to guide. London, UK: Department for Environment, Food and Rural Affairs.

Convention on Biological Diversity. (2014). Convention on Biological Diversity 2014. Global Biodiversity Outlook 4. Montréal, Canada: Author.

de Poorter, M., Pagad, S., & Irfan Ullah, M. (2007). Invasive alien species and protected areas. A scooping report. World Bank/Global Invasive Species Programme (GISP). Washington, DC: World Bank.

Diaz, S., Settele, J., Brondizio, E., Ngo, H., Guèze, M., Agard, J., ... Zayas, C. (2019). The global assessment report on biodiversity and ecosystem services. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Nairobi, Kenya: United Nations Environment Programme.

Dudgeon, D., Arthington, A. H., Gessner, M.O., Kawabata, Z., Knowler, D., Lévêque, C., ... Sullivan, C. A. (2006). Freshwater biodiversity: Importance, threats, status, and conservation challenges. Biological Reviews, 81(2), 163–182.

Dudley, N., Harrison, I. J., Kettunen, M., Madgewick, J., & Maunder, V. (2016). Natural solutions for water management of the future: Freshwater protected areas at the 6th WORLD parks congress. Aquatic Conservation: Marine and Freshwater Ecosystems, 26(Suppl. 1), 121–132. https://doi.org/10.1002/aqc.2657

Fiedler, P. A., & Karieva, P. M. (1997). Conservation biology for the coming decade. London, UK: Chapman and Hall.

Finlayson, C. M., Arthington, A. H., & Pittock, J. (2018). Freshwater ecosystems in protected areas. Oxford, UK: Routledge.

Fricke, R., Eschmeyer, W., & van der Laan, R. (2019). Catalog of fishes: Genera, species, references: California Academy of Sciences. Retrieved from http://researcharchive.calacademy.org/research/ichthyology/catalog/SpeciesByFamily.asp

Gallardo, B., Aldridge, D. C., González-Moreno, P., Pergl, J., Pizarro, M., Pyšek, P., ... Vilá, M. (2017). Protected areas offer refuge from invasive species spreading under climate change. Global Change Biology, 23(12), 5331–5343. https://doi.org/10.1111/gcb.13798
Geist, J. (2015). Seven steps towards improving freshwater conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 25, 447–453.

Geldmann, J., Geldmann, J., Barnes, M., Coad, L., Craigie, I. D., Hockings, M., & Burgess, N. D. (2013). Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. *Biological Conservation*, 161, 230–238.

Genovesi, P., & Monaco, A. (2013). Guidelines for addressing invasive species in protected areas. In L. C. Foxcroft, P. Pyšek, D. M. Richardson, & P. Genovesi (Eds.), *Plant invasions in protected areas* (pp. 487–506). Dordrecht: The Netherlands: Springer.

Grantham, T. E., Fesenmyer, K. A., Peek, R., Holmes, E., Quiñones, R. M., Bell, A., … Moyle, P. B. (2016). Missing the boat on freshwater fish conservation in California. *Conservation Letters*, 10(1), 77–85. https://doi.org/10.1111/conl.12249

Hermoso, V., Abell, R., Linke, S., & Boon, P. (2016). The role of protected areas for freshwater biodiversity conservation: Challenges and opportunities in a rapidly changing world. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 26(S1), 3–11.

Hermoso, V., Filipe, A. F., Segurado, P., & Beja, P. (2018). Freshwater conservation in a fragmented world: Dealing with barriers in a systematic planning framework. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 28, 17–25.

Hockings, M., Stolton, S., Leverington, F., Dudley, N., & Courrau, J. (2006). Evaluating effectiveness: A framework for assessing management effectiveness of protected areas (2nd ed.). Gland, Switzerland: IUCN.

Howard, J. K., Fesenmyer, K. A., Grantham, T. E., Viess, J. H., Ode, P. R., Moyle, P. B., … Wright, A. N. (2018). A freshwater conservation blueprint for California: Prioritizing watersheds for freshwater biodiversity. *Freshwater Science*, 37(2), 417–431.

LaRance, W. F., Useche, D. C., Rendeiro, J., Kalka, M., Bradshaw, C. J. A., Sloan, S. P., … Zamzani, F. (2012). Averting biodiversity collapse in tropical forest protected areas. *Nature*, 489, 290–294.

Le Saout, S. (2013). Protected areas and effective biodiversity conservation. *Science*, 342(6160), 803–805.

Linke, S., Turak, E., & Nel, J. (2011). Freshwater conservation planning: The case for systematic approaches. *Freshwater Biology*, 56, 6–20.

Maltby, E., & Accredor, M. C. (2011). Ecosystem services of wetlands: Pathfinder for a new paradigm. *Hydrological Sciences Journal*, 56(8), 1341–1359.

McIntyre, P. B., Reidy Liermann, C., Childress, E., Hamann, E. J., Hogan, J. D., Januchowski-Hartley, S. R., … Prachet, B. M. (2016). Conservation of migratory fishes in freshwater ecosystems. In G. P. Cluss, M. Krkoske, & J. D. Olden (Eds.), *Conservation of freshwater fishes* (pp. 324–360). Cambridge, UK: Cambridge University Press.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Med.*, 6, e1000097. https://doi.org/10.1371/journal.pmed.1000097

Naiman, R.J., Decamps, H., & McClain, M.C. (2005). *Riparia: ecology, conservation, and management of streamside communities*. Academic Press: San Diego, USA.

Oldekop, J. A., Holmes, G., Harris, W. E., & Evans, K. L. (2016). A global assessment of the social and conservation outcomes of protected areas. *Conservation Biology*, 30(1), 133–141.

Pitlick, J., Finlayson, M., Arthington, A. H., Roux, D., Matthews, J. H., Bigs, H., … Viers, J. (2015). Managing freshwater, river, wetland and estuarine protected areas. In G. L. Worboys, M. Lockwood, A. Kohari, S. Feary, & I. Pulford (Eds.), *Protected area governance and management*. Canberra, Australia: ANU Press.

Ramsar Convention on Wetlands. (2018a). *Global wetland outlook: State of the world’s wetlands and their services to people*. Gland, Switzerland: Ramsar Convention Secretariat.

Ramsar Convention on Wetlands. (2018b). Report of the Secretary General pursuant to Article 8.2 concerning the List of Wetlands of International Importance. 13th Meeting of the Conference of the Contracting Parties, Dubai, United Arab Emirates.

Ramsar Convention on Wetlands. (2018c). Report of the Secretary General on the implementation of the Convention. 13th Meeting of the Conference of the Contracting Parties, Dubai, United Arab Emirates.

Reis, V., Hermoso, V., Hamilton, S. K., Ward, D., Fluett-Chouinard, E., Lehner, B., & Linke, S. (2017). A global assessment of inland wetland conservation status. *Bioscience*, 67(6), 523–533. https://doi.org/10.1093/biosci/bix045

Sheldon, F., Peterson, E. E., Boone, E. L., Sippel, S., Bunn, S. E., & Harch, B. D. (2012). Identifying the spatial scale of land-use that most strongly influences overall river ecosystem health score. *Ecological Applications*, 22, 2188–2203. https://doi.org/10.1890/11-1792.1

Strayer, D. L., & Dudgeon, D. (2010). Freshwater biodiversity conservation: Recent progress and future challenges. *Freshwater Science*, 29, 344–358. https://doi.org/10.1899/08-171.1

WWF. (2018). *Living planet report (2018) risk and resilience in a new era*. Gland, Switzerland: WWF International.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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