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REVIEW

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

Michael Acreman[1,2] | Kathy A. Hughes[3] | Angela H. Arthington[4] | David Tickner[3] | Manuel-Angel Dueñas[1]

[1]Centre for Ecology & Hydrology, Wallingford, UK

[2]Hydro-ecology Consulting Ltd, Wallingford, UK

[3]WWF-UK, Woking, UK

[4]Australian Rivers Institute, Griffith University, Brisbane, Australia

Correspondence
Michael Acreman, Centre for Ecology & Hydrology, Crowmarsh Gifford, Wallingford, OX108BB, UK.
Email: man@ceh.ac.uk

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WWF-UK

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.

KEYWORDS

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

1 | 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

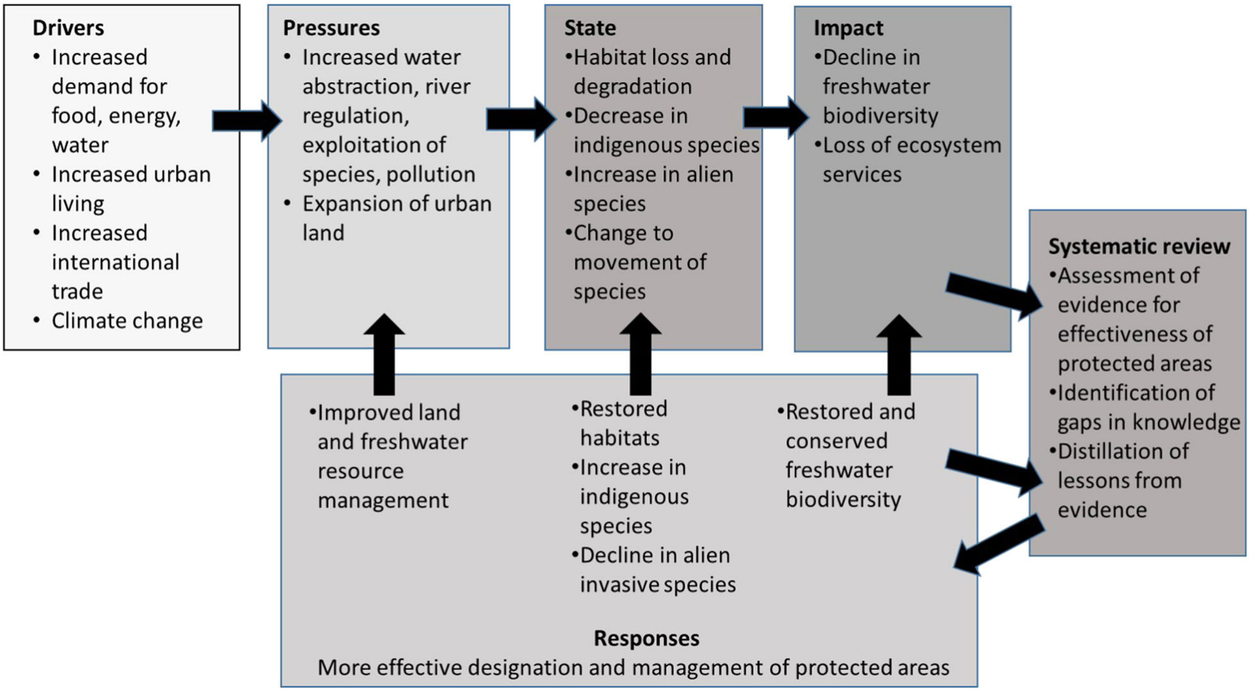

FIGURE 1 Conceptual diagram of the role of protected areas in freshwater biodiversity

Convention's definition of wetlands (https:\\www.ramsar.org) that includes rivers and their floodplains, streams, lakes, springs, marshes, bogs, fens, swamps, and peatlands.

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 km^2 (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

Documents containing quantitative evidence of the effectiveness of protected areas for freshwater biodiversity or habitat quality were used to answer the following questions.

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?

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 few 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.

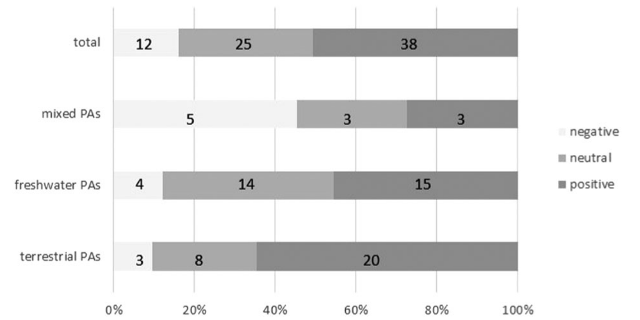

FIGURE 2 Differences in effectiveness of protected areas (PAs) designated for terrestrial conservation, freshwater conservation, and mixed objectives for conservation of freshwater biodiversity

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

TABLE 2 Case study characteristics showing number of case studies of positive (+), neutral (0), and negative (–) biodiversity outcomes for each region (column 1) along with details of each study (columns 2-7)

Region	Change	Abell et al., 2008 Freshwater ecoregion	Protected area name	No.	Authors	Metric
Africa 4 + 3 0 1 –	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
	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
	Negative	Tropical and subtropical floodplain rivers and wetland complexes	Chongwe & Mana Pools	7	Mutusva, Kativu, Mapaure, and Gandiwa (2016)	Plant density
Asia 16 + 5 0 6 –	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
						Invertebrate diversity
		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
						Fish diversity
						Fish richness
		Tropical and subtropical upland rivers	Corbett & Rajaji	16	Gupta et al., 2015	Fish richness
						Fish abundance
						Fish body length

(Continues)

TABLE 2 (Continued)

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
						Vegetation coverage
	Neutral	Tropical and subtropical upland rivers	Corbett	18	Atkore et al. (2011)	Fish richness
						Fish abundance
		Montane freshwaters	Zoige	12	Zhang et al. (2016)	Net primary production
		Temperate floodplain rivers and wetlands	various	10	Cui et al. (2014)	Bird abundance
		Tropical and subtropical floodplain rivers and wetland complexes	Bueng Boraphet	19	Srinoparatwatana and Hyndes (2011)	Fish diversity
						Fish richness
	Negative	Temperate floodplain rivers and wetlands	Shengjin Lake	20	Li et al. (2015)	Bird abundance
			various	10	Cui et al. (2014)	Bird abundance
		Temperate upland rivers	Momoge	17	Jiang et al. (2016)	Bird abundance
		Tropical and subtropical floodplain rivers and wetland complexes	Central Catchment	14	Kwik and Yeo, 2015	Fish abundance
			Bukit Timah	21	Ng, Yeo, Sivasothi, and Ng (2015)	Invertebrate abundance
			Various	22	Sung et al. (2013)	Reptile abundance
Europe 3 + 2 0 2 –	Positive	Temperate coastal rivers	Doñana	23	Bustamante, Aragones, and Afan (2016)	Hydroperiod
		Temperate floodplain rivers and wetlands	Grande Brière Mottière	24	Cucherousset et al. (2007)	Fish production
		Polar freshwaters	Various	25	Virkkala, Poyry, Heikkinen, Lehikoinen, and 7 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	Aiguas Tortas & Lago de San Mauricio	29	García-Marín, Sanz, and Pla (1998)	Fish frequency
Neotropics 10 + 7 0 3 –	Positive	Tropical and subtropical upland rivers	Gama–Cabeça de Veado	30	Ledo and Colli (2016)	Reptile abundance
						Reptile richness
		Tropical and subtropical coastal rivers	Sete Cidades, Serra da Capivara, Uruçuí-Una & Serra das Confusões	31	Madella-Auricchio, Auricchio, and Soares (2017)	Reptile diversity
			Yurubí	32	Rodríguez-Olarte et al. (2006)	Fish richness

(Continues)

TABLE 2 (Continued)

Region	Change	Abell et al., 2008 Freshwater ecoregion	Protected area name	No.	Authors	Metric
			La Selva	33	Snyder, Pringle, and Tiffer-Sotomayor (2013)	Invertebrate abundance
			Calakmul	34	Vega-Cendejas, Santillana, and Norris (2013)	Fish abundance
		Tropical and subtropical floodplain rivers and wetland complexes	Los Amigos	35	Pitman et al. (2011)	Bird abundance
						Mammal abundance
						Reptile abundance
		Large river deltas	Amapá	36	Norris et al. (2018)	Reptile egg predation by humans
	Neutral	Tropical and subtropical floodplain rivers and wetland complexes	Pantanal	37	Penha et al. (2014)	Fish biomass
						Fish diversity
						Fish richness
						Fish abundance
		Tropical and subtropical coastal rivers	Calakmul	34	Vega-Cendejas et al. (2013)	Fish diversity
						Fish richness
		Large river deltas	Amapá	38	Arraes and Tavares-Dias (2014)	Reptile egg predation by humans
	Negative	Temperate coastal rivers	Carlos Anwandter	39	González and Fariña (2013)	Bird abundance
		Large river deltas	Amapá	36	Norris et al. (2018)	Reptile egg predation by humans
		Tropical and subtropical coastal rivers	Yurubí	32	Rodríguez-Olarte et al. (2006)	Fish abundance
North America 4 + 5 0 0 –	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
						Reptile richness
	Neutral	Temperate floodplain rivers and wetlands	Voyageurs National Park lakes	40	Christensen and Maki (2015)	Depth transparency
						Total phosphorus
						Chlorophyll a
		Large lakes	Various	41	Chu et al. (2018)	Fish abundance
						Fish diversity
Oceania 1 + 2 0 0 –	Positive	Tropical and subtropical coastal rivers	Kakadu Park	43	Adams et al. (2015)	Vegetation coverage
	Neutral	Temperate floodplain rivers and wetlands	Various	44	Chessman (2013)	Fish abundance
						Fish richness

TABLE 3 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

(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, & Gibbs, 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 scienstists, 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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SUPPORTING INFORMATION

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

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