
Freshwater Protected Areas: Strategies for Conservation

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Abstract: *Freshwater species and habitats are among the most threatened in the world. One way in which this growing conservation concern can be addressed is the creation of freshwater protected areas. Here, we present three strategies for freshwater protected-area design and management: whole-catchment management, natural-flow maintenance, and exclusion of non-native species. These strategies are based on the three primary threats to fresh waters: land-use disturbances, altered hydrologies, and introduction of non-native species. Each strategy draws from research in limnology and river and wetland ecology. Ideally, freshwater protected areas should be located in intact catchments, should have natural hydrological regimes, and should contain no non-native species. Because optimal conservation conditions are often difficult to attain, we also suggest alternative management strategies, including multiple-use modules, use of the river continuum concept, vegetated buffer strips, partial water discharges, and eradication of exotic species. Under some circumstances it may be possible to focus freshwater conservation efforts on two key zones: adjacent terrestrial areas and headwaters.*

Áreas Protegidas de Agua Dulce: Estrategias para la Conservación

Resumen: *Las especies y hábitats de agua dulce se encuentran entre los más amenazados del mundo. Una forma en la que esta creciente preocupación por la conservación puede ser abordada es la creación de áreas protegidas de agua dulce. Aquí presentamos el diseño de tres áreas protegidas de agua dulce y las estrategias de manejo: manejo global de la cuenca de captación, mantenimiento del flujo natural y exclusión de las especies no nativas. Estas estrategias están basadas en las tres amenazas principales que tienen las aguas dulces: perturbaciones por uso del suelo, hidrologías alteradas e introducciones de especies no nativas. Cada estrategia está planteada como resultado de la investigación en limnología y ecología de ríos y pantanos. Idealmente, las aguas protegidas de agua dulce deberán ser ubicadas en cuencas de captación intactos, que tengan regímenes hidrológicos naturales y que no contengan especies no nativas. Puesto que las condiciones óptimas de conservación son frecuentemente difíciles de alcanzar, también sugerimos estrategias alternativas de manejo que incluyen módulos de uso múltiple, uso del concepto de río continuo, bandas de amortiguamiento con vegetación, descargas parciales de agua y erradicación de especies exóticas. Bajo ciertas circunstancias, puede ser posible enfocar los esfuerzos de conservación de aguas dulces en dos zonas clave: áreas adyacentes terrestres y nacientes.*

Introduction

Around the world, freshwater habitats are being subjected to unprecedented levels of human disturbance.

Globally, freshwater withdrawals have almost doubled since 1960, and more than half of all accessible freshwater runoff is currently used by humans (Loh et al. 1998). Increased water demands for irrigation, industrial, and domestic uses already threaten freshwater resources in many parts of the world (Szöllosi-Nagy et al. 1998). The Nile in Egypt, the Ganges in South Asia, the Amu Dar'ya and Syr Dar'ya in central Asia, the Yellow River in China,

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and the Colorado River in North America are among the major rivers that are dammed, diverted, and overused to the extent that for parts of the year little or none of their fresh water reaches the sea (Postel 1995). It has been estimated that two-thirds of the total world population will face severe water shortages by the year 2025 (Szölosi-Nagy et al. 1998). Not surprisingly, these pressures have led to the degradation of many freshwater habitats. An index of the health of the world's freshwater ecosystems shows a decline of 50% between 1970 and 1995 (Loh et al. 1998).

The species dependent on these freshwater habitats are in danger of disappearing. Freshwater fishes are thought to be the world's most threatened group of vertebrates after amphibians (Bruton 1995): unless they are protected, 20% of the world's freshwater fishes may become extinct in the next 25–50 years (Moyle & Leidy 1992). The future extinction rate of freshwater animals is predicted to be almost five times greater than that for terrestrial animals and three times that of coastal marine mammals (Ricciardi et al. 1999). In North America, one of the best-studied regions of the world, the status of freshwater species reflects a growing crisis. By one estimate, 28% of the native freshwater fishes of North America are listed as endangered, vulnerable, or extinct under criteria of the World Conservation Union (Williams & Miller 1990). Freshwater mussels are in even greater peril, with 72% of their taxa recognized as endangered, threatened, or of special concern in the United States, home to one-third of the world's freshwater mussel species (Williams et al. 1993; Abramovitz 1996).

Protected areas are one partial solution to habitat degradation, but few such areas have been created specifically for fresh waters. Instead, freshwater habitats are commonly protected only incidentally as part of their inclusion within terrestrial reserves (Lake 1980; Skelton et al. 1995). Unfortunately, inclusion does not guarantee protection. Terrestrial parks often fail to address important aquatic concerns such as whole-catchment integrity, hydrology, and introductions of non-native species (Lake 1980; Skelton et al. 1995; Moyle & Randall 1998). Activities such as building park roads may have minor effects on terrestrial habitats, but they damage fresh waters by increasing sedimentation rates (Skelton et al. 1995). Practices such as dam building or diverting water for agriculture can occur outside park boundaries and still have negative consequences for freshwater habitats within the park. A telling example of freshwater mismanagement within terrestrial parks is the practice of stocking non-native sport fishes. The intentional introduction of trout and salmon has reduced indigenous fish densities and caused the decline of native frog populations (McDowall 1984; Bradford et al. 1993). In a particularly extreme case, the removal of native eels in Fiordland National Park, New Zealand was permitted to

protect introduced salmon populations (McDowall 1984).

We urgently need protected areas that specifically target freshwater habitats and protect biodiversity, representative habitats, rare or endangered species, and intact habitat remnants (Lake 1980; Moyle & Sato 1991; Doppelt et al. 1993). Such freshwater protected areas (FWPAs) must guard against the primary threats to freshwater species and habitats. Increased sediment and nutrient loads from agriculture, altered hydrological regimes and non-native species introductions are of most concern in the protection of imperiled freshwater fauna in the United States (Richter et al. 1997b). Studies in Asia, Europe, Africa, and Australia confirm that these are the most common causes of habitat degradation and species loss in fresh waters throughout the world (Lake 1980; O'Keeffe 1989; Boon 1992; Dudgeon 1992; Allan & Flecker 1993).

Although still rare, some protected areas have been established specifically to protect freshwater species and habitats (Table 1). Unfortunately, reserve designation does not guarantee protection for freshwater ecosystems. Threats from land-use disturbances, altered hydrologies, and non-native species introductions can continue to plague FWPAs (Table 2). Part of the problem may lie in the goal of many FWPAs to protect particular species rather than the ecosystem as a whole. The continued intrusion of these threats may also be due to faulty or uninformed reserve design.

Research into the theoretical basis for the design of FWPAs has focused primarily on general conservation principles—species diversity, population dynamics, population genetics, habitat quality—without integrating the specific processes particular to freshwater species and habitats (McDowall 1984; Maitland 1985; Moyle & Sato 1991). Recently, several papers have drawn attention to the need to focus on hydrologic and water-chemistry regimes (Poiani et al. 2000; Valle Ferreira 2000) and on processes such as invasions (Knapp & Matthews 2000), but no standard protocols exist on which to base the design and management of FWPAs. As with marine and terrestrial reserves, the creation of FWPAs has been determined primarily by economic, cultural, and political factors rather than by theoretical conservation strategies (Soulé & Simberloff 1986; Meffe & Carroll 1997). Human demands and jurisdictional divisions both within and across national boundaries can impede efforts to protect specific areas (Allan et al. 1997). These problems are compounded in the case of rivers because of the long distances over which these systems extend (O'Keeffe 1989; Moyle & Leidy 1992).

Although little study has been specifically devoted to the design of freshwater protected areas (Lake 1980; McDowall 1984; Maitland 1985; Moyle & Sato 1991), freshwater ecology has been an extremely active field of research. The development of initial design strategies for

Table 1. Examples of protected areas created specifically to protect freshwaters.*

<i>Protected area</i>	<i>Date established</i>	<i>Protection goal</i>	<i>Area protected (km²)</i>	<i>Freshwater protected</i>	<i>Freshwater and watershed inclusion</i>	<i>Designation</i>
Keoladeo National Park, India	1956	maintain rich avifauna	29	wetland	total wetland	bird sanctuary (1956), Ramsar site (1981), national park (1982), World Heritage site (1985)
Pacaya-Samiria National Reserve, Peru	1972	protect fish (<i>Arapaima gigas</i>)	21,508	rivers and alluvial plain	total; alluvial plain and entire watershed of two rivers	part of Peruvian national system of protected areas
Nahanni National Park Reserve, Canada	1972	maintain wilderness values	4,766	lakes and rivers	partial river; 1/7 of the South Nahanni watershed	Canadian Heritage River (1987), UNESCO World Heritage site (1978), national park reserve (1976)
Danube Delta Biosphere Reserve, Romania	1991	preserve unique ecosystem	6,792	wetland	partial delta; 85% of a total of 7990 km ²	Ramsar site (1991), MAB Biosphere Reserve (1992)
Lake Baikal Basin, Russian Federation	1996	maintain endemic fauna, one of the world's oldest and largest freshwater bodies	88,000	lake	total lake; partial watershed includes land buffer from 5 to 70 km	Ramsar site (1994), World Heritage site (1996), Lake Baikal Region MAB (1986), smaller national reserves (1916, 1969, 1974, 1976, 1987)

*We selected better-known sites from around the world to illustrate the diversity of freshwater protected areas.

FWPAs can therefore draw from research in limnology and river and wetland ecology. In response to the need for FWPAs, we present three strategies with which to address the three primary threats to freshwater systems: land-use disturbances, altered hydrologies, and non-native species introductions.

Land-Use Disturbance: Whole-Catchment Management

Freshwater systems are affected by any activity taking place upstream or uphill in the catchment (Leopold 1941). Researchers studying rivers in Michigan (U.S.A.) found that both habitat quality and the complexity of fish assemblages (as assessed by the index of biotic integrity) declined as the proportion of upstream catchment area devoted to agriculture increased (Roth et al. 1994, as reviewed by Allan et al. 1997). In Madagascar, the occurrence of native species in freshwater communities has been strongly linked to the presence of undisturbed rainforest (Reinthal & Stiassny 1990).

Land-use practices can affect fresh waters by modification of nutrient loads, sediment accretion, changes in water temperature, and increases in pollution. These types of habitat alteration can have a negative effect on the mortality rates, reproductive success, growth, and behavior of aquatic organisms (Lynch et al. 1984; Moyle

& Leidy 1992; Abramovitz 1996). Terrestrial-based pollutants have been implicated as one of the primary causes of freshwater habitat destruction in the Thames River of the United Kingdom and the Great Lakes of North America, among others (Allan & Flecker 1993; Abramovitz 1996). Non-point source pollution, particularly from agricultural activities, remains the leading cause of the deterioration of water quality across the United States (Richter et al. 1997a).

Conservation efforts for freshwater habitats and species must be based on whole-catchment management. For example, the catchment has been identified as the focal conservation unit of aquatic diversity-management areas (ADMAs), proposed protected areas to conserve aquatic biodiversity in California (Moyle & Yoshiyama 1994). All activities taking place within the catchment must be assessed for their effect on waterbodies. Ideally, the boundaries of freshwater protected areas should be defined by catchment boundaries (Fig. 1). Unfortunately, it is not always possible to include entire catchments, particularly larger ones (e.g., greater than third-order) within protected areas. Several alternatives are available in circumstances where protection of the entire catchment is not feasible. The principle of whole-catchment management may still be incorporated in managing activities taking place within the catchment.

The best alternative to whole-catchment protection is the creation of multiple-use modules (MUMs) (Noss &

Table 2. Examples of threats to freshwater protected areas presented in Table 1.

Protected area	Management concerns				Reference*
	land use	hydrology	non-native species		
Keoladeo National Park, India	agricultural activities in catchment causing eutrophication, toxic effects from pesticides, increased salinity from soil erosion	dam construction created park wetland; large variation in rainfall and reservoir releases causes large-scale diebacks of plants and animals	several non-native plants live within the park, including <i>Eichhornia crassipes</i> and <i>Hydrilla verticillata</i>		Gopal 1994
Pacaya-Samiria National Reserve, Peru	agriculture, deforestation, and petroleum exploitation within the catchment	potential for changes in hydrology due to deforestation	water buffalo live within the reserve		Bayley et al. 1991 Durand & McCaffrey 1999
Nahanni National Park Reserve, Canada	potential mining development increasing heavy-metal concentrations	no management concerns at this time	no management concerns at this time		WCMC 1998a Halliwell 1998
Danube Delta Biosphere Reserve, Romania	pollution leading to algal blooms, increased salt content, high concentrations of heavy metals	Iron Gates Hydroelectric facility located on the Danube River	extensive fish farming of Chinese carp, leading to virtual extinction of wild carp		WCMC 1998b
Lake Baikal Basin, Russian Federation	deforestation and agriculture leading to erosion, largest inflowing river polluted with industrial and municipal waste	construction of hydropower station and dam on outflow of the lake, leading to a rise in water levels	aquatic plant <i>Elodea canadensis</i> and several non-native fishes have been introduced		WCMC 1998c Kozhava & Silow 1998

*World Conservation Monitoring Centre is WCMC.

Harris 1986) (Fig. 1). A terrestrial MUM consists of a central, well-protected core surrounded by a series of buffer zones in which varying amounts of human activity are permitted. Only low-impact activities are permitted near the core; potentially detrimental practices are excluded or relegated to the most distant zone. This design could easily apply to FWPA's if the central core consisted of a target waterbody and the riparian zone. Multiple-use modules have the additional advantage of being relatively easy to integrate with community-based conservation initiatives, because some human activities continue to be permitted within some zones of protection. Minimum-impact activities such as backpacking and canoeing could be permitted within the core protected area. Secondary zones could be used for relatively low-impact activities such as selective harvesting of forest products, low-density residential development, and conservation-tillage organic agriculture.

A second option is to use the river-continuum concept to determine which portions of the catchment require the most protection (Vannote et al. 1980; Cummins 1992; Dudgeon 1992) (Fig 1c). With this concept, the strong influence of debris from riparian vegetation on headwater streams is considered. Farther downstream, in-stream production increases, reducing dependence on terrestrial material as an energy source. Because pro-

cesses occurring upstream depend primarily on terrestrial production, and downstream regions are influenced by upstream processes for which resources are limited, protection efforts should focus on headwaters. Downstream sites primarily require riparian vegetation to provide shading, dampen hydrological fluctuations, and prevent erosion and nutrient loading (Vannote et al. 1980; Cummins 1992).

Where no other options are possible, vegetated buffer strips (VBS) adjacent to aquatic ecosystems may reduce the negative effects of deleterious land-use practices (Moyle & Sato 1991) (Fig. 1d). Researchers reviewing VBSs found that widths of 10–50 m were capable of maintaining ambient stream temperatures and retaining sediments and nutrients (Osborne & Kovacic 1993). Nutrient retention by buffer strips varies with vegetation type and slope, however, and VBS widths must be determined on a site-specific basis. Buffer zones have been suggested for aquatic diversity-management areas in California as a means of protecting upstream portions of catchments that contain freshwater reserves (Moyle & Yoshiyama 1994). Protected riparian zones designed as corridors to link larger terrestrial reserves also serve as VBSs, extending protection of aquatic habitats into parts of the catchment outside the terrestrial reserves (Noss & Harris 1986). In many areas, government regulations already re-

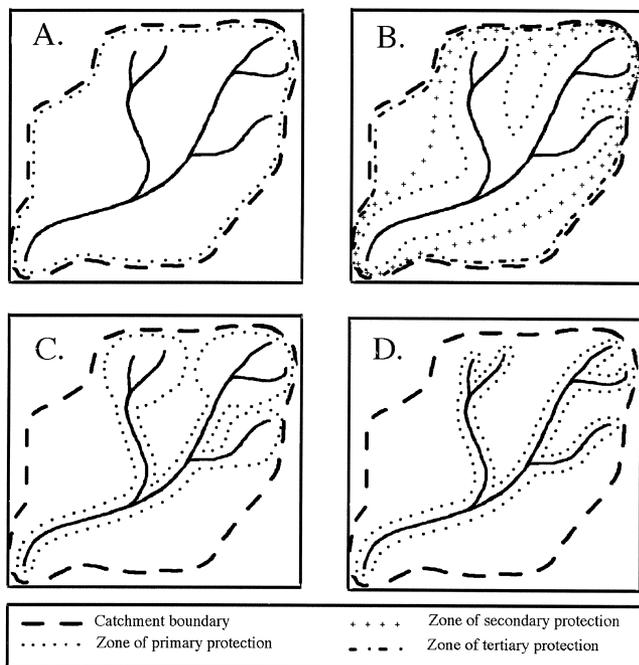


Figure 1. Strategies for protection against land-use disturbances: (a) whole catchment management, (b) multiple-use modules (MUMs), (c) river continuum concept (RCC), and (d) vegetated buffer strips (VBSs).

quire that minimum-width VBSs surround lakes or rivers when adjacent land is subject to deleterious land-use practices such as logging. Buffer strips may also provide essential nesting sites for aquatic species. A study of freshwater turtles in a Carolina Bay wetland (U.S.A.) found that a buffer strip of 73 m would provide protection for 90% of turtle nesting sites (Burke & Gibbons 1995). The success of buffer strips in reducing the effect of damaging land-use activities depends on the nature and magnitude of catchment disturbances and the location and size of the buffer strips. In cases of extreme disturbance, a VBS may provide an inadequate level of protection. The potential for buffer strips to sufficiently reduce or alleviate negative effects must be determined on a site-specific basis.

Alternatives to whole-catchment management, such as MUMs and VBSs, may provide adequate protection against some forms of mismanagement but not others. For example, VBSs can protect against increased sedimentation rates but will have no effect on the direct discharge of municipal and industrial wastes into fresh waters. In such circumstances, therefore, point sources of pollution must be addressed independently. Proper sewage treatment, combined with strict regulation and enforcement of industrial, municipal and agricultural discharge, will offer the best alternatives in these situations (Mason 1990). Freshwater species have benefited from improvements in water quality in many places around

the world. In the Thames River of England, for example, advances in sewage treatment have permitted the recovery of some native fish and waterfowl populations (Allan & Flecker 1993). Similarly, the benthos of Lake Erie, at the Canada-U.S. border, have shown some signs of recovery after nutrient-loading reductions (Schloesser et al. 1995). The establishment of pollution-monitoring programs is essential to ensure that water-quality standards continue to be met (Mason 1990). Finally, where water quality is low, the establishment of FWPAs may provide the necessary incentive to improve local conditions and enforce stricter controls on polluters.

Hydrological Alterations: Natural Flow Maintenance

Hydrological alterations are one of the top threats to freshwater species and habitats (Dudgeon 1992; Poff et al. 1997; Richter et al. 1997a; Moyle & Randall 1998;). Streamflow has been referred to as the "master variable" limiting the distribution of riverine species and regulating the ecological integrity of flowing water systems (Poff et al. 1997). Freshwater systems are defined largely by their hydrology; indeed, one of the primary abiotic differences among rivers, lakes, and wetlands is the supply and movement of water (Mitsch & Gosselink 1986; Ryder & Pesendorfer 1989). Key environmental parameters such as water temperature, dissolved oxygen levels, suspended sediment loads, nutrient availability, and physical habitat structure all vary among hydrological regimes (Mitsch & Gosselink 1986; Richter et al. 1997b).

Given the importance of hydrology, dramatic alteration of flow regimes by human activities is of grave concern. Natural hydrological patterns are altered by dams, diversions for irrigation, channelization, groundwater pumping, and catchment conversion through urbanization, deforestation, and agriculture (Poff et al. 1997). Of the total water discharge of the 139 largest river systems in Canada, United States, Europe, and the republics of the former Soviet Union, 77% is significantly altered by fragmentation and flow regulation (Dynesius & Nilsson 1994).

Changes in species composition are commonly associated with flow regulation (Welcomme 1994). In northern California, rivers with altered flow regimes (e.g., dams) have more predator-resistant invertebrates and fewer fish than unaltered rivers (Wotten et al. 1996). The more uniform flows created by river regulation allow non-native species to replace locally adapted native fauna (Gehrke et al. 1995; Moyle & Marchetti 1999). Barriers to flow also can affect the movement of animals and plants, thereby altering metapopulation dynamics (Meffe & Carroll 1997).

The most useful concept in assessing the hydrological requirements of freshwater systems is the natural-flow

paradigm (Poff et al. 1997; Richter et al. 1997b), which stresses the importance of maintaining the full range of variation in natural hydrological regimes to sustain the native biodiversity and integrity of aquatic ecosystems (Richter et al. 1997b). Although the natural-flow paradigm was originally developed for rivers, it is equally applicable to other freshwater systems. Changes in any of the five components of flow (magnitude, frequency, duration, timing, and rate of change) influence water quality, energy sources, physical habitat, and biotic interactions (Poff et al. 1997).

The principles of the natural-flow paradigm suggest that FWPAs ideally should be located at sites where natural hydrological regimes are relatively intact or can be restored. Because of the increasing demand for freshwater supplies and services (Szöllosi-Nagy et al. 1998), maintaining such natural regimes may require active management. Reservoir releases, interbasin transfers, groundwater withdrawals, and periodic drawdowns (temporary drainages) can be used to maintain flows and mimic natural discharge patterns, whereas weirs, embankments, and sluices can be used to maintain water levels (Kadlec & Smith 1992; Poff et al. 1997). Such strategies have sometimes been successful in partially restoring natural hydrological cycles to the benefit of local ecosystems (Table 3). Terrestrial buffer strips may also have a significant effect on hydrology. Vegetated buffer strips representing 20% of the total hillslope length have been proposed to reduce overland flow effectively, thereby

providing more natural flow regimes to streams (Herron & Hairsine 1998). In New Zealand pasture catchments, forested buffer strips 25–35 m wide reduced annual water yields to stream channels by up to 55% (Smith 1992).

Efforts to manage or restore hydrology should be directed where they will be the most effective. Because more than 90% of a river's flow may be derived from catchment headwaters (Kirby 1978, cited by Haycock et al. 1993), efforts to maintain or restore natural flow regimes should focus most intensely on these zones because this will benefit both upstream and downstream habitats. Although species diversity is typically higher in downstream habitats (Sheldon 1988; Peres & Terborgh 1995), the hydrology of these sites depends directly on what occurs upstream. Where efforts are constrained, therefore, benefits can be maximized by focusing on upstream hydrology. This may not hold true, however, for freshwater ecosystems in which upstream and downstream hydrologies have become disconnected (e.g., due to dam construction). At these sites, active management practices, such as reservoir releases mimicking natural flow patterns, may help ensure that the benefits of intact, upstream hydrologies are transmitted to downstream habitats. But the focus should remain on headwaters, for the reasons cited above and because the effects of impoundments do decrease with distance (Imbert & Stanford 1996). Finally, rivers or wetlands are generally more affected by seasonal variation in water flow than are lakes (Gehrke et al. 1995). First priority, therefore,

Table 3. Examples of successful application of flow-regime management for conservation.

<i>Location</i>	<i>Flow component</i>	<i>Ecological success</i>	<i>Reference</i>
St. Mary River, Alberta, Canada	increased minimum flows and maintained more gradual flow reductions after high-flow periods	cottonwood recruitment	Rood et al. 1995
Pecos River, New Mexico, U.S.	maintained minimum flow and mimicked natural flow variation by regulating withdrawals for irrigation	increased reproductive success of Pecos bluntnose shiner	Poff et al. 1997
Kissimmee River wetlands and floodplain, Florida, U.S.	increased water flow using notched weirs and diverted water over former floodplains	recolonized native aquatic plants and insects, increased fish and waterfowl biomass	Toth 1991
Winous Point Marsh, Ohio, U.S.	simulated natural drought conditions with periodic drawdowns	reestablished semiaquatic vegetation	Meeks 1969
Roanoke River, Virginia, U.S.	dampened unnatural flow fluctuations	increased juvenile abundance of striped bass	Rulifson & Manooch 1993
Glasson Moss and Wedholme Flow, Cumbria, England	dammed drainage ditches	regenerated <i>Sphagnum</i> sp.	Mawby 1995
Headwater streams, northeastern Finland	decreased current velocities	increased moss cover and invertebrate abundance	Laasonen et al. 1998
Panshet Dam, Pune, India	impounded water below dam into ditches	colonized fish, frogs, and aquatic vegetation	Middleton 1999
Groot River, South Africa	released water at irregular intervals from Beervlei Dam	induced spawning in smallscale redfin minnow	Cambray 1991

should be given to the conservation of natural hydrological patterns in rivers and wetlands.

Conflicting human demands for freshwater resources may make it impossible to restore natural flow regimes in all potential FWPAs. Nevertheless, sites with altered hydrologies may still provide considerable conservation benefits. In fact, small improvements may be sufficient to allow the persistence of some threatened species, even if total hydrological restoration is not possible (Poff et al. 1997). For example, Canning Dam in Western Australia caused dramatic flow reductions that significantly altered downstream aquatic macroinvertebrate communities (Storey et al. 1991), but a relatively small discharge from a downstream tributary (a mere 7% of the original discharge) was sufficient to allow their recovery (Storey et al. 1991). The effect of altered flow regimes and the potential for restoration are specific to each site and must be evaluated independently at all FWPAs. The most effective management strategies maximize conservation benefits from functioning ecosystem components that are already in place.

One way in which the effect of altered flow regimes may be assessed is by using the river-continuum concept, which predicts that the headwaters of rivers will be dominated by shredders, with scrapers in the middle reaches and filterers, gatherers, and predators occurring rarely throughout (Vannote et al. 1980). Work on the impounded Colorado (U.S.A.) and Duratón (Spain) rivers shows clear departures from this pattern (Camargo & Voelz 1998). We suggest that the magnitude of departure from this expected distribution indicates the magnitude of the disturbance. The river-continuum concept may therefore be used to quantify the effect of altered hydrological regimes on river ecosystems. Sites identified as relatively intact should be given high priority in the creation of FWPAs.

Introductions and Releases of Non-Native Species: Active Exclusion

The introduction of non-native species is widely recognized as one of the most serious threats to native biodiversity. The purple loosestrife wild flower (*Lythrum salicaria*) and the Eurasian zebra mussel (*Dreissena polymorpha*) are two examples of non-native introductions that have had catastrophic effects on North American ecosystems because they have outcompeted native species (Malecki et al. 1993; Ricciardi et al. 1998). The introduction of non-native aquatic plant species has sometimes had detrimental effects on the entire ecosystem. The introduction of water hyacinth (*Echhornia crassipes*), water lettuce (*Pistia stratiotes*), and hydrilla (*Hydrilla verticillata*) to fresh waters has resulted in changes in dissolved oxygen, pH, water temperature, turbidity, and composition of native plant and animal communities (Schmitz et al. 1991).

In addition to the unintentional introduction of non-native species, deliberate efforts to "improve" local faunas are common in fresh waters (Moyle & Cech 1996). Coldwater lakes and streams often contain several species of introduced trout and/or salmon for the benefit of anglers (Moyle 1986). Non-native sportfishes also have been stocked in the waters of terrestrial protected areas (McDowall 1984). Freshwater communities are particularly vulnerable to non-native species introductions because hundreds to thousands of potentially invasive species are routinely transported to other freshwater habitats outside their native ranges in, for example, ballast water, bait buckets, and live wells of boats (Lodge et al. 1998).

The effect of non-native species varies, but in many cases their establishment has been to the detriment of native species. In Britain native, mixed-fish communities are being replaced gradually by virtual monocultures of non-native sportfishes (Maitland 1985). In the western United States, native fish assemblages are commonly completely replaced by non-native fishes (Moyle 1986). A review of 31 case studies of fish introductions to streams around the world found reduction or elimination of native species in 77% of the studies (Ross 1991). In southern Africa, non-native fishes are a major threat to 58% of the region's threatened native fishes (Skelton 1990). The introduction of salmonid fishes in Sequoia and Kings national parks in California has been responsible for the decline of native frog populations (Bradford et al. 1993). Invasive fishes also have been implicated in the local extinction of stream invertebrates (Samways 1994).

The most effective manner of addressing the invasion of non-native species to fresh waters is to actively prevent introductions and their negative effects. Intentional introductions have been commonplace in fresh waters, and little effort has been devoted to reducing the risk of accidentally introducing non-native species. Where non-native species have already become established, active management needs to be focused on reducing their harmful effects and preventing further spread. In the development of all non-native species strategies for FWPAs, World Conservation Union (IUCN) guidelines for the prevention of biodiversity loss due to biological invasion (IUCN 1999) should be consulted.

Every effort must be made to prevent the invasion of non-native species to FWPAs by regulating activities associated with intentional and accidental introductions and by promoting barriers to the spread of non-native species. Introducing and stocking non-native fish populations should be prohibited in FWPAs or in connected waterbodies. The release of ballast water should be controlled, especially in FWPAs, because ballast-water discharge has been identified as the source of many accidental introductions of non-native species (IUCN 1999). Actions should also be taken to prevent the introduction

of non-native species by sportfishers and aquarium hobbyists. These can include prohibitions on the use of live fish bait and education programs regarding the threat of releasing non-native aquarium fishes, invertebrates, and plants into open waters (IUCN 1987).

Freshwater protected areas should incorporate natural barriers that permit the migration of native species but preclude the invasion of non-natives whenever possible (Moyle & Sato 1991). The maintenance of natural flow regimes provides one of the best such barriers, because native species are generally better adapted to those conditions (Moyle & Yoshiyama 1994). Sites with native mussel populations where calcium concentration, pH, or substrate type are unsuitable for zebra mussel colonization should be targeted for protection (Mellina & Rasmussen 1994). Indeed, Swan Lake, adjacent to the Illinois River (U.S.A.), has been identified as a refuge for native mussels because zebra mussels are unable to establish high densities at this site, probably because of low calcium concentrations in the water (Mellina & Rasmussen 1994; Tucker & Atwood 1995).

Where non-native species have already become established, eradication is preferable and more cost-effective than long-term control (IUCN 1999). This is particularly true for new or recent introductions. But eradication should be attempted only where it is ecologically feasible and has sufficient financial and political support to be completed (IUCN 1999). Where eradication is not feasible, control is the next-best alternative. Non-native species control programs should focus on the areas of highest value for native biodiversity and those most at risk from non-native invaders (IUCN 1999).

Efforts to remove introduced species are usually expensive and time-consuming but can yield enormous benefits to native species. After non-native rainbow trout (*Salmo gairdneri*) populations were reduced by backpack electrofishing in the streams of Great Smoky Mountains National Park, Tennessee (U.S.A.), native brook trout (*Salvelinus fontinalis*) densities increased rapidly (Moore et al. 1983). The intensive control program launched by the Great Lakes Fishery Commission to reduce non-native sea lamprey (*Petomyzoa marinus*) in the North American Great Lakes, combined with reduced fishing pressure, has allowed native lake trout (*Salvelinus namaycush*) and whitefish (*Coregonus clupeaformis*) populations to rebound (Smith & Tibbles 1980). Despite these benefits, the principal removal technique, lampricide (3-trifluoromethyl-4-nitrophenol [TFM]) application in streams used by adult sea lamprey for spawning and larval rearing, has not had entirely positive results. The use of TFM has been linked to the near extirpation of stonecat (*Noturus flavus*), a native fish species, and to increased mortality rates in aquatic worms, mayflies, caddisfly larvae, and amphibians (Dahl & McDonald 1980; Gilderhus & Johnson 1980). The costs and benefits to native communities of eradication

and control techniques must always be assessed carefully prior to their implementation.

Discussion

Freshwater protected areas have the potential to be effective conservation and management tools in the protection of freshwater organisms and habitats and the safeguarding of natural freshwater ecosystem services (i.e., ensuring potable water, recycling nutrients, providing flood control, producing exploitable plants and animals). The relative absence of research into the design and management of FWPA's, however, has been a serious obstacle to the achievement of conservation goals. Fortunately, this appears to be changing; interest in freshwater conservation has been growing in both the scientific community and among conservation organizations (i.e., Allan & Flecker 1993; Trout Unlimited 1993; Moyle & Yoshiyama 1994; McAllister et al. 1997; Richter et al. 1997a; Young 1997; Master et al. 1998; IUCN 1999; Braun et al. 2000).

The three strategies we present can be used effectively to address threats to freshwater ecosystems. Ideally, FWPA's should be located in intact catchments, should have natural hydrological regimes, and should contain no non-native species. The probability of achieving even one of these ideal conditions is often low, but the strategies we present provide a framework by which the feasibility of alternative management strategies may be investigated. Whole-catchment management, natural-flow maintenance, and active exclusion of non-native species are concepts that can be applied to the assessment of site-specific requirements. It is important to note that the threats these strategies address are themselves interconnected. For example, land-use disturbances such as agriculture may also affect natural hydrological patterns by diverting surface water for irrigation. Similarly, hydrological alterations may increase an ecosystem's susceptibility to invasion by non-native species (Moyle & Yoshiyama 1994). The potential effect of management decisions on other threats to freshwater ecosystems should always be considered carefully.

Alternatives to ideal management strategies should be used with caution, because conservation goals will be compromised when and where the degree of FWPA protection is reduced. We suggest, however, that it may sometimes be possible to focus conservation efforts on two key zones: adjacent terrestrial areas and headwaters. The land immediately bordering freshwater ecosystems is of the utmost importance because it serves as the final buffer to land-use activities and hydrological flows (Osborne & Kovacic 1993; Herron & Hairsine 1998). Along a freshwater system, the protection of headwater systems should be given high priority (Doppelt et al. 1993). Headwater streams and rivers are more vulnera-

ble to land-use disturbances because the organisms inhabiting these systems depend on terrestrial materials for their primary energy (Vannote et al. 1980). Protecting headwaters will help maintain natural flows throughout a river's length, because unaltered flow upstream will benefit downstream habitats. Finally, upstream sites are less likely to be threatened by the spread of non-native species because of their relative isolation and highly variable hydrologies (Williams 1991; Moyle & Marchetti 1999). These two basic principles—protection of surrounding land and of headwaters—may be used in combination with the other management alternatives when the ideal implementation of whole-catchment management, natural-flow maintenance, and non-native species exclusion is not possible.

In addition to the strategies we present, the design and management of FWPAs can also benefit from the concepts developed for terrestrial and marine protected areas. The notions of metapopulation theory, minimum viable population (MVP), minimum dynamic area (MDA), intermediate disturbance hypothesis, and keystone species are directly relevant to the design and management of FWPAs (Pickett & Thompson 1978; Shaffer 1981; Paine 1995; Meffe & Carroll 1997; Poiani et al. 2000). For example, population viability analysis could be used to predict the probability of freshwater species' long-term survival in habitats fragmented by dam construction and thus would support arguments for natural-flow maintenance (Meffe & Carroll 1997; Freidenburg 1998). Similarly, metapopulation theory could be used to select core protected areas within large freshwater ecosystems in the design of FWPAs.

Experiences with sustainable resource use in marine protected areas may also be applied to fresh waters. Managers may wish to permit some form of fishing or other resource extraction within FWPAs as part of recreational or subsistence use of the resource, perhaps within a multiple-use module. Because many marine reserves have been created expressly to enhance or maintain fisheries (Roberts & Polunin 1991), their successes and failures will provide important guidelines for FWPA management. Freshwater protected areas can also benefit from the experiences of the Man and the Biosphere program and the Great Barrier Reef Marine Park Authority, both of which use zoning to manage the effects of human activities within and outside park boundaries (Batisse 1990; Valentine et al. 1997).

In turn, the strategies developed for FWPAs are relevant to the management and design of terrestrial and marine protected areas. Although traditional conservation theories such as the island biogeography theory (MacArthur & Wilson 1967) have been instrumental in the creation of many protected areas, they have also perpetuated the myth that these reserves may be managed as "islands" of biodiversity. By incorporating the strategies we present here, the management of marine and terres-

trial protected areas could become more effective. For example, the principle of whole-catchment management could be applied to the adjacent coastline of marine reserves and to the "airshed" (the larger area over which air currents flow, potentially carrying air pollution) of terrestrial reserves. Similarly, the importance of natural-flow maintenance could be recognized in considering the connectivity of habitats, whether by oceanic currents in marine habitats or through terrestrial corridors linking larger protected areas on land (Poiani et al. 2000). The principle of non-native species exclusion is generally applicable: programs have been well developed for many terrestrial protected areas but have received less attention in marine reserves.

Freshwater species and habitats are undoubtedly among the most threatened in the world. Freshwater protected areas are one strategy that may be used to protect fresh waters from the threats of land-use disturbances, altered hydrologies, and non-native species introductions. The simple creation of FWPAs, however, does not guarantee the long-term survival of these vital ecosystems. Fresh waters will continue to be affected at some level by activities that occur outside protected area or buffer boundaries. This is particularly the case where less-than-ideal alternatives to whole-catchment management, natural-flow maintenance, and non-native species exclusion are implemented. Management plans should incorporate strategies that address activities both within and outside FWPA boundaries.

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