Recovery Potential Metrics
Summary Form

Indicator Name: AQUATIC BARRIERS

Type: Stressor Exposure

Rationale/Relevance to Recovery Potential: This metric is often relevant to evaluating restoration prospects for bio-impairments. Unlike “hydrologic alteration” metric, this metric refers to barriers that fragment aquatic populations of marginal size and may reduce the viability of each fragment. Barriers often also can prevent or delay recolonization of areas with diminished or absent populations. Barriers may be natural (waterfalls, major habitat changes) as well as artificial (perched culverts, buried streams, dams), and may be physico-chemical (temperature, toxicity) as well as structural. Unless species reintroduction is feasible to circumvent a problem that cannot be removed or modified, barriers are sometimes insurmountable obstacles to aquatic community recovery.

How Measured: Barrier influence is most simply scored on the basis of relative isolation from waters of similar (+ or – 1 Strahler order) size. Depending on motility of the species of interest, the height considered impassable and the barrier’s upstream or downstream location may be considered. A basic scoring scheme for barriers is:

0 – no known upstream, downstream or tributary barriers
1 – upstream or downstream barriers partially isolate the impaired water segment
2 – impaired water segment completely isolated from similar waters

Where information on the dam types is limited, the metric can be measured in terms of barriers presence/absence.

Geo-Spatial Data Source: Aquatic barriers for fish passage are documented through the US Fish and Wildlife Fish Passage Decision Support System (See: http://fpdss.fws.gov/home). Major dams have been mapped through the US Army Corps of Engineers’ National Inventory of Dams (See: http://www.usace.army.mil/Library/Maps/Pages/NationalInventoryofDams.aspx) but the large numbers of smaller dams on small to medium-scale streams and rivers are not uniformly documented. In addition, National Hydrography Dataset (NHD) contains data on dams and divergence structures (http://nhd.usgs.gov/). Some types of barrier information may be available from monitoring.

Indicator Status (check one or more)

_______ Developmental concept.
___x__ Plausible relationship to recovery.
_______ Single documentation in literature or practice.
___x__ Multiple documentation in literature or practice.
_______ Quantification.

Comments: Operational but sometimes data-limited; some forms of physico-chemical barriers may be incompletely documented, and multiple barrier types may be difficult to compare evenly. Widely applicable in all regions and waterbody types, but primarily appropriate for flowing waters. Yet, it is possible to have consistent data on structural barriers sufficient to assess this indicator. See also recolonization access measurement method, which scores similar traits from the viewpoint of ecological capacity instead of stressor exposure effects.

Supporting Literature (abbrev. citations and points made):

- (Detenbeck et al. 1992) Recovery was enhanced by the presence of refugia but was delayed by barriers to migration, especially when source populations for recolonization were relatively distant.

- (Freeman et al., 2007) A compelling example of how important it is to consider the large-scale effects of altered hydrologic connectivity concerns alterations in the biogeochemical transport and cycling of silica as a result of the cumulative effects of dams. Rivers supply over 80% of the total silicate input to oceans (Treguer et al., 1995). Silicate stimulates production of diatoms, which fuel food webs and play a critical role in CO2 uptake (Smetacek, 1998). Increasing evidence links dam construction to decreased silicate transport and alterations in coastal food web structure (Conley et al., 2000). Moreover, reduced riverine inputs of other elements such as iron, may have far-reaching effects beyond coastal ecosystems (Hutchins and Bruland, 1998). Iron availability has been linked to patterns of silicate uptake. Therefore, reductions of riverine-transported iron (as a result of hydrological alterations) might also affect silicate uptake in nutrient- rich upwelling zones far from the coasts (Ittekkot et al., 2000). Further declines in the delivery of sediments, dissolved silicate, and other elements to estuaries and coastal oceans can be expected as new dams are constructed, with consequences to coastal food webs and wildlife.

  Environmental effects of altered nutrient transport in regulated rivers have emerged within the last two decades. This and other examples (e.g., mobilization of methylmercury in reservoirs) suggest that the current extent and magnitude of hydrologic alterations and pollutant loading will result in new, perhaps unexpected, environmental problems, and raise questions of the larger scale effects of other alterations in hydrologic connectivity (Pringle, 2003c) (7-8).

- (Sondergaard and Jeppesen 2007) The construction of dams and reservoirs disturbs the natural functioning of many streams and rivers and shore-line development around lakes may reduce habitat complexity. New methods demonstrate how reservoirs may have a severe impact on the distribution and connectivity of fish populations, and new techniques illustrate the potential of using graph theory and connectivity models to illustrate the ecological implications (1089).

- (Sondergaard and Jeppesen 2007) The Worldwide, and not least in arid areas, the construction of dams and reservoirs is one of the most important stressors of rivers (Gehrke *et al*. 2002; Schilt 2007). Besides affecting the natural flow, sediment transport and the pulse and water quality of the downstream river system, it also reduces the migration of the natural fish stock, leading to a fragmented fish distribution (1091).

- (Sondergaard and Jeppesen 2007) The Here [in the central valley of California], a large water storage dam had blocked access to spawning and this has resulted in a dramatic decline in the distribution and number of fish (1091).

- (Schick and Lindley 2007) The addition of large water storage dams to rivers in California’s Central Valley blocked access to spawning habitat and has resulted in a dramatic decline in the distribution and abundance of spring-run chinook salmon *Oncorhynchus tshawytscha* (Walbaum 1792) (1116).

- (Schick and Lindley 2007) The Dams constructed in larger spatially proximate populations had a strong impact on the independence of remaining populations. Specifically, the addition of dams resulted in lost connections, weaker remaining connections and an increase in demographic isolation (1116).

- (Schick and Lindley 2007) While the role of ecological connectivity in regulating and maintaining population distribution and population persistence has been documented in both the terrestrial (Fahrig & Merriam 1985; Taylor *et al*. 1993) and aquatic realms (Wiens 2002), the direction of the connectivity can have important impacts on a given system (Gustafson & Gardner 1996) (1117).

- (Schick and Lindley 2007) The Spring-run chinook salmon occupied much of the Central Valley, although the installation and continued presence of major dams has blocked and restricted access to much of their historical habitat (Yoshiyama *et al*. 2001; Lindley *et al*. 2004) (Fig. 2). The first of 10 'keystone' dams in the Central Valley, i.e. the lowest-elevation dam that completely blocks upstream habitat, was installed in 1894. The addition of such keystone dams proceeded until 1968, removing a total of 19 populations from the ESU (1118).

- (Schick and Lindley 2007) While the impact of dams on fish populations has long been known, our examination of the sequential dam addition in the Central Valley showed clearly how a single dam can impact almost the entire ESU. This impact meant a loss of source populations to the ESU, resulting in fewer edges and increased isolation for the remaining nodes. This translates to decreased opportunity for recolonization after extinction or disturbance events (1123).

- (Schick and Lindley 2007) Connections are the mechanism by which recolonization can occur following disturbance, and they add stability and resilience to a system. It is intuitive that with more connections the removal of any one edge has less effect on the overall stability of the graph. Given the historical level of connections, then the graph as of 1968 (Fig. 5d) suffers from a lack of connections, and must be viewed as less resilient. This is echoed by the demographic isolation seen in Fig. 6, and adding connections back into the system would decrease demographic isolation and increase stability. There is a limit to this, however, in that a graph can have too many connections. While an increase in connectivity increases the likelihood of rescue (Brown & Kodric-Brown 1977), it also increases both the likelihood of pathogen spread (Hess 1996a) and spatial coupling. Hess (1996a,b) has shown that intermediate levels of connectivity provide a balance between extinction and persistence (1124).

- (Schick and Lindley 2007) Because this is a riverine setting, edge removal between two populations means typically that there are no alternate edges between that pair of populations (Fagan 2002). This means that fragmentation events lower down in the trunks of a watershed (Fagan 2002) can have dramatic effects – witness the effect of two single such events (Shasta and Oroville Dams) in our ESU, which removed a total of seven populations from the ESU (Fig. 5b,d). Clearly, the Pit River (7) had a major impact on the ESU, and were it not for the considerable complexities involved with removing major dams like Shasta *and* Keswick (just downstream of Shasta and the one depicted in Fig. 2), this would be an obvious place to highlight conservation and restoration efforts (1124).

- (Lake et al., 2007) The latter point brings in the need for stream connectivity to allow movement of the target species over the appropriate spatio-temporal scales. For example, a project in Victoria, south-east Australia, has aimed at restoring native fish populations, including western carp gudgeons (Hypseleotris klunzingeri Ogilby) and mountain galaxias (Galaxias olidus Gu¨ nther), in stream sections degraded by excessive sedimentation by sand (Bond & Lake, 2003a, 2005a,b). In the target system, differences in the life-history dynamics (in particular upstream spawning movements by galaxiids) means that while one species, the carp gudgeon, is likely to respond to localised habitat restoration (pool formation) alone, whereas another, the mountain galaxias, will require not only residential habitats to be restored, but also longitudinal connectivity between adult, spawning and larval habitats for populations to recover. These differences in habitat requirements over the life cycle of each species results in markedly different scope diagrams (Fig. 1), and hence the concept of scope encompasses, and draws attention to, the need for connectivity (598-599).

- (Lake et al., 2007) Dispersal for fully aquatic species between adjoining sub-catchments may be difficult, involving travel over considerable distances (Fagan, 2002), and thus may be limited (Hughes et al., 1996). Even for insect species with winged adults, dispersal within catchments may be very limited (Wishart & Hughes, 2003; Briers et al., 2004). Thus, the loss of connectivity (i.e. fragmentation) may be particularly severe, and recovery may be slow, even in the absence of artificial barriers to movement (600).

- (Lake et al., 2007) For many organisms the levels and patterns of connectivity between resource patches is critical and loss of connectivity by various means, human or otherwise, increases the degree of fragmentation. Greater fragmentation increases the risk of local species extinction, biodiversity loss (Fagan, 2002; Fahrig, 2003) and possibly the weakening of processes, such as the movement of nutrients. Landscape restoration often seeks to restore connectivity through the installation of corridors between isolated patches (Turner et al., 2001).

  In stream ecosystems the axes of connectivity – longitudinal, lateral and vertical – are critical to both ecosystem structure and function (Ward, 1989).The functional dependency of longitudinal connectivity (espoused in the River Continuum Concept; Vannote et al., 1980) in stream ecosystems and the breaking or reduction in the strength of barriers is key to many restoration projects. Linked with connectivity there has been a steady realisation of the overriding importance of the natural flow regime in determining patterns of connectivity and community dynamics (Poff et al., 1997), in a large part because of flows needed for lateral connectivity to floodplains (600).

- (Lake et al., 2007) Dams disrupt both longitudinal and lateral connectivity. Besides being barriers, dams with accompanying river regulation change flow regimes and by creating lentic reservoirs cause major changes in sediment, nutrient and organic matter dynamics and transport. As dams age, uses may alter and with public attitudes changing, dam removal is increasingly becoming a restoration strategy (Doyle et al., 2003). If the removal of small dams is carefully managed, it is quite possible to greatly reduce the harmful effects of nutrient and sediment release and to restore both habitat and connectivity (Hart et al., 2002; Stanley & Doyle, 2003) (600).

- (Andersen et al., 2007) Water resources development, particularly dam construction, is often cited as the most significant impact to rivers around the world (Dynesius and Nilsson 1994; Tockner and Stanford 2002). Tens of thousands of large and small dams have been built for water storage, power production, or flood abatement in the United States alone (Graf 1999). These developments have resulted in dramatic shifts in river flow regimes, sediment transport and deposition patterns, and floodplain land use (454).

- (Freeman and Marcinek 2006) For example, isolation by reservoirs (upstream and downstream) as well as close proximity to downstream urban areas and point-source discharges are likely to diminish local species assemblages, whereas connections with nearby tributary systems having intact faunal communities are likely to augment local species richness, independently of flow alteration effects. The observation that water supply variables do improve predictive models for richness of fluvial-dependent species (or probability that a site scores as impaired) implies that decisions concerning how to supply water for offstream uses will have measurable consequences for biotic integrity, even though other landscape factors may add to or modify those effects (445-446).

- (Gregory et al. 2002) Particularly in the Pacific Northwest, the adverse effects that large dams have on endangered anadromous salmon require extensive mitigation measures, such as transporting salmon around dams by barge (figure 1), and are a major factor driving dam removal proposals (713).

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- (Gregory et al. 2002) Even if natural flows are closely simulated in dam operation, the geomorphic effects of trapping sediment behind the dam and loss of connectivity for migrating organisms persist (715).

- (Gregory et al. 2002) Installation of dams has caused the decline of indigenous aquatic fauna and changes to riparian vegetation worldwide (Li et al. 1987, Pfleiger and Grace 1987, Friedman and Auble 1999,Hughes and Parmalee 1999,Aparecio et al. 2000, Jansson et al. 2000, Penczak and Kruk 2000, Sharma 2001).Dams influence changes in species diversity in several ways. The stream and riparian habitats are changed by inundation, flow alterations, and influences on groundwater and the water table (Friedman and Auble 1999, Shafroth 1999,Rood and Mahoney 2000). Because dams are barriers that limit the dispersal of organisms and propagules, migration patterns are interrupted, breaking key links in the life history of riverine and aquatic organisms (Andersson et al. 2000, Jansson et al. 2000, Morita et al. 2000) (716).

- (Gregory et al. 2002) In several ways, dams have become killing fields for native aquatic species. Each dam can be thought of as a density-independent source of mortality, a type of predator that kills through the shear forces caused by the cavitation of turbine electrical generators (Coutant and Whitney 2000). In the Columbia basin, each dam is estimated to kill 5% to 20% of all the juvenile salmonids migrating downstream (Raymond 1979, Skalski 1998) (716).

- (Gregory et al. 2002) Moreover, negotiating each dam causes elevated levels of serum cortisol as a result of stress. This suppresses the immune system and exposes fish to higher risks of disease (Maule et al. 1988). Dams create conditions that cause fishes to die from gas supersaturation, a condition similar to the bends (decompression sickness) in humans (Bouck 1980, Crunkilton and Czarnezki 1980, Penney 1987).When water spills over dams into deep water, atmospheric gases are dissolved in water under high pressure. This can lead to supersaturation of nitrogen at 110%–120% levels (Montgomery and Becker 1980,Ryan et al. 2000) (716).

- (Gregory et al. 2002) Dams are sediment traps that can keep nutrients such as silica sequestered behind dams, thereby changing community composition of phytoplankton downstream, as witnessed in the Black and Baltic Seas (Humborg et al. 2000).Retention of nutrients behind dams due to the reduced velocity and longer residence time of water in the reach changes the availability of nutrients and composition of plant and microbial communities. Sediment trapping by dams will accumulate and store toxic materials that are adsorbed physically on sediment particles or absorbed actively by the biota attached to the sediments (Dauta et al. 1999).Gravels and cobbles are sequestered behind dams, which limits their recruitment downstream and leads to habitat changes in streams and estuaries (Gosselink et al. 1974, Kondolf 1997). Dams can change the natural variation of stream temperatures, depending upon the dam's size and mode of operation. Releases of hypolimnetic water (the colder, most dense layer of water in a reservoir that is thermally stratified) from high dams can lower stream temperatures, thereby limiting the reproduction of warmwater fishes and shifting downstream communities to coldwater organisms (Clarkson and Childs 2000). Conversely, low-head dams can act as heat traps and shift community composition in the opposite direction (Walks et al. 2000) (716).

- (Gregory et al. 2002) Sediment trapping has clarified normally turbid streams in the Colorado and Missouri basins. One result has been that native fishes are now exposed to greater predation by piscivores (Pfleiger and Grace 1987, Johnson and Hines 1999, Petersen and Ward 1999). Dams in streams of the Columbia basin created migration bottlenecks for migrating salmonids, exposing them to greater contact time with native predators such as northern pikeminnow *(Ptychocheilus oregonensis)* and avian predators (Buchanan et al. 1981) (717).

- (Gregory et al. 2002) In the Colorado River, the combination of the change in seasonal patterns of river discharge, water clarity, temperature, and the introduction of exotic species—all products of regulating the river—complicates recovery of the indigenous minnows and suckers. Radiotracking studies indicate that suitable habitats for native species still exist, but dispersal becomes problematic (Irving and Modde 2000) (717).

- (Gregory et al. 2002) In the Pacific Northwest, dams on the Columbia River system have eliminated access of anadromous salmonids to an estimated 55% of the total area and 33% of the total stream miles (Lichatowich 1999) (718).

- (Gregory et al. 2002) Such cumulative effects of multiple dams on mainstem rivers are widely accepted as a major influence on the decline of anadromous salmon in the western United States (718).

- (Gregory et al. 2002) A study of historical patterns of survival of different stocks of chinook salmon in the Columbia River basin concluded that survival dropped sharply in reaches affected by dams soon after construction, but survival did not change abruptly in reaches not influenced by dam construction (Schaller et al. 1999). Removal of these dams might decrease the risk of extinction for these species (720).

- (Morita and Yamamoto 2002) Dam construction has serious consequences for aquatic ecosystems, and one of the most serious is the “barrier effect,” the prevention of organism migration throughout a system (1318).
- (Morita and Yamamoto 2002) Our findings imply that extirpation of small, dammed-off populations is inevitable unless efficient fish ladders are installed or dams are removed (1318).
- (Morita and Yamamoto 2002) Dam construction has serious consequences for aquatic ecosystems (Pringle et al. 2000). Besides environmental changes, one of the most serious impacts the “barrier effect,” which is the prevention of migration throughout each system. Dams prevent aquatic animals from reaching upstream habitats; so upstream populations become isolated. The high incidence of damming in the twentieth century has cut connections to many upstream aquatic habitats (Dynesius & Nilsson 1994). Habitat fragmentation has a harmful influence on population persistence (Wilcox & Murphy 1985). Various studies have shown that some freshwater fishes (e.g., Winston et al. 1991; Reyes-Gavilan et al. 1996; Morita & Suzuki 1999), shellfishes (Watters 1996; elner & Sietman 2000), and crustaceans (Miya & Hamano 1988; Holmquist et al. 1988) were extirpated and that species rishness decreased in dammed-off habitats, but few studies have clarified the factors responsible for population persistence (1319).
- (Morita and Yamamoto 2002) Even small (2-10 m high) erosion-control dams prevent fish from moving upstream (Morita et al. 2000) (1319).
- (Morita and Yamamoto 2002) Among the 52 dammed-off sites surveyed, white-spotted charr were present in 35 and absent in 17; charr occurred in all undammed sites (1320).
- (Morita and Yamamoto 2002) Dammed-off absent sites were suitable habitats before fragmentation (1320).
- (Morita and Yamamoto 2002) White-spotted charr often did not occur in dammed-off habitats, even though the charr occupied all undammed upstream reaches (1321).
- (Morita and Yamamoto 2002) Our findings suggest that the disappearance of small, dammed-off fish populations is inevitable. Installations of efficient fish ladders or removal of dams is necessary to restore dammed-off populations. However, artificial barriers sometimes protect populations of native fishes from encroaching on non-native fishes (Thompson & Rahel 1998; Nakamura 2001) (1322).

- (Pringle 2001) Olympic National Park (Fig. 4A; 373 km2), located in Washington, USA, provides a temperate example of how the loss of connectivity in lower watersheds has upstream effects. Threats include: existing dams and numerous proposed hydropower projects on rivers that flow out of the park; proposed offshore oil leasing; existing oil barge and tanker traffic; logging of lower watersheds; water withdrawals from streams outside of the park; and acid precipitation (NPCA 1993). Both the Elwha and Skokomish Rivers have been devoid of migratory fishes within Olympic National Park boundaries (Fig. 4A) since they were dammed. Dams block migration of several species of anadromous salmon and trout that, after maturing in the ocean, return to rivers in the park to lay their eggs or spawn. The dams modify downstream flow of nutrients, sediment, and woody debris necessary for successful spawning and rearing of juvenile fishes. Dams also inundate fish habitat and elevate downstream water temperatures (National Park Service 1995) (988).
- (Rahel 2007) Much has been written about the loss of connectivity in aquatic ecosystems because of the construction of dams and levees (Pringle, 2003). Such a loss of connectivity can prevent seasonal migrations of aquatic organisms and reduce the diversity and productivity of aquatic habitats (697).
- (Rahel 2007) Barriers to movement can involve physical obstructions such as dams or highway culverts or river reaches with poor physical or chemical habitat conditions such as low oxygen or chemical contaminants. Removing such obstructions would allow native species to recolonise areas within their historic range, which most biologists would consider beneficial (Roni et al., 2002). However, removal of barriers also may facilitate upstream expansion of non-native species, which would contribute to the homogenization of biotas (Freeman et al., 2002). In fact, construction of barriers is a common approach for protecting isolated populations of native fishes when it is impractical to eliminate non-native fishes from an entire catchment. For example, barriers are important for the conservation of native trout in North America (Novinger & Rahel, 2003) and native galaxids in Australia (Jackson et al., 2004). Barriers formed by low-head dams also prevent expansion of non-native sea lampreys into new spawning areas in tributary streams of the U.S. Great Lakes (Hunn & Youngs, 1980). In some cases, stream reaches with poor water quality can serve as barriers to expansions by nonnative species (705).
- (Ward et al., 1998) A meandering reach will exhibit different responses from a braided reach to a given impact, such as damming or diversion, and position along the longitudinal profile may greatly influence response variables (Ward and Stanford, 1995a) (275).
- (Ward et al., 1998) Anthropogenic impacts on riverine landscapes, such as damming, dredging, and channelization, disrupt natural disturbance regimes, truncate environmental gradients, and sever interactive pathways (Ward and Stanford, 19891) (276).
- (Morgan and Cushman 200) In many areas, housing developments and individual home sites are increasingly invading previously forested or farmed headwater catchments, often far upstream of urban centers. Within a catchment, headwater fish assemblages also may become isolated from downstream source populations by downstream barriers in urban channels (e.g., impoundments; Pringle et al. 2000) (643).
- (Novotny et al., 2005) Fragmentation has been recently quantitatively recognized as an important risk (Hanski et al., 1996). Fragmentation can result from any factor (biotic or abiotic) that causes decrease in the ability of species to move/migrate among subpopulations or between portions of their habitat necessary for different stages of their life (e.g., spawning migrations) and it can be both physical (e.g., biologically impassable culverts, dams, waterfalls, road crossings and bridges) and caused by pollutants (e.g., localized fish kills or a polluted mixing zone without a zone of passage or a thermal plume or stratification). Thermal plumes may create longitudinal fragmentation by creating zones that fish will avoid. Concrete lined segments (or culverts) may create supercritical flow with velocities that may be too high for fish to traverse and lack resting places. Loss of riparian vegetation reduces cover along the banks, and increases predation risk for

fish. Barriers to movement of organisms and exchange of food, such as those mentioned above are one of the most obvious sources of fragmentation. Refugia serve the purpose of providing a source for recolonization of disturbed habitats or aquatic systems affected by periodic abiotic stresses (Sedell et al., 1990). Independent abiotic population reductions caused by disturbance events (e.g., floods, droughts, toxic spills) may cause dramatic changes in communities, depending on the severity and periodicity of their occurrence relative to the intensity of resource competition and predation. Habitat linkages for dispersal are the most important type of connectivity because the resultant gene flow counteracts isolation due to fragmentation (Noss and Cooperrider, 1994). Connectivity is the opposite of fragmentation (190).

- (Novotny et al., 2005) Stream modification is an important parameter affecting the IBIs as well as water quality in general. Impounding a stream generally decreases IBI. Fig. 4 presents IBI (fish) values of modified streams in Northern Illinois affected both by pollutant discharges and by ‘‘pollution’’ due to impoundments (AquaNova/Hey Associates, 2003; Novotny et al., 2004) (191).
- (Novotny et al., 2005) The Fox River is a partially impounded water body without significant commercial navigation. Of note is the study by the US EPA on the Fox River that compared free flowing and impounded section (0.5km below and above the dams) in the same reach of the Fox River. The difference of the IBI (fish) values between the free flowing and impounded reaches was 12–15. The Green and Rock Rivers are the reference modified rivers minimally affected by pollutant discharges. The IBIs of these reference rivers are less than those for unmodified reference streams by the same margin (191).
- (Pegg et al., 2003) Altered flow has been one of the primary consequences of impoundment and channelization. Impoundments designed primarily for flood control, navigation, and water supply tend to dampen natural flow variation by storing large amounts of water for later, controlled release (Bravard and Petts, 1996). Conversely, dams built for power generation tend to accentuate natural variability by creating daily high and low flow periods to meet electrical demands (Bravard and Petts, 1996). Channelization, accomplished by armoring the shorelines, diverting water out of side channels, and straightening the channel, also influences flow by facilitating rapid transport of water downstream. Other direct consequences of channelization include loss of river connectivity to the floodplain (Ward and Stanford, 1995), changes in water quality (Whitley and Campbell, 1974), and loss of aquatic habitat (Mosley, 1983).

  Flow in many large river systems is affected by a combination of alterations, including impoundments, channelized reaches, water diversions, and numerous landscape changes in the catchment. These alterations are likely to result in complex changes to the flow regime, and the precise nature of these changes may be difficult to predict. Many factors including flow reduction in impounded reaches, increased velocities in channelized reaches, loss of diverse habitat complexes, changes in runoff and sedimentation loading rates, and altered nutrient cycles, all a result of human alteration, create an environment seldom if ever historically experienced by the native fauna in these lotic systems (Ligon et al., 1995; Ibanez et al., 1996) (63-64).
- (March et al., 2003) Large dams can significantly alter the distribution and abundance of island faunas by blocking migratory pathways (Miya and Hamano 1988,Holmquist et al. 1998,Concepçion and Nelson 1999).However, the extent of alteration depends on characteristics of both the dam and the native faunas. For example, in Puerto Rico, large dams without spillways are impermeable barriers to migratory organisms and result in complete extirpation of all native fishes and shrimps from upstream habitat (Holmquist et al. 1998) (1070).
- (Stanley and Doyle 2003) Four years later, the WCD concluded that, although dams have significantly contributed to human development and the benefits derived from dams have been considerable, the economic, social, and environmental price has been unacceptably high (WCD 2001) (15).
- (Stanley and Doyle 2003) By blocking flow, dams raise water heights, inundate surrounding terrestrial habitats, and slow the velocity of flowing water in rivers. Sediments

and debris that would normally remain suspended in the water column and continue to move downstream instead settle out and collect within reservoirs. Accumulation is often so substantial that some reservoirs shift from their original function of water storage to becoming sediment storage devices (Figure 1). The filling process greatly decreases the functional lifespan of a reservoir (Palmieri *et al*. 2001) and increases the likelihood of eventual dam failure (Evans *et al*. 2000) (16).

- (Thompson et al. 2005) Dams impede the flux of water, sediments, biota, and nutrients, and can strongly alter the structure and dynamics of upstream and downstream aquatic and riparian habitats and biota (Ward and Stanford 1979, Petts 1984, Poff et al. 1997) (192).
- (Ekness and Randhir 2007) The fragmentation of rivers by dams and other impediments impairs the distribution of vegetative species along a river's edge. A significant difference in water quality can exist along the longitudinal gradient from the headwaters to the outlet (1470).
- (Angeler and Alvarez-Cobelas 2005) The more isolated pond B is less likely to be colonized to substitute the original propagule bank. There will be a slower colonization feed back and consequently slower resilience of residents in pond B than in pond A (423).
- (Morita and Yamamoto 2002) Because charr occupied all undammed upstream reaches, the damming would cause the absence of charr upstream (1318).
- (Morita and Yamamoto 2002) We have surveyed that white-spotted charr on the Oshima Peninsula from 1996 to 2001 (Morita & Takashima 1998; Morita & Suzuki 1999; Morita et al. 2000; Morita & Yamamoto 2001), but we could not find unoccupied stream reaches except for above barriers and in apparently poor habitats, such as sulfur springs and channels paved with concrete. All undammed upstream reaches were occupied (n=32), and we used those as controls (1319).
- (Morita and Yamamoto 2002) Our study confirmed the importance of habitat connectivity for the persistence of populations, particularly for small populations (1321).
- (Morita and Yamamoto 2002) Second, the loss of habitat connectivity among populations could promote extinction. Recent evidence suggests that the population structure of some salmonids may fit the characteristics of a metapopulation (that is, a group of populations inhabiting discrete habitats connected by the migration of individuals) (Dunham & Rieman 1999; Rieman & Dunham 2000). Before damming, most dammed-off habitats are assumed to have been interconnected via the sea (1322).
- (Morita and Yamamoto 2002) According to a source-sink metapopulation model (Pulliam 1988), sink populations that have a negative growth rate would deterministically become extinct after being dammed off. Source populations with good-quality habitat would provide a continual source of immigrants to sink populations that might otherwise become extinct (cf. Cooper & Mangel 1998).
- (Morita and Yamamoto 2002) The occurrence of white-spotted charr increased with increasing watershed area, with decreasing isolation period, and with increasing gradient (1320).
- (Morita and Yamamoto 2002) Nevertheless, our results revealed that probability of occurrence decreased with decreasing watershed area (a surrogate for habitat size), with increasing isolation period, and with decreasing gradient (1321).
- (Freeman at al., 2007) Aspects of hydrologic connectivity are essential to maintaining the ecological integrity of ecosystems, where ecological integrity is defined as the undiminished ability of an ecosystem to continue its natural path of evolution, its normal transition over time, and its successional recovery from perturbations (Westra et al., 2000). Conversely, hydrologic connectivity also directs and facilitates the flow of exotic species, human-derived nutrients, and toxic wastes in the landscape (6-7).
- (Han et al., 2008) Non-native species richness was significantly higher in areas above dams (i.e., reservoirs and their inlet streams) compared to areas without dams. As a result, the proportion of native fish species was lower above dams (1).

- (March et al., 2003) Although dams with spillways allow the passage of migratory aquatic biota, shrimp and fish abundance upstream of these dams is lower than in stream reaches downstream of dams or in comparable reaches without dams (Holmquist et al. 1998, Concepçion and Nelson 1999). Dams with spillways can also extirpate native faunas from upstream reaches if the native faunas are unable to climb or to migrate past lakelike reservoirs. For example, in Guam, the native fish *Kuhlia rupestris,* which does not have modified pelvic fins, is absent from streams upstream of Fena Dam (26 m high, with a spillway; Concepçion and Nelson 1999). Similarly, native neritinid snails are absent from streams above the dam. While neritinid snails can climb near-vertical surfaces, they also require flowing water as a directional cue to orient themselves upstream, which the low-flow conditions of the lake-like reservoir remove (Concepçion and Nelson 1999).

  Dams with hydroelectric facilities can disrupt the upstream migration of faunas by altering the location of freshwater flow into the ocean. Postlarval gobies in coastal areas use the input of flowing freshwater as a directional cue to locate rivers. When hydroelectric facilities discharge river water directly into the ocean, postlarval gobies can have difficulty differentiating between river outflow and hydroelectric facility discharge. For example, in Guadeloupe, West Indies, large upstream migrations of postlarval *Sicydium* (Gobiidae) have been observed entering canals leading to a hydroelectric facility that does not have access to the stream (Fievet and Le Guennec 1998) (1070-1071).
- (March et al., 2003) Large dams and associated reservoirs may also disrupt the downstream migration of fish and shrimp larvae by reducing water flow, thereby lengthening the time water takes to reach the estuary (1071).
- (March et al., 2003) Although reservoir-induced starvation has not been documented, it is highly probable. Furthermore, reduced flows through reservoirs may also increase predation on larvae.

  Small low-head dams also interfere with the migration of tropical island faunas (Benstead et al. 1999, Fievet et al. 2001a). The effects of low-head dams on the upstream migration of faunas appear to be similar to those of large dams with spillways (1071).
- (March et al., 2003) While fishes and shrimps can surmount the low-head dam when water is flowing over it, the dam does appear to slow their migration, resulting in increased densities below the dam compared with those above it (figure 8) (1073).
- (Light and Marchetti 2007) In the analysis of variable importance, native richness was the most important single predictor of number of fishes of conservation concern in a watershed, entering every highly ranked model. The variable nonindigenous richness was next in importance, followed by the variables aqueduct density and dams (Table 3). In the analysis of category importance, the cumulative rank of all models including water development variables (0.919) was the highest, followed closely by models including nonindigenous richness (0.811) and more distantly by models including land-use variables (0.187) (441).
- (Han et al., 2008) Dams alter physical and hydrologic aspects of riverine systems affecting both quality and quantity of water flows. The majority of the largest river systems in the northern hemisphere are currently affected by fragmentation of river channels by dams (Dynesius & Nilsson 1994). Consequently, dams are considered one of the most significant obstacles in restoring the biodiversity and integrity of riverine systems (The Heinz Center 2002). A number of studies have demonstrated the negative effects of dams on native fish species. Dams can be a barrier to migration and degrade habitats because of altered flow and sediment regime (e.g., Morita & Yamamoto 2002; Wofford et al. 2005; Fukushima et al. 2007; Han et al. 2007; Isaak et al. 2007) (2).
- (March et al., 2003) However, the low-head dam did act as a bottleneck that increased the densities of upstream migrating animals below the dam. This high concentration of migrating juvenile fishes and shrimps attracted a variety of predators, such as green herons *(Butorides virescens),* adult shrimps and crabs, and mountain mullet

(Agonostomus monticola), probably resulting in increased mortality of migrating fishes and shrimps (1071).

- (Novotny et al., 2005) The models [for assessing ecological integrity] (functions) link the individual risks and consider their synergy, addictivity, or antagonism. The risks include:
    - (1) Pollutant (chemical) risks, acute and chronic, in the water column
        - Key metrics: Priority (toxic) pollutants, DO, turbidity (suspended sediment), temperature, pH.
    - (2) Pollutant risk (primarily chronic) in sediment
        - Key metrics: Priority pollutants, ammonium, DO in the interstitial layer (anoxic/anaerobic or aerobic), organic and clay content.
    - (3) Habitat degradation risk
        - Key metrics: Texture of the sediment, clay and organic contents, embeddedness, pools and riffle structure, bank stability, riparian zone quality, channelization and other stream modifications.
    - (4) Fragmentation risk
        - Key metrics:
          Longitudinal—presence of dams, drop steps, impassable culverts.
          Lateral—Lining, embankments, loss of riparian habitat (included in the habitat evaluation), reduction or elimination of refugia.
          Vertical—lack of stream-groundwater interchange, bottom scouring by barge traffic, thermal stratification/heated discharges, bottom lined channel (190).
- (March et al., 2003) The low-head dam also appears to entrain more downstream-drifting shrimp larvae. As mentioned previously, during a 69-day study the low-head dam caused direct mortality of 42% of downstream-drifting larvae (Benstead et al. 1999). Furthermore, during periods of low river flow, there was no discharge over the dam, causing 100% mortality of drifting larvae (Benstead et al. 1999) (1073).
- (Han et al., 2008) The mean native species richness (± SD) was significantly higher at grids with no dams (3.62 ± 2.63) than sites in inlet streams (2.73 ± 1.71) and lowest at sites in reservoirs (2.44 ± 0.14; Kruskal–Wallis rank sum test, v2 = 91.5, d.f. = 2, P < 0.001). In contrast, the mean non-native species richness was significantly higher at sites in reservoirs (1.20 ± 1.09) compared to sites in inlet streams (0.53 ± 0.74) and lowest at sites with no dams (0.42 ± 0.86) (Kruskal–Wallis rank sum test, v2 = 160.7, d.f. = 2, P < 0.001) (4).
- (Han et al., 2008) The dam variable however was a significant predictor for non-native species richness and proportion of native species. Sites in reservoirs had the greatest nonnative species richness followed by sites in inlet streams after the effects of all the other environmental variables were taken into account (Fig. 2t). Conversely, reservoirs were predicted to have the smallest proportion of native fish species followed by sites in inlet streams (Fig. 2u) (4-5).
- (Han et al., 2008) While elevation, a natural environmental variable was the second most important predictor for native species richness after survey year as the most significant variable, variables related to human activities, dam construction and land use patterns were more important to determine non-native species richness (7).
- (Han et al., 2008) Non-native fish species richness had a clear linkage with the presence of dams. The non-native species richness was highest in reservoirs, followed by inlet streams above reservoirs. It was lowest in reaches with no dams. This is consistent with the findings from previous studies (Holmquist et al. 1998; Pringle et al. 2000; Leprieur et al. 2006), where exotic fishes generally are introduced in reservoirs and favoured by regulated flow. The spatial linkage must be interpreted cautiously, however, because it did not apply to non-native fish species in general but was only specific to salmonids. Numerous reservoirs in Hokkaido have experienced prolific releases of rainbow and brown trout for sport fishing (Takami & Aoyama 1999; Takayama et al. 2002). The introduction of large non-native piscivores such as salmonids can lead to dramatic shifts not only in the fish assemblage structure but also the entire food-web structure as a result of the cascading nature of trophic levels (Carpenter et al. 1985). This may be especially

true for Japan where native large piscivores were originally absent (Iguchi et al. 2004) (7).

- (Han et al., 2008) Our hypothesis that the invasion of non-native fish species is spatially linked to the location of dams was partly supported. Although species richness of nonnative fishes was significantly higher above dams, the species that increase in reservoirs and inlet streams comprised only salmonids. Non-native salmonids can be a significant threat to the indigenous fish fauna of Hokkaido, especially native salmonids (Hasegawa et al. 2004). Located higher in latitude, Hokkaido has historically supported healthy populations of various native salmonids, such as Sakhalin taimen (Hucho perryi), whitespotted char (Salvelinus leucomaenis), Dolly Varden (S. malma), masu salmon (O. masou), chum salon (O. keta) and pink salmon (O. gorbuscha) (Miyadi et al. 1996). Large dams have land-locked some of the native salmonid populations in reservoirs and inlet streams (Edo et al. 2000; Tamate & Maekawa 2002), potentially intensifying the interaction between native and non-native salmonids. Competition with predation by and hybridization with the introduced non-native salmonids could increase the risk of extinction of the land-locked native salmonids. Constructing fish ladders may not provide a solution to dams because it also enables non-native fishes to escape from reservoirs and to enlarge their distribution. It is most desireable to prevent the introduction of non-native species. If this occurs, their populations can multiply at the expense of native species (7-8).
- (Bernhardt and Palmer 2007) Infrastructure thus limits site-specific options, but it also reduces connectivity between segments of river networks, with important implications for populations of stream biota dependent on upstream–downstream dispersal (746).
- (Han et al., 2008) Damming generally exerts negative effects on native fish species, especially on migratory species (Holmquist et al. 1998; Joy & Death 2001; Fukushima et al. 2007). In this study, however, native species richness was not significantly correlated with the presence of dams (7).
- (Pringle 2001) The isolation of upper watersheds within reserves can sometimes be used as an opportunity to reintroduce and/or manage endangered species (990).
- (Morita and Yamamoto 2002) Exotic fishes approach just below the dams, turning dammed-off habitats into refuges for native fishes in some rivers (e.g. Takami et al. 2002). Therefore, managers should consider this potential benefit of dams before fish ladders are installed (1322).
- (Palmer et al., 2005) Degraded running water systems (e.g. following dam construction) are typically characterized by a major reduction or alteration in variability (Baron *et al*. 2002; Pedroli *et al*. 2002). Often the limits have been so far exceeded that resilience has been lost (Suding, Gross & Housman 2004). Unless some level of resilience is restored, projects are likely to require on-going management and repair, the very antithesis of self-sustainability. Thus, we argue that, to be ecologically successful, projects must involve restoration of natural river processes (e.g. channel movement, river–floodplain exchanges, organic matter retention, biotic dispersal). Restoring resilience using hard-engineering methods should not be the first method of choice as they often constrain the channel. However, there are situations in which engineered structures may enhance resilience (e.g. grade restoration facilities that prevent further incision and promote lateral channel movement, Baird 2001; projects providing fish access to spawning reaches through culvert redesign or by establishing pathways to the floodplain, NRC 1992) (211-212).
- (Filipe et al., 2004) Once reserve areas have been selected, they must be integrated within a basin management approach to harmonize development opportunities and exploitation of aquatic resources (Meffe 2002). There is also a need for ecologists, conservationists, social scientists, and stakeholders to negotiate use rights (Cullen et al. 1999). In multinational water bodies, such as the Guadiana River basin, international collaboration is needed and all social, economic, and political constraints should be considered. Additionally, the establishment of discrete reserves is not enough to protect freshwater fishes (Angermeier 2000; Meffe 2002). Interventions upstream or

downstream must be considered in the management of reserves because these activities could have implications for the species for which the reserve is designed (Cowx & Collares-Pereira 2002). In particular, the construction of a dam outside of the reserve network has implications for the recolonization of each reserve area because it may disrupt migration pathways. Similarly, the introduction of alien species elsewhere in the watershed may have long-term implications if the introduced species is able to disperse into the reserves. In our case study, the Alqueva and Pedrogao reservoirs will create unsuitable habitats for native fishes by affecting their movement and enhancing the populations of exotic species. In addition, the lack of facilities for fish passage around Alqueva has permanently isolated the populations upstream and downstream of the dam (197).

- (Filipe et al., 2004) Human influence also constrained species distributions, in particular for *B. microcephalus, C. willkommii, B. comizo, B. microcephalus, B. steindachneri/sclateri* group, and *S. fluviatilis* all occurred in large streams, and the last species occurrences were close to the Alqueva Dam area. The first species occurred in reaches distant from the main river and away from sources of pollution (194).
- (Ekness and Randhir 2007) Lateral [riparian] and longitudinal [stream order] connectivity and flow regime are critical factors that influence watershed health. The latter can be impaired by land and water use practices that affect biotic diversity, water quality, esthetics and hydrology (Brooks et al., 1997) (1469).
- (Palmer et al., 2005) Some relatively undisturbed river ecosystems are impacted by upstream impoundments or water withdrawals. In these systems, ecologically effective restoration will move the system closer to the natural hydrograph. Ecologically ineffective restoration will focus exclusively on maintaining some minimum instream flow, but will fail to re-establish the natural flow regime. The first approach will be successful in that it may restore cues for fish spawning and riparian plant germination, high flows for nutrient regeneration and channel maintenance, and groundwater connectivity. The latter approach will maintain the river channel but without re-establishing these additional ecosystem benefits (213).
- (Stan et al., 2002) Dams are a primary cause of its severe decline. Many of these dams did not provide fish ladders, thus blocking passage to spawning areas upstream, and altered habitat conditions for pelagic eggs and shad larvae (figure 3a) (Walburg and Nichols 1967) (717).
- (Stan et al., 2002) daily hydrological regimes are modified by the dams. But these dams block fish passage and trap more than 13 million m3 of sediment, mostly behind Glines Canyon Dam (719).

- (Stan et al., 2002) Return of anadromy could also affect food webs upstream. For example, resident steelhead and Dolly Varden would lose some spawning habitats associated with reservoirs and also be subject to greater competition and predation by juveniles of other salmonid species (720).
- (Stan et al., 2002) The lake-like conditions of the reservoir reaches have created favorable conditions for almost a century for some plants and animals that will be adversely affected by dam removals. Shoreline cover along Lake Aldwell will greatly diminish and thus significant habitat for lacustrine mink will be removed (FERC 1991). Surprisingly, beaver are likely to increase with recolonization of hardwoods along riverine terraces. Wetland biomes that have developed along lake edges will disappear with their associated plants, one of them a bicolored linanthus unique to the Elwha valley (FERC 1991). Eventually other wetlands are expected to develop along stabilized backwater and meanders of the reestablished floodplains (720).
- (Stan et al., 2002) Despite dam passage improvements that have dramatically mitigated direct mortality associated with dams, the NMFS concluded that the removal of the dams would not reduce the risk of extinction under current conditions (721).
- (Stan et al., 2002) Dams in northwestern rivers influence salmonids and other species by eliminating spawning and rearing habitats in the area covered by reservoirs, changing

water velocities that influence migration rates, altering currents that are attractants for migrating fish, forcing some fish through turbines where they experience extreme pressures, increasing river temperatures as the sun warms the slower waters of the reservoir, exposing migrating juvenile fishes to fish and avian predators, and modifying flood patterns that shape river habitats and maintain spawning gravels.Removal of dams potentially restores river temperature patterns, flow patterns for migrating fish, and flood dynamics. The potential negative impacts of dam removal on salmonids are associated primarily with the instabilities of sediments and terraces stored behind the dam (716).

- (Stan et al., 2002) The short-term effects of dam removal will include the redistribution of large volumes of silt downstream (Stoker and Harbor 1991), but eventually additions of gravels will open up extensive reaches of usable spawning habitat in the middle reach (719).
- (Stan et al., 2002) Overall, removing the dams will greatly enhance anadromous fish runs and, consequently, food chains. Dramatic increases in salmon carcasses are expected to provide nutrients and food resources to juvenile fishes and other aquatic predators. Changes in hydrology and return to natural flow patterns will influence downstream temperatures and instream dynamics (720).
- (Stanley and Doyle 2003) Dam removal can result in decades of accumulated material being released downstream in a rapid and catastrophic fashion (17).
- (Stanley and Doyle 2003) Despite these apparent successes, removal of dams as a means of restoring fish species that migrate up rivers to breed has been an area of contention in dam and fisheries management (19).
- (Stanley and Doyle 2003) Mortality rates of virtually all reservoir populations, except fish, will be extremely high and can be expected to approach 100% if dewatering is rapid. For some groups of organisms, replacement of reservoir assemblages by more typical riverine taxa can occur relatively quickly after the dam is taken out. For example, fish and macroinvertebrates adapted to slow-moving water and silty sediments gave way to riverine taxa within a year of removal of two separate dams in Wisconsin (Kanehl *et al*. 1997; Stanley *et al*. 2002). Much to the delight of local anglers, changes in the fish community included declines in common carp (*Cyprinus carpio*) and increases in smallmouth bass (*Micropterus dolomieu*) and darters (*Etheostoma* and *Percina* spp). In both studies, the recovery of riverine taxa reflected both recolonization of individuals that had previously resided upstream or downstream from the dam and successful reproduction within this newly created habitat (16).
- (Stanley and Doyle 2003) One of the most widely publicized ecological aspects of dam removal is the elimination of barriers to fish migration (19).
- (Stanley and Doyle 2003) Following the removal of the Edwards Dam in Maine's Kennebeck River, striped bass, alewife, shad, Atlantic salmon, and sturgeon all traveled past the former dam site (American Rivers 2002) (19).
- (Thompson et al., 2005) Removal of small dams can be expected to restore lotic habitat within the former impoundment (Bushaw-Newton et al. 2002, Stanley et al. 2002), and may improve fish passage (Stanley and Doyle 2003), but downstream benefits are less certain. For example, removing low-head, run-of-river dams that have short hydraulic residence times and limited storage volumes may have little impact on downstream water quality, thermal dynamics, or flow regimes (Hart et al. 2002). Downstream biota, particularly benthos, will not necessarily benefit from such removals. Small dam removals may have negative effects on downstream biota. In particular, the downstream transport of sediments previously stored in impoundments has potentially serious consequences for downstream communities (Shuman 1995, Wood and Armitage 1997, Bednarek 2001, Poff and Hart 2002). Severe depletion of downstream benthos could reduce the effectiveness of dam removal as a restoration method. For example, the benefits associated with increased access by fish to upstream habitats following dam removal might be offset by corresponding reductions in food availability within downstream habitats (193).