Recovery Potential Metrics Summary Form

Indicator Name: RECOLONIZATION ACCESS

Type: Ecological Capacity

Rationale/Relevance to Recovery Potential: Loss or degradation of aquatic life, usually affecting a more sensitive subset of the resident fish or stream invertebrates, is an impairment whose recovery can be highly influenced by access and proximity to the nearest appropriate source for recolonization after conditions improve. Same or similar-sized streams within the same drainage are more likely to support similar aquatic life and act as biotic refugia and recruitment sources for recolonizing the impaired segment. Most relevant where aquatic life use support is impaired (many, perhaps most, listed waters). Impaired waters with unimpaired tributary confluences or bracketed by unimpaired upstream and downstream segments may be good prospects, as are listed waters where species of concern are reduced in number but not totally lost. In contrast, impaired waters isolated from similar systems may have poor prospects for recruitment or even be dependent on manmade reintroductions to recover fully, even if physical conditions have become suitable.

How Measured: count # of confluences with + or – 1 Strahler stream order unimpaired channels per mile of impaired segment (also counts both up and downstream of segments within longer watercourses).

Data Source: Impaired segment shapefiles are available from ATTAINS (See: http://www.epa.gov/waters/ir/) and can be measured for length. Strahler Order is available from NHD plus (See: http://www.horizon-systems.com/nhdplus/) for both impaired segments and their tributaries. Confluence count can be manual or automated. Where available, dam locations should be used to further assess and verify accessibility. Note that both the ATTAINS dataset and NHD plus are at 100K resolution missing many finer order streams. When possible, high resolution data on Strahler order should be used.

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. Potentially local to national applicability at a range of scales. Developed and used in Illinois pilot study. Has also been called confluence density, recolonization potential, recolonization source proximity. More supporting evidence should exist in invertebrate drift, fish habitat, migration and movement literature.

Use could be improved by automating the procedure for identifying impaired segment length and Strahler order of impaired segment and its confluences using NHDplus data now available. Algorithms would be useful, but instructions may suffice.

Examples from 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.

- The number of confluences of an impaired stream with unimpaired tributaries may be a useful indicator of refugia or sources for recolonization, identified by several studies as an important aide to biotic recovery (Niemi et al. 1990, Detenbeck et al. 1992).
- (Lonzarich, D.G., Warren, M.R., Jr., Lonzarich, M.R.E. 1998) We removed fish from pools in two Arkansas streams to determine recolonization rates and the effects of isolation (i.e., riffle length, riffle depth, distance to large source pools, and location), pool area, and assemblage size on recovery. The findings of this study have potentially important implications for research aimed at understanding the ecology of stream fishes and predicting the consequences of land-use activities.
- (Peterson, J.T., and Bayley, P.B 1993) The colonization of **Illinois (USA) streams** by fishes was measured during late spring and early summer in 18 experimentally depopulated reaches that ranged from 46 to 113 m in length. The results of this and previous studies indicate that in drainages dominated by surface runoff, disturbed fish communities in short stream reaches can quickly return to their original structures and abundances without any aid, provided that fish have unrestricted access to the reaches and that the environment returns to its original state.
- (Poiani 2000) “the rate of recovery of an ecosystem or species at any scale following disturbance is influenced strongly by the availability of nearby organisms or propagules and biological “legacies” for recolonization (Holling 1973). When recolonization sources are available and plentiful, recovery will be optimal. The area needed to ensure survival or recolonization has been called the minimum dynamic area (Pickett and Thompson 1978).
- (Parkyn et al 2003) Inadequate recolonization sources or pathways may limit invertebrate community rehabilitation, even when habitat is suitable.
- (Lake et al. 2007) One way by which organisms survive natural disturbances is by the use of refugia, many forms of which may have been lost with degradation. Restoring refugia may therefore be critical to survival of target populations, particularly in facilitating resilience to ongoing anthropogenic disturbance regimes (597).
- (Lake et al. 2007) A critical habitat requirement for population persistence is the availability of refugia from natural disturbances (Sedell et al., 1990; Lancaster & Hildrew, 1993), even if they are only used occasionally (599).
- (Lake et al. 2007) In many degraded situations not only have residential habitats been reduced or lost, but so have the required refugia (Bond & Lake, 2005a,b). Thus, for particular species, residential habitat requirements must be restored along with the adequate provision of suitable refugia capable of enhancing the resistance and resilience to both natural and anthropogenic disturbances (Bond & Lake, 2005a). For example, channelisation increases the severity of floods directly, but also reduces the availability of flow refugia, leading to a reduced capacity of biota to recover from floods (Negishi, Inoue & Nunokawa, 2002) (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) Species colonising a local site are drawn from the regional species pool (Cornell & Lawton, 1992). This presupposes that the regional pool contains species with appropriate dispersal capabilities and environmental tolerances to inhabit the site (Poff, 1997) and thus, some of its species enter the local pool (Belyea & Lancaster, 1999). This colonisation process from an intact regional pool, which involves dispersal and environmental filters, may apply in many situations. However, in heavily impacted systems the regional species pool may be greatly diminished, and only consist of opportunistic, highly tolerant, generalists (Fig. 2b). Thus, in many situations, such as in urban and degraded rural landscapes, restoration to an historical natural state may be impossible and restoration to any target may be unpredictable without knowledge of the species in the regional pool (603).

- (Lake et al., 2007) In restored (Gore & Milner, 1990) or newly constructed streams (Williams & Hynes, 1977; Malmqvist et al., 1991) close to a natural source of colonists, colonisation and full community development may be rapid (90–400 days; Gore & Milner, 1990) (604).
- (Lake et al., 2007) As an example, if a functioning metapopulation can be established by facilitating dispersal amongst restored habitat patches distributed across the catchment, long-term population persistence at the landscape scale may occur even though much of the landscape remains degraded (608).
- (Sondergaard and Jepessen 2007) Human-induced fragmentation of the landscape and loss of rivers and lakes are among the factors reducing the number of natural corridors and the possibilities of (re)-colonization of plant and animal species with poor dispersal capacities (Hughes 2007). Therefore, establishing connectivity – both laterally and longitudinally– is an important element in freshwater management: it ensures migration and dispersal of organisms and, as a delay in recovery may be due to lack of colonization (Jansson, Nilsson & Malmqvist 2007), also reinforces the recovery process. A negative effect of establishing connectivity and improving the dispersal of organisms is the potential introduction of invasive species, which may have highly negative consequences for the natural flora and fauna (Sakai *et al*. 2001) (1090-1091).
- (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) In many cases, species conservation problems can be framed in terms of problems with spatial structure, because impacts to species often take the form of lost habitat patches or dispersal corridors (1117).
- (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).

- (Ward 1998) Anthropogenic impacts such as flow regulation, channelization, and bank stabilization, by (1) disrupting natural disturbance regimes, (2) truncating environmental gradients, and (3) severing interactive pathways, eliminate upstream-downstream linkages and isolate river channels from riparian/floodplain systems and contiguous groundwater aquifers. These alterations interfere with successional trajectories, habitat diversification, migratory pathways and other processes, thereby reducing biodiversity (269).
- (Ward et al., 1998) Anthropogenic regulation of river flow reduces or eliminates the natural disturbance regime, leading to a simplification of the floodplain vegetation as pioneer stages are eliminated and successional processes are truncated (Fig. 7; Dfcamps and Tabacchi, 1994) (275).

- (Ward et al., 1998) Anthropogenic activities such as flow regulation tend to isolate the river from its flood plain, partly by suppressing the temporal dynamics of flooding that are necessary to maintain a diversity of water bodies, each encompassing a range of successional stages. This lost connectivity arrests the formation of new floodplain water bodies and accelerates terrestrialization of extant water bodies (Fig. 7). The implications for biodiversity are exemplified by the following comparison of two Danube floodplains (Loffler, 1990), one isolated from the river channel, the other with connectivity largely intact: 20 species vs 60 species of macrophytes, respectively, in disconnected and connected floodplains; 16 species vs 35 species of molluscs; and 4 species vs 30 species of fishes (275).

- (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).

- (Poiani et al., 2000) Regardless of whether a shifting mosaic or metapopulation model is most appropriate, the rate of recovery of an ecosystem or species at any scale following disturbance is influenced strongly by the availability of nearby organisms or propagules and biological “legacies” (e.g., seed banks, underground biomass) for recolonization (Holling 1973). When recolonization sources are available and plentiful, recovery will be optimal. The area needed to ensure survival or recolonization has been called the minimum dynamic area (Pickett and Thompson 1978). For certain small-patch ecosystems and species, this concept may be better described as “minimum dynamic number.”

  Minimum dynamic area has already become and important consideration in the design of conservation areas and should be a primary factor in assessing function sites, landscapes, and networks. For example, Shugart and West (1981) suggested that, as a rule of thumb for forested ecosystems, the minimum dynamic area is typically 50 times the mean disturbance patch size. Baker (1992) emphasized that reserves should be large relative to maximum disturbance sizes, thus minimizing their vulnerability to catastrophic loss of organisms, reducing the chance of disturbance spreading to adjacent developed lands, and minimizing the influence of adjacent lands on the size and spread of disturbance at the margins. In addition, Peters et al. (1997) suggested that a minimum dynamic area must be large where disturbance events are either large or common. They recommended that managers use simulation models to analyze system response to natural disturbances and to determine the minimal area needed to absorb the largest disturbance event expected within a 500-1000-year period (139).
- (Poiani et al., 2000) The minimum dynamic area for the Yampa River riparian ecosystem must maintain recolonization sources for each internal patch type and provide room for the geomorphic processes that reshape the floodplain and create and destroy the complete array of patch types (143).
- (Poiani et al., 2000) Not only is riparian vegetation more vulnerable to widespread destruction by floods, but future sources of propagules for post-disturbance recovery may also be severely reduced as a result of a narrowed and fragmented riparian corridor (143).
- (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).

- (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).
- (Angeler and Alvarez-Cobelas 2005) Nevertheless several landscape features (e.g. hydrologic, habitat connectivity or the degree of ''geographic isolation'') importantly regulate ecological processes in temporary wetlands (see the special issue of Wetlands 23(3), 2003). They may play a key role in the strength of impact of and recovery from contamination (420).
- (Angeler and Alvarez-Cobelas 2005) Landscape ecology provides a complementary view, emphasizing the structure of the surrounding upland on species diversity of habitat islands (Harris, 1984). It adds several features to how populations interact with spatial patterns such as the isolation-continuum. Those features are (Turner et al., 2001): (1) the variation in patch quality (i.e. the ecosystem health of temporary wetlands); (2) the variation in the quality of the surrounding environment (e.g. upland use and degradation processes); (3) boundary effects (e.g. the changing transport of pollutants across boundaries depending upon the type of boundary); and (4) how the landscape influences connectivity among patches (i.e. the connectivity of temporary wetlands). These characteristics importantly mediate colonization and extinction events and can be crucial in the outcome of species responses to human stressors in temporary wetlands (421-422).
- (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).
- (Poole and Downing 2004) Increased mortality, decreased potential for recolonization, or increased fragmentation of the metapopulation will likely accelerate widespread species losses (122).
- (Poole and Downing 2004) Successful protection or restoration of mussels in regions that have undergone major alterations in land use over the past century must address the factors degrading stream conditions for the biota and the factors impeding recolonization. Restoration and long-term protection of mussel biodiversity should therefore address the restoration of riparian zones and the increased protection of streams from agricultural influences (124).
- (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).
- (Ekness and Randhir 2007) The flow of water in a stream adds connectivity between reaches in a watershed acts as a vehicle for seed dispersal, and helps to maintain species diversity in a watershed (1470).
- (Ekness and Randhir 2007) Connectivity of the river-continuum allows for the colonization of sandbars, point bars, and disturbed sites by native vegetation. The riparian corridor also acts as a longitudinal vegetative connection between habitats and larger vegetative areas along waterways (Fischer et al., 2000). Jansson et al. (2000) found that a regulated river has lower plant species richness and cover than free-flowing rivers (1470).
- (Ekness and Randhir 2007) The longitudinal component of the riverine-riparian system acts as a vehicle for the sometimes rapid movement of materials downstream and fauna upstream into the headwaters. The dynamic transport and storage of key elements in the

sediments along riverways provides a mechanism for these plant and animal movements within a watershed (1470).

- (Grau et al., 2003) Second, the unique socioeconomic history of Puerto Rico has generated a human-dominated landscape characterized by small farms interspersed with forest fragments, which facilitates the availability of seed and tree establishment and creates conditions unfavorable for fire spread. In large areas of the continental Neotropics, land-use patterns are very different. These areas are usually dominated by large properties with extensive cattle ranching managed with fire, which generates degraded soils and very long distances to seed sources (e.g., Cavelier et al.1998, Nepstad et al. 2001).Under these conditions, forest recovery is expected to be much slower than in Puerto Rico (1166).
- (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).
- (Russell et al., 1997) The proximity criterion reflects the ecological importance of connectivity and patch size for species habitat requirements (Meffe & Carroll 1994). We believe that a maximum benefit from restoration efforts may be gained by restoring areas near existing sites. These benefits may be in the form of reduced habitat fragmentation, as well as enhanced species recruitment into the restored site. All eligible pixels within 90 m (3 pixels) of either water or an existing riparian area were given high-priority restoration status. The 90-m proximity boundary was largely arbitrary in nature, but it is consistent with the findings of Keller et al. (1993), who identified a 100-m corridor width as a minimum for many avian species dependent on riparian habitat in the eastern United States (64-65).
- (Morgan and Cushman 2005) Loss of fish refugia needed to maintain biodiversity within streams in urbanizing catchments is an environmental concern within Maryland (Richter et al. 1997). Maintenance of source populations and dispersal should be key considerations in urban planning efforts (Lowe 2002). Connectivity within catchments is being destroyed by urbanization, along with daily destruction of small perennial and intermittent streams (CWP 2003) (653).
- (Filipe et al., 2004) All watercourses that link the selected catchments must be considered to act as corridors and ensure continuation of the regional ecological processes necessary for maintaining freshwater fish diversity (193).
- (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).

- (Ricketts 2001) Terrestrial habitat patches, however, are often surrounded by a complex mosaic of other land cover types, which may differ in their resistance to the movement of individuals among the patches. Therefore, patches may be more or less effectively isolated than simple distance would indicate, depending on the type of intervening matrix (87).
- (Ricketts 2001) Several authors have discussed the idea that the "connectivity" of a landscape depends not only on the distance between habitat patches but also on the presence of movement corridors or stepping stones of natural habitat between fragments and the resistance of the matrix to interpatch movement by individuals (e.g., Taylor et al. 1993; Fahrig and Merriam 1994; Rosenberg et al. 1997) (87).
- (Ricketts 2001) The results presented here indicate that the type of intervening matrix can significantly influence the effective isolation of habitat patches (95).
- (Ricketts 2001) For example, comparatively resistant matrix types should result in decreased species richness in isolated patches (Lomolino 1994; Aberg et al. 1995), lower patch occupancy within a metapopulation (Moilanen and Hanski 1998), and lower levels of gene flow among isolated populations (Westerbergh and Saura 1994) (96-97).
- (Ricketts 2001) One of the central concerns regarding fragmented landscapes is the genetic and demographic risk of isolation (Meffe and Carroll 1994; Sutcliffe and Thomas 1996; Rosenberg et al. 1997; but see Simberloff et al. 1992). In efforts to increase the connectivity of fragmented landscapes (Taylor et al. 1993), conservation biologists have focused on the distribution of remnant fragments and the presence of stepping stones and corridors of natural or seminatural habitat (Doak et al. 1992; Sutcliffe and Thomas 1996; Schultz 1998; Haddad 1999*a*). It often may be more feasible, however, to reduce the effective isolation of fragments by altering management practices in the surrounding matrix than to reconnect them with restored corridors (Simberloff et al. 1992; Mann and Plummer 1995; Bowne et al. 1999) (97).
- (Ricketts 2001) Nevertheless, in these systems, the patches and matrix also differ markedly in thermal characteristics, and these factors will likely be important to butterflies in human-fragmented landscapes as well (Daily and Ehrlich 1996). In general, the resistance of a given matrix type will depend on the interaction between autecological traits of species and characteristics of the matrix (Dennis and Shreeve 1997; Henein et al. 1998; Gascon et al. 1999). Matrix resistance therefore may be expected to vary among differing species (e.g., homothermic vs. poikilothermic animals) (97).