A Method for Comparative Analysis of Recovery Potential in Impaired Waters Restoration Planning

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Abstract Common decision support tools and a growing body of knowledge about ecological recovery can help inform and guide large state and federal restoration programs affecting thousands of impaired waters. Under the federal Clean Water Act (CWA), waters not meeting state Water Quality Standards due to impairment by pollutants are placed on the CWA Section 303(d) list, scheduled for Total Maximum Daily Load (TMDL) development, and ultimately restored. Tens of thousands of 303(d)-listed waters, many with completed TMDLs, represent a restoration workload of many years. State TMDL scheduling and implementation decisions influence the choice of waters and the sequence of restoration. Strategies that compare these waters' recovery potential could optimize the gain of ecological resources by restoring promising sites earlier. We explored ways for states to use recovery potential in restoration priority setting with landscape analysis methods, geographic data, and impaired waters monitoring data. From the literature and practice we identified measurable, recovery-relevant ecological, stressor, and social context metrics and developed a restorability screening approach adaptable to widely different environments and program goals. In this paper we describe the indicators, the methodology, and three statewide, recovery-based targeting and prioritization projects. We also call for refining the scientific basis for estimating recovery potential.

Keywords Clean Water Act · Indicators · Recovery · Resilience · Restorability · Restoration · Stressors · Total Maximum Daily Load

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Introduction: Impaired Waters Restoration Under the Clean Water Act

In 1990, a special issue of *Environmental Management* (1990) on lotic systems recovery identified the importance of recovery science as a foundation for restoration practice. While acknowledging the uncertainties of prediction (Cairns 1990), the issue's governmental and academic authors displayed optimism about developing the theoretical basis and technical tools to apply recovery concepts in restoration programs. Despite progress, common geospatial data, tools, and scientific knowledge about aquatic ecosystem recovery are still not used systematically in guiding large state and federal restoration programs affecting thousands of impaired waters. Case-by-case decisions and 'worst-first' approaches without systematic use of recovery information can have several undesirable outcomes: (1) more restorable waters may be overlooked, resulting in a lost opportunity for easier environmental gains; (2) already-limited resources can be depleted by relatively few, severely impaired systems that may never recover, making it hard to demonstrate program success; (3) priority-setting without a transparent and consistent basis may be vulnerable to political or legal pressure; and (4) the tools and scientific knowledge of recovery are not being fully utilized in restoration decisions meant to bring about recovery.

The primary goal of the federal Clean Water Act (CWA) is "to restore and maintain the chemical, physical and biological integrity of U.S. waters" (FWPCA 1972). Through the CWA and similar programs, aquatic restoration has become one of the most broadly implemented environmental activities in recent decades, with annual investments exceeding $1 billion (Bernhardt and others 2005), and many years of continuing effort lie ahead. Priority decisions loom large without the resources to restore every impaired water concurrently. The sequence in which waters are restored may significantly influence the types of goods and services sustained, overall restoration success rates, and net gain or loss of ecological resources and human benefits at greater scales of space and time.

Sections 305(b) and 303(d) can be viewed as the "engine" of the CWA impaired waters identification and restoration process. Under Section 305(b), states[1] assess the condition of their waters biennially and place pollutant-impaired waters that do not meet Water Quality Standards on the Section 303(d) list. To guide restoration actions, states then develop Total Maximum Daily Loads (TMDLs) that quantify necessary pollutant loading reductions for each 303(d)-listed water body. States are required to develop schedules that prioritize the order of impaired waters for TMDL development (USEPA 2005). Implementation of completed TMDLs also involves prioritizing among numerous waters.

Currently more than 41,000 waters are 303(d)-listed nationwide (USEPA 2009a) and await the development of TMDLs or other restoration plans. More than 39,000 TMDLs already exist, and many of these still await implementation. De facto priority-setting is inevitable, yet little information exists on how to set priorities that optimize restoration results. The U.S. Environmental Protection Agency (USEPA) does not require specific prioritization methods, and the Agency does not have approval authority over state-prioritized schedules. Early TMDL program guidance listed water-body benefits and public support as considerations for priority-setting, but mainly emphasized degree of impairment or risk (USEPA 1991). The 2006 listing guidance advised only that states should "consider the severity of the impairment" when developing TMDL schedules (USEPA 2005). A 2005 analysis of impaired waters priority-setting in 7 of 10 USEPA regions revealed that prioritization is typically done by states on a case-by-case, often 'worst-first' basis, without consideration of all impaired waters systematically (Norton 2005, unpublished). Performance tracking has recently increased the interest in tools for restoration targeting.

Systematic and case-by-case approaches each have merits and weaknesses in screening large numbers of waters for restoration. The merits of a case-by-case approach are that unique circumstances of a given water body can be considered, but the complexity of setting priorities among thousands of waters can undermine expert judgment unless aided by some uniformity of information and decision criteria. The decision sciences have long claimed that the human mind can simultaneously weigh a very limited number of factors in coming to a complex decision (Miller 1956; Lindblom 1959), further complicated by the number of entities (i.e., waters) about which those factors are being considered. Where consistent data are available, systematic approaches aid complex but even-handed comparisons. The flexibility needed to apply expert judgment exists in systematic approaches with the freedom to select and weight the comparison metrics. The common weakness in complex evaluations is the difficulty of capturing every significant consideration or expert insight in a systematic formula. A hybrid approach that merges expert judgment with a systematic screening process may remedy this weakness.

We see a need to supplement, not replace, the use of expert judgment in setting restoration priorities. Water program managers bring substantial experience and insights to restoration planning and are focused appropriately on recovery as the primary goal. Nevertheless, comparative screening methods and consistent data can better support their decisions. In this paper, our purposes are fourfold: (1) to describe a practical working concept of recovery potential drawn from the restoration literature and practice; (2) to identify spatial indicators used to compare relative recovery potential; (3) to demonstrate how comparative assessment of recovery potential can help prioritize restoration efforts among large numbers of waters; and

[1] 'States' is used throughout this paper as shorthand for "states, territories, and authorized tribes."

(4) to call for enhancing the scientific basis and tools for estimating recovery potential.

Methods

Recovery is a complex and varied ecological concept. We developed the following working definition of recovery potential to operate within the scope of CWA programs:

> the likelihood of an impaired water to reattain Water Quality Standards or other valued attributes, given its ecological capacity to regain lost functionality, its exposure to stressors, and the social context affecting efforts to improve its condition.

This working definition is supported by an extensive literature review of traits that appear to influence the likelihood of recovery. Traits fell into three broad classes of candidate indicators: (1) ecological, (2) stressor, and (3) social context. Recovery-relevant traits also sorted out as properties of the site and of the restoration technique. We found it crucial to differentiate between these, as success or failure might be due to either site/setting characteristics (recovery potential) or proper application of the restoration technique (management potential); effective techniques can fail at unsuitable sites. Further, it is sequentially efficient to assess recovery potential before management potential (see Fig. 1). We packaged review outputs as state assistance tools, including a 1600-citation Restoration and Recovery Literature Database (USEPA 2009b) and wiki-style information reference files by specific indicator.

We chose to focus on recovery potential in our methods, as it appeared to be scientifically supported but underutilized in practical application. Our working concept is consistent with theories of ecological dynamics including resilience, resistance, stability, inertia, and assimilative capacity. As offered by Westman (1978), Pimm (1984), and Cairns (1999), these concepts reflect the idea that ecological systems are homeostatic and will tend to recover once a disturbance has run its course. In contrast, nonequilibrium dynamics as described by Holling (1973) defined resilience in more complex terms as an envelope of possible ecosystem states with many potential equilibria (O'Neill 1999).

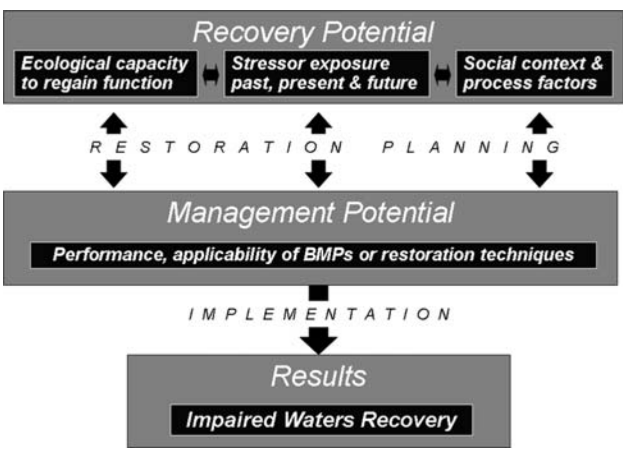

Fig. 1 A strategic approach for sequencing recovery potential and management potential in restoration planning and implementation

Evidence supporting both homeostatic recovery and nonequilibrium dynamics has been reported in the literature. Niemi and others (1990) reviewed 150 case studies of aquatic system recovery (primarily lotic) across the United States and Canada. Disturbances included chemical application, flooding, drought, and habitat alteration, with measurement of recovery based on benthic, floral, and faunal endpoints. They found that most systems showed some recovery, generally within 3 years. The main reasons for rapid recovery were disturbance-adapted life history traits, refugia, and the dynamic nature of lotic systems (Yount and Niemi 1990). A similar meta-analysis by Detenbeck and others (1992) reported relatively rapid fish recovery enhanced by the presence of refugia but hindered by migration barriers. Storey and Cowley (1997) found that after streams had passed through 600 m of native forest, benthic communities and abiotic endpoints such as temperature showed improvement. Others have found that return to pre-existing conditions was more elusive (see Bond and Lake 2003). Keller and others (1999) did not find equivalent recovery in all lakes studied following release from atmospheric sulfate deposition. Also, the meta-analyses by Niemi and others (1990) and Detenbeck and others (1992) cited individual cases where recovery was not apparent.

Contemporary ecological restoration practice had an initially homeostatic focus (Bradshaw 1993) and viewed restoration as a means to bring ecosystems back to a pre-existing condition. Nonequilibrium dynamics now plays an increasingly important role in defining restoration goals (Davis and Slobodkin 2004). More broadly, others (e.g., Lackey 2001) have concluded that restoration may be appropriately viewed as a complex activity that should address sociological, economic, and ecological factors. We also see ecological capacity, stressor exposure, and social context as general but complex classes of restoration driving factors, within which numerous recovery potential metrics might be found.

Data Requirements for Estimating Recovery Potential

Developing 303(d) list schedules and TMDL implementation strategies is time-consuming. Tools to address recovery potential in these programs should function at a screening level, use common and consistent data, and be adaptable to variation in impairments and program goals from state to state. Given these requirements, we developed recovery potential metrics based in the literature that could be measured on geographic data sets or, in the case of field monitoring data, georeferenced. We generally limited our data sources to widely used GIS data sets and georeferenced data on 303(d)-listed waters from USEPA databases (Dewald 2006; USEPA 2006, 2009c). Fine-scale catchments based on every mapped reach in the National Hydrography Dataset (NHD) were available for expedited 303(d) watershed delineation (Dewald 2006; USEPA 2009d).

Landscape indicators and CWA monitoring data do not encompass every factor that may influence recovery potential, but a wide variety of relevant factors is detectable in relatively few geospatial or georeferenced data sets; our first study found more than 100 metrics measurable from 10 common data sources. Table 1 provides selected examples of the broad array of metrics available. Below, we discuss the relevance of these metrics to recovery potential in the context of the three indicator classes and name several other metrics in each class that merit additional development.

Ecological Capacity Metrics

A central tenet of ecosystem resilience and recovery potential is the ability to re-establish or maintain primary structural and functional components. We found a variety of measurable, physical structure metrics at the channel, corridor, and watershed scales, as well as biotic community metrics that are plausibly linked with the likelihood or rate of recovery of impaired aquatic ecosystems. Radwell and Kwak (2005) found that watershed physical characteristics were more influential in their efforts to rank rivers' integrity than biotic attributes. Among the physical attributes, *natural channel form* (e.g., impaired reach length without channelization) is a key component of lotic physical structure with implications for habitat potential, sediment dynamics, and stability. Ecological memory in the form of this structural template is a prerequisite to recovery following disturbance (Bengtsson and others 2003; Lundberg and Moberg 2003). *Bank stability* is enhanced by erosion-resistant soil types as well as by the presence of rooting systems of woody vegetation near the land/water interface; both attributes can be generalized from mapped data. Soils that are unstable are prone to continual erosion and greater likelihood of excess sediment load, both of which are often linked to instream habitat degradation and diminished spawning success of lithophilic spawners (Novotny and others 2005) and contribute to impairments such as elevated water temperature or nutrients (Ducros and Joyce 2003; Norton and Fisher 2000).

The *proportion of forest cover* in the watershed (for naturally forested regions) or the riparian corridor is associated with numerous properties affecting recovery. Watersheds with less forest cover are at higher risk for degraded water quality and stream habitat conditions, and forest cover can serve as a predictor of biotic integrity (Wang 2001; Potter and others 2004). High forest cover has also been associated with healthier fish communities, less eutrophication, and lower levels of chloride and lead (Gergel and others 2002; Detenbeck and others 1992), reduced nitrogen (Fennessy and Cronk 1997; Norton and Fisher 2000; Wickham and others 2005, 2008), and positive influences on infiltration and erosion control (Grau and others 2003; Peterjohn and Correll 1984). Although these findings primarily relate forest cover to current condition, there are also implications for recovery. *Watershed size* is a physical metric with mixed effects on the rate and complexity of recovery. It is widely assumed that smaller systems generally recover along more rapid time lines than very large systems, and nonpoint source control practices are most frequently designed, implemented, and put into practice at smaller scales. Schlosser (1990) pointed out that the life history traits of fish in headwater streams are more suited to recovery from disturbance. Fish in headwater streams tend to have shorter life spans, earlier sexual maturity, and smaller body size. Smaller streams (i.e., within smaller watersheds) also may be more likely to recover from nutrient overenrichment than larger streams. The ability of streams to remove nutrients decreases with increasing discharge, and high-order streams may actually conserve nutrients (Smith and others 1997; Alexander and others 2000; Peterson and others 2001).

Several ecological metrics focus on interaction of biotic and abiotic components. For example, *recolonization access* tracks an impaired water's confluences with unimpaired tributaries. This metric may be a useful indicator of refugia or sources for recolonization, identified by several studies as an important aide to biotic recovery (Niemi and others 1990; Wallace 1990; Detenbeck and others 1992). The rate of recovery following disturbance is influenced strongly by the availability of nearby organisms and biological legacies for recolonization (Holling 1973). Recovery is enhanced when recolonization sources are available (Poiani and others 2000). Inadequate recolonization sources or pathways may limit invertebrate community rehabilitation, even when habitat is suitable (Parkyn and others 2003). As habitat connections are the pathway by which recolonization can occur and stability and resilience are rebuilt (Schick and Lindley 2007), an impaired water's *proximity to green infrastructure* further enhances its recovery potential. Green infrastructure "hubs and corridors" increase connectivity among suitable habitats and habitat extent, afford migration and movement to avoid

Table 1 Example metrics of recovery potential measurable in the water body, watershed, riparian corridor, or streambank

Metric	How measured	Data
Ecological capacity		
Natural channel form	Unchannelized length divided by total length	NHD
Bank stability	Percentage of channel passing through erosion-resistant soils and/or woody land cover. From SSURGO soils and other sources	303(d) NLCD
Percentage forest	Percentage forest by area in watershed or riparian corridor	NLCD
Watershed size	Area of watershed	NHD+
Recolonization access	Number of unimpaired waters of +1 or −1 Strahler Order per river mile that intersect a 303(d)-listed water	303(d) NHD
Contiguity with green infrastructure (GI)	Contiguity with, or distance from, GI corridor or hub. From existing state GI mapping sources or from NLCD	NLCD, STATE
Biotic integrity	When available, generally fish or benthic IBI. Monitoring data from state sources	STATE
Rare taxa presence	Number of taxonomic groups with vulnerable aquatic species as defined by Natural Heritage Programs (NatureServe 2008)	STATE, other
Stressor exposure		
Percentage urban	Percentage urban land cover by area in the watershed or riparian corridor	NLCD
Percentage agriculture	Percentage agricultural land cover by area in the watershed or riparian corridor	NLCD
Corridor road density	Road length per riparian corridor unit area. From ESRI transportation dataset	Other
Percentage impervious cover	Percentage of watershed in impervious cover. Derived national dataset from NLCD 2001; also sometimes available as state data	NLCD
Percentage legacy land uses	Percentage agriculture or urban at an earlier point in time. From ca. 1970 LUDA historical land cover data (Fegeas and others 1983)	Other
Hydrologic alteration	Flow regime alteration from dams or withdrawals. From National Inventory of Dams (NID) and state records on water withdrawals	STATE, other
Invasive species risk	Existing or impending invasions and their feasibility of control or remediation. From http://nas.er.usgs.gov/links/generallinks.asp	Other
Impairment complexity	Number of impairments (pollutants) causing 303(d) listing	303(d)
Impairment severity	Based on specific 303(d) listing causes and/or necessary load reduction magnitude, where known	303(d)
Social context		
Watershed organizational leadership	Groups involved in aquatic restoration that are active in the watershed. From EPA's ADOPT database	Other
Funding eligibility	Sum of eligibility for National Resource Conservation Service (NRCS) and other programs. Interpreted from land use patterns	NLCD
Watershed-based management potential	Co-occurrence with other listed waters at a given watershed, or whether part of a watershed-scale multiple TMDL	303(d)
Percentage protected lands	Percentage of protected land, from GAP stewardship database	Other
Jurisdictional complexity	Number of local to state-scale jurisdictions potentially involved in restoration. From city/county shapefiles in USEPA BASINS data	STATE, other
Landownership complexity	Number of riparian corridor landowners per river mile. Commonly available from county/state property ownership data	STATE
TMDL or other plan existence	Whether a TMDL or 319 watershed plan has been approved or established for the 303(d) water	WATERS
Certainty of causal linkages	Whether pollutants/stressors causing impairment and their sources are known. From 303(d) data reported by states.	303(d)
University proximity	Proximity of colleges with technical expertise, grant eligibility, and student labor. From http://www.univsource.com/region.htm	Other
Residential value	Value of owner-occupied residential units in watershed. From Census data	Other
Human health and safety	Relationship to defined health/safety risks, e.g., abandoned minelands, hazards, fish advisories. From state program data	STATE
Recreational resource	Presence or absence of state or federal conservation areas, forests, parks, and fish and wildlife areas. State public lands datasets	STATE
Iconic significance	Broad community awareness of the water body or a specific, valued ecological attribute	Other

Main spatial data sources included the National Land Cover Dataset (NLCD) (Homer and others 2007), the National Hydrography Dataset (NHD) (USGS 2008), NHD+ Value-Added Attributes (USEPA 2006), National Elevation Data (NED) (Gesch and others 2002), Census, USEPA 303(d) listing and TMDL tracking [303(d)], state data (STATE), and other USEPA databases (WATERS), unless otherwise noted temporary stressors, and subsequently may support more diverse and resilient ecological communities (Benedict and McMahon 2006). Several states have mapped green infrastructure hubs and corridors as statewide or regional-scale GIS datasets (e.g., Weber 2004; Weber and others 2006; Durbrow and others 2001).

The condition of the aquatic community also helps prediction of recovery potential. Unlike the abiotic metrics expressed in mapped sources, these traits are dependent on monitoring data that are usually not comprehensive across all waters. Fish or benthic invertebrate *biotic integrity* (Karr 1991) is sometimes a component of statewide biomonitoring programs that provide input for impaired waters assessments. Current biotic condition information, when available, can help predict effects on biological integrity in stream systems (Freeman and Marcinek 2006). *Rare taxa presence* is often associated with more diverse and functionally intact ecosystems, including aquatic ecosystems. Due to national and state natural heritage programs (NatureServe 2008), georeferenced rare species data are more consistently available than assessments of biotic integrity. Rare taxa are often more sensitive to stressors, and their presence may imply that an impairment is less severe. Increased eligibility and options for protection or restoration, elevated public and scientific concern and motivation to act, and other social factors influencing recovery prospects are also associated with rare taxa (Wall and others 2004; Palik and others 2000). The added value of both metrics in recovery-oriented screening is that they are both associated with differences in ecosystem quality, above and beyond condition. Other ecological metrics that appeared to be potentially measurable and relevant to recovery included *trophic state, historical species occurrence, channel slope,* and *watershed percentage wetlands.*

Stressor Exposure Metrics

Stressor exposure metrics characterize the importance of watershed and water-body modifications in the form of land use and flow alteration, species change, and the number and complexity of impairments. The *percentage of urban and agricultural use* is intuitive for evaluation of recovery potential because of the number of research publications that show declining biotic and abiotic condition of water bodies with increasing amounts of these land uses (Frink 1991; Brabec and others 2002; Paul and Meyer 2001; Diamond and Serveiss 2001). Riparian corridor *road density* is strongly correlated with urban percentage and its effects in urban areas but also impacts erosion, sediment delivery, and conductivity in nonurban settings (Trombulak and Frissell 2000; Forman and Alexander 1998). Brabec and others (2002), synthesizing other studies, report declines in aquatic biota of about 8% (total) *impervious cover*. The impacts of urbanization and impervious cover on aquatic biota are compounded by hydrological changes including loss of infiltration (watershed storage) and increased flashiness and runoff (Paul and Meyer 2001). Excess sediment, nutrients, pathogens, pesticides, and salts from agriculture occur nationally (USEPA 2002), and stream biotic integrity may decline as watershed percentage agriculture rises (Roth and others 1996; Fitzpatrick and others 2001). The impact of agriculture and urban land on water quality can also have *legacy land use effects* (Harding and others 1998), suggesting that a homeostatic response to removal of stressors may not occur (Holling 1973; O'Neill 1999).

The presence of dams provides a measurable attribute of *flow alteration*. Dams alter the magnitude and frequency of discharge events, change sediment deposition patterns, alter thermal regimes, and act as barriers to the migration of several aquatic organisms (Poff and others 1997; Power and others 1996). The presence of *invasive species* is another factor that may limit recovery potential by deterring recolonization of native species from nearby sources (Mack and others 2000). Waters can be placed on the 303(d) list for more than one cause (e.g., sedimentation and nitrogen), thus the *number and severity of impairments* represents a cumulative impact that can infer lesser likelihood of recovery due to greater complexity and magnitude of impairments. Other stressor metrics that appeared to be potentially measurable and relevant to recovery included *percentage tile-drained cropland*, *channelization at the watershed scale*, *stressor persistence*, and *rates of land use changes*.

Social Context Metrics

Social context factors provide an essential dimension for assessing recovery potential that can and should be evaluated separately from the waters' ecological condition (Gregory and others 2002; Lackey 2001; Palmer and others 2005). Studies at the nexus of social and environmental sciences have accumulated evidence of the social driving factors associated with successful environmental projects, including TMDLs (Sabatier and others 2005; Benham and others 2006; Benham and others 2007). We characterized many of these factors as *social context* after Sabatier and others (2005), who recognized that pre-existing socioeconomic, civil, and institutional conditions heavily influence watershed management approaches and their likelihood of success. Other social factors connote organizational process factors that define and affect the rules and procedures followed in implementing restoration.

Watershed organizational leadership and *funding eligibility* help define a positive social context for recovery. For example, there are numerous local watershed management organizations spread across the country (USEPA 2009e). Recovery of impaired water bodies has appeared to be more successful in watersheds with active watershed groups and well-funded local programs (Palmer and others 2005; Benham and others 2006; Industrial Economics Inc. 2006). Our own experience in restorability screening in four mid-Atlantic states was first catalyzed by eligibility for funding and collaboration among three different restoration programs. The importance of 'critical mass' and collaboration evident in social metrics also points to the positive effects of considering a single impaired water's larger-scale, *watershed-based management potential*. State impaired waters programs are increasingly developing watershed plans and TMDLs on the basis of whole watersheds containing multiple impaired waters, rather than individual actions for specific impaired segments alone. Efficiencies include modeling one larger system rather than numerous smaller segments, more efficient and consistent community and stakeholder interactions, attention to downstream effects, and consideration of decisions that may shift land use pressures among different subwatersheds (USEPA 2009f). The *percent protected lands* also can enhance prospects for recovery at watershed scales. Complexity, however, may sometimes work against restoration logistics; *jurisdictional complexity* and *landownership complexity* are two complicating factors that may negatively affect the social context for restoration.

Information availability also plays a strong role in determining the social context for recovery. An increasing number of studies reveal that *existence of a completed management or restoration plan* increased the likelihood of restoration success (Benham and others 2007; Sabatier and others 2005). Further, the *certainty of causal linkages* responsible for impairments is key to TMDL development, as plans to reduce pollutant loading cannot proceed very far when the pollutant is unknown. Also important to information availability is *university proximity*, cited by several state TMDL program coordinators as a valued source of technical expertise, trusted objective information, open scientific inquiry, and economical student labor (ASIWPCA, personal communication 2007).

Numerous economic factors influence the social context for recovery potential. There is empirical evidence that *residential values* are influenced by local water quality and can help motivate public and private investments in restoration (Michael and others 2000; Bergstrom and others 2001; Poor and others 2001). For example, declining residential property values along the north shore of Lake Okeechobee was one of the motivating factors behind the restoration of the Kissimmee River (Warner 2005). Interpreting socioeconomic metrics, however, can be complex; economic well-being may imply greater likelihood of recovery in one case due to a stronger tax base, whereas lower economic status in another case may qualify entirely different waters for external restoration funding.

Community values also help define social context. Impairments with *human health and safety* implications can dominate priority-setting (e.g., SMCRA 1977). Use as a *recreational resource* frequently provides a strong stimulus for community backing of restoration or protection efforts.

Widespread appreciation of a water's value to the community can be described as *iconic significance* when interwoven with local community identity, providing a significant boost to public support for restoring impairments affecting well-known water bodies such as the Chesapeake Bay. Other social metrics that appeared to be potentially measurable and relevant to recovery included *role of applicable regulation, landowner engagement, agency involvement, existing priority recognition*, *community information flow*, *economic incentive*, and measures of *economic well-being*.

A Restorability Screening Methodology

We offer a generic, flexible screening approach below. Appropriate to the geographic area and purpose of the screening, users control the choice and number of indicators, their assigned weights if any, options for combining metrics, and the size of the subset of waters desired as output. Basic steps include indicator selection, scoring each indicator for each of the waters, rank-ordering the waters by indicator-specific score, and, where known, use of indicator value thresholds that separate groups of waters with distinctly different recovery prospects. Single-indicator scores are aggregated into three multimetric summary scores for each water's ecological capacity, stressor exposure, and social context. These scores compare the relative recovery potential among waters.

Users may select one to many metrics. Screening a single indicator can be appropriate where one factor, such as impervious cover or biotic integrity, is believed to play an exceptionally important role in determining recovery potential. Choosing several metrics in each of the three classes, however, will enable use of a screening process that differentiates ecological condition, as a product of ecological and stressor summary scores, from social context influences on recovery. In this process, the selected ecological capacity metrics are first scored, weighted, and summed before rank-ordering all waters on the basis of the ecological metrics, with higher scores being better. The process is repeated for the stressor exposure metrics. Here, the lower-scoring waters are generally the better recovery prospects, although the midrange stressor scores for some indicators may represent an optimal setting of limited impacts with substantial improvement opportunities.

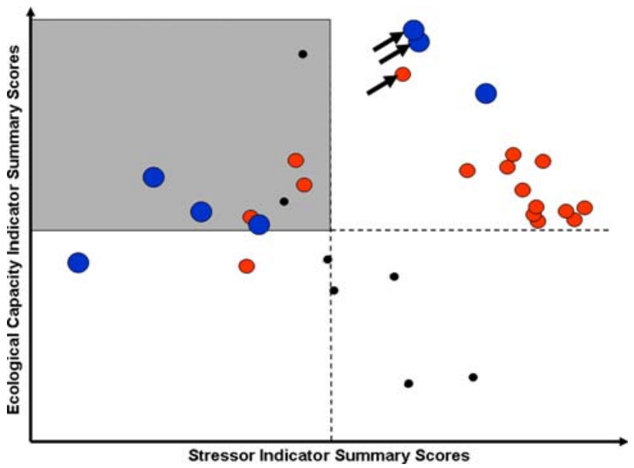

Fig. 2 Three-dimensional plot comparing recovery potential among water bodies in a Maryland watershed. *Dots* represent waters plotted by summary score relative to the ecological and stressor axes. Social context scores (higher = better) are incorporated as dot size and color. Median values for ecological and stressor scores (*dashed lines*) are added to enable a coarse sort by quadrant that initially targets high ecological/low stressor waters (upper left, *shaded*), with selected waters (*arrows*) added where special information warrants. This example screening has flagged 11of 30 waters as more restorable

Scoring these indicators by difference from a midrange optimal value enables them to be rank-ordered like the other (lower equals better) stressor indicators. Plotting the waters by summary score in a two-dimensional matrix (i.e., ecological × stressor) identifies the relative recovery potential of the waters based on condition variables (see Fig. 2). Waters with high ecological/low stressor summary scores (Fig. 2; shaded upper left quadrant) emerge as the better recovery prospects at this stage, but other individual waters can be added where special consideration is warranted.

The second part of this method introduces the social context metrics that are distinct from ecological condition but often have a strong influence on recovery potential. All or a high-potential subset of waters based on the ecological/stressor metrics scoring can be screened. As above, the social metrics are scored, weighted, and summed before rank-ordering the waters on the basis of the social metrics. The three-dimensional technique in Fig. 2 translates social score into relative dot size, which enables the user to compare recovery potential based on ecological condition and social context alone or together in the same plot. Advantages of this two-part screening method include the targeting of a reduced number of waters commensurate with available resources, the merging of systematic methods and expert insights, and the ability to separate condition versus social factors to guard against inadvertently investing in a water with a strong social context for recovery but ecologically irrecoverable.

Results: Restorability Screening Case Studies

Three demonstration studies are briefly described below. These studies concern different types of areas and recovery goals, demonstrate the flexible interaction of systematic data and professional judgment, and compare relative likelihoods of recovery among a large group of waters.

Illinois: Statewide Screening of 303(d)-Listed Waters

Our screening of the Illinois 2002 303(d) list piloted the development and testing of 104 metrics on 723 impaired waters. This pilot project emphasized single indicator development and measurement and explored comparative screening methods including sum of ranks and cluster analysis. In one demonstration analysis, orthogonal measures of ecology capacity, stressor exposure, and social context were quantile rank-ordered and compared to the nominal rankings of low, medium, and high priority assigned by the state without a systematic process (Fig. 3). Recovery potential rankings in this hypothetical example were higher for smaller watersheds with fewer impairments and better funding prospects, providing an alternate view of prioritization possibilities (Wickham and Norton 2008).

The Illinois pilot project revealed the variety of metrics that had a plausible association with relative recovery potential and were measurable from commonly available data sources. Further, this project revealed the flexibility inherent in indicator selection, weighting, and analysis methods, all of which we saw as positive attributes for adaptability to highly varied state settings and assessment purposes. We noted that single-indicator analyses (e.g., channelization, tile-drained agriculture) could be individually relevant to prominent impairment issues in the State. The project also revealed that, if a highly varied set of waters is assessed very generally (i.e., for recovery potential alone without greater specificity) using a high number of indicators, complexity may obscure interpretation of the results.

Mid-Atlantic States: A Regional Screening

We carried out a regional-scale assessment of the recovery potential of impaired native trout waters in the highlands of four mid-Atlantic states (Pennsylvania, Maryland, Virginia, and West Virginia), in collaboration among the CWA 303(d) program, the National Fish Habitat Action Plan (NFHAP), and abandoned mine lands remediation programs (Busiahn and Kosa 2008; SMCRA 1977). The purpose of the screening was to identify strong candidate waters for native fisheries restoration that also could catalyze collaboration among the three programs above. Through NFHAP's Eastern Brook Trout Joint Venture, GIS

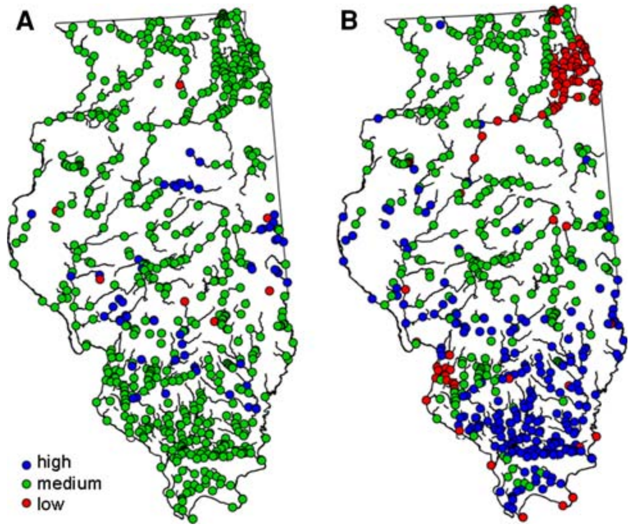

Fig. 3 Comparison of 2002 303(d) list prioritization by the State of Illinois (**a**) and an example prioritization based on recovery potential (**b**) that used cluster analysis of selected metrics from Table 1. *Dots* represent 2002 State impaired waters list segments color-coded by priority

coverage of impaired Brook Trout subwatersheds was available (Hudy and others 2005; EBTJV 2008). GIS datasets for abandoned mine lands (AMLs) and AML-impaired 303(d) waters were initially merged with the fish habitat data to identify eligibility for all three programs. These candidate waters were then further assessed for recovery potential factors including protected public lands, recolonization access, contiguity with green infrastructure corridors and hubs, other priority recognition, and active watershed collaboration (Fig. 4).

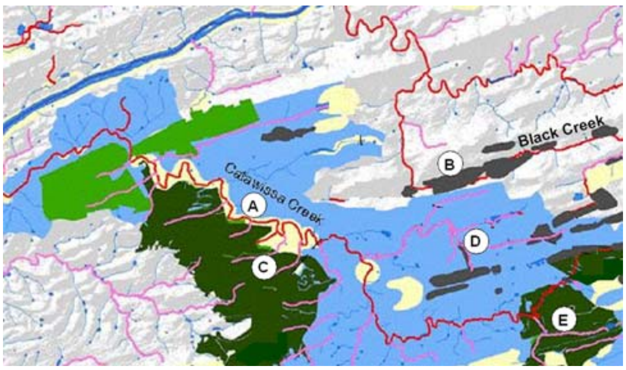

Fig. 4 Restorability screening in four mid-Atlantic states first targeted potential native trout restoration waters eligible for three programs: CWA 303(d), abandoned mine lands, and fisheries restoration. Recovery indicators that elevated this Catawissa Creek, PA example (A) over nearby Black Creek (B) included protected land (*light and dark green* at C), recolonization access (trout waters in *pink*, e.g., at D), plan existence (319 watershed plan area in *blue*) and contiguity with headwaters green infrastructure (*dark green* at C and E). Restoring downstream from "green hubs" also links previously fragmented trout waters

Unlike the Illinois assessment of overall recovery potential, this assessment was narrowly focused in purpose and able to use fewer, more relevant metrics. As a result, each of the state screenings in this project was completed in days and strong candidate waters were successfully proposed for restoration funding in Pennsylvania. Whereas the opportunity to add detail in indicator selection or weighting was evident, the generation of a useful analysis in a short time frame demonstrated that restorability screening and application to decision support can be done rapidly for large areas when the basic data are available and the screening purpose is well defined.

Maryland: Screening at Two Complementary Scales

A project with the State of Maryland's TMDL program is demonstrating additional ways to apply recovery metrics and screening. In contrast to the water body segment 303(d) listing in most states, Maryland lists its impairments on a whole-watershed basis and analyzes the small catchments within a given watershed to plan restoration actions. The state has accumulated robust statewide bioassessment and stressor identification datasets at the small catchment scale that have added recovery-relevant metrics beyond those that we were able to measure in previous studies.

This dual-scale perspective has revealed an opportunity to screen and target restoration actions at complementary watershed scales, with potential differences between the scales in indicator selection, purpose for screening, and even recognition of priority waters. At the larger scale the primary interest is to identify ecologically valuable, best-bet watersheds for restoration, thus it is likely that watersheds with higher ecological and social scores and lower stressor scores would be preferred. Once these restorable watersheds are identified, single-watershed screenings of their component catchments can help inform the choice and placement of restoration with both scales in mind. The recovery potential of the catchment remains relevant, but in the interest of restoring the larger watershed, it is also desirable to address limiting factors operating at the larger scale.

Discussion

Together, these three studies demonstrate the potential for use of consistent data in a systematic, yet relatively rapid and flexible, comparative analysis for prioritizing restoration activities. Each example made systematic use of easily accessed and consistent data while maintaining an appropriately strong role for expert judgment. Recovery potential metrics and methods were applied in a broad, general statewide assessment (Illinois), in a narrowly targeted restoration issue (mid-Atlantic states), and in an assessment of specific management units at complementary scales (Maryland).

Over 41,000 impaired waters reported nationwide attest to the workload facing state and federal restoration efforts. Although case-by-case development of TMDL schedules and other multisite restoration plans without systematic comparison can still restore impaired waters, carefully sequencing the waters to be restored is a strategic investment opportunity. Optimizing restoration strategies may yield quicker recoveries, higher overall success rates, and potentially more net ecological goods and services maintained over longer time periods. A stronger scientific basis and practical methods for recovery prediction are needed to help programs achieve these results. In particular, more research thoroughly documenting and measuring numerous recovery indicators would complement the heavy emphasis on understanding degradation that has long dominated water quality research.

Our efforts identified many variables that influence recovery and are measurable. Despite the fact that many of these metrics capture just a part of more complicated ecological or social properties, collectively they represent lines of evidence that can help restoration strategies. We may never fully understand recovery, but programs aimed at bringing about recovery can use what is known about recovery potential. Single-indicator as well as multi-indicator analyses would aid statewide priority-setting. Many variations in approach are possible, particularly in selecting the indicators appropriate for a given state. Our applications demonstrated that use of available data and recovery-based prioritization tools can aid restoration planning, especially if used to apply existing state insights about their impairments more evenly, effectively, and defensibly. Further, the linkage between state monitoring and restoration programs is a natural fit for postproject monitoring of recovery, which can build our understanding of recovery processes in general and useful recovery metrics in particular.

Additional opportunities to apply recovery may accelerate rates of restoration. This approach provides a new basis for pooling multi-TMDL studies on larger-scale watersheds encompassing numerous, similarly impaired and restorable waters. The large watershed TMDL approach has already successfully accelerated the rate of TMDL development in Ohio and Indiana (D. Maraldo, USEPA Region 5, personal communication). A cluster analysis of the Illinois recovery potential data revealed that impairment types were not uniformly distributed across cluster groups, and impairment types seemed to be associated with proximity factors that could be the basis for new large watershed TMDL studies (Wickham and Norton 2008). A second opportunity is the potential to improve the knowledge base of the linkages between aquatic condition and the suite of environmental factors that govern recovery. Study of ecological recovery has been dominated by a focus on biological endpoints (Niemi and others 1990; Yount and Niemi 1990; Detenbeck and others 1992; Kolar and others 1997; Roni and others 2002; Bond and Lake 2003). Many variables potentially associated with the biotic elements of recovery should be researched further, and abiotic endpoints of recovery such as the influence of channel morphology on sediment dynamics, temperature, and other natural processes also merit recovery-focused research. Additional efforts to strengthen recovery indicators will be needed to improve the ability to estimate the *absolute* recovery potential of a water body, compared to assessing the *relative* recovery potential among different waters using the weight of evidence from multiple measures.

The recovery potential concept may also play a useful role in the periodic refinement of Water Quality Standards. In some cases, the types of disturbances (see Niemi and others 1990; Detenbeck and others 1992) may make reattainment of Water Quality Standards difficult or unachievable. Also, on occasion, a higher standard may be within reach. The Use Attainability Analysis (UAA) process exists to authorize rewriting Water Quality Standards for single water bodies (USEPA 1984). Although the concept of recovery potential is clearly relevant to use attainability, the focus of UAA differs from that of impaired waters restoration. The UAA process aims in part to determine if a single water body's recovery potential does not match its standards and readjusts them accordingly. Application of recovery concepts and tools may be useful in UAA or in the efforts of many states to develop Tiered Aquatic Life Uses that estimate possible recovery in terms of a biological condition gradient (Davies and Jackson 2006).

Over time, linking recovery-oriented prioritization, restoration, and long-term monitoring of recovering waters can strengthen the empirical evidence connecting geospatial metrics to recovery. Our metrics and methods are a starting point that could be strengthened with more research, tested against empirical recovery results, and refined in practice. The combination of recovery indicators with geospatial analysis techniques provides a rapid, comparative assessment opportunity where such screening has not regularly occurred and recovery potential can play a stronger role.

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