The Case for Regime-based Water Quality Standards

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Conventional water quality standards have been successful in reducing the concentration of toxic substances in US waters. However, conventional standards are based on simple thresholds and are therefore poorly structured to address human-caused imbalances in dynamic, natural water quality parameters, such as nutrients, sediment, and temperature. A more applicable type of water quality standard—a "regime standard"—would describe desirable distributions of conditions over space and time within a stream network. By mandating the protection and restoration of the aquatic ecosystem dynamics that are required to support beneficial uses in streams, well-designed regime standards would facilitate more effective strategies for management of natural water quality parameters.

Keywords: water quality standards, regimes, ecosystem dynamics, watershed management

Natural factors that fundamentally influence aquatic ecosystems include streamflow, light, heat, sediment, nutrients, and dissolved gases. The distributions of these factors across space and time within a stream network make up the physical and chemical regimes that drive dynamics within stream ecosystems (Stanford et al. 1996, Poff et al. 1997, Poole 2002). The concept of a regime emphasizes the importance of a distribution of conditions, which has both temporal and spatial dimensions. Poff and colleagues (1997) considered streamflow regimes in terms of the magnitude, frequency, timing, duration, and rate of change in discharge. These components describe aspects of a flow regime through time. Streamflow regimes also vary across space, including regional streamflow patterns (Poff and Ward 1989) and variation in flow and sediment regimes within local stream networks (Benda et al. 1998).

Increasingly, scientists argue that information on natural regimes should be integrated into management strategies for aquatic habitat conservation (e.g., Stanford et al. 1996, Poff et al. 1997, Fausch et al. 2002). Indeed, protecting or recreating appropriate levels of structural and functional heterogeneity has become a central focus of river conservation and restoration science (Ward and Stanford 1995, Petts 2000, Ward et al. 2001, Bunn and Arthington 2002). This emerging view has important management implications for aquatic ecosystems that have yet to be fully integrated into management strategies (Poff et al. 1997, Fausch et al. 2002, Rieman et al. forthcoming). In this article, we consider the challenge of designing water quality standards that would enhance the protection and restoration of natural regimes in aquatic systems. To help illustrate the potential interplay between regimes and water quality standards, we describe our

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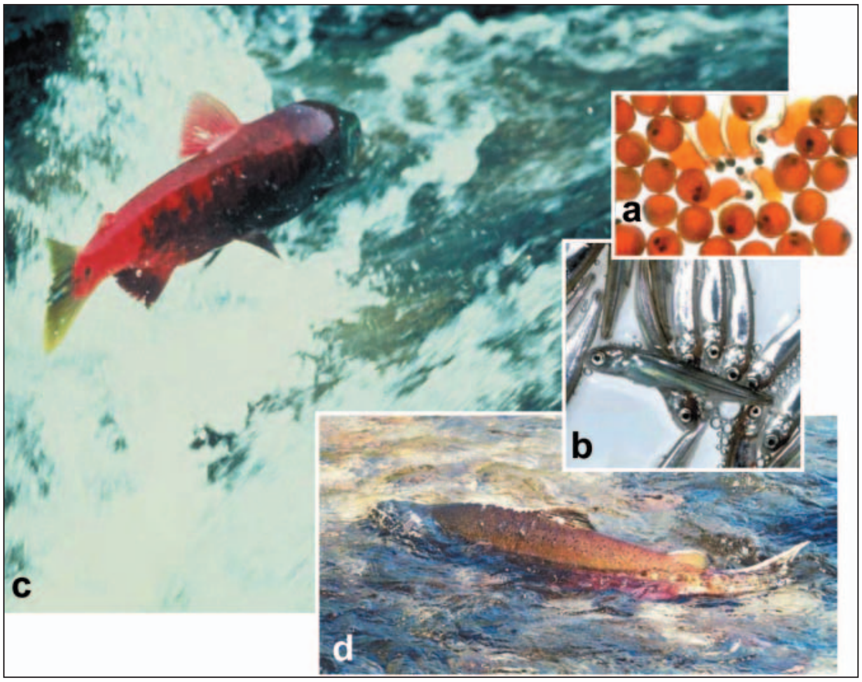

Figure 1. Freshwater life stages of Pacific salmon include (a) eggs and alevin, (b) fry, (c) migrating adults, and (d) spawning adults. Each life stage has different habitat requirements. To match the needs of each life stage with available habitat, salmon have evolved a variety of strategies (e.g., spring, summer, and fall spawning runs) that are timed to correspond with natural regimes of rivers in the US Pacific Northwest. Several species of Pacific salmon are now considered threatened or endangered under the Endangered Species Act, in part because of habitat loss, including human-caused alteration of natural regimes (NRC 1996). Photographs: US Fish and Wildlife Service National Image Library (a, b, and c); Debra Sturdevant (d).

experience of attempting to design water temperature standards under the US Clean Water Act to support self-sustaining populations of salmonid fishes (salmon, trout, and charr; figure 1) in the US Pacific Northwest (Poole et al. 2001). As background, we discuss (a) the dichotomy between appropriate management goals for toxic pollutants and goals for natural water quality parameters and (b) how conventional water quality standards are poorly suited to describing in-stream conditions that would fulfill appropriate management goals for natural water quality parameters.

Threshold standards and natural water quality parameters

In 1972, Congress authorized the Clean Water Act to protect and restore the quality of the nation's water. Over the past 30 years, the Clean Water Act and subsequent government regulation have helped to improve water quality in a number of ways. Most of these improvements involve either the reduction of point source pollution (e.g., specific wastewater or industrial discharges) or overall reductions in concentrations of specific toxic or man-made pollutants that do not exist naturally in streams (e.g., pesticides, oil and grease; NRC 1992, Birkeland 2001).

Although pollution from point sources and toxic compounds receives greater public recognition, the most intractable water quality problems in the United States today involve diffuse, nonpoint sources. Often, nonpoint source pollution manifests as degraded ecosystem function caused by imbalances in natural water quality parameters such as sediment, nutrients, and temperature. For example, a variety of land-use practices can artificially elevate sediment levels in streams and impair water quality (Waters 1995). Imbalances can result from human-caused changes in the rate at which substances enter a stream or from changes in the flow regime of a stream (e.g., changes due to dams or water withdrawal). When imbalances in natural parameters occur, the parameters are subject to regulation as pollutants under the Clean Water Act. Of the 10 most common pollutant categories in waters listed as impaired under the Clean Water Act, 8 are dominated by imbalances in natural water quality parameters (table 1).

Table 1. The 10 most common water quality impairments in the United States.

Impairment category	Number of water bodies	Percentage of national listings
Sediment/siltation	7703	15.7
Pathogens	6183	12.6
Metals	5770	11.8
Nutrients	5487	11.2
Dissolved oxygen/organic enrichment	4733	9.7
pH	2569	5.2
Habitat alterations	2357	4.8
Thermal modifications	1954	4.0
Biological criteria	1858	3.8
Flow alteration	1692	3.5
Total	40,306	82.3

Note: Italicized impairment categories are composed predominantly of natural water quality parameters driven by regimes.

Source: US Environmental Protection Agency (12 January 2004; *http://oaspub.epa.gov/waters/national_rept.control*).

Under natural conditions, toxic compounds seldom occur at levels detrimental to aquatic biota (figure 2a). In all but exceptional cases, managers can be confident that violations of conventional threshold standards for toxic compounds result from human actions. Additionally, a threshold standard for a given toxic compound applies to almost all water bodies, and the same management goal of minimizing or eliminating the compounds applies in all cases. In contrast, levels of sediment, nutrients, and other natural water quality parameters vary naturally within and among streams. Minimization or elimination of these parameters is neither an attainable nor a desirable management goal. Instead, an appropriate goal would include seeking a balance in natural parameters to maintain beneficial water uses. Further, naturally occurring conditions can overlap with conditions that are detrimental to biota (figure 2b). Therefore, the existence of localized or temporary conditions detrimental to biota is not necessarily the result of water quality degradation. Instead, degradation of natural water quality parameters manifests as changes in the magnitude, frequency, timing, location, and spatial extent of habitats that have water quality suitable to support native biota.

For several reasons, inherent spatial and temporal variations in natural water quality parameters confound the identification of a threshold value to distinguish between natural ecosystem dynamics and unacceptable human alteration of natural regimes. First, natural conditions cannot be used as the basis for threshold values, since natural conditions can sometimes be stressful for or even lethal to stream biota (figure 2b). Second, managing natural water quality parameters with a goal of meeting a threshold value encourages homogenization of naturally diverse and dynamic systems (Bisson et al. 1997); high-quality habitat may be degraded to the threshold value, while naturally marginal habitat may be targeted for restoration (figure 3). Finally, the biological relevance of a specific threshold standard for a population of organisms is difficult to define, in part because threshold-based water quality standards are derived from data that describe the stress response of individual organisms rather than the habitat requirements for entire populations.

Explicit recognition of these basic incompatibilities between conventional threshold standards and management of natural water quality parameters is critical for improving current management approaches. Regulation of natural water quality parameters through the use of threshold standards may fail to protect biota while simultaneously creating unattainable expectations for water quality (figure 3). Problems associated with threshold standards are often assumed to result from a poorly chosen threshold value, though the source of the problem may be incompatibility between the static and homogenous nature of a threshold standard and the naturally dynamic water quality parameter in question.

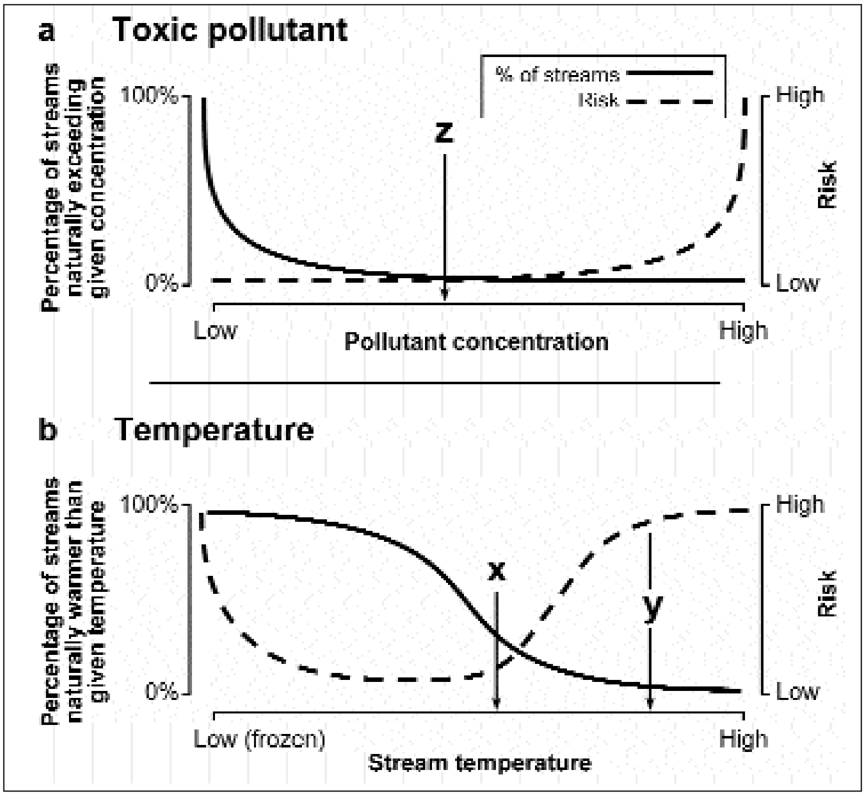

Figure 2. Conceptual plot of the biological risk (dashed line) associated with each x*-axis value and cumulative frequency of streams (solid line) where natural conditions exceed each* x*-axis value. (a) Few streams contain naturally high levels of toxic substances. Therefore, a threshold can be identified (e.g., at point z) that is seldom exceeded naturally but that avoids unacceptable levels of risk. (b) However, for natural water quality parameters such as water temperature, natural conditions in some streams can impart high levels of risk to biota at some places and times. Therefore, if a threshold is chosen to avoid risk associated with elevated temperature (e.g., at point x), compliance may be unattainable in many streams. A threshold that is attainable in virtually all streams (e.g., point y) may be associated with unacceptable levels of risk. Modified from Poole and colleagues (2001).*

Regime standards

Development of water quality standards that describe and maintain desired characteristics of natural regimes would improve the chance of ecosystem functions remaining intact to supply natural goods and services important to society, such as drinking water, recreation, and fisheries (Poff et al. 1997, Petts 2000, Ward et al. 2001, Rieman et al. forthcoming). Although designing and implementing regime standards would be difficult, recent scientific thought in the fields of aquatic ecology, conservation biology, and landscape ecology provides some general guidance:

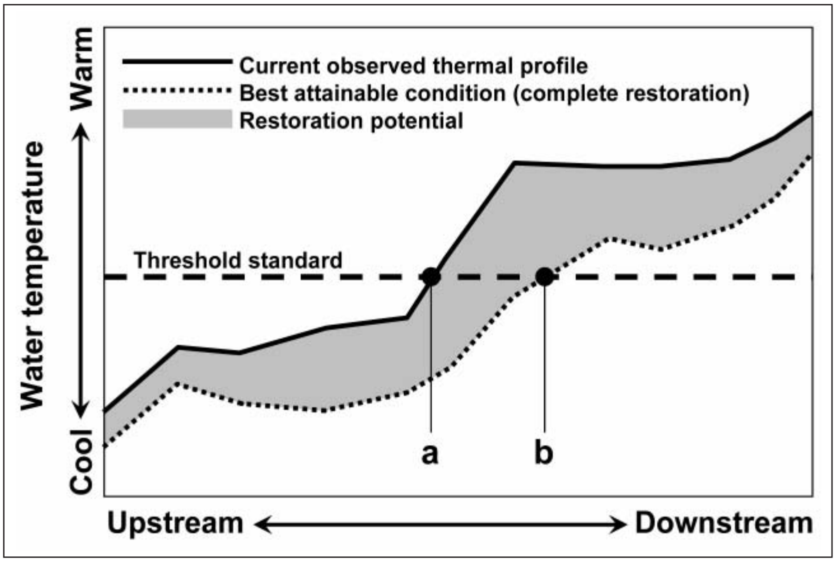

Figure 3. Conceptual diagram using water temperature to illustrate the limitations of applying a threshold standard to a naturally heterogeneous stream segment. The zone upstream (left) of point a has experienced substantial degradation yet remains below the threshold. Downstream (right) of point b, no amount of restoration will bring the stream temperature below the threshold. Modified from Poole and colleagues (2001).

- Regime standards should describe a desirable distribution of conditions for water quality over space and time, rather than rely on a single threshold value (Bisson et al. 1997, Poff et al. 1997, Rieman et al. forthcoming). This approach recognizes the importance of the dynamics associated with healthy ecosystems and focuses the development of water quality standards on supporting and protecting important patterns of natural variability. For example, the effects of natural peak flow events could be built into standards using targets with associated recurrence intervals that reflect the expected patterns within a catchment.
- A regime standard should be applied at coarse spatial scales (e.g., across entire catchments) and should consider natural cycles at multiple temporal scales. This application allows natural spatial and temporal variation to be incorporated within a standard and emphasizes ecologically important patterns and dynamics within the stream network and landscape (Rieman and Dunham 2000, Fausch et al. 2002, Poole 2002). In this context, a regime standard could describe desirable yet dynamic distributions of conditions within a catchment, apportioned in connection with relevant physical features, such as stream order or elevation, and according to pertinent temporal drivers, such as seasonal or interannual variation in weather patterns.

Developing water quality standards according to these principles would require managers to expand their concept of the structure, design, and implementation of a standard. Because stream temperature regimes in the Pacific Northwest are complex, and salmonid fishes have varying thermal requirements at different life stages (Poole et al. 2001), development of a temperature standard to support salmonids provides an excellent illustration. At coarse spatial scales, the temperature regime determines whether suitable thermal conditions in streams are contiguous enough to support local populations, well enough distributed across the landscape to support life history diversity, suitably interconnected to maintain metapopulation dynamics, and stable or predictable enough over time to allow successful adaptation of life history strategies. At coarse temporal scales, interannual temperature variability, climatic cycles (e.g., El Niño events), and disturbance–recovery cycles can influence the abundance and distribution of suitable thermal habitat for salmonids. During warm years, fish populations may be lost from otherwise suitable habitat only to recolonize those areas when high temperatures abate. At fine spatial and temporal scales, localized thermal refugia may be important for the short-term survival of individuals migrating through marginal habitats or during thermally stressful seasons or times of day (Berman and Quinn 1991).

A regime standard for water temperature would describe a desired distribution of temperatures across a catchment and through time, while addressing important patterns of variation at different spatial and temporal scales. To implement such a standard, all of the streams in a catchment might be considered as a single management unit. In this way, the patterns of water temperature across the catchment and over time could be compared against regime standards with similar spatial and temporal components (figure 4). The entire catchment would be listed as noncompliant if the spatial and temporal distribution of temperatures in the catchment did not meet the regime standard. In such instances, managers and stakeholders in the catchment would be charged with developing a catchment-wide restoration plan to comply with the regime standard.

Cycles of disturbance and recovery occur in many ecosystems and are another important temporal aspect of natural regimes. After infrequent but catastrophic natural events (e.g., large and infrequent wildfires, storms, floods, or mass wasting events), the expected spatial and temporal patterns of water quality may be altered during the recovery phase, regardless of the level of human-caused water quality degradation in the stream network (Bisson et al. 1997, Benda et al. 1998, Rieman et al. forthcoming). Although the timing of these events is often unpredictable, the events themselves are generally foreseeable (Poff 1992) and could be integrated into regime standards with careful planning. First, in undisturbed basins, a regime standard could require a distribution of habitat sufficient to support biota in the face of habitat loss associated with foreseeable disturbances. Second, in the period following a disturbance, a regime standard could promote

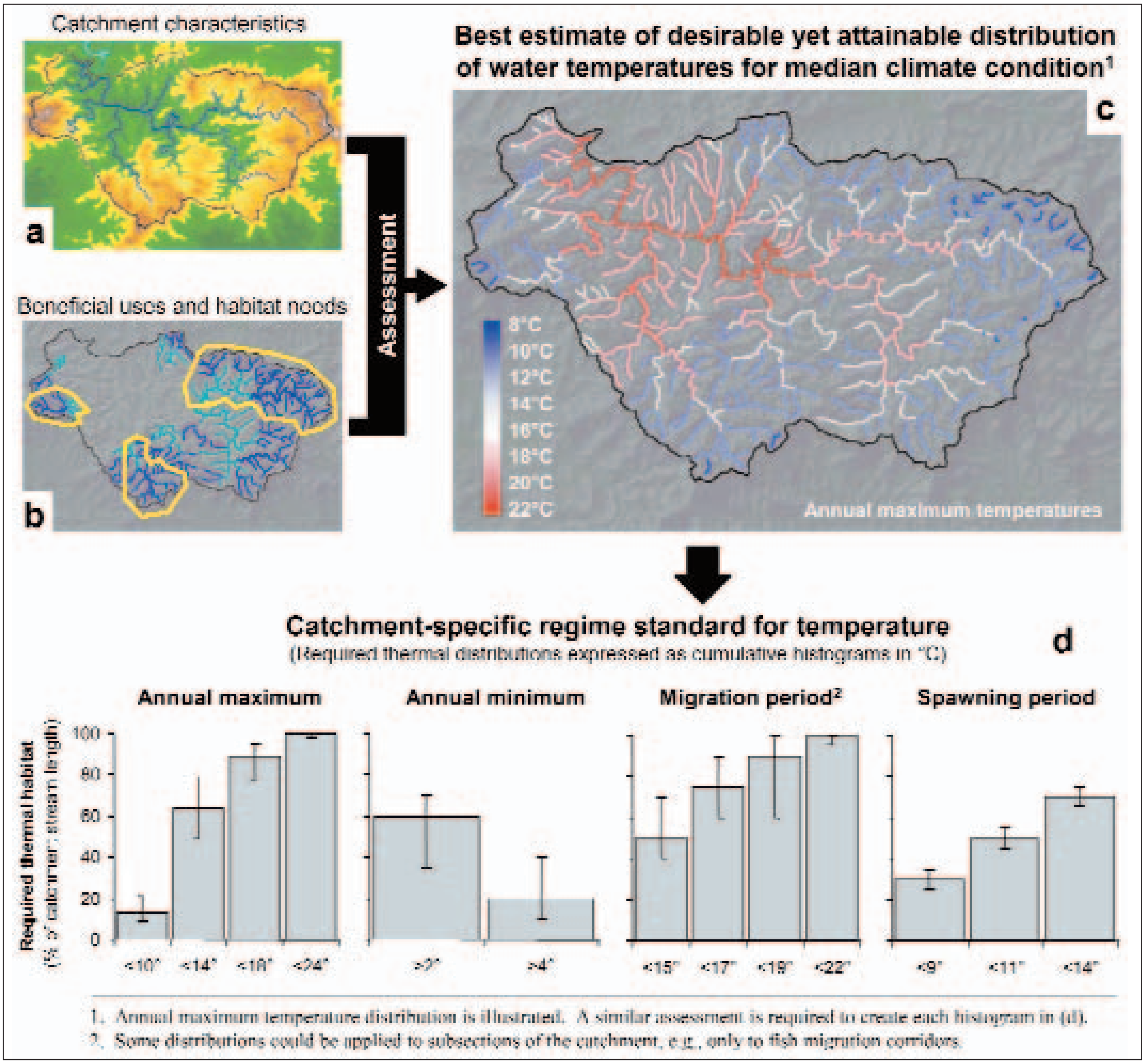

Figure 4. Schematic of a regime standard for water temperature to support populations of anadromous cold-water fishes (marine species that spawn in fresh water). An analysis of basin characteristics might consider simultaneously (a) the potential of the catchment to provide high-quality thermal habitat on the basis of the physical character and climate of the catchment and (b) prioritized locations on the landscape where specific beneficial uses (e.g., spawning, rearing, migration) must be supported. The analysis would yield (c) a catchment-specific distribution of water temperatures that is likely to be attainable and compatible with robust, self-sustaining populations of anadromous fish. The resulting distribution could be implemented as a water quality standard for median climate conditions that are based on (d) cumulative histograms for temperatures at those times of the year critical to the species' life cycles. Histogram error bars represent expected deviations of water temperature distributions caused by interannual climate variation and climate cycles. During warm years, a rightward shift in the distribution of catchment water temperatures would be allowed; during cool years, a leftward shift would be required to meet the standard. If the percentage of catchment stream length in any category exceeds an associated histogram value, the basin would be deemed out of compliance with the standard. Note that this figure illustrates only one approach to implementing a regime standard. (See the next section, "Meeting the challenges ahead.")

recovery of disturbed habitat by prescribing expected or acceptable rates of recovery toward undisturbed distributions. Using this approach, disturbed catchments need not be exempted from water quality standards. Instead, a postdisturbance catchment would be deemed to be in compliance with the regime standard if management agencies documented an acceptable rate of recovery toward standardized distributions of conditions such as those shown in figure 4d. However, for this approach to succeed, the remaining high-quality habitat in the area surrounding the disturbance must provide acceptable landscape-scale refugia and source populations for the recovery of affected species. To ensure this, managers must carefully consider the number and spatial distribution of catchments that are managed under a rate-of-recovery standard at any given time, along with the length of time a rate-of-recovery standard could be applied to a single catchment.

Describing a desirable distribution of conditions across space and time is an approach to water quality management that differs substantially from implementation of conventional site-specific or water body–specific standards. Yet a distributional approach is consistent with the Clean Water Act, incorporates recent guidelines for watershed analysis (Reid 1998, Bohn and Kershner 2002), and is similar to existing progressive approaches to setting and applying water quality standards (ODEQ 1995).

Although our vision for regime standards and catchment-scale implementation represents a marked departure from convention, it offers several potential benefits. First, while conceding that marginal or poor habitat may occur naturally in some places and at some times, a well-designed regime standard would also require a specific minimum amount of high-quality habitat within the catchment. This approach may encourage more efficient and effective use of management agencies' limited resources, because water quality standards would be less apt to require remediation of marginal habitats (NRC 2001) and more apt to encourage protection and restoration of high-quality habitat, thereby addressing the problem illustrated in figure 3. Second, a regime standard would help prioritize management actions within the catchment (e.g., Bohn and Kershner 2002), because managers would be motivated to identify the simplest, most cost-effective and efficient path toward creating the desired distribution of conditions across the entire catchment rather than engage in developing case-by-case management plans for individual water bodies regardless of their potential to provide high-quality habitat. This is especially important because catchment-scale management plans are frequently the most effective means of addressing nonpoint source degradation of natural water quality parameters (Reid 1998). Third, application of a regime standard across an entire catchment would provide incentive for all landowners in a basin to work with management agencies to resolve water quality problems.

Meeting the challenges ahead

New approaches to water quality standards will pose risks that must be carefully considered and managed. Indeed, much of the risk associated with any new form of water quality standard derives from uncertainties associated with implementation (NRC 2001). Clearly, the vision we present is incomplete. There are legitimate and difficult questions surrounding implementation of regime standards: How can managers identify desirable or acceptable distributions of conditions over space and time for a given catchment? How can researchers collect the monitoring data that are necessary to document the distribution of conditions across catchments and over time? While the amount of high-quality aquatic habitat may be sufficient once the standards are met, how can we be sure that the spatial and temporal distribution of high-quality habitat is appropriate? Although the questions surrounding the implementation of regime standards are daunting, addressing these questions may hold the key to maintaining aquatic ecosystem integrity in the face of human-caused changes in naturally occurring water quality parameters.

Fortunately, there are incremental approaches to reducing uncertainties. For instance, pilot projects could provide the basis for developing implementation strategies on a larger scale. In addition, iterative and adaptable approaches to implementing water quality standards could be used to hedge against uncertainty and could serve as the basis for multiscale, empirically based monitoring programs to document the influence of land-use activities and the effectiveness of restoration actions (Ralph and Poole 2003). In the end, however, the specific means of implementing a regime standard for any particular water quality parameter can be determined only by attempting implementation.

We hope that the concepts presented here will stimulate the thinking and imagination of a broader community of scientists and managers and encourage the development of approaches for incorporating natural regimes into water quality standards and implementing the resulting strategies. Regardless of its ultimate structure or the means of its implementation, a successful regime standard would recognize and protect ecologically important patterns of spatial and temporal variation in naturally occurring water quality parameters, while identifying and disallowing regime disruptions that impede the beneficial water uses described in the Clean Water Act.

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