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Condition of stream ecosystems in the US: an overview of the first national assessment

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Steven G. Paulsen[1,8], Alice Mayio[2,9], David V. Peck[1,10], John L. Stoddard[1,11], Ellen Tarquinio[2,12], Susan M. Holdsworth[2,13], John Van Sickle[1,14], Lester L. Yuan[3,15], Charles P. Hawkins[4,16], Alan T. Herlihy[5,17], Philip R. Kaufmann[1,18], Michael T. Barbour[6,19], David P. Larsen[7,20], AND Anthony R. Olsen[1,21]

[1]*Office of Research and Development, US Environmental Protection Agency, 200 SW 35th Street, Corvallis, Oregon 97330 USA*
[2]*Office of Water, US Environmental Protection Agency, Ariel Rios Building, 1200 Pennsylvania Avenue, NW 4503T, Washington, DC 20460 USA*
[3]*Office of Research and Development, US Environmental Protection Agency, 1200 Pennsylvania Avenue, NW 8623P, Washington, DC 20460 USA*
[4]*Western Center for Monitoring and Assessment of Freshwater Ecosystems, Department of Watershed Sciences and the Ecology Center, Utah State University, Logan, Utah 84322-5210 USA*
[5]*Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon 97331 USA*
[6]*Tetra Tech, Inc., 400 Red Brook Blvd., Suite 200, Owings Mills, Maryland 21117 USA*
[7]*Pacific States Marine Fisheries Commission, c/o US Environmental Protection Agency, Western Ecology Division, 200 SW 35th St., Corvallis, Oregon 97333 USA*

Abstract. The Wadeable Streams Assessment (WSA) provided the first statistically sound summary of the ecological condition of streams and small rivers in the US. Information provided in the assessment filled an important gap in meeting the requirements of the US Clean Water Act. The purpose of the WSA was to: 1) report on the ecological condition of all wadeable, perennial streams and rivers within the conterminous US, 2) describe the biological condition of these systems with direct measures of aquatic life, and 3) identify and rank the relative importance of chemical and physical stressors affecting stream and river condition. The assessment included perennial wadeable streams and rivers that accounted for 95% of the length of flowing waters in the US. The US Environmental Protection Agency, states, and tribes collected chemical, physical, and biological data at 1392 randomly selected sites. Nationally, 42% of the length of US streams was in poor condition compared to best available reference sites in their ecoregions, 25% was in fair condition, and 28% was in good condition. Results were reported for 3 major regions: Eastern Highlands, Plains and Lowlands, and West. In the West, 45% of the length of wadeable flowing waters was in good condition. In the Eastern Highlands, only 18% of the length of wadeable streams and rivers was in good condition and 52% was in poor condition. In the Plains and Lowlands, almost 30% of the length of wadeable streams and rivers was in good condition and 40% was in poor condition. The most widespread stressors observed nationally and in each of the 3 major regions were N, P, riparian disturbance, and streambed sediments. Excess nutrients and excess streambed sediments had the highest impact on biological condition; streams scoring poor for these stressors were at 2 to 3× higher risk of having poor biological condition than were streams that scored in the good range for the same stressors.

Key words: monitoring, streams, regional assessment, biological condition, ecological condition, stressors.

[8] E-mail addresses: paulsen.steve@epa.gov
[9] mayio.alice@epa.gov
[10] peck.david@epa.gov
[11] stoddard.john@epa.gov
[12] tarquinio.ellen@epa.gov
[13] holdsworth.susan@epa.gov
[14] vansickle.john@epa.gov
[15] yuan.lester@epa.gov
[16] chuck.hawkins@usu.edu
[17] alan.herlihy@oregonstate.edu
[18] kaufmann.phil@epa.gov
[19] michael.barbour@tetratech.com
[20] larsen.phil@epa.gov
[21] olsen.tony@epa.gov

Development of effective national policies for managing the region-wide quality of water resources depends heavily on access to credible, quantitative information regarding the status and trends in water resource conditions at a national scale. The US Clean Water Act expresses the national desire to protect and improve the physical, chemical, and biological integrity of US waters and requires that information on status and trends be reported (Shapiro et al. 2008). The need and desire to improve the quality of water resource assessments is not peculiar to the US. For example, the European Community instituted the Water Framework Directive in which key components are a general requirement for ecological protection and a general minimum chemical standard that is applicable to all surface waters. The Water Framework Directive called for an assessment of major river basins by 2007 (Hering et al. 2004b). Australia faces similar water-quality issues and has made assessment and management of its aquatic resources a major national focus (State of the Environment Advisory Council 1996, Ball et al. 2001, Harris 2006). Other countries and regions face or will face similar issues.

All countries face the technical challenge of how to provide assessments that quantify water resource conditions over continental scales. Many countries have adopted similar approaches to incorporating biological, chemical, and physical information into assessments of individual sites. Much of the technical work in the US and elsewhere has focused on development of biological indicators (e.g., Norris and Norris 1995, Simpson and Norris 2000, Hering et al. 2004a, Stoddard et al. 2008, Yuan et al. 2008). However, it is not clear that similar approaches have been adopted for survey design. In the US, randomized sampling designs are considered a critical element in support of regional and national surveys (e.g., Olsen and Peck 2008) because they provide a rigorous inference protocol for extending assessments of individual sites to the broader population of interest.

In 1972, the US Congress enacted the Clean Water Act (CWA) to protect US water resources. A critical section [305(b)] of the CWA calls for periodic accounting to Congress and the American public on the success or failure of efforts to protect and restore US water bodies. Over the past 30 y, multiple groups reviewed the available data and water-quality assessments in the US and concluded that we were unable to provide Congress and the public with adequate information regarding the condition of US water bodies (Shapiro et al. 2008). To bridge this information gap, the US Environmental Protection Agency (EPA), states, tribes, and other federal agencies are collaborating on a new monitoring effort to produce assessments that provide the public with improved water-quality information. This collaboration resulted in the Wadeable Streams Assessment (WSA), the first nationally consistent, statistically sound study of US wadeable streams. The EPA chose to focus the initial freshwater assessment on wadeable streams for several reasons. First, ~90% of the total length of perennial streams and rivers in the US consists of small, wadeable streams. Second, almost every state, university, federal agency, and volunteer group involved in water-quality monitoring has experience sampling these smaller flowing waters. Thus, a range of expertise was available for this nationwide effort. Our article summarizes critical sections of the WSA (USEPA 2006).

Methods

Study area

Wadeable streams of the 48 conterminous states (i.e., not including Alaska and Hawaii) were included in the WSA (Olsen and Peck 2008). This area covers 7,788,958 km^2 and includes private, state, tribal, and federal land.

Survey design

Sampling locations were selected for the WSA with a state-of-the-art survey design approach (Olsen and Peck 2008). Sample surveys have been used in a variety of fields (e.g., election polls, monthly labor estimates, forest inventory analysis, national wetlands inventory) to determine the status of populations (e.g., streams, lakes, wetlands) or resources of interest by sampling a representative set of a relatively few members or sites. This approach is especially cost-effective if the population is so large that all components cannot be sampled or if it is unnecessary to obtain a complete census of the resource to reach the desired level of precision for describing its condition.

The target population for the WSA was the perennial wadeable streams in the conterminous US. The WSA design team used the US Geological Survey (USGS) National Hydrography Dataset, a comprehensive set of digital spatial data on surface waters at the 1:100,000 scale, to identify the location of perennial streams. Olsen and Peck (2008) also used this information to improve estimates of the length of perennial streams in the US and report that the WSA findings were relevant to 1,079,721 km of streams and shallow rivers.

The 1392 sites sampled for the WSA were allocated by standard federal regions (EPA regions) and by ecological regions based on the distribution of 1st-

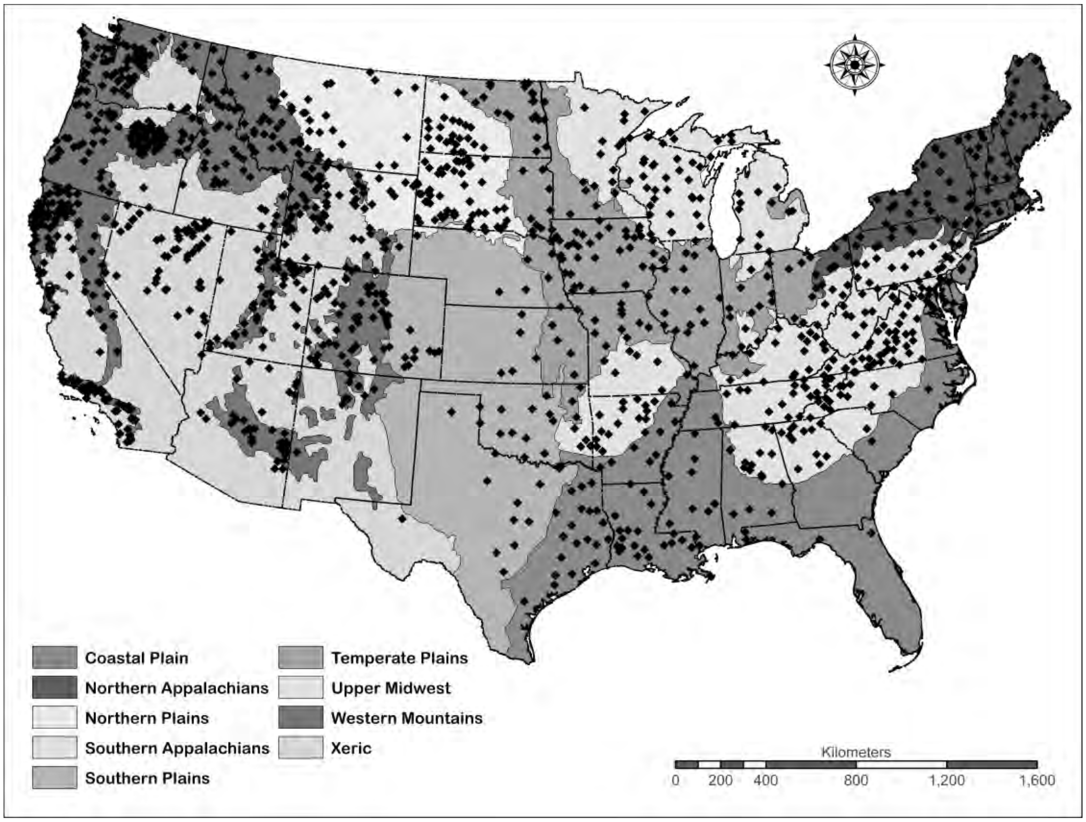

FIG. 1. Locations within each of the 9 aggregated ecoregions of the 1392 randomly selected sites used in the Wadeable Streams Assessment.

through 5th-order streams within those regions (Fig. 1). Thus, within each EPA region, random sites were more densely distributed where the wadeable streams were more densely located and more sparsely distributed where streams were sparse. The basic design drew ≥100 random sites for each of the EPA regions (regions 1 and 2 [New England and New York/New Jersey] were combined). Fifteen states, including all those in EPA regions 8, 9, and 10, increased the number of random sites to 50 sites/state to support state-scale characterizations of stream condition. Washington, Oregon, and California also added clusters of random sites to characterize areas of special interest. When sites from an area of intensification were used in the broader-scale assessment for an ecoregion, the weights associated with those sites were adjusted so that those sites did not dominate the ecoregion results. The unbiased site selection of the random design ensured that assessment results represented the condition of the streams throughout the region and nation.

Results were reported at 3 scales: national, 3 major landform and climatic reporting regions (Fig. 2A), and 9 aggregated ecoregions (Fig. 2B). This design ensured that sufficient sample size was available for reporting by each of the 10 federal regions and 12 major hydrologic basins within the conterminous US. Here, we summarize results for the nation and for the 3 major reporting regions (see USEPA 2006 for results for each of the 9 aggregated ecoregions).

Field sampling

Each site was sampled by a 2- to 4-person field crew during a low-flow index period (typically summer) between 2000 and 2004 (Hughes and Peck 2008). More than 60 trained crews, constituted primarily of state environmental staff, sampled 1392 random stream sites with standardized field protocols. The field protocols were designed to produce comparable data regarding the ecological condition of stream resources and the resources' key stressors at all sites (USEPA 2004).

During each site visit, crews laid out the sample reach and transects to guide data collection. Crews recorded site data and instream and riparian physical-habitat measurements on field forms for each site. Each crew was audited, and 10% of the sites were revisited as part of the quality assurance plan for the

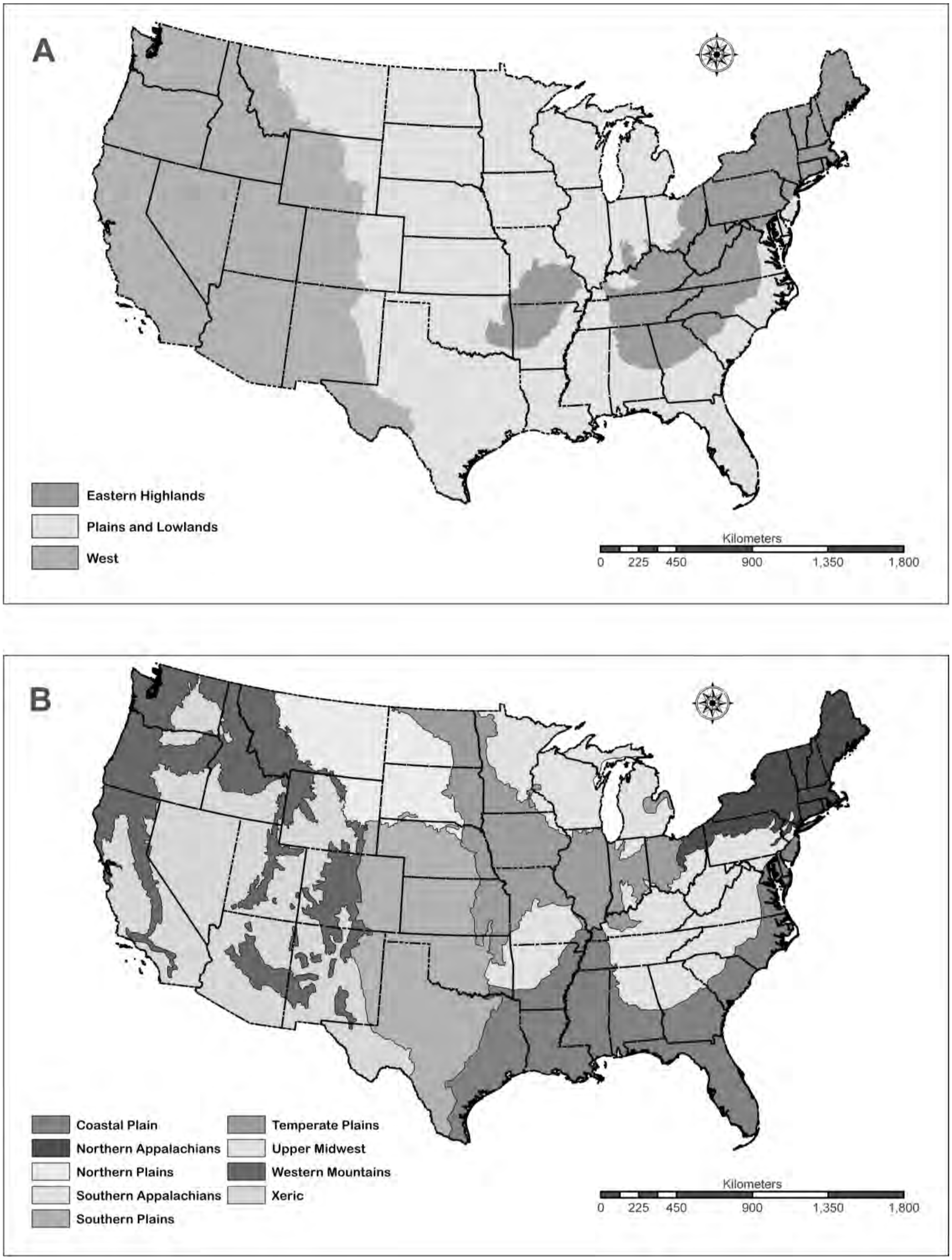

FIG. 2. A.—Three major landform and climate reporting regions in the Wadeable Stream Assessment (WSA). B.—Nine aggregated ecoregions in the WSA.

survey. Field crews sent water samples to a laboratory for basic chemical analyses. Macroinvertebrate samples, collected from 11 transects along each stream reach, were sent to taxonomists for identification (Stribling et al. 2008). Measurements of key stressors that might affect stream condition also were collected. Stressors are the chemical, physical, and biological components of the ecosystem that have the potential to degrade stream macroinvertebrate assemblages. Some of these stressors vary naturally and as a result of human activities.

The use of standardized field and laboratory protocols for sampling was a key feature of the WSA (USEPA 2004). Standardization allowed the data to be combined to produce a nationally consistent assessment. In fact, this nationwide sampling effort provided an opportunity to examine the comparability of different sampling protocols by applying both the WSA method and various state or USGS methods to a subset of the sites (e.g., Carlisle and Hawkins 2008, Ode et al. 2008).

Setting expectations: reference conditions

Setting reasonable expectations for an indicator is one of the greatest challenges to making an assessment of ecological condition (Stoddard et al. 2008). For the WSA, ecological condition assessments based on chemical, physical, and biological measurements were compared to a benchmark of what one would expect to find in a relatively undisturbed stream within that region (Herlihy et al. 2008). Reference sites were used to: 1) develop and calibrate multimetric indices (MMIs) and observed/expected (O/E) indices, and 2) set thresholds for 3 condition classes: good, fair, poor (Herlihy et al. 2008).

In the WSA, reference conditions were defined directly from sampled data rather than on the basis of expert professional judgment approach as recommended in the application of Tiered Aquatic Life Use (TALU) framework and the biological condition gradient (Davies and Jackson 2006). The conditions at a set of least-disturbed sites were used as the reference condition in the WSA. The condition at these least-disturbed sites represents the best-available chemical, physical, and biological habitat conditions given the current state of the landscape. Least-disturbed sites were identified by evaluating data collected at sites that were screened based on a set of explicit thresholds used to define the condition that was least disturbed by human activities in each of the 9 aggregated ecoregions. These thresholds varied from region to region because of natural variability and variability in the intensity of human activities across the US landscape.

A similar screening process based on physical and chemical data collected at each site (e.g., riparian condition, nutrients, Cl^-, turbidity, excess fine sediments) was used to identify a set of least-disturbed reference sites in each ecological region. Land use within watersheds did not necessarily preclude sites from consideration; for example, sites in agricultural areas might be considered least disturbed provided they exhibit chemical and physical conditions that are among the best for their region. Biological data were not used to screen reference sites because biologically screened sites could not have been used in independent, objective assessments of biological condition without concerns about circular reasoning.

The range of values at the reference sites within an ecoregion were examined for each biological or stressor indicator. The 5th and 25th percentiles of the reference-site distributions were used as thresholds for assigning any individual site to a condition class. These thresholds were then applied to the random sites to generate the percentage of stream length in each condition class. Sites with indicator scores <5th percentile of reference distribution were considered significantly outside of the least-disturbed reference distribution and were classified in poor condition. Sites with indicator scores >25th percentile of the reference distribution were considered within the range of least-disturbed sites and were classified in good condition. Sites with indicator scores between the 5th and 25th percentiles of reference distribution were classified in fair condition.

Indicators of condition: biological quality

Macroinvertebrate assemblages were sampled to represent stream biological quality. Future surveys of streams and rivers will include macroinvertebrate, fish, and algal assemblages. Two measures of the macroinvertebrate assemblage were used to communicate biological quality: an MMI of macroinvertebrate integrity (MIBI) (Stoddard et al. 2008) and an O/E index of taxon loss (Yuan et al. 2008). Separate indices were developed for each of the 9 aggregated ecoregions and were compared with the reference conditions determined for that ecoregion (Herlihy et al. 2008). O/E values were interpreted as the percentage of the expected taxa present at a site. Each tenth of a point less than 1 represents a 10% loss of taxa in a sample; thus, $O/E = 0.9$ indicates that 90% of the expected taxa are present and 10% are missing at a site. Three O/E models were developed to predict the extent of taxon loss across streams of the US: 1 each for the Eastern Highlands, Plains and Lowlands, and West (USEPA 2006, Yuan et al. 2008). Taxon loss estimates were presented in 4 categories: <10%, 10 to 20%, 20 to 50%, and >50% taxon loss.

Indicators of stressors impacting streams

When humans alter the landscape, their actions can change stream environmental conditions and increase stress on these ecosystems. These aquatic stressors can be chemical (Herlihy and Sifneos 2008), physical, or in some cases, biological (Ringold et al. 2008). The primary purpose of including data on stressors is to provide policy makers and the public with a sense of the relative importance of the stressors so that they understand: 1) which stressors are most widespread, 2) which stressors are affecting aquatic biota, and 3) whether reducing or removing a stressor would be likely to result in improved stream quality. A short list of stressors was selected from among the chemical, physical, and biological measures available. Some potentially important stressors were not included because they could not be assessed easily at the site scale (e.g., water withdrawals for irrigation). Future assessments of US streams and rivers will include a more comprehensive list of stressors from each category.

WSA stressor indicators were based on direct measures of stress in the stream or adjacent riparian areas, rather than on landuse or land-cover alterations, such as row crops, mining, or grazing. Many human activities and land uses can be sources of ≥1 stressors to streams. However, the stressors, rather than their sources, were the focus in the WSA. The general philosophy was to understand the most significant stressors first and then to undertake the potentially expensive process of source tracking, a logical future step for the WSA and similar national assessments.

Eight stressors were selected for measurement. Four stressors were chemical, and 4 were related to habitat alterations. The chemical stressors were excess total N, excess total P, excess salinity, and acidification. Each of these stressors had been listed in previous 305(b) reports from the states or had been the subject of national legislation (e.g., acidification caused by atmospheric deposition). The indicators of habitat alteration were excess fine sediments, alterations of instream fish habitat, alteration of riparian vegetation cover, and disturbance of the riparian zone. Excess fine sediment had been identified by many states as a stressor of concern. Alterations to the riparian vegetation and habitat have been linked with temperature changes in streams, which is also a major concern, particularly in the western US.

Ranking of stressors: extent and risk

An important prerequisite to making policy and management decisions is an understanding of the relative magnitude or importance of potential stressors across a region. Both the prevalence (i.e., extent of stream length with significant levels of the stressor and extent relative to that of other stressors) and the severity (i.e., influence on biological condition and influence relative to that of other stressors) of each stressor must be considered. Separate rankings of the relative extent and the relative severity of stressors to US flowing waters were presented in the WSA.

The concept of *relative risk* (from the field of medicine) was used to address the question of severity of stressor effects because this term is familiar to most people. For example, many people are familiar with the notion that they run a greater risk of developing heart disease if they have high cholesterol levels. Often such results are presented in terms of a relative risk ratio, e.g., the risk of developing heart disease is 4× higher for a person with total cholesterol level >300 mg than for a person with total cholesterol <150 mg. Relative risk values for stressors can be interpreted in the same way as the cholesterol example. For each of the key stressors, the relative risk value indicates how much more likely a stream was to be in poor biological condition if a stressor was rated as poor (found in high concentrations) than if the stressor was rated as good (found in low concentrations). Different aspects of the macroinvertebrate assemblage (i.e., biological condition vs taxon loss) are expected to be affected by different stressors, so relative risk was calculated separately for the MIBI and O/E index. A relative risk value = 1 indicates no association between the stressor and the biological indicator, whereas values >1 suggest that poor stressor conditions pose greater relative risk to biological condition. Confidence intervals for each relative risk ratio also were calculated. When the confidence intervals for any given ratio do not include 1, the relative risk estimate is statistically significant.

Results

MIBI

Nationally, 42% of stream length was in poor condition, and 25% of stream length was in fair condition as measured by macroinvertebrate biotic integrity relative to the least-disturbed reference condition in each of the 9 WSA aggregated ecoregions (Fig. 3). Five percent of stream length was not assessed because 1st-order streams in New England were not sampled. Based on macroinvertebrate integrity, 52% of

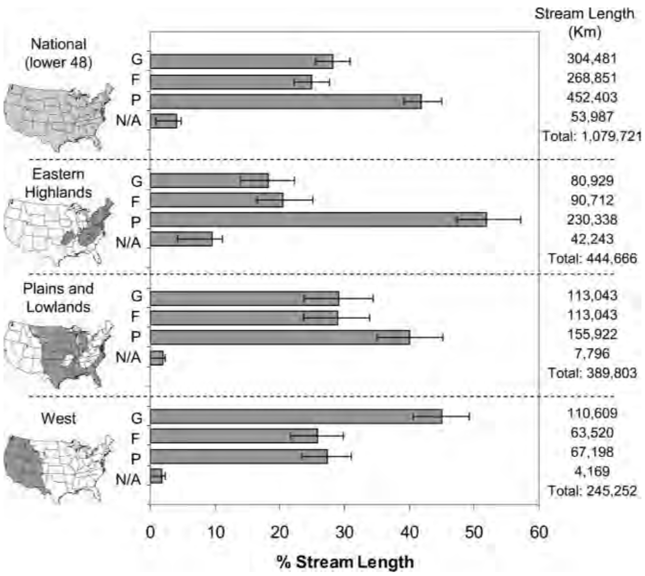

FIG. 3. National and regional results for the Multimetric Index of Macroinvertebrate Integrity (MIBI) presented as both % stream length and absolute stream length (km) for 4 condition classes. G = good, F = fair, P = poor, and N/A = not assessed. Error bars represent 95% confidence intervals.

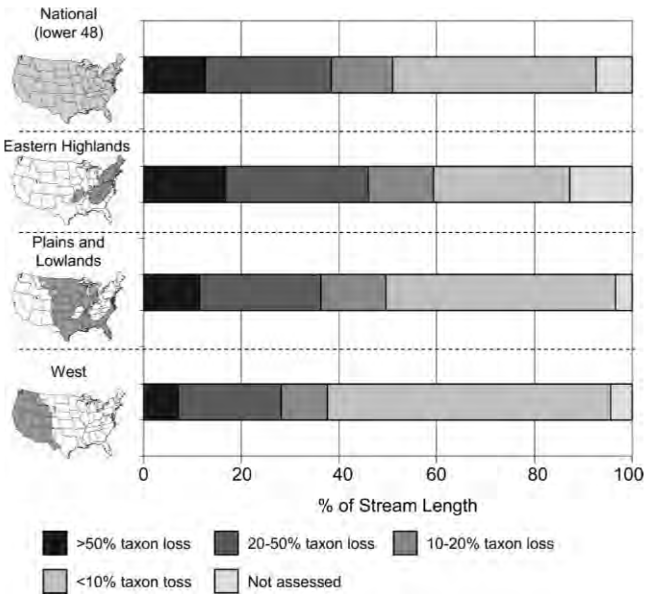

FIG. 4. National and regional results for the macroinvertebrate observed/expected (O/E) index of taxon loss presented as % stream length in 5 categories of taxon loss.

stream length in the Eastern Highlands, 40% of stream length in the Plains and Lowlands, and 27% of stream length in the West were in poor condition. Detailed results for the 9 WSA aggregated ecoregions are available elsewhere (USEPA 2006).

O/E index

Nationally, 42% of stream length had lost <10% (retains >90% of expected taxa), 13% of stream length had lost 10 to 20%, 26% of stream length had lost 20 to 50%, and 13% of stream length had lost >50% of expected taxa (Fig. 4). The Eastern Highlands had experienced the greatest loss of expected taxa; 17% of stream length had <50%, 29% had 20 to 50%, 13% had 10 to 20%, and only 28% of stream length had >90% of expected taxa.

Relative extent of stressors

Excess quantities of several stressors occurred throughout US streams. Excess total N was the most widespread stressor for the nation overall, but it was not the most pervasive in each region. Nationally, ~32% of stream length had excess total N compared with reference conditions (Fig. 5A). In the Plains and Lowlands, 27% of stream length had excess total N, and 42% of stream length in the Eastern Highlands had excess total N. Even in the West, where stressor levels were generally lower than in other major regions, excess total N was found in 21% of stream length. Patterns of excess total P were similar to those for excess total N, and excess total P was the 2nd most pervasive stressor nationally. The least common stressors nationally were salinity and acidification (Fig. 5A). Only 3% and 2%, respectively, of stream length had salinity and acidification levels in the poor or most-disturbed category.

The most extensively occurring stressors varied across the 3 major regions (Fig. 5A). In the Plains and Lowlands, loss of instream fish habitat was the most extensive stressor and was rated poor in 37% of stream length. In the Eastern Highlands, excess total N and excess total P were the most extensive stressors and were rated poor in >42% of stream length. In the West, stressors were found in ≤21% of stream length, and excess total N, excess total P, riparian disturbance, and excess fine sediments were the most widespread stressors.

Relative risk of stressors

Almost all stressors evaluated in the WSA were associated with increased risk for poor macroinvertebrate condition (Fig. 5B, C). Excess N, P, and streambed sediments were the stressors most likely to be associated with significant impacts on biological condition based on both MIBI and O/E indicators. Streams with excess nutrients or streambed sediments were 2 to 4× more likely to be in poor macroinverte-

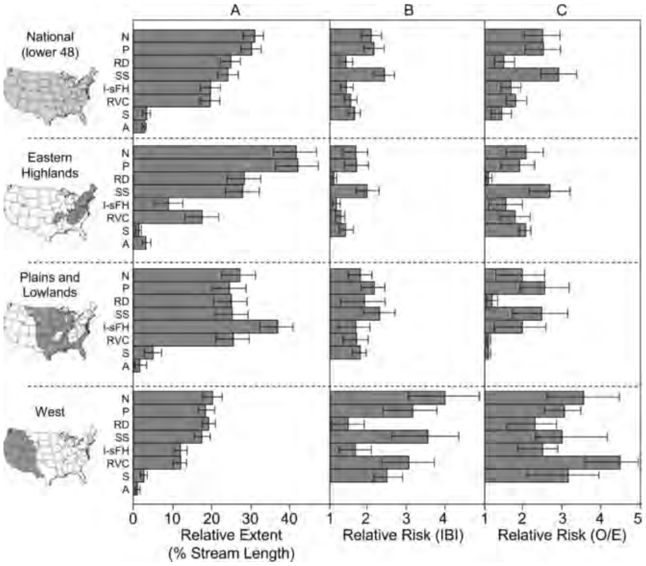

FIG. 5. Relative ranking of stressors nationally and regionally. A.—Relative extent is the % of stream length in poor condition class for each of the 8 stressors. B.—Relative risk of observing poor Multimetric Index of Macroinvertebrate Integrity (MIBI) values given poor stressor conditions. C.—Relative risk of observing poor observed/expected (O/E) values given poor stressor conditions. N = excess total N, P = excess total P, RD = riparian disturbance, SS = excess fine streambed sediments, I-sFH = excess alteration of instream fish habitat, RVC = riparian vegetation change, S = excess salinity, A = acidification. Error bars represent 95% confidence intervals.

brate condition than were streams in good condition for these stressors.

Relative risk ratios differed among major WSA regions (Fig. 5B, C). In general, streams in the West had a higher relative risk for most stressors than did streams in the Eastern Highlands and the Plains and Lowlands. This result might reflect the higher quality of reference streams in the West than elsewhere. For most stressors, relative risk ratios were higher for the O/E index than for the MIBI.

Combining stressor extent and relative risk

The most comprehensive assessment of the relative importance of stressors is obtained by combining estimates of relative extent and relative risk (Fig. 5A–C). Stressors that posed the greatest overall risk to biological condition were those that were widespread and had potentially severe effects (i.e., high relative risk ratios). Van Sickle and Paulsen (2008) explored the concept of *attributable risk* for the WSA. Attributable risk combines relative extent with relative risk to produce a single number that can be used to rank stressors and to inform management decisions.

Nationally, excess total N, total P, and fine streambed sediments posed the greatest relative risk to biological condition (relative risk >2), and they occurred in 25 to 32% of stream length. Thus, national or regional management decisions directed toward reduction of sedimentation and nutrient loadings to streams could have the greatest overall positive effect on macroinvertebrate biological condition. In the West, high salinity was strongly associated with poor MIBI (relative risk = 2.5) and O/E (relative risk = 3.2) values. However, salinity affected only 3% of stream length in the West. Thus, excess salinity is a local issue requiring a local targeted management approach rather than a national or regional effort.

Discussion

The WSA was the first national assessment of water resources conducted in the US that was based on consistent field protocols and a statistically robust sampling design. The results of the WSA and the data on which they are based constitute a baseline from which future trends can be evaluated. Much was learned during the implementation of the field survey and the resulting assessment. The articles in this special issue capture many of the technical challenges encountered during implementation of the WSA. Several challenges are of special concern from the national perspective.

Biological assessment field protocols (Barbour et al. 1999, Peck et al. 2006) and assessment tools (MMIs and O/E indices; Stoddard et al. 2008, Yuan et al. 2008) have been refined during the past 20 y and are now well developed and highly accessible. As a consequence, unique protocols and indices and predictive models often are developed for each new study and are being applied at increasingly smaller scales. However, WSA analyses have shown that standard field protocols can be used across very large areas and that a few comparable MMIs worked reasonably well across all 9 aggregated ecoregions (Stoddard et al. 2008). Thus, it might be time to weigh the relative merits of highly refined local or regional indices vs. consistent and comparable assessment tools that can be applied or combined across large areas.

Reference sites are critical for developing and interpreting MMIs and O/E indices. An underlying assumption of the use of reference sites is that they represent least-disturbed conditions for that region. Reference sites must be of similar quality across regions if assessment results are to be compared across regions. WSA analyses show that reference-site quality differs markedly among regions of the US (Herlihy et al. 2008). It might be possible to define reference-site quality along a biological condition gradient (Davies and Jackson 2006). However, how to apply the notion of a biological condition gradient to large-scale assessments is not clear. The problem of differing reference-site quality is a key technical issue requiring further research.

The WSA was only the first of several national-scale assessments of aquatic resources. In the WSA, the subpopulations of interest were the wadeable streams in each of 9 aggregated ecoregions. Planning for new surveys must include further definition of the subpopulations to be assessed. For example, urban waters were added as a subpopulation of interest in the national rivers and stream survey that began field sampling in 2008. Of course, every added subpopulation carries with it implications related to sample size that translate into increased field and laboratory costs.

Last, institutional challenges among various federal agencies, states, and tribes must be resolved to ensure long-term implementation of national assessments. Each organization has specific mandates that it must address. The value of collaboration among institutions as they work toward the common goal of improving ways to assess and manage natural resources is undeniable, but the needs of local and state monitoring also must be met. Many options exist for implementing future surveys and assessments, and the approach used during the WSA was just 1 option for arriving at a credible national assessment. We must continue to seek approaches that address monitoring needs across spatial and geopolitical scales that range from local to national.

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