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A Stream–Wetland–Riparian (SWR) index for assessing condition of aquatic ecosystems in small watersheds along the Atlantic slope of the eastern U.S.

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Abstract As part of a regional study by the Atlantic Slope Consortium (ASC) to develop ecological and socioeconomic indicators of aquatic ecosystem condition, we developed and tested a protocol for rapidly assessing condition of the stream, wetland, and riparian components of freshwater aquatic ecosystems. Aspects of hydrology, vegetation, in-stream and wetland characteristics, and on-site stressors were measured in the field. The resulting metrics were used to develop an index of overall condition, termed the Stream–Wetland–Riparian (SWR) Index. Values of this Index were compared to existing biotic indices and chemical measures, and to a Landscape Index created using satellite-based land cover data and a geographic information system (GIS). Comparisons were made at several levels of spatial aggregation and resolution, from site to small watershed. The SWR Index and associated Landscape Indices were shown to correlate highly with biological indicators of stream condition at the site level and for small contributing areas. The landscape patterns prevalent throughout the entire watershed do not necessarily match the patterns

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found adjacent to the stream network. We suggest a top-down approach that managers can use to sequentially apply these methods, to first prioritize watersheds based on a relative condition measure provided by the Landscape Index, and then assess condition and diagnose stressors of aquatic resources at the subwatershed and site level.

Keywords Assessment · Ecological indicators · Mid-Atlantic · Riparian · Streams · Wetlands

Introduction

The headwater portions of watersheds play a key role in determining the overall health of aquatic ecosystems (Brooks et al. 2006a; Freeman et al. 2007). In the eastern U.S., headwaters, including the combined areas of terrestrial habitats, wetlands, and headwater streams and their floodplains, typically occupy about two-thirds to three-quarters of the total drainage basin for larger rivers (Fig. 1a and b). Given this influence on downstream portions of large river watersheds and estuaries, understanding the impacts of human activities on the ecological structure and function of small watersheds is foundational for optimizing their conservation and management.

It is essential that both scientists and managers move away from considering streams in isolation from their surroundings, and integrate all components of aquatic ecosystems, including the associated wetlands, floodplains, riparian corridors, and the influence of contributing terrestrial areas. This is critical to understanding and protecting watersheds because these headwater portions of larger watersheds are often subjected to a wide range of stressors.

There are many conceptual models of riverine systems in the literature, variously describing the physical, chemical, and biological components (see Vannote et al. 1980; Minshall et al. 1985; Ward 1989; Forman 1995; Ward et al. 2002; Thorp et al. 2006). These models can provide insight into how the characteristics of small watersheds along the Atlantic Slope relate to their condition, and the impact of stressors upon them. Of particular relevance to this paper are the ideas that characterize riverine ecosystems as a series of interconnected hydrogeomorphic patches (Church 2002; Poole 2002; Thorp et al. 2006) and the relationship of these dynamic patches to aquatic biodiversity (Townsend et al. 1997; Lake 2000; Ward et al. 2002; Thorp et al. 2006). Increasingly, these syntheses have begun to move beyond the stream or river channel alone, to incorporating linkages between streams and the landscape through which they flow, thus recognizing longitudinal, lateral, and vertical aspects of the tributary network (e.g., Forman 1995; Ward et al. 2002; Wiens 2002). Still missing, however, are attempts to develop conceptual models and assessment approaches that directly integrate stream, wetland, riparian, and terrestrial components for headwater watersheds.

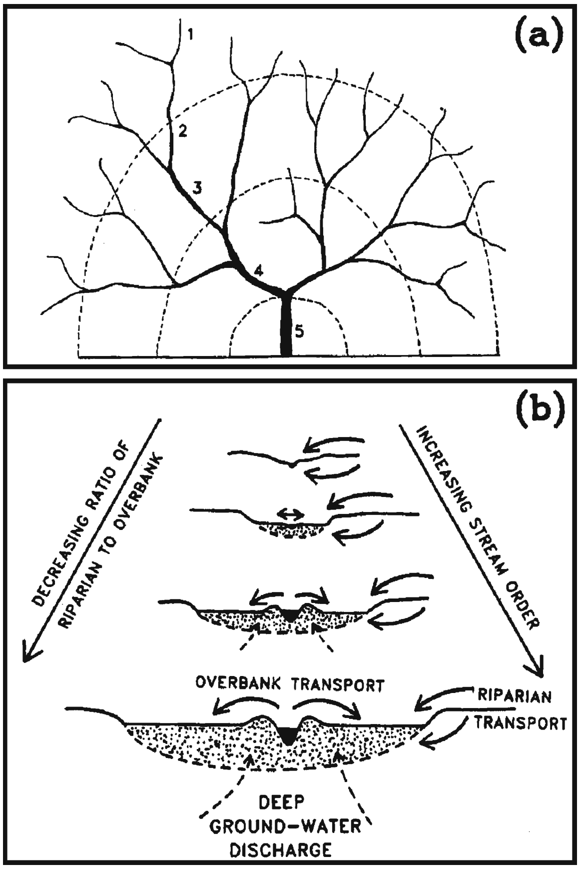

Fig. 1 **a**, **b** Representations of relative contributions of stream order to watershed area, flooding, and discharge showing the significant effects of headwaters

We followed the lead of Brooks et al. (1998, 2006a) in considering streams, wetlands, and riparian areas as definable landscape units that support characteristic water-dependent biota (i.e., stream- and wetland-dependent species of invertebrates, vertebrates, and vascular plants) and that respond predictably to a set of anthropogenic stressors. We believe that such an approach will assist those concerned with their protection, conservation, and management. The interactive relationships among the stream, wetland, riparian and upland components of watersheds for different stream orders are illustrated in Fig. 2a–c. A key feature of these illustrations is the relative contribution to the functioning of these systems by upstream portions of the watershed, versus immediately adjacent or lateral components.

Our approach to assessing condition, presented here as a first step toward understanding the linkages among aquatic components, involves three levels of effort that increase in detail and diagnostic reliability as data collection shifts from remote-sensing to intensive sampling on the ground (Brooks et al. 2004, 2006b). A Level 1 or Landscape Assessment can be accomplished in the office using only remote-sensing data and geographic information systems (GIS). A Level 2 or Rapid Assessment builds upon the findings at Level 1 by adding rapidly implemented ground reconnaissance at the site level. A Level 3 or Intensive Assessment typically requires more intensive data collection, involving HGM functional models (Smith et al. 1995), IBIs (Karr and Chu 1999), or other labor-intensive methods. As anticipated, the degree of confidence in the data

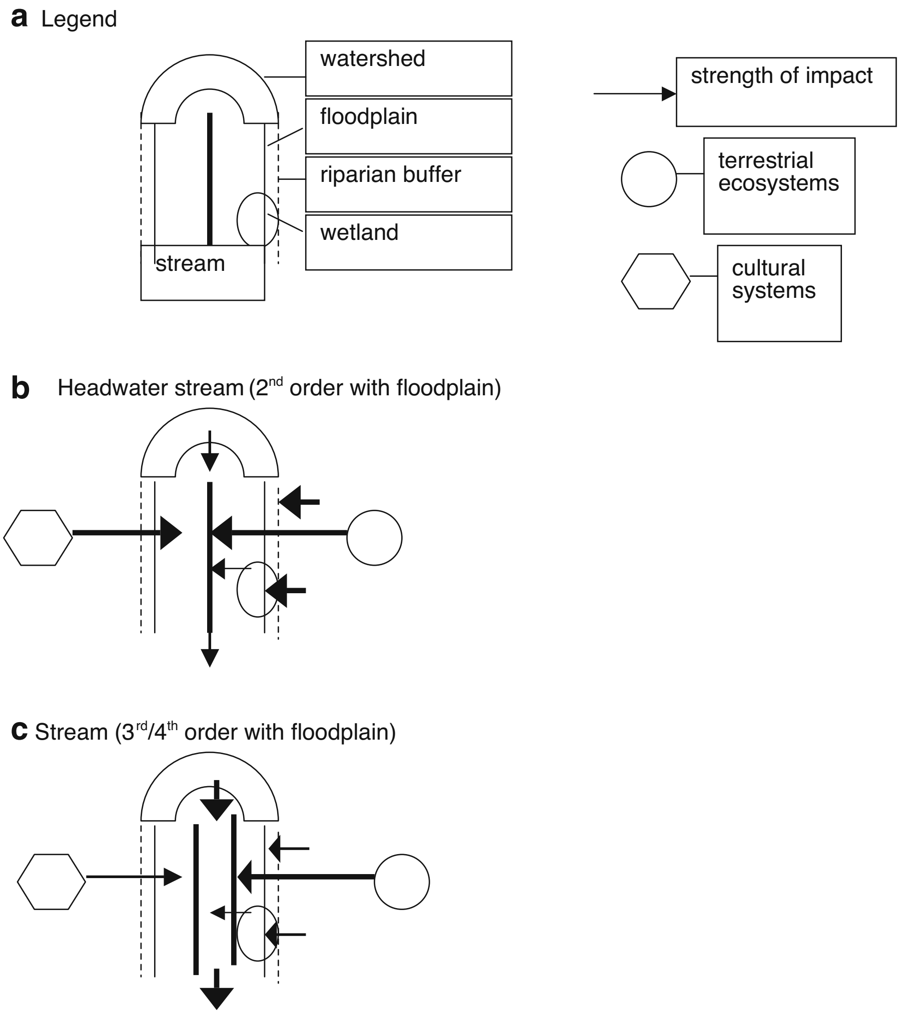

Fig. 2 **a**–**c** Hypothesized conceptual model of relative contributions to ecological integrity in headwaters of small watersheds

used and the reliability of decisions made based on those data increases with greater amounts of effort. However, the spatial coverage of Level 3 data will typically be lower, given the greater level of data collection effort required.

As a first step toward finding ways to integrate condition assessments across aquatic resources, in this paper we describe the development of a new, integrative index that combines information collected rapidly (Level 2) for stream, wetland, and riparian portions of a watershed: a Stream–Wetland–Riparian (SWR) Index of aquatic ecosystem condition. We developed the SWR Index as a rapid assessment method, and then used data collected with intensive methods to validate the Level 2 findings. Once validated, the SWR Index was compared to a Landscape Index (Level 1). Thus, in developing the SWR Index, we used primarily a bottom-up approach, whereas when used operationally, a top-down sequence is recommended to provide increasingly detailed condition and diagnostic information. Our primary objective was to develop an index based on a rapid assessment protocol that would yield a reliable estimate of aquatic ecosystem condition for a site, and to "scale up" the site-level assessment to produce a condition estimate for a small watershed.

Methods

Field protocols

A sampling protocol for streams and wetland–riparian areas was compiled and field-tested. We incorporated existing methodologies into the protocol when available. We included portions

Table 1 Characteristics of small watersheds measured in the field, and corresponding site-level metrics considered for inclusion in the Stream, Wetland, Riparian (SWR) Index for the Mid-Atlantic Region

Measurement type	Description	Site-level metrics
Adjacent land use	Index of riparian cover∼inverse distance weighted biomass	Buffer score 0–300 m; buffer score 0–30 m; buffer score 0–100 m; buffer score 0–3 m
Riparian classification	Cover type of each distinct riparian feature or "patch" (e.g., levee, floodplain, wetland, upland) present within sample plot	Number of patches; average cover code (∼ biomass index) of patches
Bankfull parameters	Stream channel measurements	Incision ratio; width/depth ratio; floodprone height
Wetland classification	Hydrogeomorphic (HGM) and National Wetlands Inventory (NWI) classification of each wetland present	Wetland presence/ absence; no. of wetlands; no. of wetland types
Hydrology, wetland and soils assessment	Checklist of indicators of wetland hydrology—used to confirm presence of wetland hydrology and determine wetness of each wetland present	Wetness of wettest wetland on site
Vegetation assessment (trees)	3 Bitterlich tree points combined with DBH measurements for each tree	Total basal area; basal area by species; number of tree species; median DBH
Invasive species	Invasive species cover class, by species	Percent cover of invasive species, total and by species; number of invasive species present
Stressor checklist	Checklist of stressors organized by stressor category, including their location and distance from stream	Total number of stressors, and number of stressor categories, for stream, floodplain, and wetlands; total number of unique stressors, regardless of their location
Stream habitat assessment (SHA)	Based on EPA's Rapid Bioassessment Protocol—separate assessment forms for (1) high gradient, (2) low gradient, and (3) coastal plain streams	SHA score (normalized to a 0–1 scale);
Other	Additional field measures include reference site (yes/no) based on Best Professional Judgment in field; beaver site (yes/ no)	

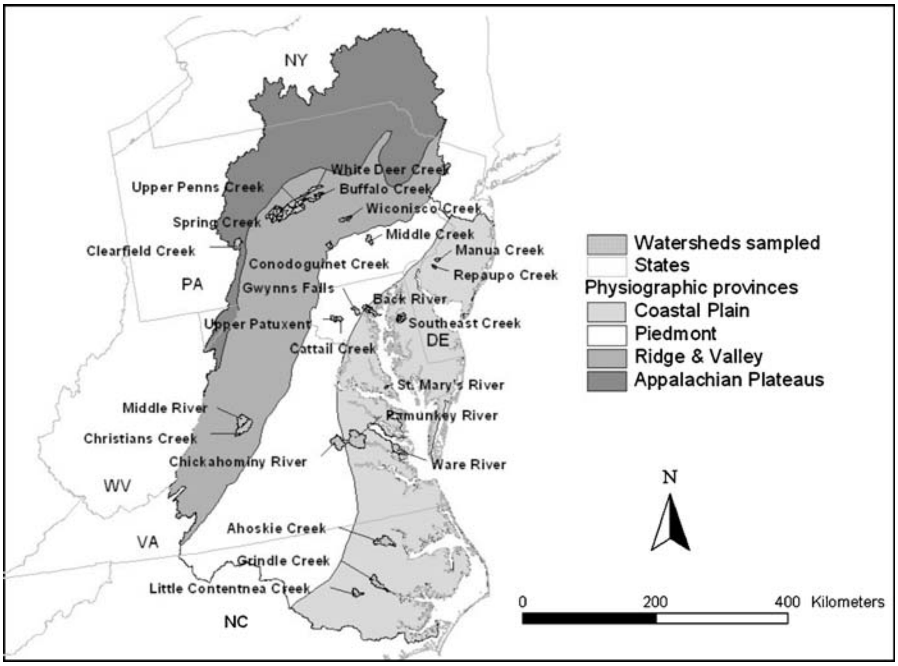

Fig. 3 Small watersheds in the Mid-Atlantic Region selected for developing the Stream–Wetland–Riparian (SWR) Index with representation across ecoregions

of the Stream Habitat Assessment (SHA) from the Rapid Bioassessment Protocol (RBP, Barbour et al. 1999) used to assess in-stream and riparian conditions only. We expanded a wetland stressor checklist (Brooks et al. 2004) to include a wider range of stressors that might affect streams and riparian areas. Stressors were grouped into ten categories, and their location in the stream, floodplain, or wetland was recorded.

An eight-page field data form was developed to guide data collection. At each sample site, aspects of hydrology, soils, vegetation, and topography were measured in a 100 m × 100 m plot. For most sites, the plot was centered on the stream. For sites where representative stream widths were >10 m, the plot was shifted so that one side of the square paralleled one bank of the stream, and only one side of the associated floodplain was sampled. Table 1 summarizes the types of data collected. Total sample time per site averaged approximately 2 h.

Study area and site selection

For the purpose of developing the SWR Index, we selected a subset of 24 small (approximately HUC-14) watersheds in the Mid-Atlantic portion of the Atlantic Slope (>3,000 were available), based on a stratification of ecoregions, land use type, and topographic slope classes (Wardrop et al. 2005) (Fig. 3, Table 2). The amount and quality of existing Level 3 data on stream biota (especially Indices of Biological Integrity (IBIs)), physical habitat, and water chemistry was also

Table 2 Physiographic region and land cover cluster (Wardrop et al. 2005) membership of watersheds in the Mid-Atlantic Region selected for Stream–Wetland–Riparian (SWR) sampling

Physiographic region	Land cover cluster	No. of watersheds sampled
Coastal plain	Agriculture	1
	Forest/low slope	3
	Mixed/high nodal variance	2
	Mixed/low nodal variance	2
	Urban	2
Piedmont	Agriculture	1
	Mixed/low nodal variance	2
	Urban	2
Ridge and valley	Agriculture	2
	Forest/high slope	3
	Mixed/ high nodal variance	2
	Mixed/ low nodal variance	1
	Urban	1
Grand total		24

taken into consideration in watershed selection, since we planned to use these data to cross-validate our rapid assessment data.

A geographic information system (GIS) was used to select 20 random stream-centered sample points within each watershed. Prior experience had suggested that 20 sample points would be an adequate compromise for characterizing a HUC-14 watershed, and coping with the logistics of sampling a large region and gaining access to sites under both public and private ownership. Sampling more than 20 points would have reduced the number of watersheds assessed, and in some cases, the 20 points with their associated 1-km radius landscape circles resulted in nearly full coverage of the smaller watersheds of the set.

Streams data were derived from the U.S. Geological Survey National Hydrography Dataset (NHD) 1:100,000-scale data (USGS 2000) for all states except Pennsylvania, where the data source was a higher-resolution streams layer maintained by the Pennsylvania Department of Environmental Protection. Randomization of point selection was accomplished using a GIS algorithm available from the webpage of Environmental Systems Research Institute (ESRI) (http://www.esri.com) (Brooks et al. 2004), which uses an Avenue script to place random points along line shapefiles. The random selection process was stratified by stream order (Strahler 1952) in roughly the same proportional area that each order class occupies within the study region (i.e., 13–14 1st–2nd order, 4–5 3rd order, 1–2 4th or 5th order stream points). A duplicate set of 20 points was generated for each watershed, to be used in cases where the initial points were inaccessible, or where no stream could be found at an assigned point. In addition, where possible, the geographic coordinates of existing Level 3 sample sites (e.g., Environmental Monitoring and Assessment Program (USEPA 2000) or Maryland Biological Stream Survey (MBSS, Boward et al. 1999)) were identified and sampled instead of the nearest random point, in order to provide pairs of points that were coincident in space, though not in time.

To test the adequacy of this sample size, two sets of 20 randomly selected points were sampled in one watershed (Conodoguinet) by the same team, so that the two data sets could be compared. In addition, we tested for observer bias by having two different field teams sample the same watershed (St. Mary's) using different sets of points.

Testing of the SWR Index

To assess the utility of this protocol, pilot sampling of four watersheds (Spring, Upper Penns, Ware, and Clearfield) took place during late summer and early fall of 2002. Following pilot sampling, the protocol was reviewed and modified to streamline the sampling process. Some changes were made to data collection procedures such that the earlier sites lack data for some measurements. Although these revisions effectively reduced our sample size for analyses that included those measurements, the changes resulted in an improved sampling protocol. The remaining field data collection occurred during between April and September 2003. A total of 521 sites on 24 watersheds were sampled, primarily by a team of two trained technicians.

Our selected watersheds differed in their size and thus, sampling density. This variation was due to two different factors. First, although the majority of the selected watersheds consisted of a single HUC-14 unit, four (Spring and Upper Penns in Pennsylvania, and Back and Southeast in Maryland) were comprised of multiple HUC-14 watersheds. These watersheds were included because they had already been studied intensively by members of the project team. Second, there were considerable variations and inconsistencies among the nine states in the Atlantic Slope Consortium (ASC) region as to the mean size of their delineated HUC-14 units, despite being labeled as such. Mean size ranged from less than 30 km^2 in New Jersey and Maryland, to over 200 km^2 in Virginia, with most having intermediate areas of about 100 km^2. The number of sample points in a given watershed also varied slightly. Although the target number of points was 20, some watersheds had fewer due to their small size (Mantua and Repaupo in New Jersey, and St. Mary's in Maryland), or other factors such as difficult or denied access. Finding comparable datasets over such large geographic areas is often challenging, and compromises are commonly made. The extremes in watershed area, however, were within one order of magnitude. By applying the

SWR Index across multiple states, ecoregions, and watershed areas, we can demonstrate its utility for varied physiographic and hydrogeomorphic settings.

Data were entered into a Microsoft Access database using a web-based interface developed specifically for this purpose. Quality assurance was accomplished using Access queries to perform data cross-checks. Histograms and basic statistics were generated to check for outliers, and data sheets were spot-checked against the database. A review meeting of field crews, data analysis personnel, and principal investigators took place at the beginning of the 2003 field season to facilitate resolution of any discrepancies and ensure consistency in the database.

Development of the SWR Index (Level 2)

Metric selection

For each distinct section of the sampling protocol, we identified and computed one or more measures to summarize the data (Table 1). These measures were then evaluated for inclusion in our multimetric index. The goal was to choose a subset of metrics to reflect site condition, both in-stream and in the riparian-wetland area, without undue redundancy. We examined correlations among the variables, their frequency distributions, and the distribution of values for reference sites as compared to non-reference sites. "Reference"—defined as sites in the best obtainable condition with minimal human disturbance—was determined by best professional judgment in the field. Existing assessment studies reported in the literature were also consulted for guidance (Smith et al. 1995; Karr and Chu 1999). Correlations between the metrics and IBI data were also examined. Taking the above information into account, best professional judgment was applied to make the final selection of metrics (Table 3).

Table 3 Site-level metrics selected for inclusion in the Stream, Wetland, Riparian (SWR) Index for the Mid-Atlantic Region

Metric	Location
Buffer Condition 0–300 m from stream	Wetland–riparian
Incision ratio	Stream
Invasives cover class	Wetland–riparian
Basal Area	Wetland–riparian
Number of wetland–riparian stressors	Wetland–riparian
Number of stream stressors	Stream
Stream Habitat Assessment (SHA) score	Stream

Metrics that were examined, but ultimately not retained, included: width-depth ratio (appeared to have a weaker relationship with reference condition and IBI data than did incision ratio); number of tree species (low correlation with IBI data, not strongly supported by literature); riparian buffer score at 0–3 m, 0–30 m, and 0–100 m from stream (highly correlated with score for 0–300 m interval); wetland presence/absence (dichotomous variable—low resolution); number of wetland types (weak relationship to reference condition); number of distinct cover types or "patches" and average cover code-roughly analogous to a biomass scale-of patches (lack of information on the aerial extent of each cover type limited the utility of these measures).

Metric scoring

The raw values of the metrics varied in their range of possible values, as well as whether their relationship to condition was positive or negative. For example, incision ratio varied over a range of approximately 1 to 21, with a higher value indicating more degraded conditions. Conversely, the Stream Habitat Assessment (SHA) score varied over a range of 0 to 200, with a higher value indicating better condition. In order to combine the metrics into a composite or multi-metric index it was necessary to convert each to the same scale, such that the magnitude and range of each metric had a similar relationship to condition.

Blocksom (2003) examined different methods for converting metrics to a similar scale, or "scoring". Some of these methods require the use of a set of reference sites—or sites in best obtainable condition—to set scoring thresholds. Our random sampling method was unlikely to detect many true reference sites, except perhaps in the watersheds that fell into the least disturbed (i.e., forested) land cover category. Therefore, we looked at the distribution of each metric across all sites to set thresholds, taking into consideration our estimate of whether or not a site was reference as determined by observers in the field.

Following Blocksom's terminology, we used a modified version of "classification" scoring, where a series of categorical scores are assigned to ranges of metric values. To avoid the loss of information that would typically occur when one takes a continuous variable and divides it into a limited number of discrete units, we extrapolated each raw metric between the high and low point of its tier assignment. Scored values were constrained to the range of 0 to 1, as is commonly done with Habitat Suitability Index models (U.S. Fish and Wildlife Service 1980) and Hydrogeomorphic Functional Assessment models (HGM, Smith et al. 1995). Tiers, following Davies and Jackson (2006), were defined based on a variety of factors, including examination of frequency distributions and quantiles for the full suite of sites in the ASC, review of prior studies, the distribution of values for reference sites vs. non-reference sites and, ultimately, best professional judgment. We also examined the distribution of the metrics broken down by physiographic province and, in the case of incision ratio, by stream order, to look for evidence that these should be treated separately. We did not see sufficient variation to warrant creating different tiers for each province at this time, particularly given that further subdivisions would create small sample sizes, especially with respect to reference sites. If there was an existing scoring system for the metric, that system was used. This occurred only for the SHA score (Barbour et al. 1999).

The general equation used for scoring was:

$$\begin{aligned}&\{[(\text{Value} - \text{low end of tier})\\&\quad/(\text{tier width in raw data units})]\\&\quad\times \text{width of scores tier}\} + \text{low end of tier}\end{aligned}$$

This conversion did not work well for metrics with integer values and narrow tier widths (e.g., number of stressors). In this case, values were "manually" coded to distribute them along the 0–1 scale.

For guidance in combining the scored metrics into a multi-metric index, we developed a conceptual model of stream–wetland–riparian condition (Fig. 4). Our conceptual model shows that overall stream condition should be determined by factors that influence biogeochemical processes, habitat structure, and hydrology (Karr and Chu 1999; Brooks et al. 2004, 2006b). We measured characteristics in the field that are either direct measures of condition (e.g., stream incision ratio),

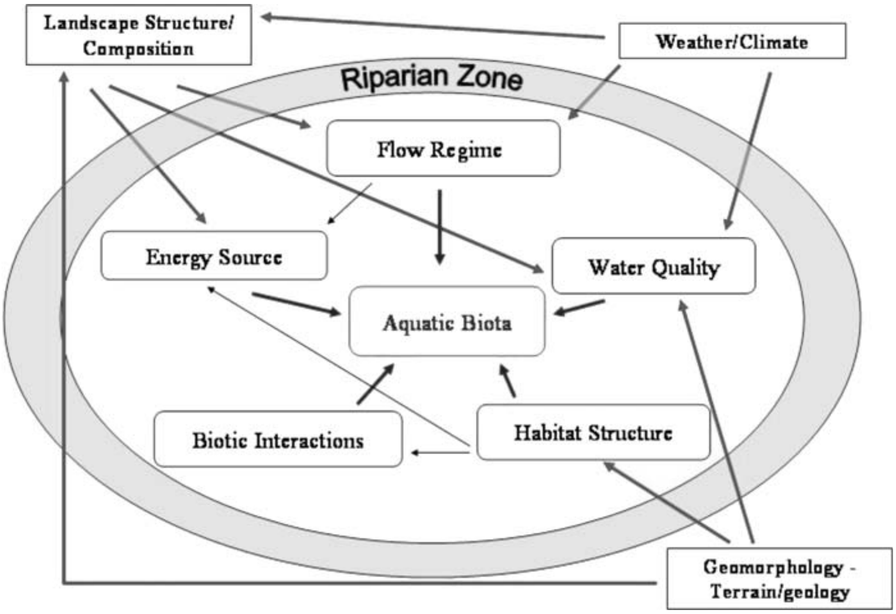

Fig. 4 Conceptual model of a stream/river ecosystem and its riparian elements (modified from Karr and Chu 1999; Brooks et al. 2006a)

or surrogates for the causes of degraded condition (i.e., stressors). The floodplain–wetland component (FL–WL) of the aquatic system is viewed as distinct from, but related to, the in-stream component. Initially, separate models were developed for the in-stream and wetland–riparian components of the aquatic system. These were then integrated into a single model that we term the Stream–Wetland–Riparian (SWR) Index (Fig. 5).

With scoring complete, we referred to the conceptual model described above, and computed two indices as follows:

$$\begin{aligned}\text{FP} - \text{WL Index} &= \text{Average (Buffer Score, Basal Area Score,}\\ &\qquad \text{Invasives Score,}\\ &\qquad \text{FP} - \text{WL Stressor Score)}\end{aligned}$$

$$\begin{aligned}\text{SWR Index} &= \text{Average(FP} - \text{WL Index,}\\ &\qquad \text{Incision Ratio Score,}\\ &\qquad \text{SHA Score, Stream Stressor Score)}\end{aligned}$$

Because of missing data values for some metrics, the above indices were computed only for the 350 sites with a full suite of measurements.

Development of landscape indices (Level 1)

To explore the relationship between site level (Level 2) and landscape level (Level 1) assessments of condition, we developed two GIS-based Level 1 indices: one based on the watershed boundary, and the other based on a 1-km circle around each Level 2 sample point (Brooks et al. 2004).

Metric selection

First, a tentative set of landscape metrics was selected based on a review of the literature and professional experience. Values of these metrics were generated for each delineated watershed in the ASC, for a 1-km radius circle around each SWR sample point, and for the contributing area to each MBSS-IBI point. The primary data source was the National Land Cover Data (NLCD) dataset (Vogelmann et al. 2001), which was derived from early to mid-1990s Landsat Thematic Mapper satellite data. Histograms and descriptive statistics were computed for each metric for the entire suite of >3,000 watersheds in the ASC.

Of the initial metrics considered, Mean Proximity Index-Forest (or the mean distance between each forest patch and the next closest forest patch) was ultimately excluded from further consideration due to its highly skewed distribution and questionable behavior when constrained to a 1-km circle. In addition, the Core Forest metric was used in the Landscape Index for watersheds, but not for the 1-km circles. The relatively small

Fig. 5 Conceptual relationship of metrics used to compute a Stream, Wetland, Riparian (SWR) Index

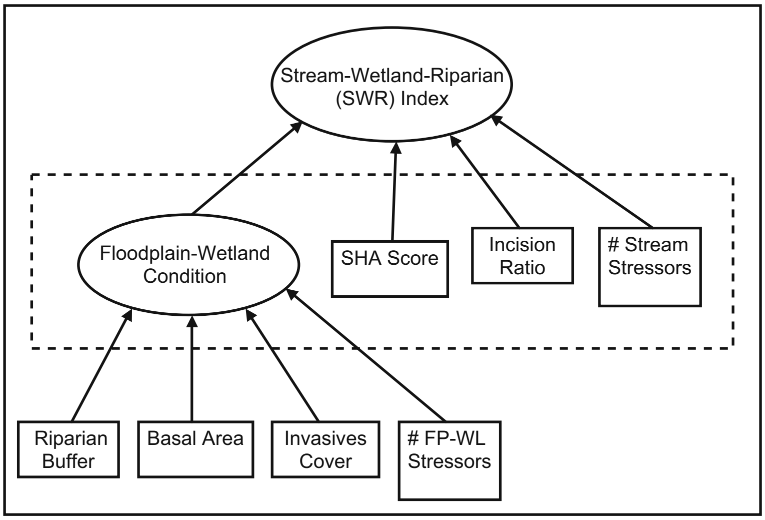

Table 4 Metrics used in the computation of Landscape Indices for assessing aquatic condition of small watersheds in the Mid-Atlantic Region

Metric	Type	Description	Citation	Index for 1 km circles	Index for watershed
Forest cover (%)	Land cover	Percent of area that is forest (combined deciduous, coniferous, and mixed forest categories)	NA—computed in ArcView	√	√
Land Development Index (LDI)	Urbanization	An index of human disturbance	Brown and Vivas (2005)	√	√
Impervious Surface (%)	Urbanization	Considers the % of each NLCD land cover class that is impervious, and the density and width of roads	B. Griscom et al. (unpublished)	√	√
Mean forest patch size (ha)	Fragmentation	Average size of forest patches	FRAGSTATS—McGarigal et al. (2002)	√	√
Core forest/total forest (%)	Fragmentation	The sum of the area of forest patches that is further than 100 m from the patch perimeter, divided by the total area of forest	FRAGSTATS—McGarigal et al. (2002)		√

size of the 1-km circle appeared to artificially constrain values of this metric. The final set of metrics used in computing the index is shown in Table 4.

Metric scoring

As with the Level 2-SWR metrics, it was necessary to score the individual Level 1 metrics before they could be combined into an index. Since we were able to generate Level 1 metrics for the entire population of ASC watersheds ($n > 3000$), in contrast to the much smaller ($n = 24$) set of watersheds for which we had Level 2-SWR data, we relied on the distribution of metric values across the entire study region for guidance in fitting the raw data to a 0–1 scale.

In general, the following formula was used to convert to a 0–1 scale: (value—low)/(high—low), where low and high refer to the high (99.5th percentile) and low (0.5th percentile) ends of the distribution of that metric across all watersheds in the ASC. If the resulting score fell outside the 0–1 range (as was the case for raw values that fell into the upper and lower 0.5th percentiles of the distribution), the score was set to 0 or 1, respectively. If necessary, scores were adjusted so that, for each metric, a high score indicated good condition and a low score indicated poor condition. This was accomplished by subtracting the score from 1. Highly skewed metrics (IMP and CORFOR) were log-transformed (natural log) before scoring. In addition, for the 1-km circles, Mean Forest Patch Size was set to 1 for all circles where the percent forest exceeded 90%.

Results

Performance of the SWR Index

For validating the SWR Index, a large quantity of existing biological data and, where available, corresponding physical and water chemistry data, was compiled by the ASC from federal (e.g., EMAP), state (e.g., Maryland Biological Stream Survey, MBSS), interstate (e.g., Susquehanna River Basin Commission, SRBC), and local (e.g., Spring Creek Community) sources. Initially, we intended to combine these data to create a large Level 3 dataset for the region that could be used to calibrate and cross-validate our Level 2 and Level 1 indices. However, as we examined the details of the data sets, it became apparent that they differed in many of respects. For example, the datasets differed in their criteria for site selection (random vs. targeted), sampling season, sample methods (e.g., equipment and sampling density), sample processing (i.e., sub-sample size and method, and taxonomic level of identification), and data analysis (i.e., the types of metrics and multi-metric indices computed). All of these factors can affect the comparability among these data sets, and influence our ability to distinguish signal from noise. For this reason we chose not to combine Level 3 data for analysis within our HUC-14 units for this development phase of the index.

Although we lacked a sufficient number of IBI data points to compare average IBI scores to average SWR index scores for all of our watersheds, we used data from the MBSS (Boward et al. 1999), which includes sites in selected Coastal Plain and Piedmont watersheds, to make a series of comparisons using non-parametric correlation analysis (Spearman's rho, SAS 2003) (Table 5). We looked at three MBSS indices/metrics: an IBI for benthic macroinvertebrates, a fish IBI, and nitrate concentration (NO_3 in mg/l).

To compare our SWR Index (Level 2) to Level 3 and Level 1 assessments, we formulated a series of questions. Our analysis proceeds through the logic path posed by those questions, so each relevant question is listed as a subheading for the respective results. The comparisons were made to assist us in parsing out where the condition estimates were in agreement, and where their estimates diverged.

Validation of Index with IBI data (Level 2 vs. Level 3 comparisons)

Question 1: How well does aquatic condition (as determined by SWR rapid assessment) at a site reflect biotic and chemical condition at the same site?

First, we considered locations where Level 2 and 3 measurements occurred within 250 m of each other as co-located sites ($n = 28$). We found a highly significant correlation between the SWR Index and the benthic IBI ($r = 0.64$, $p \leq 0.001$), but the correlation with the fish IBI was weaker ($r = 0.36$, $p = 0.08$), and the link with NO_3 was very weak ($r = 0.04$, $p = 0.88$). One would expect benthic invertebrates to be more influenced by site-level conditions than fish (which are more mobile) or NO_3 (which integrates over a larger upstream area).

Question 2: How well does average site-level aquatic condition in the upstream contributing area reflect biotic condition at a site?

When Level 3 measurements were compared with the average SWR Index in their upstream contributing area ($n = 60$), all three Level 3 indices were correlated with the SWR Index. The relationship was strongest for the benthic IBI, followed by the fish IBI, and NO_3. This suggests that looking at multiple sites in the upstream area may give us a broader representation of condition at a point. Although the correlation with the benthic IBI was somewhat weaker than the site-to-site comparison, the relationship of the SWR Index with fish and nitrate was strengthened.

Question 3: How well does average site-level aquatic condition in the watershed, as sampled at 20 points, reflect average biotic condition in the watershed, as measured at 4–19 different points?

Lastly, we compared the average of all SWR points in each watershed with the average of all Level 3 points for the same watershed ($n = 6$ watersheds). The correlation was statistically significant ($r = 0.95$, $p = 0.004$) for the fish IBI, nearly so for the benthic IBI ($r = 0.76$, $p = 0.08$), but not for the nitrate ($r = 0.22$, $p = 0.67$). The very small sample size made relationships difficult to discern and statistical significance difficult to achieve. However, the indication is that our sample of 20 SWR points provides a reasonable estimate of biological condition, but not of chemical condition, at the watershed level.

Comparisons of Level 1 landscape indices with Levels 2 and 3

To examine the agreement between our Level 1 landscape indices and Level 2 SWR Index, we made several comparisons.

Question 4: How well does the landscape condition in a 1-km radius circle surrounding a site (as measured using GIS and satellite-based land cover data) agree with aquatic condition at that site?

Table 5 Spearman's rho (non-parametric) correlation coefficients for Level 2 (SWR Index) vs. Level 3 measures (*BIBI* benthic IBI, *FIBI* fish IBI, *NO_3* nitrate, *MBSS* Maryland Biological Stream Survey) for small watersheds in the Mid-Atlantic Region

	Level 3—MBSS site	Level 3—avg for watershed	Level 1—1 km circle	Level 1—watershed
Level 2—SWR site	BIBI—0.64 *** FIBI—0.36 (ns) NO3—0.04 (ns)		0.63 *** ($n = 28$), 0.42 *** ($n = 351$)	
Level 2—average of SWR sites in MBSS contributing area	BIBI—0.58 *** FIBI—0.48 *** NO3—0.35 **			
Level 2—average of SWR sites for small watershed		BIBI—0.76 (ns) FIBI—0.95 ** NO_3—0.22 (ns)		0.26 (ns)
Level 1—1 km circles averaged for contributing area to MBSS site	BIBI—0.69 *** FIBI—0.63 *** NO_3—0.42 ***			
Level 1—for 1 km circle around SWR site	BIBI—0.69 *** FIBI—0.46 * NO_3—-0.30 (ns)			0.95 ***
Level 1—for overall watershed		BIBI—0.77 (ns) FIBI—0.89 * NO_3—0.03 (ns)		

ns not significant

*$0.01 < p < 0.05$

**$0.001 < p < 0.01$

***$p \leq 0.001$

We found that the association was highly significant for both the entire set of SWR points with non-missing data ($n = 351$, $r = 0.42$, $p < 0.001$), and for the subset of 28 matched Level 2 SWR and Level 3 data points ($r = 0.63$, $p < 0.001$). In fact, the correlation between the Level 1 and Level 2 data was essentially as strong as that between the Levels 2 and 3 for the benthic IBI when the same set of data points was examined, suggesting that looking at landscape conditions around a sample point can provide as good an estimate of condition as making site-level measurements at that point, for relatively immobile organisms such as benthic macroinvertebrates. This conclusion is strengthened by a direct comparison between Level 1 and Level 3 data for the same set of 28 points, which shows a highly significant relationship between the benthic IBI and the landscape index for the 1-km circle surrounding the sample point ($r = 0.69$, $p < 0.001$). However, the relationship is weaker for fish, and non-significant (negative) for nitrate, suggesting that knowing something about the landscape surrounding a sample point does not yield much insight into characteristics that are more dependent on upstream inputs from a larger contributing watershed.

Indeed, when we examined the Landscape Index for the upstream contributing area to a Level 3 sample point, we found a highly significant relationship with the benthic IBI, the fish IBI, and nitrate, suggesting that this may provide a better estimate of condition than a 1-km landscape circle, especially for more mobile indicators of stream condition. However, contributing area to a sample point is also more difficult to estimate than a 1-km circle. The algorithm for estimating contributing area used here was developed by researchers of the ASC as part of this project (M. Baker, personal communication).

Question 5: How well does average biotic condition in the watershed, as measured at 4–19 different points, agree with landscape condition in the watershed?

Finally, we made comparisons at the overall watershed level ($n = 21$). If the Landscape Index for watersheds is compared to the average Level 3 indices for watersheds, the relationship is strongest for the fish ($r = 0.89$, $p = 0.02$), weaker, but non-significant for the benthic macroinvertebrates ($r = 0.77$, $p = 0.08$), and non-responsive for nitrate ($r = 0.03$, $p = 0.96$). Recall that the Level 2 versus Level 3 comparison at the watershed level showed a similar pattern, in that the fish IBI was easier to predict at the watershed level than the benthic IBI or nitrate.

Question 6: Finally, how well does site-level aquatic condition in the watershed, measured as the average over 20 points, agree with overall landscape condition in the watershed?

If the Landscape Index for the overall watershed is compared with the average SWR Index, the relationship is weak and not statistically significant ($r = 0.26$, $p = 0.26$), suggesting that the average of 20 site-level physical habitat scores does not agree well with landscape patterns throughout the overall watershed. Possible explanations for this disagreement can be found in the Discussion.

The Landscape Index for the overall watershed was highly correlated with the average Landscape Index for the 1-km radius circles in the watershed ($r = 0.95$, $p = 0.000$), suggesting that these circles represented an adequate sample of the landscape condition within the overall watershed despite being proximal to the stream network. The landscape circles, however, show a stronger association relative to the spatial distribution and condition of aquatic sampling points than that of the overall watershed, because they characterize the land cover closest to the aquatic habitats of interest.

Condition of sampled watersheds based on average values of the SWR Index

The 20 SWR Index values within each watershed can be averaged to yield an estimate of overall watershed condition (Table 6). Figure 6 shows examples of site-level scores within two watersheds of similar area, but different land use. Although averaging the SWR Index obscures the considerable site-to-site variability within a watershed, we made the initial choice to use 14-digit HUC watersheds as our units of data collection for this study on the premise that this is a typical

Table 6 Mean and SD of Steam–Wetland–Riparian (SWR) Index, and Landscape Index, for each watershed sampled in the Mid-Atlantic Region

Watershed	Land cover classification	Physiographic region	Avg SWR index for watershed	SD SWR index	Watershed landscape index
Chickahominy	Urban	Piedmont	0.566	0.176	0.368
Conodoguinet A	Urban	Ridge and valley	0.555	0.088	0.314
Mantua	Urban	Coastal Plain	0.704	0.101	0.277
Gwynn Falls	Urban	Piedmont	0.548	0.103	0.166
Back River	Urban	Coastal Plain	0.454	0.113	0.123
Pamunkey	Mixed	Coastal Plain	0.626	0.122	0.644
Middle Creek	Mixed	Piedmont	0.583	0.120	0.514
Upper Patuxent	Mixed	Piedmont	0.704	0.106	0.476
Southeast Creek	Mixed	Coastal Plain	0.661	0.133	0.413
Grindle Creek	Mixed	Coastal Plain	0.415	0.103	0.611
Little Contentnea	Mixed	Coastal Plain	0.705	0.175	0.497
Middle River	Mixed	Ridge and valley	0.459	0.151	0.356
Ahoskie	Forest	Coastal Plain	0.425	0.135	0.669
Saint Mary's A	Forest	Coastal Plain	0.658	0.130	0.611
White Deer Creek	Forest	Ridge and valley	0.864	0.096	0.887
Wisconisco	Forest	Ridge and valley	0.698	0.202	0.757
Clearfield Creek	Forest	Ridge and valley	0.557	0.087	0.701
Buffalo Creek	Agriculture	Ridge and valley	0.634	0.166	0.470
Repaupo	Agriculture	Coastal Plain	0.717	0.086	0.432
Cattail Creek	Agriculture	Piedmont	0.590	0.112	0.420
Christian Creek	Agriculture	Ridge and valley	0.522	0.110	0.397
Watersheds missing data for one or more SWR metrics					
Spring Creek	Mixed	Ridge and valley	–		0.473
Ware River	Forest	Coastal Plain	–		0.704
Upper Penns Creek	Mixed	Ridge and valley	–		0.750

watershed size on which management decisions are commonly made. The SWR Index can be used to rank a group of watersheds according to their overall relative condition. The variability of the SWR Index can be used as an indicator of the magnitude of within watershed variation of condition. Portraying the SWR Index values spatially in a watershed graphic (Fig. 6) can serve to identify potential problem areas within the watershed. For sites with low SWR Index values, individual

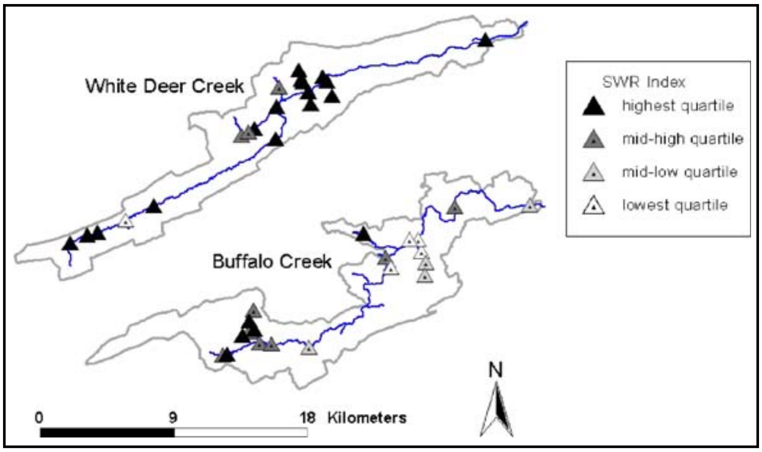

Fig. 6 SWR Index values for two proximal watersheds, demonstrating the ability to discern differences in condition between forested (White Deer Creek) and agricultural (Buffalo Creek) landscapes based on rapid assessment of condition at sampling points throughout each watershed

metrics can be examined to investigate the cause of their degraded condition. The stressor checklist for those sites can provide additional insight and diagnostic capability (e.g., Wardrop et al. 2007).

Discussion and conclusions

In summary, based on the data that were examined, we conclude the following:

- If the landscape condition within the contributing watershed area to a sample point is known, the biotic and chemical conditions at that point (as reflected by benthic invertebrates, fish, and nitrate) can be ascertained with some confidence.
- An alternative to the above is to average multiple sample points of site-level condition in the contributing area to a point of interest; however, the association may be slightly weaker.
- Knowledge of the landscape in the contributing area to a sample point appears to be more valuable than knowledge of landscape patterns in a 1-km circle around that point.
- In general, one needs information from a larger area to assess mobile indicators of condition (fish and nitrate) than relatively sedentary indicators (benthic invertebrates).
- In general, nitrate was most strongly related to aggregations of sites in a contributing area to a sample point (Level 1 or Level 2) versus single sites or the larger watershed.
- Although the link between Level 1–Level 2–Level 3 indices at a sample point or 1-km circle around that point, is fairly strong for the benthic IBI, the relationship among these three assessment levels is much less strong when index values are averaged over the watershed, and compared with landscape patterns throughout the entire watershed. This may be attributed to one or more factors:
    - Our Level 1 overall Landscape Index for watersheds of this size includes areas of the watershed that are not adjacent to streams and wetlands, and thus, are less relevant to aquatic condition; using a distance-weighted method instead might yield more spatially relevant results (King et al. 2005).
    - Twenty SWR sample points may not capture the variability of condition found in some heterogeneous watersheds, particularly those that are larger in area.
    - Averaging point data within a small watershed does not give us a meaningful measure of overall condition due to spatial heterogeneity, and/or the Landscape Index for the overall watershed does not give us a meaningful measure of condition.
    - We need a different means of aggregating or "scaling up" from the point level to the landscape level, perhaps using a distance-weighting approach.

The SWR Index and associated Landscape Indices were shown to correlate highly with biological indicators of stream condition. Using a top-down approach, managers can prioritize watersheds based on a synoptic landscape analysis (Level 1) that can provide a relative ranking of small watersheds. Watersheds of concern can then become the focus of more labor-intensive field investigations using rapidly deployed methods (Level 2). Stressor identification and further intensive studies (Level 3) can diagnose the expected causes of observed lower levels of ecological condition. Restoration and remediation strategies can be applied to those watersheds or portions of watersheds where managers and citizens elect to focus their limited resources.

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