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Methods for Generating Multi-scale Watershed Delineations for Indicator Development in Great Lake Coastal Ecosystems

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ABSTRACT. *Watersheds represent spatially explicit areas within which terrestrial stressors can be quantified and linked to measures of aquatic ecosystem condition. We delineated thousands of Great Lakes watersheds using previously proven and new watershed delineation techniques. These were used to provide summaries for a variety of anthropogenic stressors within the Great Lakes. All delineation techniques proved useful, but each had applications for which they were most appropriate. A set of watershed delineations and stressor summaries was developed for sampling site identification, providing relatively coarse strata for selecting sites along the U.S. Great Lakes coastline. Subsequent watershed delineations were used for high-resolution site characterization of specific sites and characterizing the full coastal stressor gradient. For these delineations we used three general approaches: 1) segmentation of the shoreline at points midway between adjacent streams and delineation of a watershed for each segment; 2) specific watershed delineations for sampled sites; and 3) a Great Lakes basin-wide, high-resolution approach wherein sub-basins can be agglomerated into larger basins for specific portions of the coast. The third approach is unique in that it provides a nested framework based on hierarchies of catchments with associated stressor data. This hierarchical framework was used to derive additional watershed delineations, and their associated stressor summaries, at four different scales. Providing anthropogenic stressor metrics in such a format that can quickly be summarized for the entire basin at multiple scales, or specifically for particular areas, establishes a strong foundation for quantifying and understanding stressor-response relationships in these coastal environments.*

INDEX WORDS: *Scale, watersheds, indicators, coastal, aquatic ecology, Great Lakes.*

INTRODUCTION

Watersheds have become widely recognized as critical functional and ecological management units (Diana *et al.* 2006). Long recognized for their importance in flood control and management, watersheds are now also recognized for their importance in water quality management and protection of aquatic habitats. Watersheds also provide a summary unit for monitoring and reporting on total maximum daily loads (TMDL) (Tong and Chen 2002) currently used by the U.S. Environmental Protection Agency and state water management agencies (http://www.mda.state.mn.us/agdev/impairedwater). This focus on watersheds has led to many advances in hydrologic science. The U.S. Army Corps of Engineers' Hydrologic Engineering Center in Davis, California developed several models (HEC-RAS, HEC-HMS) using watershed data to simulate precipitation-runoff processes and flood conditions while analyzing water quality within watersheds (http://www.hec.usace.army.mil/). Several GIS software companies have developed GIS-based

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tools that help delineate and analyze watersheds using standard elevation data. Others have begun to use NEXRAD radar to map precipitation patterns and estimate precipitation amounts in a spatially (specific to each watershed) and temporally explicit manner (hourly, daily, and monthly measures) (Knebl *et al.* 2005). States within the U.S. have also started to incorporate these technologies into their monitoring programs, as described by Magner and Brooks (2007). The Environmental Systems Research Institute (ESRI), along with key state, national, and international contributors, developed the ArcHydro data model (Maidment and Morehouse 2002) to better manage and process watershed information and watershed delineation methods. The ArcHydro data model is unique in that it provides a framework for delineating small sub-catchments and linking them along the stream network so that their attributes can be accumulated as a point of reference moves downstream through the watershed. This provides a system for developing standard subcatchment characterizations that cover the entire basin, but can be queried and summarized to provide information for specific sites throughout the basin.

The importance of developing cross-jurisdictional comprehensive management plans for the Great Lakes has also become more widely recognized (International Joint Commission [IJC] 1995). This is particularly true as watersheds, the boundaries of which are shaped by geomorphic and physical processes rather than political borders, have become more accepted as functional ecological units. At the same time, Great Lakes management agencies and non-government organizations have begun to focus on the socioeconomic and ecological importance of coastal margins, where terrestrial influences and stressors meet and mix with lakeward influences and stresses (IJC 2005). Because many terrestrial stressors are delivered to the coastal margin through hydrologic processes, quantifying stresses at a watershed scale may contribute to a mechanistic understanding of ecosystem condition at the coastal margin. An understanding of the relationship between anthropogenic stresses and the condition of ecosystems is a fundamental requirement for development of effective environmental indicators, and a key precursor to the creation and implementation of management strategies (Niemi and McDonald 2004, Niemi *et al.* 2004). Since these relationships span multiple temporal and spatial scales, scalable summary units (preferably based on watershed boundaries) are essential to accurately quantify stressor-response relationships. Quantification of stressors within hierarchically structured watersheds would enable landscape summaries to be conducted over the entire extent of a study region, then queried and reconstituted for smaller watersheds.

Also, ecological patterns and processes are thought to have characteristic scales at which their properties can best be described and studied (Wu and Li 2006). Unfortunately, the characteristic (intrinsic) spatial and temporal scales that regulate key processes are usually not known; therefore, multiple observations made at different scales are necessary (Bloschl and Sivapalan 1995, Niemi and McDonald 2004). In this paper, we illustrate the development of a hierarchical watershed framework that allows for testing various stressor-response relationships at multiple scales throughout the Great Lakes.

Watershed Delineation Approaches

Here we describe six types of watershed delineations, resulting from three different approaches, defining relevant spatial units of the landscape for summarizing stressors which could impact adjacent, downstream systems. These watershed delineations form the basis of indicator development for a broad variety of Great Lakes coastal margin indicators (Danz *et al.* 2007, Reavie *et al.* 2006, Morrice *et al.* 2007). Initial watershed delineations were developed to span the entire U.S. Great Lakes in support of site selection and specific sample site characterization needs. A intermediate delineation method was developed to assess particular groups of sites sampled in the field by project researchers. Experience gained from each of these delineations led to a third, alternative approach; a high resolution, Great Lakes-wide coverage of watersheds that provides for agglomerating the smallest spatial units up to different aggregate levels, depending on the purpose and need. In this third approach, watersheds were delineated for every stream draining an area of more than 2.7 km^2 toward the Great Lakes. Watersheds were ordered sequentially along the coast, enabling each drainage basin and its associated stressor summaries to be agglomerated to represent larger portions of the coast.

The objective of the Great Lakes Environmental Indicator (GLEI) project was to quantify stressor-response relationships for novel and existing indicators, develop predictive models to infer ecological status at the coastal margin, and derive integrative metrics of that ecological status among several indicator groups (birds, amphibians, fish, macroinvertebrates, algae, and water quality). To develop and test these indicators, we sampled multiple biotic and abiotic components of ecosystems across the U.S. side of the Great Lakes (Niemi *et al.* 2007). Sample sites were selected using a probabilistic sampling design stratified across five geomorphic types and relative amounts of anthropogenic stress (Danz *et al.* 2005).

Watershed Delineation Approach 1—Segment-Sheds

One of the highest priorities in the development of a comprehensive sampling program is site selection. Since robust indicators must be capable of identifying conditions along the full gradient of anthropogenic disturbance, quantifying stressors across the U.S. side of the entire Great Lakes basin was essential. The initial delineation approach addresses two problems. First, there was no single spatial unit that encompassed the coastal areas of the Great Lakes for summarizing stressors. Existing watershed delineations were too coarse, and further, did not include the coastal areas between river mouths. Second, although many different data sets (and variables) existed that could be used to describe the dominant stressors, only limited time was available to bring them into a common mapping framework. We chose to describe, map, and stratify stressors at a broad scale for site selection purposes, while reserving higher resolution summaries for later site characterization and analysis of areas actually sampled. Anthropogenic stressor data were compiled and summarized for unique contributing areas called "segment-sheds."

We defined a segment-shed as the land area draining to the shoreline beginning and ending halfway between a second- or higher-order stream and the adjacent streams on either side (Fig. 1) on the U.S. side of the Great Lakes (Fig. 2). Seven hundred sixty-two segment-sheds were delineated, using the National Elevation Data Set (NED) and watershed delineation tools available in ArcInfo Version 9.1 (ESRI 2000). The positions of segment shed-boundaries were visually assessed for errors, and edited when necessary, using ancillary map data including streams, aerial photos, and USGS scanned quad maps (digital raster graphics 1:24,000 and 1:250,000). We then compiled 207 different stressor variables from 19 data sources (Danz *et al.* 2005), and summarized them for each coastal segment-shed. Stressors representing human activities, including land cover, population density, point-sources, and agricultural land use, were assembled for the U.S. side of the Great Lakes basin. The multi-dimensional stressor gradient was represented by principal components (PCs) calculated within seven categories of stress (Danz *et al.* 2005).

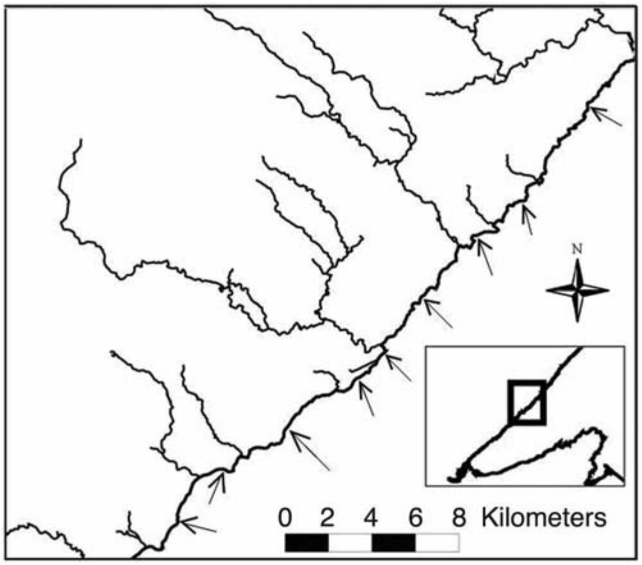

FIG. 1. Example of second-order and higher streams along the coast of western Lake Superior with arrows indicating the boundary between adjacent shoreline segments halfway between each stream mouth.

The segment-sheds were effective units for site selection, and also proved useful as an intermediate product for site stressor characterization. Because the segment-sheds covered the entire U.S. side of the Great Lakes basin, stressor summaries represent the full gradient of stress, ranging from the most pristine (reference) to most degraded. This information allows us to gauge the absolute position of sampled sites along the stressor gradient.

Watershed Delineation Approach 2—
Complex Specific Watersheds

An additional challenge was to precisely link areas sampled by research teams to the delineated-segment sheds and accompanying stressor summaries. This was complicated by the fact that the location, timing, duration, and spatial extent of sampling within segment-sheds varied greatly among GLEI research teams, reflecting the habitat, characteristics, and sampling strategies unique to

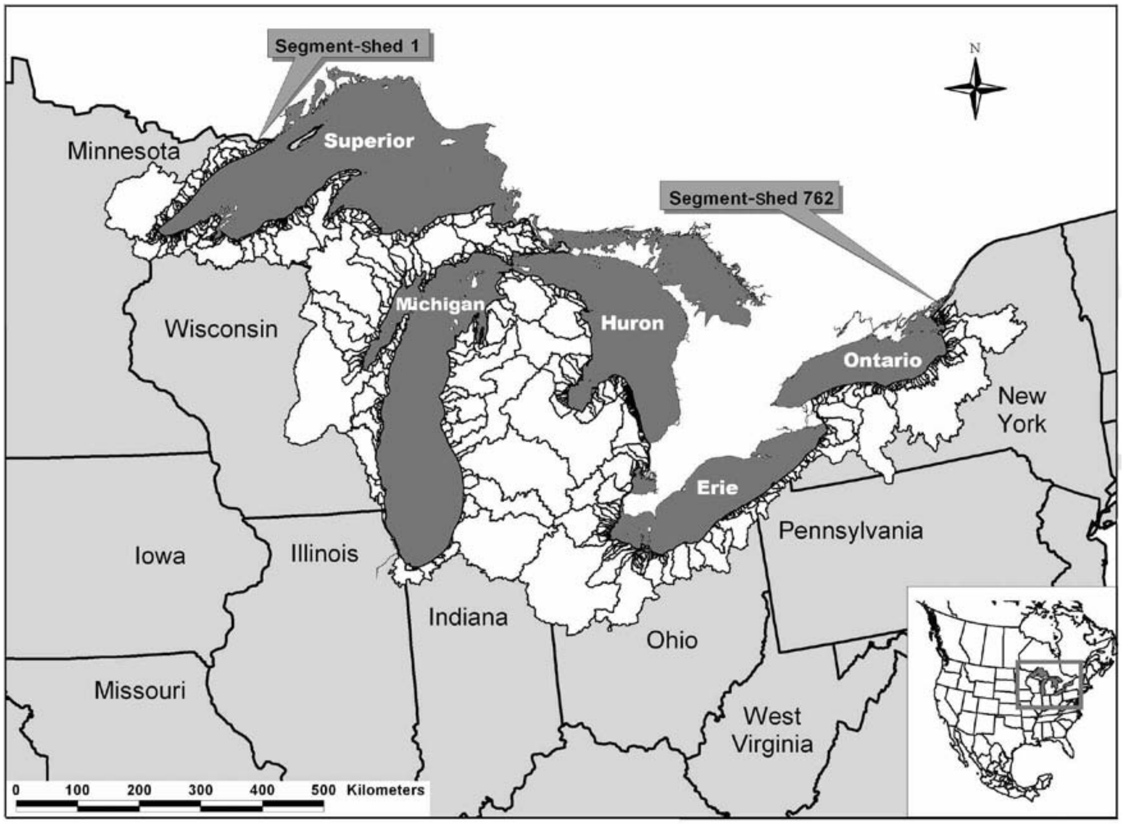

FIG. 2. Segment-sheds for the U.S. side of the Great Lakes.

the biota of interest. Unique sample units (locale polygons) were identified for each research team by combining GPS coordinates from each sample location. A total of 1,179 locale polygons was identified and delineated. These locale polygons were used to generate "complex" polygons, which encompassed the spatial boundaries of each unit sampled by all the groups (n = 530; hereafter called complexes). Watersheds draining to the sampled wetlands and embayment complexes were delineated (n = 344; wetlands and embayments only) using the NED and watershed delineation tools available in ArcInfo Version 9.1 (ESRI 2000). The delineations of the 344 complex-specific watersheds were visually assessed for errors, and edited when necessary, using ancillary map data including streams, aerial photos, and USGS scanned quad maps (digital raster graphics 1:24k and 1:250k).

This approach established a site-specific basis for defining topographic contributing areas for coastal wetlands and embayments receiving landscape-derived stressors via riverine flow paths. Subsequently, the 207 anthropogenic stressor variables previously compiled for segment- sheds were summarized across each complex watershed and analyzed using principal component analysis (PCA). Details of how GIS tools were used to support indicator development from field measurements of a variety of biota are provided in Johnston *et al.* (2006).

Watershed Delineation Approach 3—Hierarchically Nested Watersheds

The approach of using complex-specific watersheds worked well for geomorphic types that receive flow directly from the adjacent, upstream watershed (e.g., riverine wetlands and embayments), but was less applicable to lacustrine wetlands or high-energy areas where the boundaries of topographic contributing areas are not as obvious. For these areas, an alternative to the classic topographically-defined watershed was needed to quantify stressors that might be delivered from both nearby terrestrial areas as well as from the lake itself, via long-shore currents, wind, and waves.

The ArcHydro data model (Maidment and Morehouse 2002) delineates hierarchically structured sub-catchments for each steam segment (reach) be-

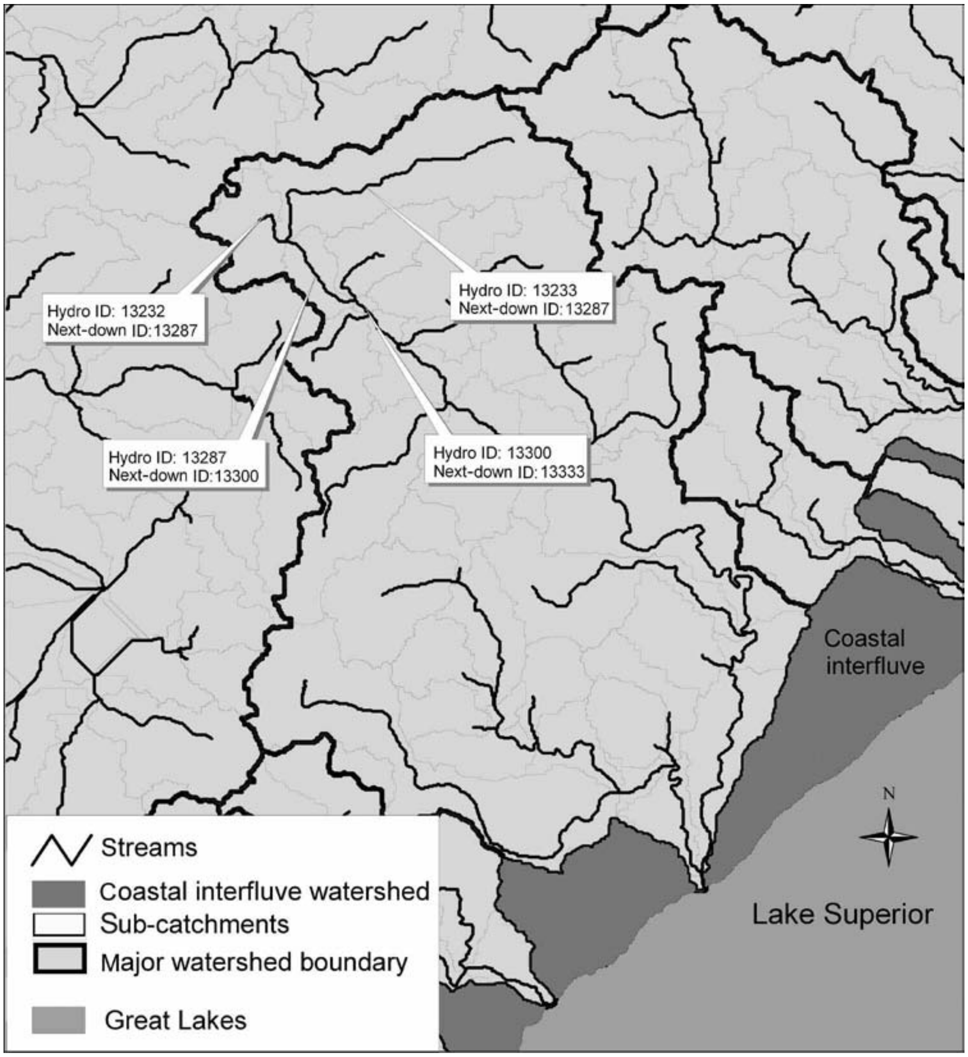

FIG. 3. Network connectivity of ArcHydro catchments. Each stream segment is identified both by its own unique numerical label (Hydro ID) and by the number of the "next-down" segment into which it flows (next-down ID). Sub-catchments (shown faintly) for each stream segment are also assigned the same IDs.

tween stream confluences. Stream reaches are numbered in sequence such that each sub-catchment includes a unique identification label and the "next-down" identification of the catchment into which it flows (Fig. 3). This allows stressor summaries to be calculated for each sub-catchment; for these values to be summed cumulatively down the hydrologic network, and for the entire watershed. This data structure better accommodates analyses of systems exhibiting different hydrology among drainage basins, and permits future analyses that incorporate different scales of influence.

The ArcHydro data model also allows for watershed delineations that incorporate existing maps of streams to create hydrologically corrected elevation models (Maidment 1997). We used map data representing connected stream networks of the National Hydrologic Data Base (http://nhd.usgs.gov) combined with National Elevation Data (http://ned.usgs.gov). Using ArcHydro, we also located and "filled" sinks (areas in the elevation data that are lower in elevation than their surroundings) to ensure that flow continuity and flow direction were properly delineated along the course of a drainage basin. Flow accumulation was calculated from these corrected delineations. Areas with high flow accu-

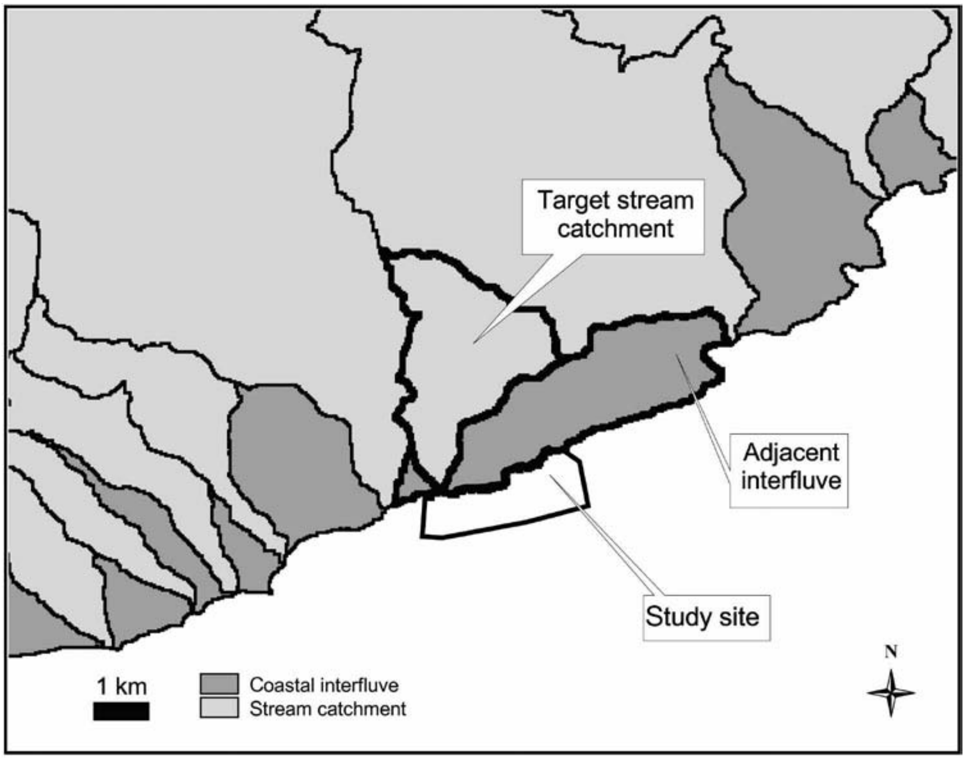

FIG. 4. The immediate watersheds (stream and interfluve) adjacent to a high-energy fish study site.

mulation were then designated as streams. To be operationally identified as a stream, an area had to receive flow from an upstream area of at least 3,000 30 × 30 m pixels (2.7 km^2), to roughly coincide with streams mapped at 1:24,000. After the streams were delineated, ArcHydro catchments were delineated for stream lengths between stream confluences.

Connected networks of streams flowing to the Great Lakes coast were individually identified, and all streams and catchments within that network were given a network-level identification number. Discrete watersheds flowing to the coast were then uniquely identified and merged to form a hierarchical network of highly detailed watersheds flowing to the Great Lakes coast.

Drainage basins narrow at their downstream terminus where their rivers discharge into the lake, and the land areas between river-mouths draining directly to the shoreline are not accounted for. These areas, referred to as coastal "interfluves" (Gilliam *et al.* 1997) were delineated by intersecting the coastal watershed boundaries with a polygon representing the terrestrial portion of the Great Lakes basin, derived from satellite imagery (Wolter *et al.* 2006). These coastal interfluves (n = 1,818), were then added to the network of stream watersheds (n = 1,773), creating a total of 3,591 coastal watersheds and interfluves (Fig. 4).

Watershed delineation approach 3a—stream interfluves delineation. After coastal interfluve polygons and stream watershed polygons were combined into a single map layer, they were ordered and numbered along the coast from the U.S./Canada border in western Lake Superior, counter-clockwise to the easternmost polygon where Lake Ontario empties into the St. Lawrence River. Like the previous watershed delineations, the boundaries were visually assessed for errors and edited when necessary, using ancillary map data including streams, aerial photos, and USGS-scanned quad maps (digital raster graphics 1:24,000 and 1:250,000). Ordering the watersheds with sequential identification numbers along the coast provided a framework for combining small watershed units and their related stressors along the entire U.S. Great Lakes shoreline. Watersheds and associated stressors adjacent to an area of interest are easily identified by their consecutive ID

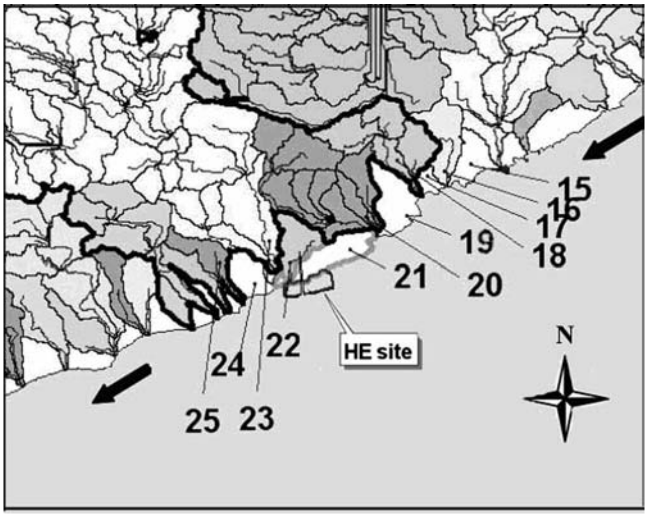

FIG. 5. Ordered and numbered stream and coastal interfluve watersheds along the Great Lakes coastline near a high-energy site (HE).

numbers (Fig. 5). These unique areas consisting of the shoreline and adjoining riverine watersheds provide a means to summarize and assess the effects of watershed-scale anthropogenic stresses delivered to specific coastal ecosystems.

The relative contribution of stressor effects flowing from adjacent land areas along the coast varies greatly based upon seasonal currents, storm and wind events, nearshore topography, and other local conditions. Spatial ordering of watersheds provides the means to account for stressor effects contributed from outside a particular ecosystem's immediate watershed (e.g., by long-shore currents) (Fig. 5). As stressor delivery mechanisms become better understood and mapped, this scalable watershed framework can be used to differentially weight the contributions to a specific site from nearby watersheds, based on their proximity and direction of prevailing currents, to represent the lakeward delivery of sediments, contaminants, and other waterborne stressors to these coastal areas. This framework might also be applied to circulation models for embayments and harbors or large lakes, providing an ordered link between stressors in the watershed and the receiving body of water.

Watershed delineation approach 3b—agglomerated stream delineation. Coastal interfluve areas are numerous and generally quite small (85% are < 5 km^2 in area), yet important because they represent a large percentage of the shoreline (all coastline between stream mouths). Not wanting to discount or over-weight stressors contributed by these interfluve watersheds, we agglomerated them with stream watersheds to provide a spatially relevant unit over which stressors could be characterized. Ideally, we would have divided the interfluve watersheds along a boundary, beginning and ending half way between stream mouths that would ascribe a hydrologically-relevant portion of the interfluve to each stream watershed in much the same way as the segment-sheds. However, there was no practical way to accomplish this in an automated fashion, due to lack of a side-to-side topographic gradient. Therefore, we calculated area-weighted stressor summaries for the interfluve stressors and assigned 50% to each adjacent stream watershed. A total of 1,773 agglomerated stream interfluve watershed units resulted from this process.

Watershed delineation approach 3c—core high energy. Since wind- and wave-exposed, high-energy coastal locations are subject to both land- and lake-based stressors, an alternative to traditional watershed delineations is needed to account for stressor effects that originate from the land, but may be transported by nearshore currents. To summarize stressors likely to affect high energy sites, we agglomerated multiple watersheds and their stressor scores, using only watersheds immediately adjacent to each "core" high-energy site. Like the other watershed agglomerations described above, area-weighted means of the immediately adjacent watershed stressors were used to calculate the combined stressor score for each "core" high energy site.

Watershed delineation approach 3d—minimum area threshold. For a broader-scale characterization of stressors associated with high-energy sites, we also agglomerated multiple watersheds and their stressor values, until a minimum area threshold was reached (Fig. 6). The stream and interfluve watersheds adjacent to the high-energy sample sites were agglomerated until a minimum area threshold was reached. Although any threshold size can be used, we set the threshold at twice the area of the median size of the 762 original segment-sheds (approach 1) (9 km^2), providing a slightly broader watershed delineation for each high-energy sample site. Watershed stressor summaries (area-weighted means) were com-

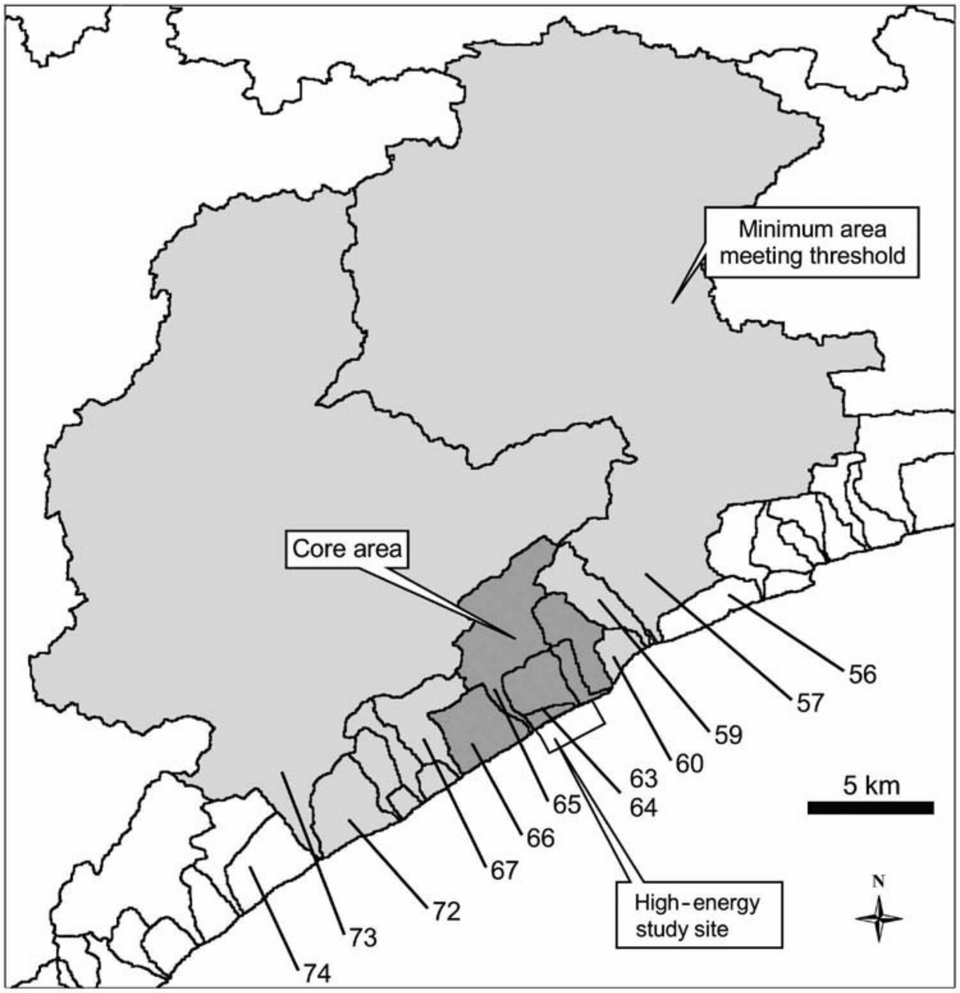

FIG. 6. Core watershed for immediate high-energy site watersheds and agglomerated watershed based on a minimum area threshold for a high-energy site.

piled for these minimum area watersheds in the same way as the core watersheds.

RESULTS AND DISCUSSION

Management of coastal ecosystems presents a particular challenge compared to lakes or rivers, because material and energy are transported to the coast from both the land and the lake (or sea). Newly developed and now readily available techniques have enabled us to overcome some of the deficiencies of traditional watershed delineation methods to facilitate studies of interactions between landscapes and coastal ecosystems. Six different types of coastal watersheds, delineated using three main approaches, were found to be useful for quantifying stressors affecting coastal ecosystems: 1) segment-sheds, 2) complex-specific site watersheds, 3) stream/interfluve watersheds, 4) agglomerated-stream watersheds, 5) "core" high-energy area watersheds, and 6) minimum area threshold high-energy area watersheds. Three of these delineations provided watershed measures comprehensively across the entire U.S. Great Lakes coastline (methods 1, 3, and 4 above). To date the other two methods have been applied to watersheds specific to sites sampled by investigators of the GLEI project, although these methods could be used to characterize additional sites in the future. The advantages and limitations of each watershed delineation approach are shown in Table 1.

Because the segment-shed and the merged

TABLE 1. Advantages and disadvantages of each watershed delineation approach.

Approach	Type	Extent	Advantages	Limitations	Best use
Standard watershed delineation	Segment-sheds (n = 762)	Basin-wide	Easy to calculate; basin-wide	Coarse resolution	Site selection; generalized stress gradient, reference/degraded designation
Standard watershed delineation	Complex-specific (n = 344)	Sampled sites	High resolution	Hard to calculate; not basin-wide (sample dependent)	Site characterization
ArcHydro	Stream/interfluve (n = 3,591)	Basin-wide	Easy to calculate; fine resolution; scalable; basin-wide	Produces many small units	Site characterization; reference/degraded designation
ArcHydro	Agglomerated-stream (n = 1,773)	Basin-wide	Easy to calculate; fine resolution; scalable; basin-wide	Small units	Site characterization; reference/degraded designation
ArcHydro	Core high-energy (n = 47)	Sampled sites	Easy to calculate; scalable	Not basin-wide (sample dependent)	Site characterization
ArcHydro	High-energy min. area threshold (n = 47)	Sampled sites	Scalable; addresses long shore currents nearby tributaries etc.	Moderately difficult to calculate; not basin-wide (sample dependent)	Site characterization

stream/interfluve watershed approaches cover the full U.S. side of the Great Lakes basin, the derived stressor scores represent the entire sampling universe of possible values for the U.S. Hence, the extreme values of the stressor distributions can potentially be used to identify reference (defined here as least disturbed; Host *et al.* 2005, Stoddard *et al.* 2006) as well as degraded "most disturbed" areas.

Size Frequency Distributions

Because large watersheds are likely to function differently than small watersheds, we calculated the size frequency distribution of watershed sizes for each of the six approaches for the Great Lakes coastal areas. Across the six watershed delineation types, watershed sizes varied widely from small (< 1 ha) coastal interfluve watersheds to large riverine watersheds, e.g., the Maumee River basin of western Lake Erie (16,837 km^2). In general, the ranges of watershed size for each of the delineation types were similar, except for the minimum-area high energy types. High-energy "minimum area threshold" watersheds had the largest median size, whereas the stream/interfluve and complex specific watersheds had the smallest median size (Fig. 7). Segment-sheds and complex-specific watersheds were fairly comparable in size and seemed to fall evenly between the smallest and largest watershed types (Fig. 7). This was likely due to the fact that segment-sheds were defined by second-order and higher streams, and selection criteria for river-influenced wetland sites included second-order and higher streams.

All three of the delineation techniques that encompass the entire basin had many outliers in the size frequency distribution, particularly on the large side of the distribution (Outliers were defined as values that are greater than 1.5 times the middle 50% range or either the bottom 25th or top 75th quantile). Stream/interfluve watersheds had the greatest number of small drainage basins; both large and small outlier values were observed. The agglomerated-stream approach, which combined the coastal interfluve watersheds with the nearby stream watersheds, eliminated all outliers on the small side of the size distribution, leaving a limited number of large watersheds as outliers in a log-nor-

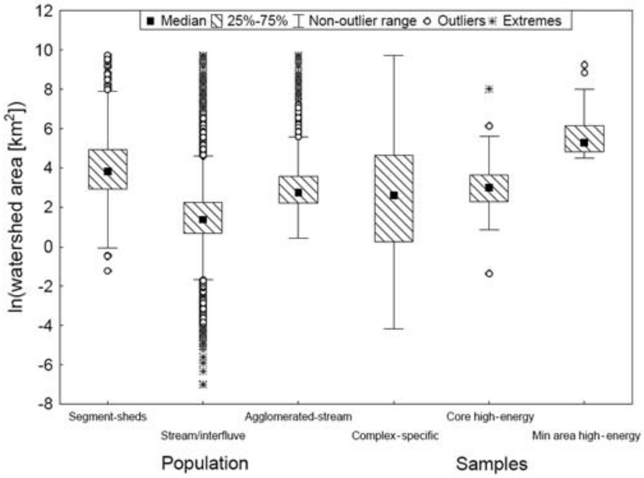

FIG. 7. Average watershed size (ln) for the six methods of watershed delineation.

mal distribution. These large watersheds could be a source of bias in some comparisons, since watershed size can affect the delivery of anthropogenic stresses to coastal ecosystems. Trends in the relationships between watershed size and the mechanisms by which stressors are delivered from the watershed to the coastal ecosystem in question are a topic of continuing study.

Fortunately, the third approach described above provides a method by which large watersheds can be disaggregated into smaller units to address this scale question. This could be accomplished by subdividing a large watershed into component tributary watersheds and interfluves that flow to the river's main stem. A similar technique could be used to disaggregate watersheds for embayments and harbors or large lakes. The ability to scale watershed units up or down in size is necessary because large watersheds are likely to function differently than small watersheds. Watershed size affects baseflows, flow velocities, and fluvial processes (Bilby and Ward 1989), which in turn affect the delivery of anthropogenic stresses to coastal ecosystems. Future indicator development should consider the relationships between watershed size and the mechanisms by which stressors are delivered from the watershed to the coastal ecosystem in question. Watershed indicators of anthropogenic stress should also be verified at multiple scales.

Wiens (1989) identified several ecosystem characteristics that he suggested depend upon the scale at which they are measured (fine or broad). These include decreasing variability with increasing data resolution, the number of variables important in correlations, the potential for deriving generalizations, and the form of the model (empirical, correlative) most appropriate for characterizing the system

TABLE 2. General characteristics of various attributes of ecological systems and investigations at fine and broad scales of study. "Fine" and "broad" are defined relative to the focus of a particular investigation and will vary between studies (Wiens 1989).

Scale	Fine	Broad
Number of variables important in correlations	Many	Few
Rate of processes or system change	Fast	Slow
Capacity of system to track short-term environmental variations	High	Low
Potential for system openness	High	Low
Effects of individual movements on patterns	Large	Small
Type of heterogeneity	Patch	Landscape mosaic
Resolution of detail	High	low
Sampling adequacy (intensity)	Good	Poor
Effects of sampling error	Large	Small
Experimental manipulations	Possible	Difficult
Replication	Possible	Difficult
Empirical rigor	High	Low
Potential for deriving generalizations	Low	High
Form of models	Mechanistic	Correlative
Testability of hypotheses	High	Low
Surveys	Quantitative	Qualitative
Appropriate duration of study	Short	Long

TABLE 3. Watershed delineation approaches used by Great Lakes Environmental Indicators (GLEI) project investigations. See text for a description of the delineation methods. Geomorphic types are wetlands (W), embayments (EB), and high-energy shorelines (HE), and open water (OW).

Delineation type	**1-Segment-sheds**	**2—Complex specific watersheds**	**3a-Stream/interfluve delineation**	**3b—Agglomerated stream delineation**	**3c-Core high-energy**	**3d—Minimum area threshold**			
Stress summary available									
Individual stressors	X	X	X	X	X	X			
PCs*	X	X	X						
Max rel**		X		X	X	X			
In this issue							**Stressor type**	**Response variable**	**Geomorphic types**
Peterson *et al.*	X						PCs	Stable N isotopes (plankton and benthos)	W, EB, HE
Brazner *et al.*	X	X					Individual stressors	Birds, amphibians, fish, macroinvertebrates, diatoms, vegetation	W
Trebitz *et al.*	X	X					PCs	Water quality	W
Reavie	X	X				X	PCs	Diatoms (diatom inferred water quality)	W, EB, HE
Howe *et al.*	X						PCs	Birds	W
Kireta *et al.*	X	X		X			PCs	Diatoms (diatom inferred water quality)	W, OW
Kang *et al.*	X						PCs	Macroinvertebrates	W, EB, HE
Price *et al.*	X						PCs	Amphibians	W
Bhagat *et al.*	X						PCs	Fish	W
Other publications									
Delineation approach	**1**	**2**	**3a**	**3b**	**3c**	**3d**	**Stressor type**	**Response variable**	**Geomorphic types**
Bhagat 2005	X	X					PCs	Fish	W, EB, HE
Bourdaghs and Johnston 2006	X						PCs	Vegetation	W
Reavie *et al.* 2006	X	X					PCs	Diatoms (diatom inferred water quality), water quality	W
Brazner *et al.* 2007	X						Human dist index	Birds, amphibians, fish, macroinvertebrates, diatoms, vegetation	W
Danz *et al.* 2007	X						PCs	Water quality, fish, birds	W, EB, HE
Hanowski *et al.* 2007	X							Birds	W
Morrice *et al.* 2007	X						PCs	Water quality	W
Reavie *et al.* 2007	X			X		X	PCs, maxrel	Diatoms (taxon characteristics, diatom inferred water quality, multimetric index)	W, EB, HE
Sgro *et al.* 2007	X	X					PCs	Diatoms (diatom inferred water quality)	W
Yurista and Kelly 2007	X						PCs	Water quality, plankton	OW
Bhagat *et al. in prep*	X	X		X		X	PC, indiv stressors	Fish	W, EB, HE
Brady *et al. in prep*	X	X		X		X	PC, indiv stressors	Macroinvertebrates	W, EB, HE
Johnson *et al. in prep*	X	X		X		X	Max-rel, PCs, indiv stressors	Fish, habitat	W, EB, HE

** Danz et al. 2005; ** Host et al. 2005*

(Table 2). Although watersheds delineated at different scales may or may not exhibit these characteristics exactly, it is informative to consider them. For instance, small watersheds may be more subject to outside influences (openness) than large watersheds. Are the effects of sampling error larger with small watersheds than with large watersheds? Wiens (1989) suggested there may be domains of scale wherein patterns change slowly or not at all. These domains are then separated by transitions in which system dynamics seem chaotic and patterns change quickly. The availability of tools to create flexible, multiple-scale, coastal watershed delineations may bring us one step closer to identifying the appropriate scales needed to best understand the relationship between environmental stress and ecologic response.

The watershed delineations described above and their subsequent stressor summaries have been used to evaluate stress response relationships for different taxa in a variety of coastal ecosystems. Many of those efforts are described in the following papers presented in this special issue. Table 3 summarizes those studies by taxonomic emphasis and indicates the watershed delineations used. Although most groups applied the segment-shed delineations for site selection and many used the complex-specific watershed delineations for site-specific characterizations, work continues using the detailed stream/interfluve delineations and agglomerations for predicting water quality, plankton, fish, and invertebrate communities.

SUMMARY

We used three approaches to delineate the contribution of water and anthropogenic materials from land to aquatic habitats at Great Lakes coastal margins. They have all proven useful in facilitating the development of indicators for the Great Lakes, particularly in providing a means for *a priori* site selection across a stressor gradient, and in characterizing the locally derived stresses on sites that had been sampled to estimate biological condition. These alternative approaches have much higher resolution than our initial segment-shed delineations, and permit the stressor data to be queried and scaled to a particular area of interest using area-weighted means. Because of their scalability, we believe stream/interfluve watersheds, and their associated stressor summaries will be useful for many applications, in addition to indicator development, including setting conservation priorities for minimally-disturbed areas, developing restoration endpoints, and prioritizing management actions.

A limitation of the work to date is that it addresses only the U.S. side of the Great Lakes. Scalable stream/interfluve watersheds are currently being derived for the Canadian portion of the Great Lakes and will provide for an integrated binational set of detailed watersheds for the entire Great Lakes basin. A complete basin-wide inventory of Great Lakes watersheds, combined with unified land cover and stressor summaries, will ultimately provide a high resolution "scalable" and consistent characterization of the entire Great Lakes anthropogenic stressor gradient. A data set that quantifies the stressor gradient seamlessly across the entire basin will greatly facilitate our ability to develop binational management for the largest freshwater system in the world.

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