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Abstract–Through ecological classification, researchers both (1) identify and (2) describe naturally-occurring, ecologically-distinct, spatial units from a holistic perspective. An ecological river classification involves the identification of structurally homogeneous spatial units which emerge along the channel network as a result of catchment processes interacting with local physiographic features. Our observations of Michigan rivers suggest that the natural ecological unit, as defined by the spatial scales of riverine physical and biological processes, is most closely approximated by the physical channel unit termed the valley segment. Valley segments are generally quite large, and characterized by relative homogeneity in hydrologic, limnologic, channel morphology, and riparian dynamics. Valley segment characteristics often change sharply at stream junctions, slope breaks, and boundaries of local landforms. We followed several steps in developing an ecological classification for the rivers of lower Michigan. Step 1 – We first selected catchment size, hydrology, water chemistry, water temperature, valley character, channel character, and fish assemblages as fundamental attributes to describe ecological character of river valley segments. Steps 2-3 – Two experienced aquatic ecologists worked together, interpreting map information on catchment and valley characteristics from a GIS, using their combined knowledge of ecological processes and interactions. We initially examined several key maps to become familiar with the general landscape patterns of a particular catchment; and to then identify initial valley segment units as defined by catchment and valley characteristics, and fish assemblages. Boundary definition required the integration of terrain features observed on several thematic maps (e.g., major stream network junctions, slope breaks, boundaries of major physiographic units or land cover units; or changes in stream sinuousity and meander wavelength patterns, riparian wetlands, or valley shape), combined with knowledge of fish distributions. We next developed categorizations for each component attribute

and assigned category values for attributes to each segment unit. Assignments were based on map-interpretation rules drawn from modeling, survey data, and field experiences. Step 4 – our results were stored as a map and a table in ArcView 3.0 format. In all, we partitioned and classified the 19 largest river systems in lower Michigan. Summaries of the attributes assigned to over 270 river valley segments (covering mainstems and major tributaries) provided an initial description of the river resources of lower Michigan. Managers of lower Michigan rivers will be able to develop many of their thoughts and activities within this framework of ecological units. Development of this system is intended to be ongoing; with the extension of coverage to upper Michigan, the continued validation of attribute codings, and the addition of new attributes.

The utility of classification systems in ecosystem management is widely accepted (Anonymous 1993). The tremendous diversity of ecological systems makes it difficult to generalize our management experiences or protocols from place to place. Ecological classification (defined as integrating both physical and biological elements) provides a way of simplifying this complexity, allowing generalization across relatively homogeneous spatial units; and providing a spatial framework for organizing data, and extrapolating from site-specific models and information (Barnes et al. 1982; Rowe 1991; Hudson et al. 1992; Albert 1994; Maxwell et al. 1995). Ecological classification also has a tremendous educational value. It can provide a comprehensible summary of the complex array of physical and biological processes which, over time, shape the natural world around us. Learning to recognize the landscape as a mosaic of distinct ecological units is valuable training for resource managers, providing a short-hand for thinking and communicating about the consequences of complex ecological processes (Bailey et al. 1978; Rowe 1984, 1991; Levin 1992).

Description of ecological classification

Through ecological classification we both (1) identify and (2) describe naturally-occurring, ecologically-distinct, spatial units from a holistic perspective. Ecological classification differs from habitat classification in the explicit use of biological criteria, in addition to abiotic criteria, for delineating unit boundaries. The ecological character of each unit emerges as the unified expression of its unique, abiotic (e.g., aspects of climate and geology) and biological (e.g., photosynthesis, respiration, and population interactions) processes (Spies and Barnes 1985; Rowe and Barnes 1994). These ecological units are observable places where constituent air, water, sediment, and organisms co-occur as a distinct bio-physical system (Rowe 1984, 1991; Rowe and Barnes 1994).

Location and delineation of units is the key, first step in ecological classification; this occurs "from above", from a larger map-scale (Rowe 1984; Rowe and Barnes 1994). The operating hypothesis is that relatively-homogeneous ecological units exist; and can be recognized in the spatial correspondence of selected physical and biological traits, using ecological theory and field experience (Barnes et al. 1982; Spies and Barnes 1985; Rowe 1991; Rowe and Barnes 1994). Traits that drive numerous ecological processes are often given extra weight; in terrestrial work for example, physiography (land composition and form) is considered fundamental, as it is relatively stable and helps shape local climate, soils, and vegetation patterns (Rowe 1984; Spies and Barnes 1985; Rowe 1991). The distributions of biota are also given special weight as an important delimiting criteria, though they are inherently variable due to their dependence on both ecological and historical processes. Biota can be important driving variables that help shape the ecological unit, and their characteristics typically integrate and express the overall ecological signature of the unit (Rowe 1961;

Barnes et al. 1982). Ecological classifications describe a unique place at a specific time (typically the present); therefore, culturally-derived landscape features (e.g., land use patterns) are often included as ecological criteria (Rowe 1989).

The second step involves describing these units by assigning them ecological attributes. Attributes are typically assigned based on observed or predicted site-scale characteristics (Rowe 1984). Component attributes are usually expressed categorically and this information is often used to formulate logical groupings of similar ecological units into unit types (Spies and Barnes 1985; Rowe 1991). Davis and Henderson (1978), however, pointed out the value of retaining information on as many component attributes as possible, as this provides the most flexible information set.

Ecological classification of river units

Early river classifications included ecological, longitudinal zonation schemes that tied distinctive community composition to key physical variables such as temperature, substrate and network position; and systems built on distributions of selected biota (see review by Hudson et al. 1992). More recently, greater emphasis has been placed on describing physical channel units at various scales (Frissell et al. 1986; Hawkins et al. 1993; Rosgen 1994; Maxwell et al. 1995) to provide a physical habitat templet for description of the structure and operation of stream communities (Frissell et al. 1986). This parallels the concept of the geocoenose used by forest ecologists in Europe (Kimmins 1987; Rowe and Barnes 1994).

Our interest in a more ecologically comprehensive system can be illustrated with an example. Imagine two tributaries to Lake Michigan that are identical in catchment and valley characteristics (physical habitat template). However, only one has a barrier dam within a lower reach that excludes migratory fishes from Lake Michigan (e.g., Pacific salmon). Exclusion of these fish will arguably alter fish community structure, food webs, nutrient cycles, and toxic chemical concentrations in the dammed stream—thus the presence or absence of fishes help define a stream's fundamental ecological character.

Terrestrial ecologists have generally treated the spatial organization of the landscape as a hierarchically-nested mosaic of ecological units (Bailey et al. 1978; Albert et al 1986; Barnes et al. 1982; Rowe 1991). Sites (plots) represent basic sampling units but the smallest ecological unit is the land type association (= geo-ecosystem = biogeocoenose; Rowe 1961, 1969; Rowe and Barnes 1994; Kimmins 1987), which has a relatively homogenous floral community, and consistent edaphic and micro-climatic features. Regional ecosystems (sensu Albert et al. 1986; Albert 1994) represent units nearer the top of the hierarchy and incorporate large regions (100's to 1000's of square miles) of similar climate and physiography. A parallel hierarchy of riverine units has been suggested: ie. sites, valley segments, and watersheds (Chamberlin 1984; Frissell et al. 1986; Maxwell et al. 1995).

Ecological classification of river systems at a scale useful for management has been proposed (Hudson et al. 1992; Maxwell et al. 1995) but seldom implemented across any large region. An ecological river classification involves the identification of structurally-homogenous spatial units within the river (analogous to the terrestrial ecologists' ecosystem type but with similar aquatic chemistry, biota, temperature, hydraulics, and riparian structure), which emerge along the channel network as a result of catchment-scale ecological processes interacting with local physiographic features.

Ecological river units – valley segments

River systems are typically viewed as composed of many smaller, distinct ecological units (Balon and Stewart 1983; Chamberlin 1984; Naiman et al. 1988; Halliwell 1989; Hudson et al. 1992; Bayley and Li 1992; Maxwell et al. 1995). One can identify river segments having distinctive, relatively homogeneous (or ordered patterns of) hydrology, hydraulics, chemistry, temperature regime, channel morphology, channel habitat, sediment budget, disturbance regime, and community structure. Boundaries between these units are relatively distinct (when viewed at the appropriate scale), because:

- The abrupt junctures of unrelated hydrologic systems (e.g., the confluence of streams draining independent catchments) can result in marked changes in ecosystem properties associated with hydrology. For example, discharge itself can increase dramatically, with rapid responses in sensitive thermal and hydraulic regimes (Statzner and Higler 1985; Frissell et al. 1986). Additionally, the addition of unique waters can alter chemical, thermal, and material-load conditions (Minshall et al. 1985).

- The linear river passes across a mosaic of landscape types with abrupt boundaries (Naiman et al. 1988; Maxwell et al. 1995; Bryce and Clarke 1996; Corner et al. 1997). Local geologic features influence immediate slopes (and thus hydraulics), channel cross sections, meandering patterns, development of pools and riffles, substrates, and groundwater inputs (temperatures); and can act as mid-river base-level controls on upriver grade (Statzner and Higler 1985; Frissell et al. 1986; Cupp 1989; Rosgen 1994; Bryce and Clarke 1996). Local geomorphologies (e.g., plains, hills and mountains, or glacial valleys) also affect channel forms, including floodplain structures (Minshall et al. 1985; Frissell et al. 1986; Cupp 1989; Rosgen 1994; Baker 1995). Local vegetation influences shading of, and carbon inputs to, the stream (Frissell et al. 1986).

- The (unpredictable) presence of mid-river lakes and impoundments can likewise act as base-level controls on upriver grades (Statzner and Higler 1985), and have strong effects on downstream chemical, thermal, and material regimes (Ward and Stanford 1983; Minshall et al. 1985; Frissell et al. 1986).

The whole river system, then, is a branched, linear mosaic of these ecological units; patterned both by longitudinal (catchment-derived) factors (such as accumulating discharge; Minshall et al. 1985) and by location-specific factors (such as geology and geomorphology; Statzner and Higler 1985; Frissell et al. 1986; Cupp 1989; Hudson et al. 1992; Bryce and Clarke 1996).

Our observations of Michigan rivers suggest that the natural ecological unit, as defined by the spatial scales of riverine physical and biological processes, is most closely approximated by the physical channel unit termed the valley segment. Valley segments are variable in length, but are generally quite large (perhaps 3-60 km [2-40 mi]). A segment is characterized by relative homogeneity in hydrologic, limnologic, channel morphology, and riparian dynamics (Frissell et al. 1986; Cupp 1989; Hudson et al. 1992; Rosgen 1994; Maxwell et al. 1995). Valley segment characteristics often change sharply at stream junctions, slope breaks, and boundaries of local landforms. Segment boundaries can be interpreted from large-scale maps and segment attributes can be easily field-verified.

The valley segment scale is attractive for the study of river ecological units for several reasons:

- It is close to the scale at which rivers react to heterogeneity in the landscape by forming channel networks; and responding to local slopes, geologic materials, and land uses (Maxwell et al. 1995; Bryce and Clarke 1996). Each segment of the river bisects a fairly homogeneous landscape unit (e.g., Corner et al.'s [1997] Landtype Associations). Segments also describe relatively persistent features of channel and riparian habitats (on the order of 10^2-10^3 years; Hudson et al. 1992; Baker 1995).

- The valley segment scale is similar to that at which fish (and other aquatic organisms) operate (Hawkes 1975; Maxwell et al. 1995). One, or several adjacent, segments are large enough to likely contain the multiple habitats required by stream fishes during their life cycle (Schlosser 1991). It follows that several physically-defined valley segments might sometimes be incorporated as one ecological unit. It is clear that stream fishes are extremely mobile, especially among seasonal habitats (Gowan et al. 1994, Bayley and Li 1992); so smaller units such as reaches or channel units are inadequate to encompass population dynamics.

- Though fairly homogenous, segments also have internal organization represented by some predictable series of smaller-scale reach units (e.g., alternating stretches of relatively consistent slopes within the segment) and further-nested channel habitats (e.g., pools, riffles, substrates) that are used by organisms during specific life stages and seasons (Rowe 1969; Frissell et al. 1986; Hudson et al. 1992; Hawkins et al. 1993; Rosgen 1994). Thus segment attributes can include the description of patterns in local habitat structure and provide a framework for smaller-scale classifications where desired.
- The valley segment is probably the smallest river unit that can be interpreted from large-scale maps and analyzed across large geographic areas (states or regions; Frissell et al. 1986; Maxwell et al. 1995). The primary landscape features of interest (e.g., river networks, slopes, geologic materials, and land uses) are readily observed on maps of 1:100,000 or even 1:500,000 scales.
- Information at this scale is relevant for management and planning, since it is the scale at which important physical and biological processes operate. Individual segments have predictable ecological traits, allowing the development of local management goals and strategies. And segments are few enough that information can be easily compiled for regional analyses.

Developing an ecological classification for Michigan rivers

We used the following 6 steps in the development of our classification (modified from the more general steps provided by Davis and Henderson 1978).

- Step 1 is the selection of key attributes for identifying ecological units. Variables selected for river classification should be (1) fairly stable in time; (2) easily quantifiable; (3) representative of either catchment-scale hydrologic, or local-scale geomorphic, processes; and (4) determinate of smaller-scale habitat and biotic processes (Dunne and Leopold 1978; Dewberry 1980; Lotspeich and Platts 1982; Frissell et al. 1986; Cupp 1989; Poff and Ward 1989; Hudson et al. 1992; Newsom 1995; Rosgen 1994; Baker 1995; Maxwell et al. 1995; Vannote et al. 1980). Oft-suggested physical variables that drive stream ecosystems are stream size, hydrology, channel slope, temperature, and substrate size. Biotic groups used in classifications include fishes, macro-invertebrates, and macrophytes.
- Step 2 involves both selection of key maps that index attributes and definition of mapping rules for delineating unit boundaries. River segment boundaries are typically associated with stream junctions, major slope breaks, boundaries of local landscape ecosystems, and changes in fish assemblage structure.
- Step 3 is the development of classification categories for each attribute. Categories should be defined so as to reflect both the existing range of values for that attribute and significant changes in ecosystem unit character.
- Step 4 is the definition of rules for assigning attribute classes to each unit. Assignments are either based on existing site-level data, or based on known qualitative or quantitative relationships between map information and selected attribute classes (e.g., Hakanson 1996; Ladle and Westlake 1995).

- Step 5 is the development of a computerized information system for storage, retrieval, and display of information on ecosystem boundaries and attributes. In the past, multiple-attribute data were often integrated to describe ecosystem "types" (typically on paper maps) and useful information was lost. Today's Geographic Information System (GIS) technologies offer powerful new opportunities for development, storage, query, analyses, and display of both spatial and tabular data. Thus, all component attribute information can be retained in a flexible system that can be responsive to the needs of a variety of users (Davis and Henderson 1978; Hudson et al. 1992).
- Step 6 is the grouping of units by selected attributes to create any one of a number of possible classifications. Again, this flexibility is made possible by advances in computer technology. Multiple attributes can be selected, perhaps weighted, and integrated into a holistic ecological classification. Such a grouping would provide a sound ecological stratification useful for a wide variety of management needs, especially those stemming from a desire for holistic ecosystem management. Other, more narrow thematic classifications (e.g., water temperature or valley character) could also be created in response to specific needs.

Despite only mild variation in climate and elevation across lower Michigan, many successive glaciations have created an exceptionally-varied ecological landscape. Lower Michigan is a mosaic of glacial lakeplains, outwash plains, moraines, and tills of varying depths and textures (including some of the deepest deposits of glacial outwash sands and gravels in North America; Dewberry 1980; Farrand and Eschman 1974; Farrand and Bell 1984; Albert et al. 1986). This peninsula is laced with old glacial-fluvial channels and bedrock protrudes in a few locations. River catchment hydrology; the routing of water among evapotranspiration, groundwater, and overland flow pathways; therefore varies tremendously across systems (baseflows range from near zero to some of the highest in North America; Hendrickson and Doonan 1972; Dewberry 1980; Holtschlag and Crosky 1984; Poff and Ward 1989; Rheaume 1991; Berry 1992; Richards 1990). Additionally, a surprising variety of local valley characteristics and constraints are encountered as stream channels move across specific glacial terrains, and in and out of old glacial-fluvial channels (Dewberry 1980; Baker 1995). In the upper Midwest, distributions of stream biota have been shown to relate to patterns in catchment and local surficial geology and hydrology (Threinen and Poff 1963; Hendrickson and Doonan 1972; Dewberry 1980; Strayer 1983; Bowlby and Roff 1986; Meisner et al. 1988; Wiley et al. 1997; Zorn et al. 1997).

The only existing classification of Michigan rivers and streams was developed by the Michigan Department of Natural Resources, Fisheries Division in 1967 (Anonymous 1981). This system was not based on habitat attributes, but essentially on the distribution and abundance of game fishes (some attributes of stream size, riparian development, and potential for boating were incorporated). Attributes were assigned based on field experiences of state biologists and conservation officers, complimenting survey data where it existed. This classification was probably quite accurate regarding the distribution of waters containing trout--the most well-studied fishes--but less informative regarding other waters. No hierarchical, habitat-based or ecological classification exists for Michigan rivers, or for rivers in similar glaciated and partly-agricultural terrains. Most of the primary literature on stream classification has instead been developed in forested, mountainous areas (e.g., Frissell et al. 1986); where variables driving stream ecological characteristics are likely quite different than in Michigan.

As one component of the larger, Michigan Rivers Inventory (MRI) Project (see Seelbach and Wiley 1997), we endeavored to build an ecological classification system for the rivers of lower Michigan. Our specific study objectives were:

- To identify ecologically-distinct river valley segments within the rivers of lower Michigan.
- To develop landscape-based classifications for selected ecological attributes representing aspects of catchment hydrology, local valley constraints, and representative biota.
- Through the interpretation of maps, to assign attributes for each of these traits to each valley segment.
- To develop a digital map and database information system (GIS) for retrieving and viewing the classification data and supporting map images.
- To provide an initial ecological typing of segments.

Approach and methods

Selection of key attributes for identifying ecological units

We selected catchment size, hydrology, water chemistry, water temperature, valley character, channel character, and fish assemblages as fundamental attributes to describe the ecological character of river valley segments. Stream size indexes important longitudinal gradients in river habitats and has long been recognized as a primary classification variable (Hawkes 1975; Vannote et al. 1980). Hydrology, water chemistry, and water temperature integrate complex catchment processes and are also important proximal variables shaping local biology. Valley character reflects local physiography and constrains channel development. High in the trophic web, fishes are good integrators and express the condition of their complex environments (Fausch et al. 1990).

Selection of key maps

The general ecological character of each segment was interpreted by searching maps for "terrain features that control the intensity of key factors" (Rowe 1991). We focused on key map characters identified in prior MRI modeling efforts as important catchment- and local-scale drivers of each attribute (Table 1). Terrestrial classifiers have noted the significance of physiography as a key ecological driver (Rowe 1984; 1991; Spies and Barnes 1985). We also paid particular attention to the catchment- and local-scale physiography that influence hydrology, which is central to river ecology.

Both classification steps – identification of units and assignment of attributes – were done "from above", by the interpretation of digital maps displayed in a GIS environment. We were able to use maps to assign attributes by predicting site-scale attributes from landscape-site models developed within the MRI project. Key map themes used are described in Table 2. Two experienced aquatic ecologists worked together, interpreting map information on catchment and valley characteristics, using their combined knowledge of ecological processes and interactions. The shared experiences of, and discussion between, mappers was a critical component of this process (as emphasized by Spies and Barnes 1985; Rowe 1991). These ecologists studied a variety of maps compiled by the MRI project, using ArcView (Version 3.0; ESRI, Inc.) software running on either a SUN (UNIX) computer or a PC (Windows 95 or Windows NT) computer serving as a terminal to the SUN machine. This was an extremely flexible and powerful analytical environment; at the users' discretion, multiple map layers could be easily overlain and the viewing scale easily changed.

Mapping rules for delineating unit boundaries

Step 1. Initial identification of valley segments and segment boundaries using key map features.–We initially examined several key maps to become familiar with the general landscape patterns of a particular catchment; and to then identify initial core river segments as defined by segment boundaries. Definition of an ecological boundary first required the integration of terrain features observed on several thematic maps (sensu. Barnes et al. 1982; Rowe 1991): major stream network junctions, slope breaks, boundaries of major physiographic units or land cover units; or changes in stream sinuousity and meander wavelength patterns, local groundwater inputs, riparian wetlands, or valley shape (bottom width and side slope). Specifically:

◊ Elevation and wetland maps were examined for changes along the river's course in valley channel slopes and side slopes, valley width and origin (glacial or alluvial), and floodplain wetlands (Figure 1).

◊ Maps of surficial geology and predicted groundwater velocity were examined for changes occurring between major glacial formations (e.g., lakeplains, outwash plains, till plains, end moraines) and among drift textures (fine, medium, coarse); and to identify the positions of glacial-fluvial channels (bands of outwash in definitive valleys), and local or regional groundwater sources.

◊ Maps of stream networks, lakes, and wetlands were examined for locations of major network junctions, the break between "headwaters" and the river (largely a judgement call based on stream size; headwater tributaries generally had catchments < about 400 km^2), major tributaries (given segment status based on stream size), large lakes, and wetlands; and for changes in channel sinuosity (Figure 2).

◊ Land cover maps were examined for changes between major zones (e.g. between forested and agricultural areas).

Ecological changes suggested by physically-derived boundaries were investigated by looking for corresponding changes in fish assemblages (Balon and Stewart 1983; Spies and Barnes 1985; Rowe 1991).

◊ We cross-checked potential abrupt physical boundaries against information on fish distributions derived from site data, field experience, and landscape-based predictive models (Zorn et al. 1997).

◊ We also kept in mind that, despite potential small-scale physical variation in some areas, ecological segments needed to remain fairly large, relevant to the scale of use by fish populations (Hawkes 1975; Maxwell et al. 1995).

Frissell et al. (1986) recommended that lakes be treated as individual valley segments, in essence as ecological units. We agree but did not address the thousands of lakes and reservoirs found in lower Michigan in this initial effort. We expect to include a limited number of the larger lakes and impoundments as segments in future versions.

Step 2. Finalize segment breaks.–We then determined the final segment boundaries by applying the following system of priorities:

I. Major junctions in the hydrologic network (for mainstem and major tributary segments).

II. Corresponding breaks determined from slope, channel constraints, and geologic boundaries.

III. Changes in groundwater source, often corresponding with II.

IV. Abrupt changes in major land cover patterns.

Step 3. Review segment breaks.–During the process of assigning ecological attributes to segments (see below), we double-checked that at least one coded ecological trait changed between adjoining segments (typically this would also include a change in fish assemblage). If this criteria was not met, we combined the segments in question.

Classification categories and mapping-assignment rules for ecological attributes

Basin and watershed names.–The Great Lake basin and major watershed system to which each segment belonged were identified (Table 3).

Unique segment ID number and series of position numbers.–Each segment was given a unique identification (ID) number, as well as a series of numbers that contained information about its position in the river net. The first number in this series represented the mainstem segment ID number, beginning with "1" at the river mouth and progressing up the mainstem as "2, 3, etc." The upstream-most segment stopped short of the headwaters.

The next set of 2 numbers in the series represented the net position of the major tributary segments. The first number described the position of juncture with the mainstem segment; numbering was "1, 2, etc." working upstream along the particular mainstem segment. For example the downstream-most large stream joining the downstream-most mainstem segment would be "1 1 _"; the next-upstream large tributary would be "1 2 _"; and so forth. The second number described position within the major tributary itself; numbering was "1, 2, etc." working upstream on the tributary. For example a major tributary that has 3 segments and joins the lower mainstem segment was coded "1 1 1, 1 1 2, and 1 1 3".

Larger tributaries to major tributaries were coded using the same logical sequence in subsequent sets of 2 numbers. For example the second-upstream segment of the downstream-most major tributary to the downstream-most major tributary to the lowest mainstem segment was coded "1 1 1 1 2".

Headwaters and tributaries that flowed to a common segment and that shared fundamental ecological properties were coded as a group. These were given a unique group code, numbered as "1,2, etc." representing various groups in no particular upstream-downstream order. An example set of codes is shown in Figure 3.

Segment catchment size.–Segment catchment size, an index of stream size, was indexed as the link number determined at the downstream end of each segment. The link number is the sum of the first-order streams (streams with no upstream branches) in the upslope catchment (Osborne and Wiley 1992). We interpreted link numbers from a stream network map of Michigan built from 1:24,000 USGS maps (Michigan Resource Information System, Michigan Department of Natural Resources, Real Estate Division, Lansing). The interpretation of first-order streams on this map is slightly different than on the USGS Digital Line Graph (DLG) maps that we used throughout the rest of the project--this discrepancy should be resolved in future revisions.

Segment position in the river net.–Network position indicates the proximity of a segment to potential downstream source populations, and has been shown to influence fish community composition (indexed by d-link number; Osborne and Wiley 1992; Osborne et al. 1993). Some information on the position of a segment in the river net (e.g., high in the headwaters vs. down towards the mouth) was provided in the series of position numbers. A more specific measure of position relative to river size was measured as the d-link number (Osborne and Wiley 1992) at the downstream node of each segment. The d-link number is the link number at the next-downstream network juncture (we excluded junctures with tributaries with link numbers smaller than 10% of the exisitng link number). Figure 4 shows an example of link and d-link numbers for a segment.

Connection to the Great Lakes.–Similar to network position, connection to the Great Lakes indicates potential faunal sources influencing assemblage structure. We recorded whether a segment was openly connected to the Great Lakes or cut off by a barrier dam, as codes 1 and 2, respectively.

Hydrology codes.–We coded the hydrology for each segment as 1 of 9 general discharge patterns observed in Michigan hydrologic data (MRI, unpublished). A discharge pattern was inferred by examining the composition of catchment topography, surficial geology, and land cover. These patterns were considered to be size-independent and discharges were considered in terms of yields (cfs/km2 of catchment). [in this and following ecological codings, we also considered the ultimate sequence of codings with up- and down-stream neighbor segments--codings should change along the system in a reasonable pattern/story]. The 6 most-common patterns represent a continuous series illustrating tradeoffs between groundwater and runoff sources (Figure 5). These were divided into a group of 2 primarily groundwater-driven streams and a group of 4 primarily runoff-driven streams. Each group was further broken down based on baseflow and peakflow yields as follows:

- G1 – groundwater-driven, with very high baseflow and low peakflow. Catchment composition is fairly high-relief, ice-contact hills and coarse-textured end moraines surrounding extensive outwash plains (Figures 6a and 6b). Examples include the Au Sable, Boardman, Little Manistee, Manistee, and Platte rivers.
- G2 – groundwater-driven, with high baseflow and moderate peakflow. Catchment composition is relatively high-relief coarse end moraines draining onto outwash plains, often with some coarse till plains, medium-textured end moraines, or medium till plains present. Examples include the Black and Sturgeon (Cheboygan system), Pine (Manistee), Rifle, Pere Marquette, and Paw Paw rivers.
- R1 – runoff-driven, with fair baseflow and moderate peakflow. Catchment composition is a mixture of moderate-relief coarse end moraines, coarse till plains, and outwash plains. Examples include the Muskegon, Thunder Bay, and Kalamazoo rivers.
- R2 – runoff-driven, with moderate baseflow and fair peakflow. Catchment composition is a mixture of low-relief coarse and medium end moraines, and medium till plains, with some outwash plains (Figures 7a and 7b). Examples include the Grand, Huron, and St. Joseph rivers.
- R3 – runoff-driven, with low baseflow and high peakflow. Catchment composition is primarily medium and fine-textured till plains, and lacustrine plains, with some low-relief medium and fine end moraines present. Examples include the Cass, Shiawassee, and Maple rivers.
- R4 – runoff-driven, with very low baseflow and very high peakflow. Catchment composition is primarily lacustrine plains. Examples include the Kawkawlin, Macatawa, and Pigeon rivers.

Three somewhat unusual flow patterns were also identified (Figure 8):

- GS – groundwater-driven, with super-high baseflow and moderate peakflow. Catchment composition is similar to G2 streams, but groundwater is gained from adjacent aquifers (determined from specific hydrologic records, not from maps). Examples include the Jordan River.
- GW – groundwater-driven, influenced by extensive wetlands, with moderate baseflow and very low peakflow. Catchment composition is similar to either G1 or G2 streams, but with extensive wetland coverage resulting in high evapotransporative losses. Examples include the South Branch Au Sable and Clam rivers.
- RW – runoff-driven, influenced by extensive wetlands, with very low baseflow and very low peakflow. Catchment composition is generally similar to S3 or S4 streams, but with extensive wetland coverage and high evapotransporative losses. We have no gaged examples of this type.

Water chemistry codes.–Segment water chemistry was considered to be a product of catchment hydrology and land cover, and was determined from hydrology codes and interpretation of surficial geology, soils, and land cover maps (based on relationships developed by Kleiman 1995). Chemistry was first categorized as either oligotrophic (typical values: SRP < 15 ppb, NO_3+NO_2 < 100 ppb), mesotrophic (typical values: SRP 15-30 ppb, NO_3+NO_2 100-700 ppb), or eutrophic (Figures 9-12). These categories were further divided as follows; based on effects of upstream lakes and wetlands, and land cover intensity:

- OS – oligotrophic, with low nutrients and low alkalinity (soft water). Flow pattern is typically S2 or S3, due to catchment surficial geology dominated by shallow drifts overlying bedrock or peaty soils. Catchment land cover includes substantial wetlands. Possibly an upstream ombrotrophic lake or wetland.
- OH – oligotrophic, with low nutrients and high alkalinity (hard water). Flow pattern is G1, G2, GS, or GW. Catchment land cover is mostly forested. Possibly an upstream minerotrophic lake, springs, or wetlands.
- M – mesotrophic, with moderate nutrients. Flow pattern is G1, G2, S1, or SW. Catchment land cover is a mixture of forest and light agriculture, with some wetlands.
- MW – mesotrophic, influenced by extensive wetlands, with moderate phosphorus and low nitrates. Flow pattern is G1, G2, or S1. Catchment land cover is a mixture of forest, light agriculture, and extensive wetlands.
- E1 – eutrophic, with moderate to high nutrients. Flow pattern is S2, S3, or S4. Catchment land cover is mixed forest, light residential, and light agriculture.
- E2 – eutrophic, with high nutrients. Flow pattern is S2, S3, or S4. Catchment land cover is agriculture and suburban.
- EG – eutrophic groundwater-driven stream, with high nutrients in the groundwater. Flow pattern is G1, G2, GS or S1. Groundwater contamination is from agriculture on permeable soils (e.g., orchards).
- EU – eutrophic stream in an urban area, with high nutrients and pollutants. It could have any flow pattern. Its catchment or local area is heavily urbanized.

Water temperature codes.–Patterns in both summer temperature means and diurnal fluctuations were considered to be driven primarily by catchment hydrology and size, modified by upstream lake and shading effects (Figures 13-14).

Our codes described a matrix of 3 categories for July weekly mean temperatures by 3 categories for July weekly temperature variation (Figure 15; Wehrly et al. 1997). Matrix divisions were based on observed summer temperature boundaries in relation to the distributions of coldwater (brown trout) and warmwater (smallmouth bass) game fishes.

July temperature codes were assigned based primarily on hydrology codes and visually-estimated relative catchment size, using the relationships shown in Figures 13-14. Codes were modified according to potential impacts of upstream land cover patterns, presence of upstream lakes, and latitude (air temperature). Some codes could be attained through several alternative combinations of key variables. We also considered the downstream sequence of codes among neighboring segments. Some common sequences in temperature codings are shown in Figure 16. Codes were as follows:

- CL – cold mean and low diurnal variation. Catchment size is very small to small, with a very large groundwater source and extensive shading.
- CM – cold mean and moderate diurnal variation. Catchment size is small to medium, with a large groundwater source. Shading important on smaller streams.
- CH – cold mean and high diurnal variation. We have no examples of this uncommon type.
- KL – cool mean and low diurnal variation. Catchment size is large with a moderate to large groundwater source; or medium-sized with a medium groundwater source and substantial shading.
- KM – cool mean and moderate diurnal variation. Catchment size is medium with a large groundwater source; or small with a moderate groundwater source.
- KH – cool mean and high diurnal variation. Catchment size is small with little groundwater input.

- WL – warm mean and low diurnal variation. Catchment size is very large, with either small groundwater or moderate groundwater inputs.
- WM – warm mean and moderate diurnal variation. Catchment size is medium, with small or moderate groundwater.
- WH – warm mean and high diurnal variation. Catchment size is medium with little groundwater input.

Valley slope codes.–Valley slope was interpreted from elevation and topography maps as 1 of 3 broad categories.

- VL – very low valley slope, roughly < 4 ft/mi (< 0.00076 %). Typical of fine till plains and lacustrine plains, with abundant wetlands. Channel habitats include runs and pools.
- L – low valley slope, roughly 4-10 ft/mi (0.00076 - 0.0019 %). Typical of outwash plains, medium and coarse till plains, and some medium and coarse end moraines, and some ice-contact hills. Some riffle habitats present.
- M – moderate valley slope, roughly > 10 ft/mi (> 0.0019 %). Typical of many coarse end moraines and ice-contact hills. Channel habitats are typically alternating riffle-pool sequences.

Valley character codes.–Valley character codes described the degree of channel confinement, either by coarse-textured morainic features, old glacial-fluvial channel walls, or deeply-incised alluvial channel walls. Valley character was descriptive of constraints on the stream channel and local parent substrates. It was interpreted from local elevation, topography, surficial geology patterns, and wetland patterns as one of the 8 categories described below. A glacial-fluvial valley was created thousands of years ago by a very large, glacial meltwater river. An alluvial valley has been carved by the current river.

- GU – glacial and unconfined. Channel flows unconfined within a relatively broad glacial-fluvial valley.
- GC – glacial and confined. Channel is confined by a relatively narrow glacial-fluvial valley.
- GI – glacial and incised. Channel is confined by alluvial incision in a broad glacial-fluvial valley.
- GS – glacial and sporadically confined. Channel is sporadically-confined by morainic features within a broad glacial-fluvial valley.
- AU – alluvial and unconfined. Channel is unconfined as it cuts across broad till, outwash, or lacustrine plains.
- AC – alluvial and confined. Channel is confined in an alluvial valley.
- AS – alluvial and sporadically confined. Channel is sporadically-confined by morainic features within broad till, outwash, or lacustrine plains.
- AA – alluvial with alternating confinement. Channel cuts alternatively across morainic features and plains.

Channel character codes.–We noted whether a channel was single and meandering, multiple (braided or anastomozing), or channelized with the codes listed below. Channel character was interpreted from maps of channel networks.

- S – single, meandering channel.
- B – braided or anastomozing, multiple channels.
- D – ditched or channelized channel.

Fish species association codes.–We coded the fish species associations most likely to occur at each segment. Fish species associations were determined by Zorn et al. (1997) through a hierarchical cluster analysis using relative abundance data for the 69 most common riverine fish species, at 225 sites contained in the Michigan Rivers Inventory database (Seelbach and Wiley 1997; Table 4).

Each cluster is represented by the name of a diagnostic species.

Mean baseflow yield and catchment drainage area were calculated for sites where each species association was relatively abundant (>0.25 as standardized z-scores; Figure 17; Zorn et al. 1997). Likely species associations were determined for each segment by interpreting hydrologic patterns and catchment size from the GIS maps, taking additional map variables (land cover patterns, river net position, and connectivity) and field experience into consideration.

Initial validation of fish-association codings

We did some initial validation of the fish association codings. We focused on these, as fishes are considered to be a response variable that integrates the other, physical habitat codings. We checked our codings against stream survey records (Michigan Department of Natural Resources, Stream Collection Records, Ann Arbor). And we interviewed Michigan Department of Natural Resources District Fisheries Biologists regarding their field experiences with fish distributions and general river segment identifications. Often, field data and experiences confirmed our fish codings and our overall interpretation of the segment's ecology. When fish data and experiences did not match our original codings, we did one of the following: (1) If codings were marginal between two categories, we changed the fish codes to match the data; (2) If codings and data were very different at a particular site, we assumed that the current fishes may be reflecting site modifications not apparent from our large-scale maps and used the physically-based codings as representing potential fishes; or (3) If the codings and the data were mismatched at a series of sites, we tried to learn from this pattern and revise our coding procedures accordingly.

GIS and database Methods

Classification map and table data were stored in ArcView, Version 3.0 (ESRI, Inc.) formats, on a Unix-based Sun computer. The downstream break of each segment was marked and identified as a point in an ArcView shapefile. Attribute codings were entered into a data table (format ".dbf") where codings were fields associated with each segment (record). When joined (in ArcView) with the shapefile's associated data table, codings associated with each record were linked to the mapped points and were then accessible through either the GIS map environment or through the database query functions of ArcView. Attribute codings were also linked to mapped segment-buffer polygons (thicker stream lines), which were developed by modifying the stream network map in ArcView.

Ecological typing

The attribute table provides a basis for the development of a variety of ecological segment types, potentially varying in their emphasis and complexity. As an initial example, we did a simple cross-tabulation of 3 key attributes that index important ecological traits: hydrology, water temperature (this brought in some information on river size and was a good index of fish composition), and valley confinement (Dewberry 1980; Halliwell 1989). Our goal was to look for segment attribute sets that repeated across lower Michigan (Speis and Barnes 1985).

Results

Description of segments and attributes

We partitioned and classified the 19 largest river systems in lower Michigan, calling this initial effort MI-VSEC (Michigan Valley Segment Ecological Classification) Version 1.0. A river system was defined as having an outlet to the Great Lakes, with the exception of the large Saginaw River system, which we arbitrarily broke into 3 subsystems (Tittabawassee, Shiawassee, and Cass rivers) that meet to form the Saginaw River proper not far from Saginaw Bay (Lake Huron). We identified and described 271 river valley segments that covered river mainstems and major tributaries. (We also did initial descriptions for 504 sets of minor tributaries and headwaters of these rivers, but these are not described in this report). The number of mainstem segments per river was typically 4-5, ranging from 3 to 7. The number of major tributary segments per river system varied with basin size but was typically 1-12, with some as high as 17-27. Segments averaged 38 km in length and ranged from 3 km to 320 km in length; segments were generally longer in larger rivers.

Summaries of the assigned attributes provide an initial description of the river resources of the Lower Peninsula. Due to relatively short drainages to the Great Lakes, river size is generally small to moderate (Figure 18). Many smaller streams are linked to larger downstream waters (Figure 18); but despite their proximity, only 29% of segments are today directly connected to the Great Lakes (due to numerous dams). Lower Michigan's porous surficial deposits provide extensive groundwater inputs to almost 1/3 of segments and moderate groundwater inputs to an additional 1/3 of segments (Figure 19). Some segments show relatively low nutrient levels, reflecting catchments composed largely of sands and gravels; but most have substantial nutrients, due to more loamy soils and human influences (Figure 20). Most segments have low channel gradients and run unconfined across outwash, till, and lakeplains (Figures 21-22). Segments with moderate gradients and confined channels–these contain rocky substrates, distinct riffle-pool sequences, and perhaps rapids–are relatively rare. Although we have traditionally categorized Michigan streams as either coldwater or warmwater (Anonymous 1981), most segments had cool means and (regardless of mean) most segments also had moderate daily fluxes (Figure 23). These intermediate thermal conditions allow many segments to hold a variety of fishes (Figure 24), though they are not necessarily ideal for thermally-specialized game fishes such as trout.

Examples of ArcView maps and tables

Our results were stored as a map and a table in ArcView 3.0 format, and are available upon request from the Michigan Department of Natural Resources, Institute for Fisheries Research, 212 Museums Annex, Ann Arbor, MI (telephone 313-663-3554; web address http/www.dnr.state.mi.us/www/ifr/ifrlibra/ifrlibra.htm). Examples of map and table data for 3 contrasting river systems are shown in Figures 25-27. These illustrate the power of GIS technology in highlighting ecological relationships, e.g., those between segment locations and patterns in underlying surficial geology and topography; and in allowing the examination of spatial relationships among segment attributes within a system.

Initial classification of segment types

Our initial cross-tabulation of streams by hydrologic, thermal, and channel confinement codes produced an array of 49 segment types. We considered each type to have a distinctive character in terms of its combined attributes of size, discharge, temperature, chemistry, slope, channel habitats, and fishes (as indexed by our 3 codes). Attributes typical of the most common 22 types (eliminating those with N<4) are summarized in Table 5. Hydrology, temperature, and size were descriptive of distinctive fish associations. Remember, though, that these variables were used initially to assign the fish association codings. Channel confinement and gradient were not related to fish associations but we felt they were indicative of important ecological conditions that were not indexed by fish presence alone (e.g., substrates, pool & riffle configurations, invertebrate populations, and local thermal conditions).

Discussion

Theoretical issues

The importance of identifying valley segment ecological units.–The initial step in ecological classification, perception and identification of ecological units, is philosophically and practically the most important. However, it is often overlooked in classification discussions that focus on the second or third steps, those of assigning attribute classes and forming multi-attribute types. We want to highlight the simple, yet central, role of identifying *these fundamental units of nature* (Rowe and Barnes 1994).

First, ecological units are real, observable places in space and time (Rowe 1991). One can visit and observe (or measure) differences among terrestrial units such as particular uplands or wetlands. Likewise, a low-gradient, low-groundwater river segment flowing across a broad clay plain is a much different place than a moderate-gradient, high-groundwater segment, flowing within a tight glacial valley through rocky materials. In lower Michigan, such diverse segments can be found adjoining one another within the same river system.

Recognition of these units draws our thoughts and focus away from the organisms that tend to capture our attention, to the integrated biophysical system that ultimately sustains them. This system becomes the core object of study and the basis for resource management (Rowe 1991; Maxwell et al. 1995). Thus we begin to address management at scales closer to those at which physical and biological processes actually operate, and focus more on the reciprocal relationships that interconnect physical and biological components (Barnes et al. 1982). We also can compare structures and processes among units, exploring and mapping their landscape ecology (Rowe 1984).

And, of course, these units provide a sound basis for stratification of larger ecological realities, e.g., river systems. Stratification allows for efficient inventory, extrapolation, analyses, and communications (Spies and Barnes 1985; Hudson et al. 1992), and thus aids managers in evaluating (and responding to) particular environmental stresses or management actions.

Quaternary geology and landforms as central to hydrology.–It is important to underline the defining role of Quaternary, or surficial, geology in our descriptions of both catchment- and local-scale processes that drive Michigan stream ecosystems. Terrestrial ecologists have long recognized the fundamental role of the texture and form (physiography) of surficial materials (Rowe 1991). Likewise, geologists and hydrologists working in the Great Lakes region (Knutilla 1970; Bent 1971; Hendrickson and Doonan 1972; Holtschlag and Crosky 1984; Richards 1990) and elsewhere (Dunne and Leopold 1978; Lotspeich and Platts 1982; Frissell et al. 1986), have long recognized the strong relationships between texture and form of surficial drift deposits, and stream hydrology. Similar relationships between surficial geology, hydrology, and various stream biota (especially for coldwater forms) have been previously highlighted (Threinen and Poff 1963; Hendrickson and Doonan 1972; Dewberry1980; Strayer 1983). Drift textures in the catchment (and also typically the texture of derived soils) and elevation changes control rates of groundwater percolation and movements; and ultimately the sources of seasonal stream flows (Dunne and Leopold 1978; Wiley and Seelbach 1997).

Aquatic and terrestrial classifications.–The integral connection between landscapes, hydrology, and aquatic systems suggests that terrestrial and aquatic classifications should be integrated. Terrestrial classifications have been built upon the same variables that drive aquatic systems– aspects of climate and geology– with aspects of soils and vegetation often included. At the larger scales, ecoregions and sub-regions have been delineated for much of North America (Bailey et al. 1978; Omernik 1987). Although some correspondence has been found between ecoregions and stream characteristics (Larsen et al. 1986; Hughes et al. 1987; Rohm et al. 1987; Lyons 1989; Biggs et al. 1990), smaller units are probably more appropriate to capture the landscape variations (especially complex patterns in the surficial geology of glaciated regions) that affect streams at the valley segment or reach scale (Bryce and Clarke 1996). Using the terminology of the U.S. Forest Service (see Table 6 for comparison of terminologies between U.S. Forest Service and U.S. EPA), it is likely that the mid-scale unit of Landtype Association would be most appropriate for integration of terrestrial and aquatic classifications (Harding 1984; Maxwell et al. 1995; Bryce and Clarke 1996; Corner et al. 1997). Our analyses suggest that characteristics of the aquatic valley segment should be linked to terrestrial conditions at 2 points: (1) catchment hydrology should be linked to catchment landtype associations; and (2) segment morphology should be linked to immediate landtype conditions. We are currently exploring the integration of the MI-VSEC system with terrestrial units developed by Albert et al. (1986) and Corner et al. (1997). We expect to retain 2 separate classification systems (because watersheds naturally cross multiple terrestrial units and are therefore not spatially nested within terrestrial systems) that are built upon the same driving environmental variables, and share aspects of map scale and language.

Also, the terrestrial classification systems developed to date by U.S. Forest Service and U.S. EPA are built upon a nested, spatial hierarchy–that is, each spatial unit is unique, nested within similarly-unique larger-scale units. Davis and Henderson (1978) called this property, "place-dependent". Our MI-VSEC system used the alternative approach of designing ecological attributes that are "place-independent"; that is, attributes are predictable from certain driving variables and repeatable across the landscape. This approach provides added analytical power, in that one can examine groups of geographically-separated units that share certain characteristics.

Evaluation and status of MI-VSEC Version 1.0

Does MI-VSEC satisfy the goals of a river classification?–MI-VSEC (1.0) satisfied the requirements for a river classification set forth by Maxwell et al. (1995); specifically that it must:

- Encompass broad temporal and spatial scales. We based the classification on time-stable, landscape features across a large, hydrologically-diverse landscape.
- Integrate ecosystem structure and function. We identified ecological units that integrated key physical and biological attributes; and we developed classifications for several physical and biotic components, that together describe many aspects and processes of river ecosystems.
- Convey mechanisms that drive ecological responses. Our procedures focused on key variables that drive specific ecological responses at both catchment and local levels. These drivers were identified through statistical modeling of relationships between landscape and ecological response variables.
- Be low in cost. MI-VSEC was done entirely by viewing existing map data on a computer terminal. (However, there was considerable cost in developing the predictive models used to interpret the maps). We used a Sun Workstation, but our maps and ArcView can also be managed on a high-performance PC.
- Promote consistent understanding among managers. MI-VSEC (within ArcView) provides powerful data storage and retrieval capabilities, definition of actual river units, simplification of complex components of river ecosystems, and a language describing these components. Our discussions with state Fishery Biologists indicated that MI-VSEC was readily understandable, and relevant to their experiences and needs.

Uses of MI-VSEC.–Chamberlin (1984) felt that regional map-scale stream "reconnaissance" is primarily useful for regional summaries and strategic resource planning, while more detailed inventories are required for site-level management planning. The MI-VSEC, however, provides predictive modeling of site-scale attributes through comparative analyses and summary of regional data; and thus should be fairly useful for project-level management assessments in addition to its uses in regional planning. For example, the MI-VSEC could be used to:

- Develop sampling designs based on stratification of valley segments by selected ecological characteristics.
- Set expectations (by valley segment unit) for presence, abundance, and growth of various sport fishes. This would include both a mean and a range of expected values. Comparison of expectations with observed conditions would provide a framework for fishery assessments. Expectations could also be used in development of statewide fish stocking and harvest plans.
- Set expectations (by valley segment unit) for flow (and disturbance) regimes, water temperatures, water chemistries, and channel characteristics; thereby providing a suite of environmental targets for use in environmental assessment, protection, and rehabilitation programs.
- Determine the underlying factors limiting fish populations in specific segment types and thus aid in setting priorities for various fishery management actions such as setting regulations, stocking hatchery-raised fish, controlling pest species, or stream habitat improvement projects (Halliwell 1989; Young et al. 1990; Kauffman et al. 1993; Schlosser and Angermeier 1995).
- Encourage watershed-based thinking by: (1) providing an information base and common language for the interfacing of the multiple disciplines that address rivers: fisheries, water quality, geology, hydrology, geomorphology, aquatic ecology, conservation biology, riparian ecology; and (2) describing functional relationships between system components (e.g., between upstream catchment drivers, local drivers, and ecological responses) and spatial relationships among segment units (e.g., characters of neighboring units, connectivity, source populations, fish movements).

Limitations and weaknesses of MI-VSEC.– MI-VSEC Version 1.0 has several significant limitations and weaknesses. Building the classification required that we place absolute boundaries on what were often true continua (Dewberry 1980). Although the boundaries of river segments are meant to describe rather abrupt ecological changes, transition zones certainly occur. And our classes of hydrologic types, for example, are merely a framework that defines a true continuum of flow patterns.

Because they were not dominant variables in lower Michigan, climate and bedrock characteristics do not feature prominently in MI-VSEC (1.0). These are generally recognized as fundamental variables and would have to be incorporated for MI-VSEC to be useful on a broader geographic scale (Lotspeich 1980; Hudson et al. 1992; Maxwell et al. 1995).

Our interpretations were limited by the scale of the available digital maps. Despite its foreboding +30 m error range, the Digital Elevation Map displayed as 1 ha rasters provided good resolution of most topographic features of interest (these corresponded well with our field experiences). However, it was unable to detail small features, like small stream valleys that are readily observable at 1:100,000 and smaller map scales. As another example, some local lithologic features were not apparent from examination of the elevation and quaternary geology maps. Information on such features can be gathered at finer scales (maps or field studies) and incorporated into the system; because the intial version was built at relatively coarse map scales does not limit future development to these scales.

Fishes likely move among segments during their life histories. MI-VSEC users should note fish associations in neighboring, or connected, segments as potential species pools (Frissell et al. 1986; Osborne and Wiley 1992; Schlosser and Angermeier 1995)

Future development.–Development of the MI-VSEC system is intended to be ongoing. Extending coverage to include Michigan's Upper Peninsula has already begun, with the assistance of Dr. Ed Baker (Michigan Department of Natural Resources, Marquette), the Hiawatha and Ottawa National Forests (USDA Forest Service, Escanaba, MI), and The Nature Conservancy (Great Lakes Regional Office, Chicago, IL). The Nature Conservancy (Great Lakes Regional Office, Chicago, IL) is developing a modified version of MI-VSEC to facilitate conservation planning throughout the Great Lakes basin.

Another high priority activity will be the further ground-truthing of codings against field data, improving accuracy of the attribute table. Our work to date is inferential and thus represents a somewhat subjective, tentative classification – "a first approximation representing a set of working hypotheses to be tested against ground data" (quote from Spies and Barnes 1985; Rowe 1991).

We will continue to add component attributes to the system. For example, information on other biota, channel habitats, riparian floodplain habitats, large lakes and reservoirs, and human dimensions will all add to our knowledge of these ecological units. And we expect to use existing attributes to derive new ones that indicate various management potentials (Spies and Barnes 1985); for example thermal classes may be used to develop trout management guidelines.

Acknowledgments

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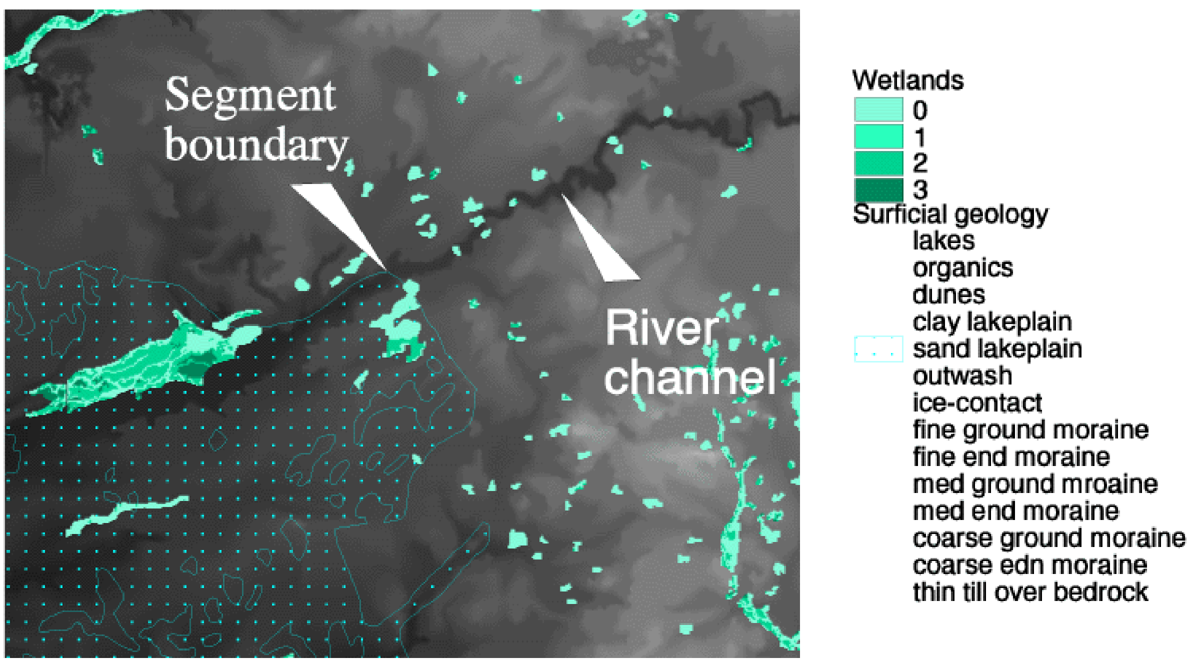


Figure 1.–The Muskegon River valley (the river flows from upper right to lower left) as a black, low-elevation feature on a grey-scale digital elevation map (black = low elevation, white = higher elevation). A segment boundary was identified where the river valley widens as it leaves a coarse-textured moraine and enters a sandy lakeplain area (extensive floodplain wetlands also appear downstream of this point. This graphic is best viewed in color and will be available on the Institute for Fisheries Research Internet web site.

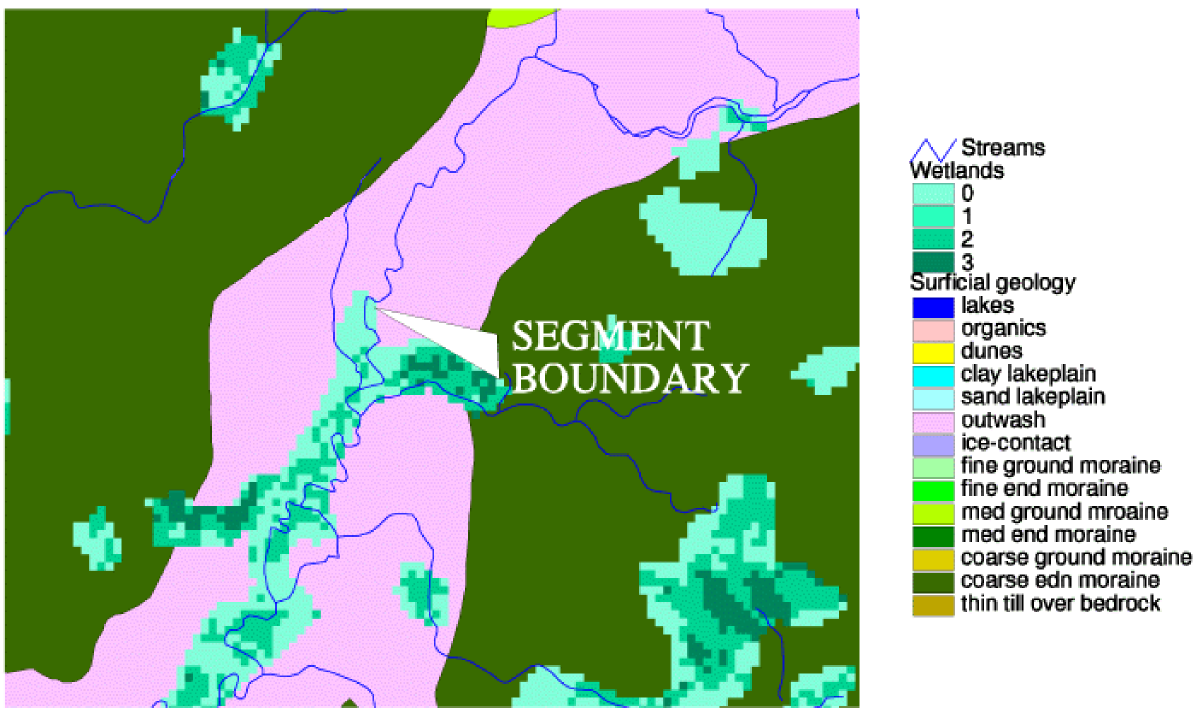


Figure 2.–The Battle Creek River flowing (from upper right to lower left) within a valley of glacial outwash sand. The segment boundary was identified where the valley flattens (not shown), river sinuosity increases, and extensive floodplain wetlands begin. This graphic is best viewed in color and will be available on the Institute for Fisheries Research Internet web site.

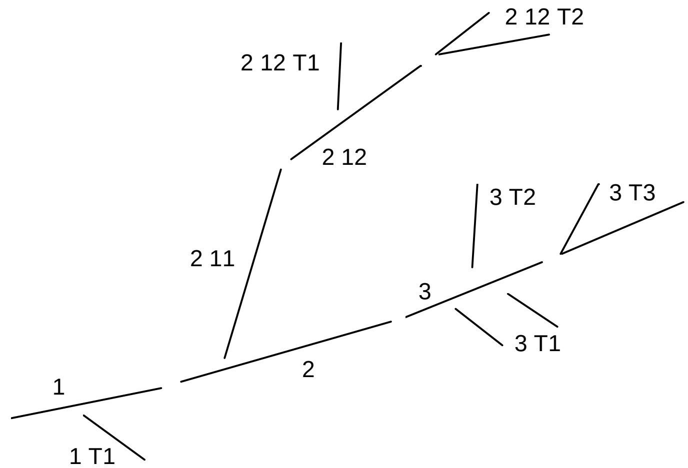


Figure 3.–Hypothetical example of VSEC segment (e.g., "2"), major segment (e.g., "211"), and tributary group (e.g., "212T1") numbering systems.

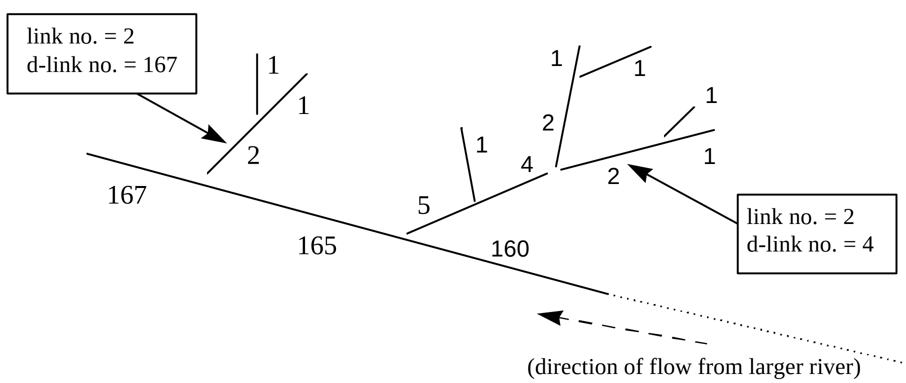


Figure 4.–Example of application of link numbers and d-link numbers to a stream network. Link numbers are shown for all pieces of the net. Link and d-link numbers are shown for 2 streams of comparable size (link = 2), contrasting the size of the river system they join.

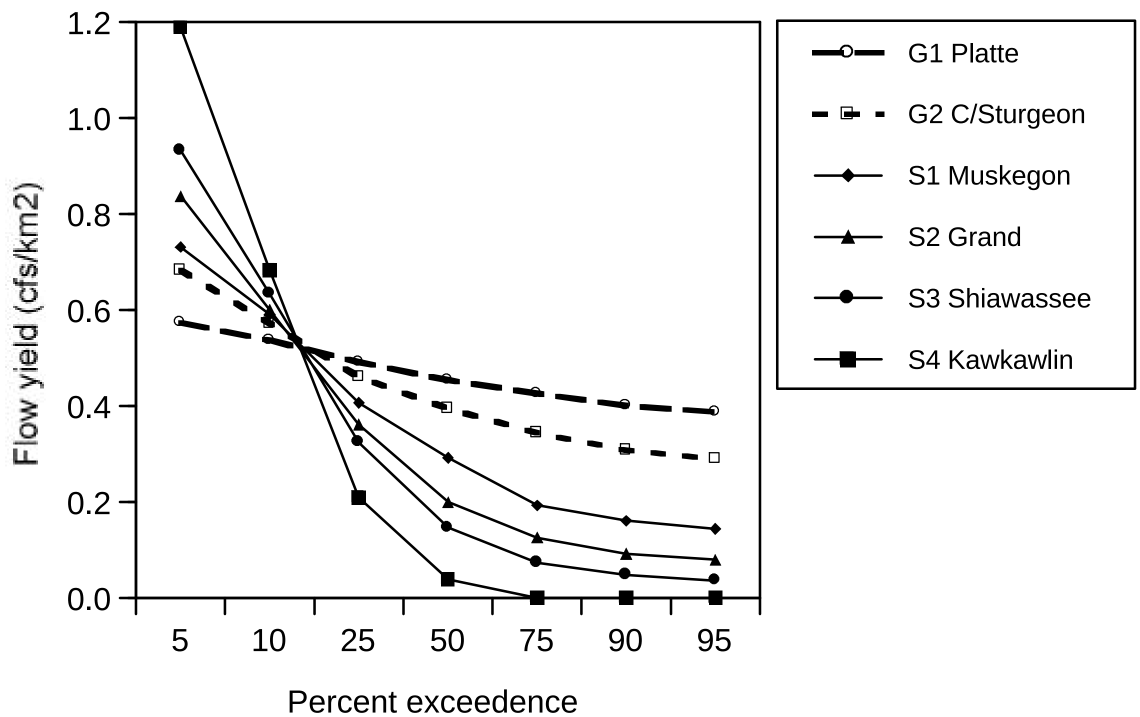


Figure 5.–Flow duration curves representing the range of discharge patterns commonly observed in lower Michigan rivers. For example, very stable groundwater-fed rivers are coded as G1 and represented by the Platte River; while the least stable surfacewater-fed rivers are coded as S4 and represented by the Kawkawlin River. Note that peakflow response is a trade-off with baseflow.

Figure 6.–Maps of the headwaters region of the Manistee (flowing from upper center to left) and Au Sable (flowing right) rivers showing surficial geology composed of high-relief, ice-contact hills surrounding valleys of permeable outwash sands (maps a. and b.); and abundant estimated groundwater loadings (c., after Darcy's Law from Dunne and Leopold 1978). These catchments were coded as having high baseflows and low peakflows (code G1). This graphic is best viewed in color and will be available on the Institute for Fisheries Research Internet web site.

Figure 7.–Maps of the headwaters region of the Little Muskegon River and Tamarack Creek (flowing from center to left), the Pine and Chippewa rivers (flowing right), and several tributaries to the Grand River (flowing down). These headwaters originate on modest-relief, coarse-textured hills that feed moderate amounts of groundwater to streams flowing in outwash valleys; and were coded as having fair baseflows and moderate peakflows (code S1). The streams that flow down and to the right increasingly drain low-relief areas with medium- and fine-textured soils that deliver little groundwater . Most of these were coded as having low baseflows and high peakflows (code S3). This graphic is best viewed in color and will be available on the Institute for Fisheries Research Internet web site.

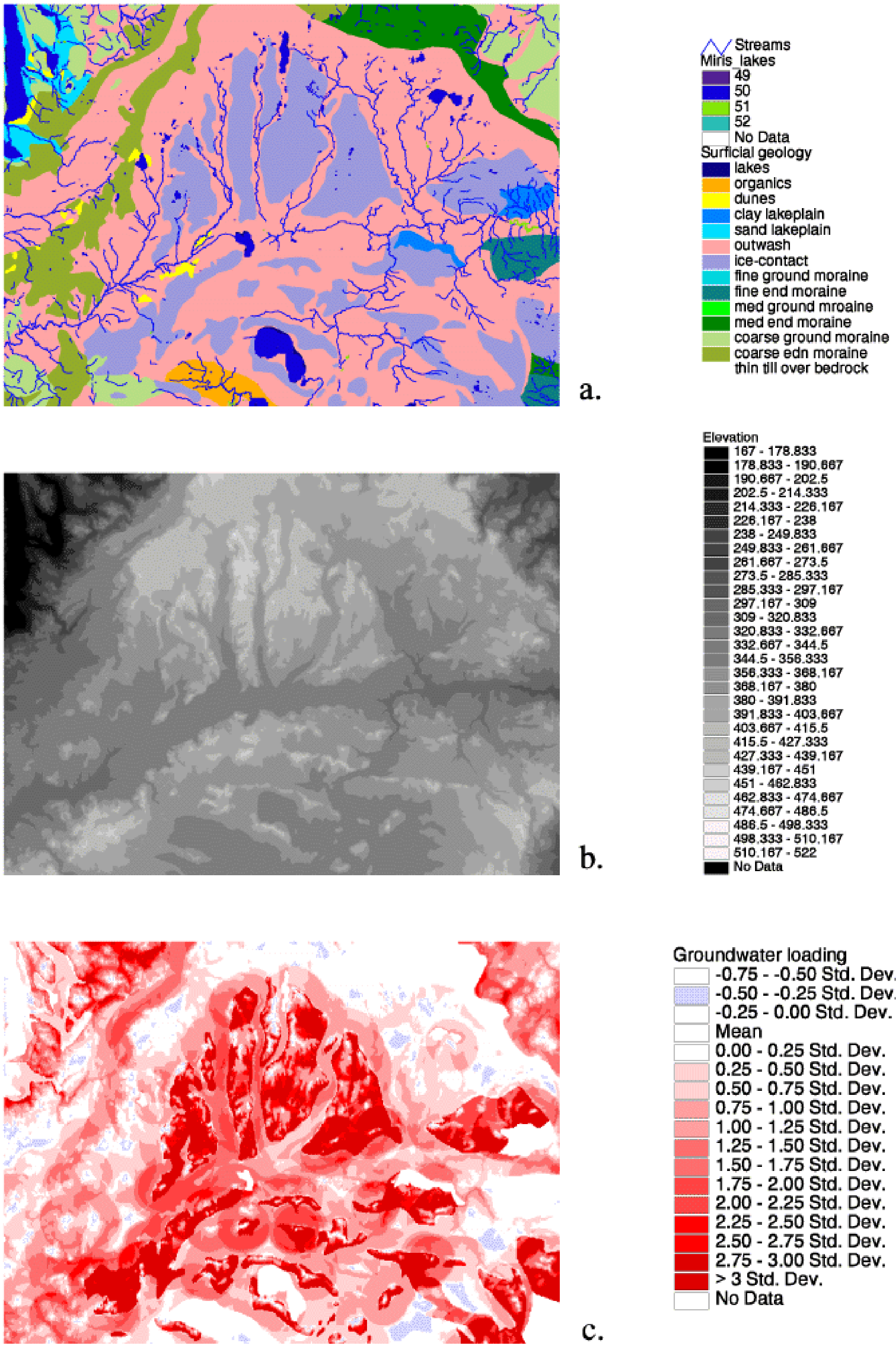

Streams
Miris_lakes
49
50
51
52
No Data
Surficial geology
lakes
organics
dunes
clay lakeplain
sand lakeplain
outwash
ice-contact
fine ground moraine
fine end moraine
med ground mroaine
med end moraine
coarse ground moraine
coarse edn moraine
thin till over bedrock
a.
Elevation
167 - 178.833
178.833 - 190.667
190.667 - 202.5
202.5 - 214.333
214.333 - 226.167
226.167 - 238
238 - 249.833
249.833 - 261.667
261.667 - 273.5
273.5 - 285.333
285.333 - 297.167
297.167 - 309
309 - 320.833
320.833 - 332.667
332.667 - 344.5
344.5 - 356.333
356.333 - 368.167
368.167 - 380
380 - 391.833
391.833 - 403.667
403.667 - 415.5
415.5 - 427.333
427.333 - 439.167
439.167 - 451
451 - 462.833
462.833 - 474.667
474.667 - 486.5
486.5 - 498.333
498.333 - 510.167
510.167 - 522
No Data
b.
Groundwater loading
-0.75 - -0.50 Std. Dev.
-0.50 - -0.25 Std. Dev.
-0.25 - 0.00 Std. Dev.
Mean
0.00 - 0.25 Std. Dev.
0.25 - 0.50 Std. Dev.
0.50 - 0.75 Std. Dev.
0.75 - 1.00 Std. Dev.
1.00 - 1.25 Std. Dev.
1.25 - 1.50 Std. Dev.
1.50 - 1.75 Std. Dev.
1.75 - 2.00 Std. Dev.
2.00 - 2.25 Std. Dev.
2.25 - 2.50 Std. Dev.
2.50 - 2.75 Std. Dev.
2.75 - 3.00 Std. Dev.
> 3 Std. Dev.
No Data
c.

Figure 6.

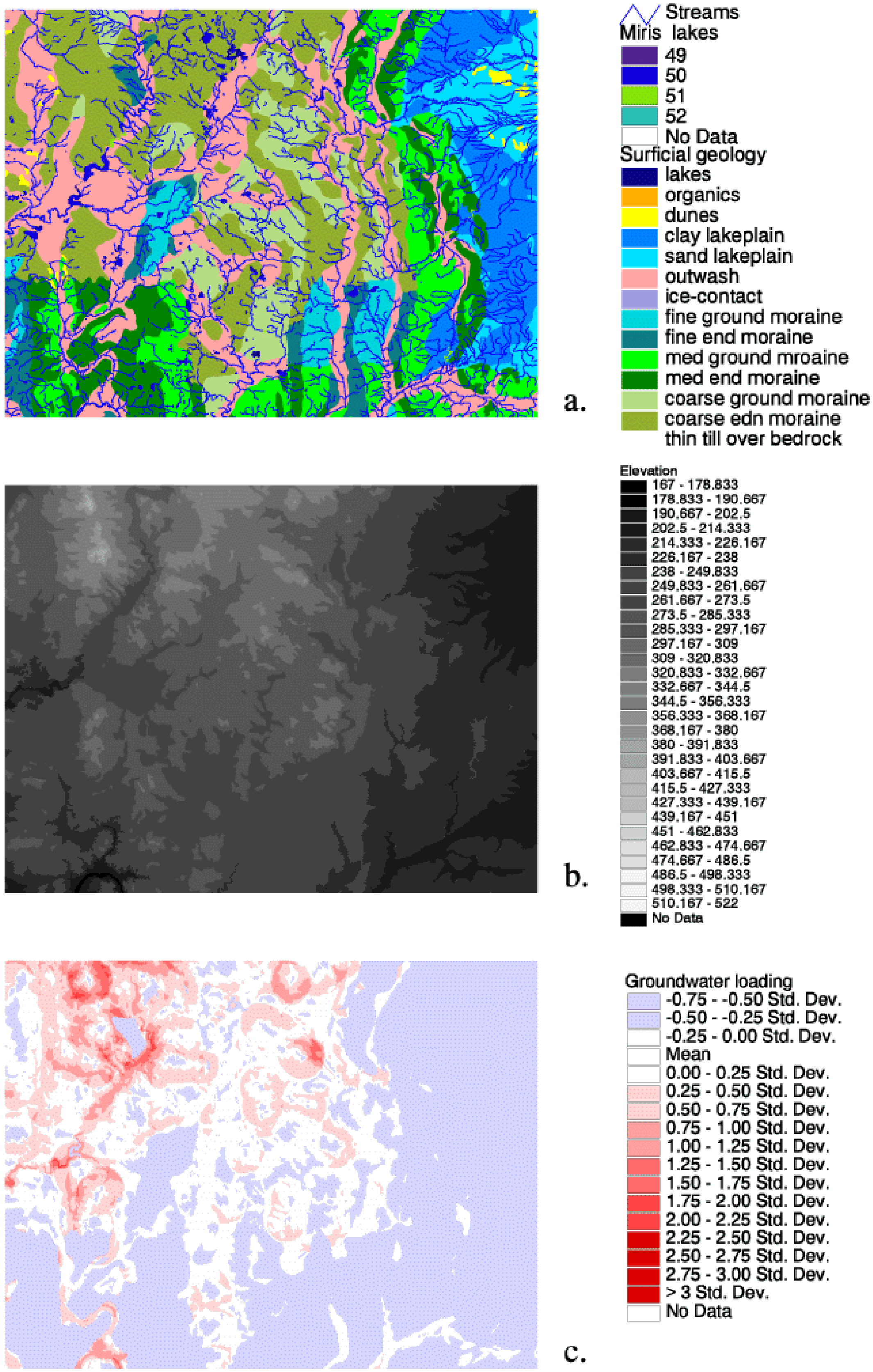

Streams
Miris lakes
49
50
51
52
No Data
Surficial geology
lakes
organics
dunes
clay lakeplain
sand lakeplain
outwash
ice-contact
fine ground moraine
fine end moraine
med ground mroaine
med end moraine
coarse ground moraine
coarse edn moraine
thin till over bedrock
a.
Elevation
167 - 178.833
178.833 - 190.667
190.667 - 202.5
202.5 - 214.333
214.333 - 226.167
226.167 - 238
238 - 249.833
249.833 - 261.667
261.667 - 273.5
273.5 - 285.333
285.333 - 297.167
297.167 - 309
309 - 320.833
320.833 - 332.667
332.667 - 344.5
344.5 - 356.333
356.333 - 368.167
368.167 - 380
380 - 391.833
391.833 - 403.667
403.667 - 415.5
415.5 - 427.333
427.333 - 439.167
439.167 - 451
451 - 462.833
462.833 - 474.667
474.667 - 486.5
486.5 - 498.333
498.333 - 510.167
510.167 - 522
No Data
b.
Groundwater loading
-0.75 - -0.50 Std. Dev.
-0.50 - -0.25 Std. Dev.
-0.25 - 0.00 Std. Dev.
Mean
0.00 - 0.25 Std. Dev.
0.25 - 0.50 Std. Dev.
0.50 - 0.75 Std. Dev.
0.75 - 1.00 Std. Dev.
1.00 - 1.25 Std. Dev.
1.25 - 1.50 Std. Dev.
1.50 - 1.75 Std. Dev.
1.75 - 2.00 Std. Dev.
2.00 - 2.25 Std. Dev.
2.25 - 2.50 Std. Dev.
2.50 - 2.75 Std. Dev.
2.75 - 3.00 Std. Dev.
> 3 Std. Dev.
No Data
c.

Figure 7.

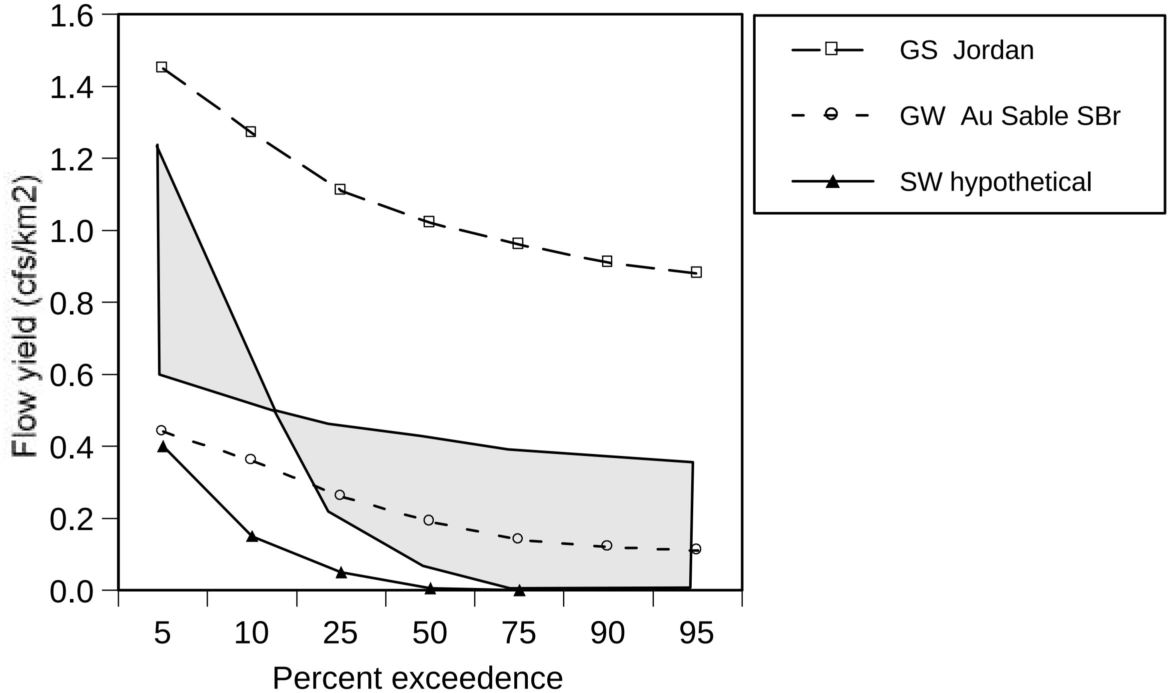
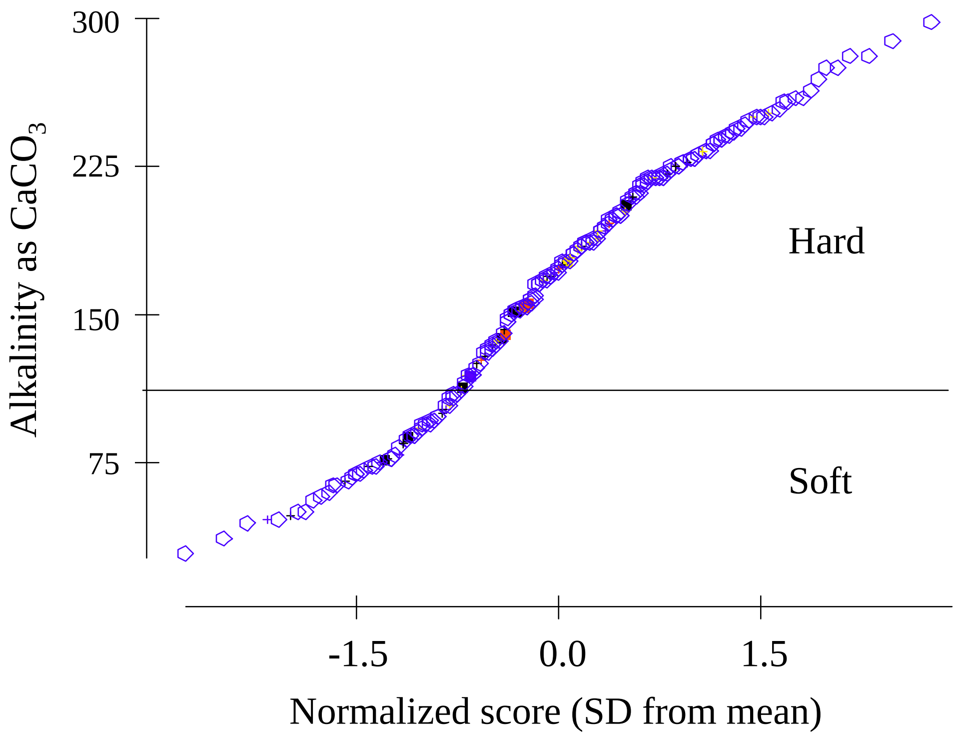


Figure 8.–Flow duration curves representing less-common stream flow patterns shown relative to the zone of more common patterns (shaded). The Jordan River curve illustrates a river gaining groundwater from adjacent surficial catchments (code GS), while wetland-dominated catchments show lower yields overall (codes GW and SW).



Figures 9.–Cumulative frequency distribution of Alkalinity measures for lower Michigan streams, showing cutoff values used in the VSEC system.

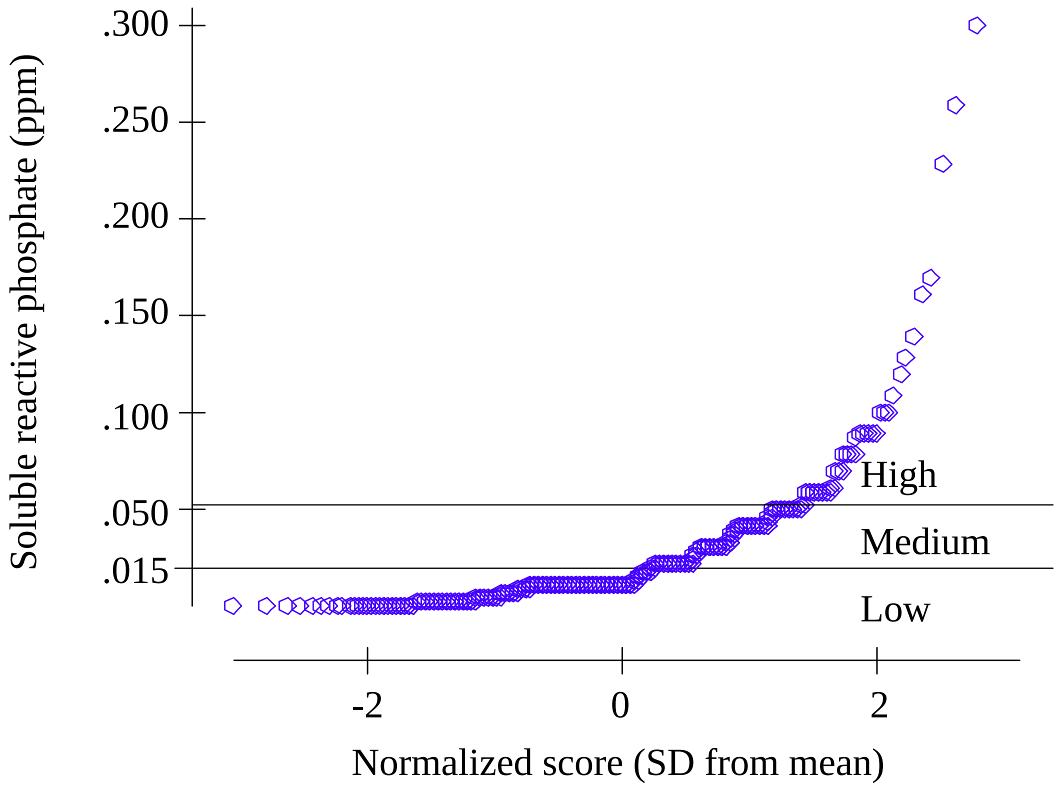


Figure 10.–Cumulative frequency distribution for Soluble Reactive Phosphate in lower Michigan rivers, showing cutoff values used in the VSEC system.

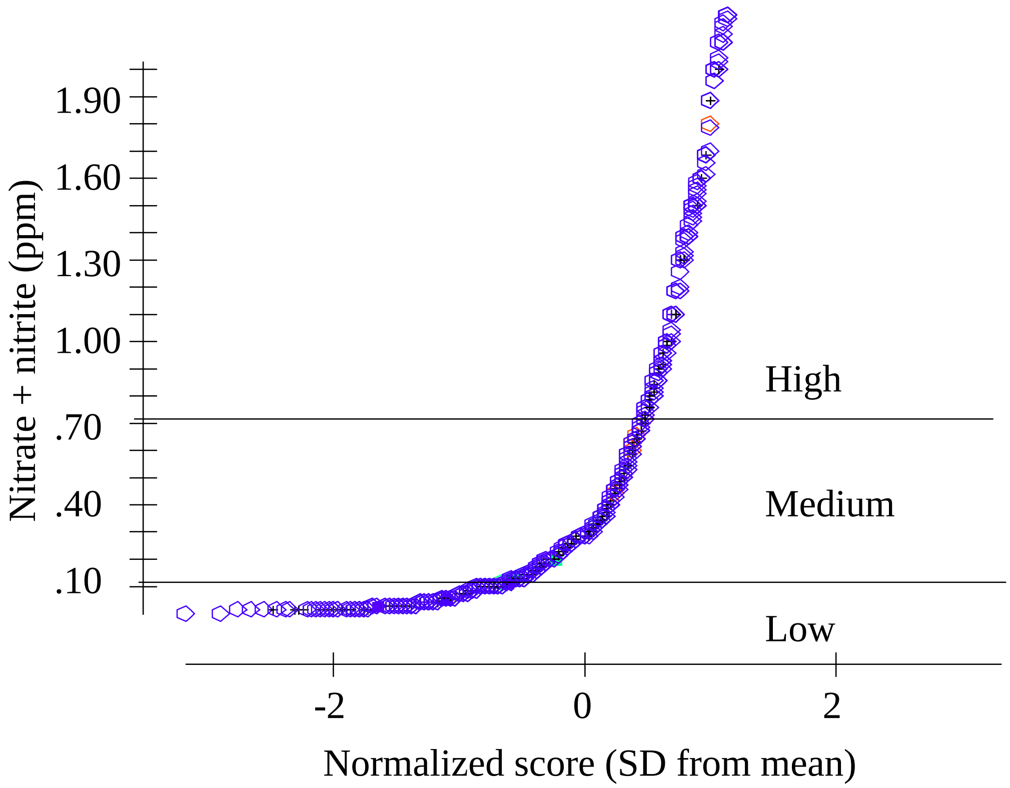


Figure 11.–Cumulative frequency diagram of Nitrate + nitrite in lower Michigan rivers, showing cutoffs used in the VSEC system.

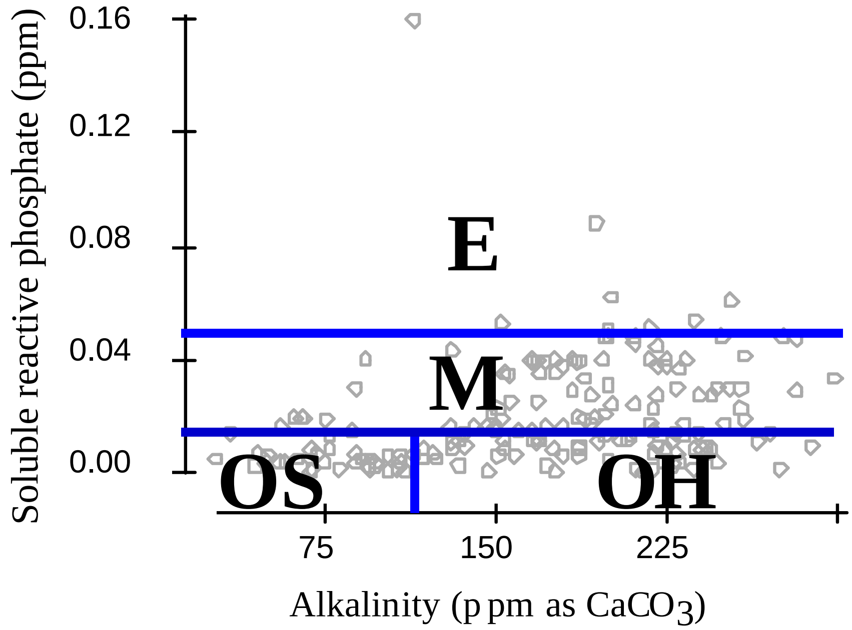


Figure 12.–Classification of stream chemistry for lower Michigan rivers used in the VSEC system, showing relationships between Alkalinity and Soluble reactive phosphorus, and the classes: Oligotrophic Soft (OS), Oligotrophic Hard (OH), Mesotrophic (M), and Eutrophic (E).

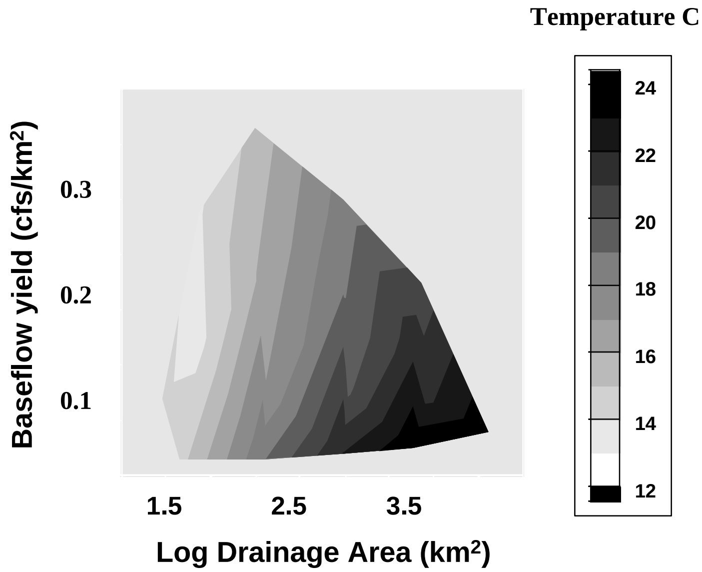


Figure 13.–Patterns in estimated July mean temperatures in lower Michigan streams plotted against catchment drainage area and baseflow yield (90% exceedence flow per km^2 of the catchment).

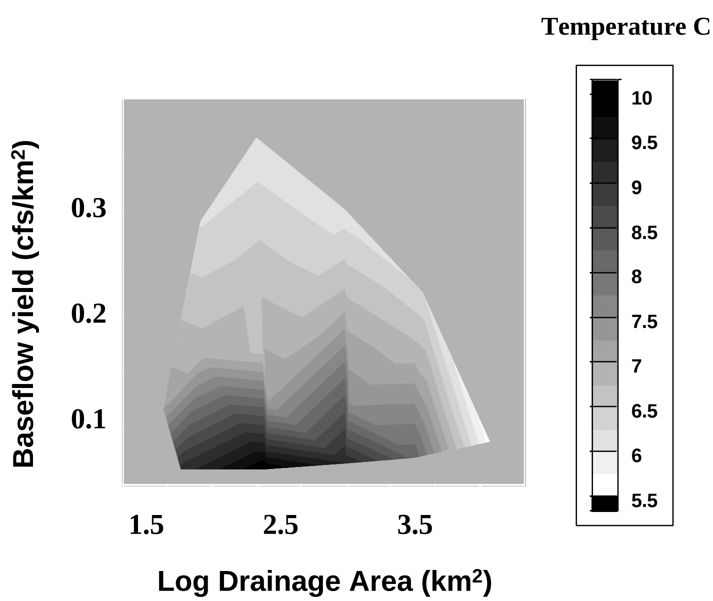


Figure 14.–Patterns in July weekly temperature variations in lower Michigan streams plotted against catchment drainage area and baseflow yield (90% exceedence flow per km^2 of the catchment).

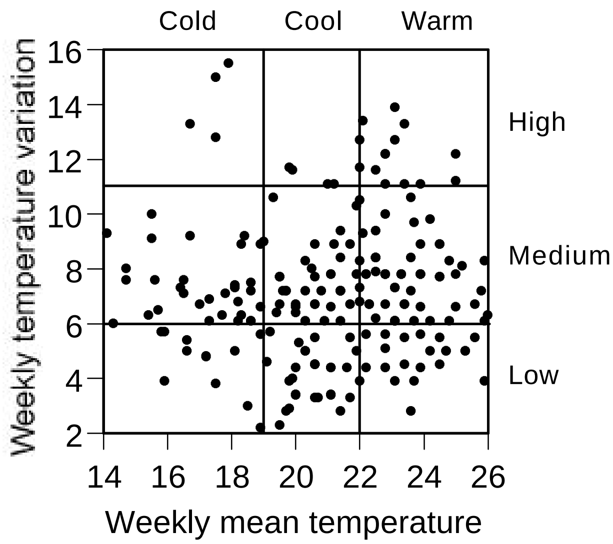


Figure 15.–July temperatures observed in Michigan streams plotted against 3 categories of weekly mean temperatures and 3 categories of weekly temperature flux (Wehrly et al. 1997).

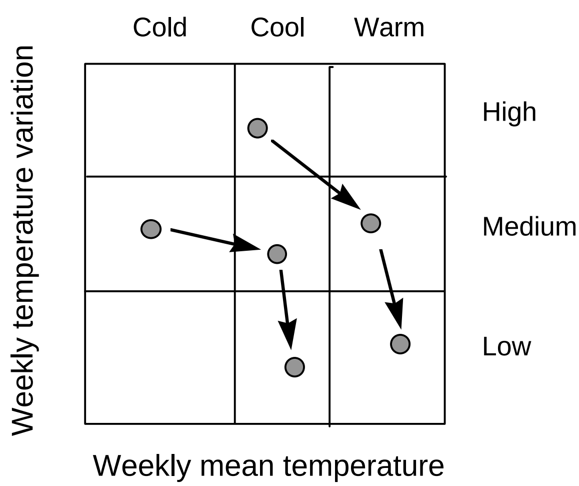


Figure 16.–Two headwater to downstream progressions of temperature categories commonly observed in Michigan rivers.

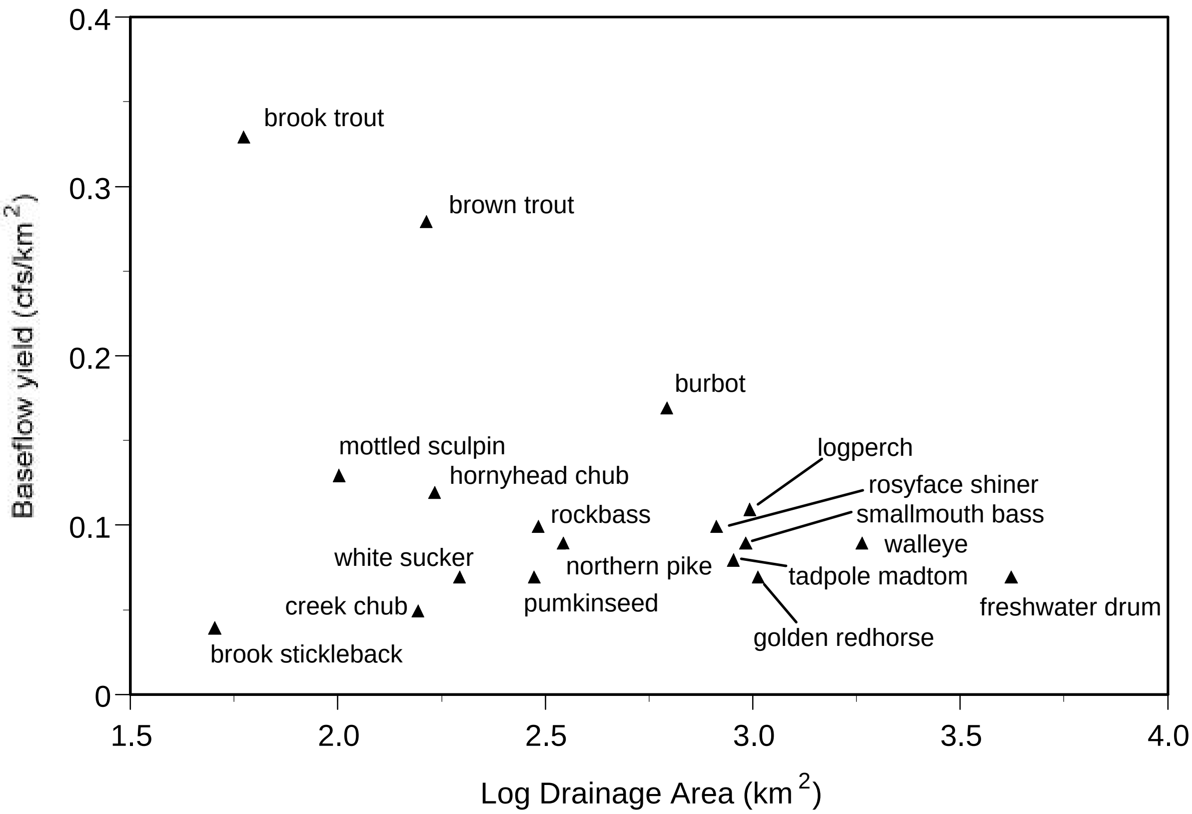


Figure 17.–Mean baseflow yield and catchment drainage area for sample sites where each fish species association was relatively abundant in lower Michigan rivers.

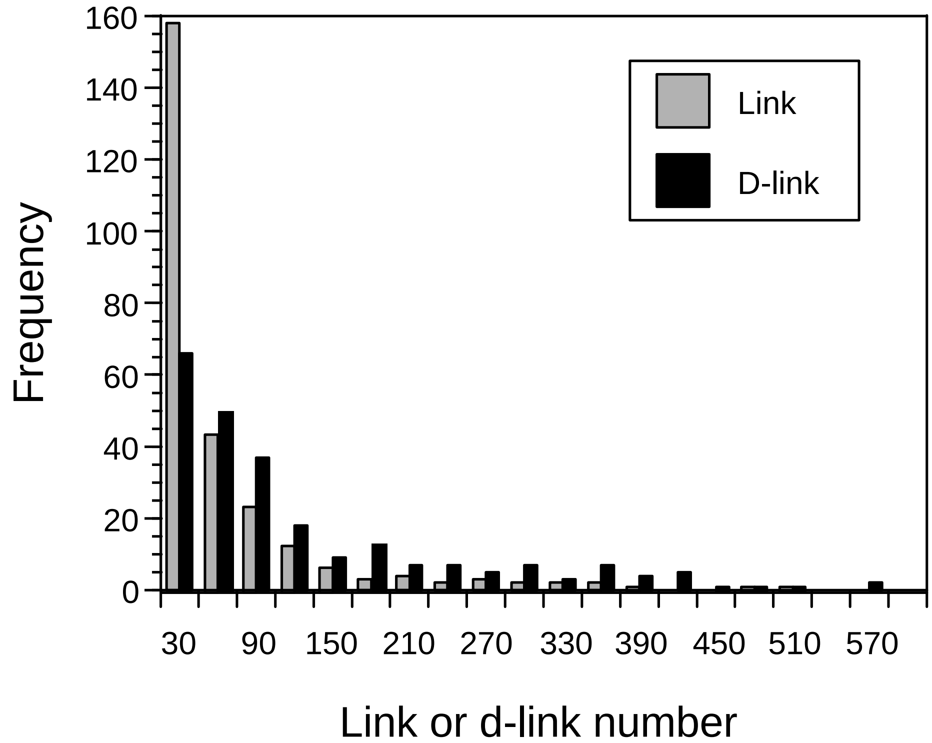


Figure 18.–Histogram of link numbers and d-link numbers for river valley segments in Lower Michigan.

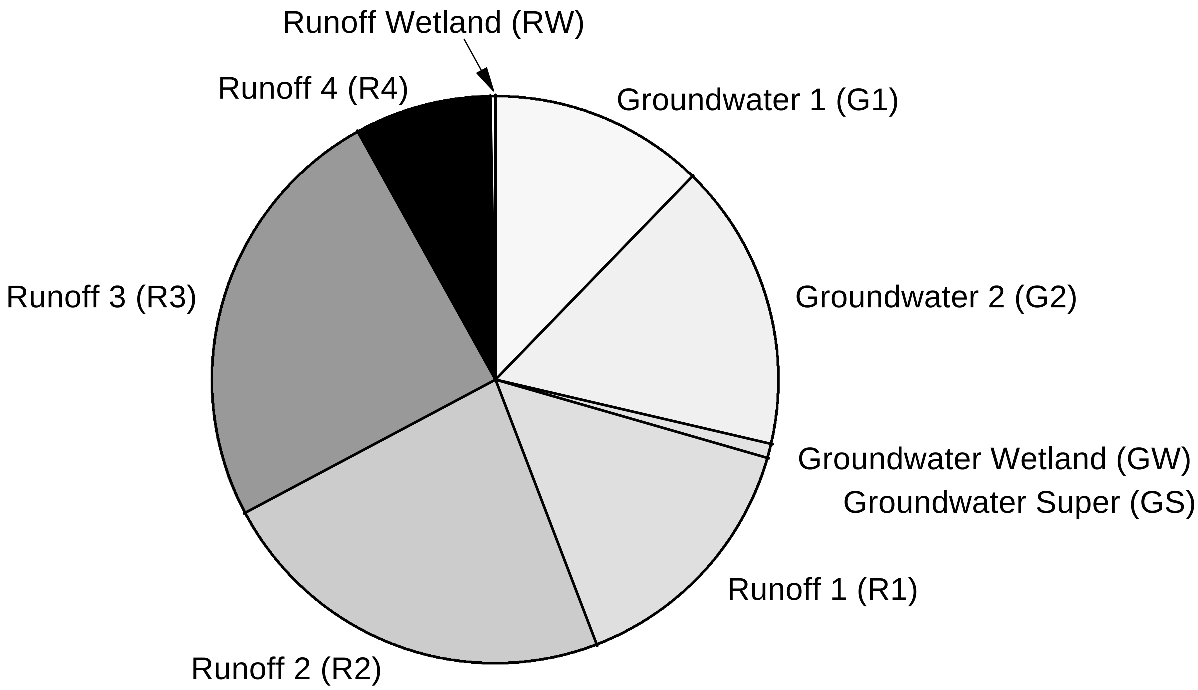


Figure 19.–Percent composition of hydrologic codings for river valley segments in Lower Michigan.

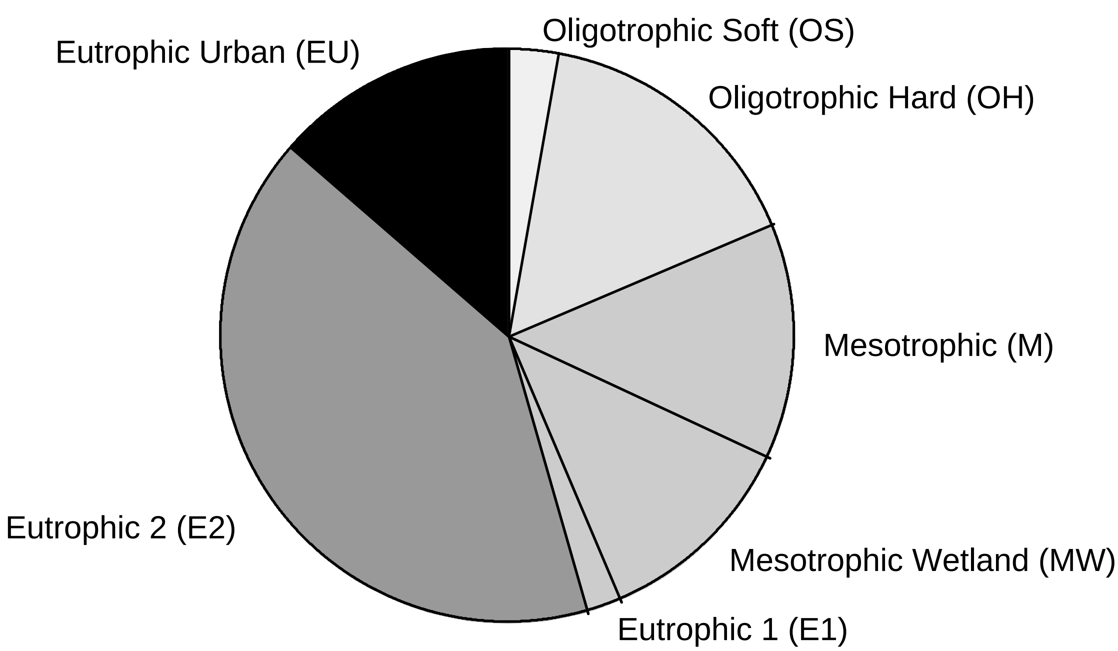


Figure 20.–Percent composition of water chemistry codings for river valley segments in Lower Michigan. No segments were cpded as Eutrophic Groundwater (EG).

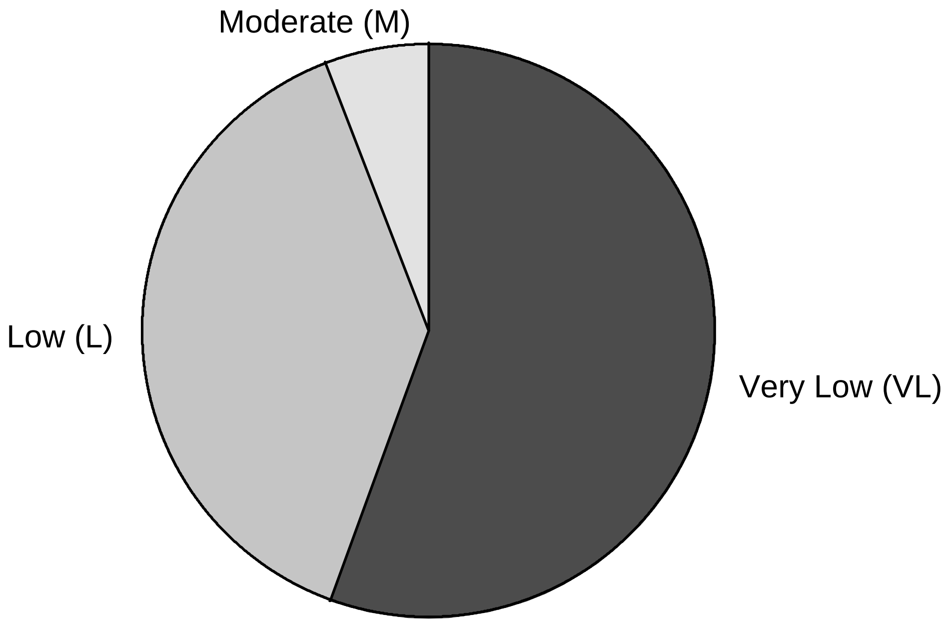


Figure 21.–Percent composition of channel gradient codings for river valley segments in Lower Michigan.

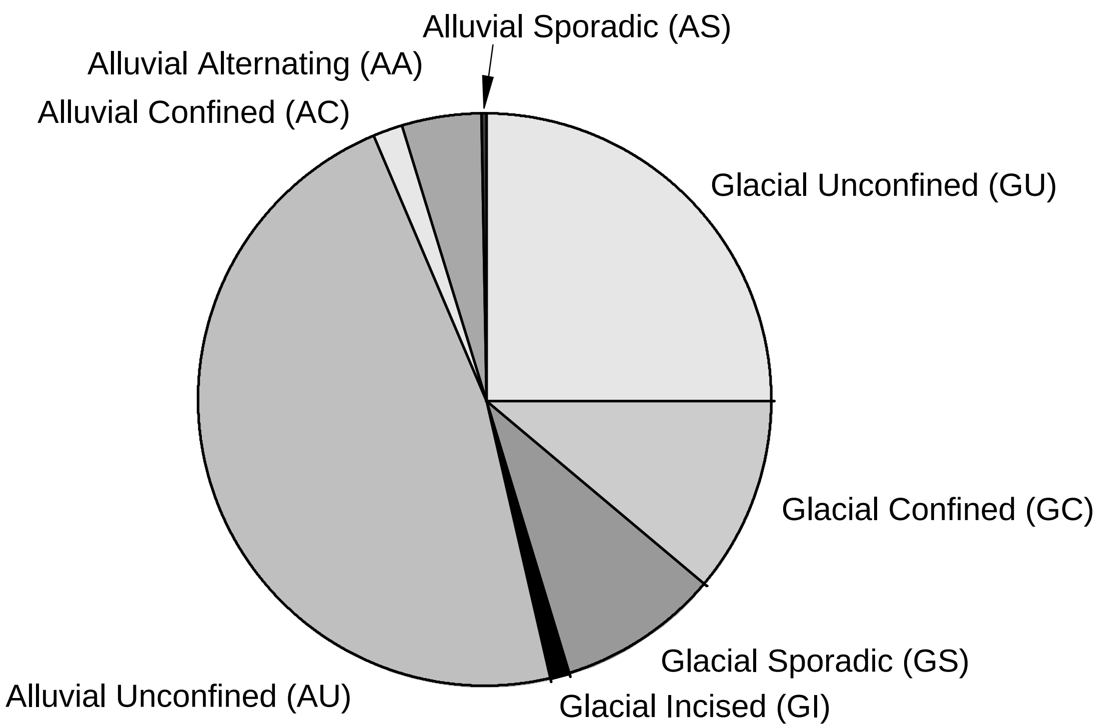


Figure 22.–Percent composition of valley character codings for river valley segments in Lower Michigan.

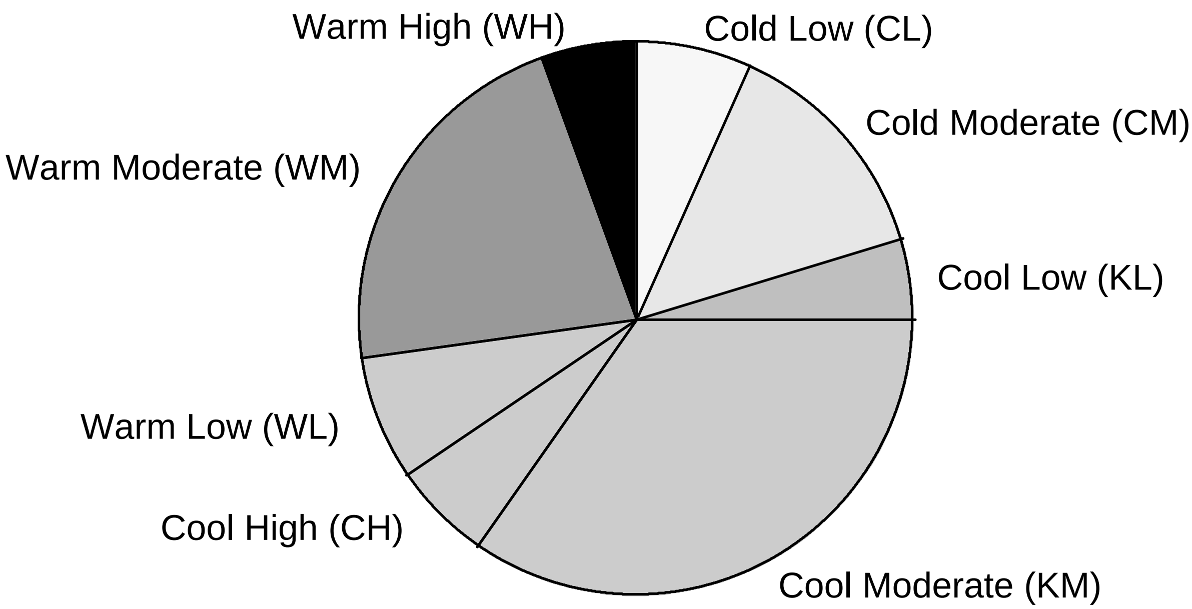


Figure 23.–Percent composition of water temperature regime codings for river valley segments in Lower Michigan. No segments were coded as Cold High (CH).

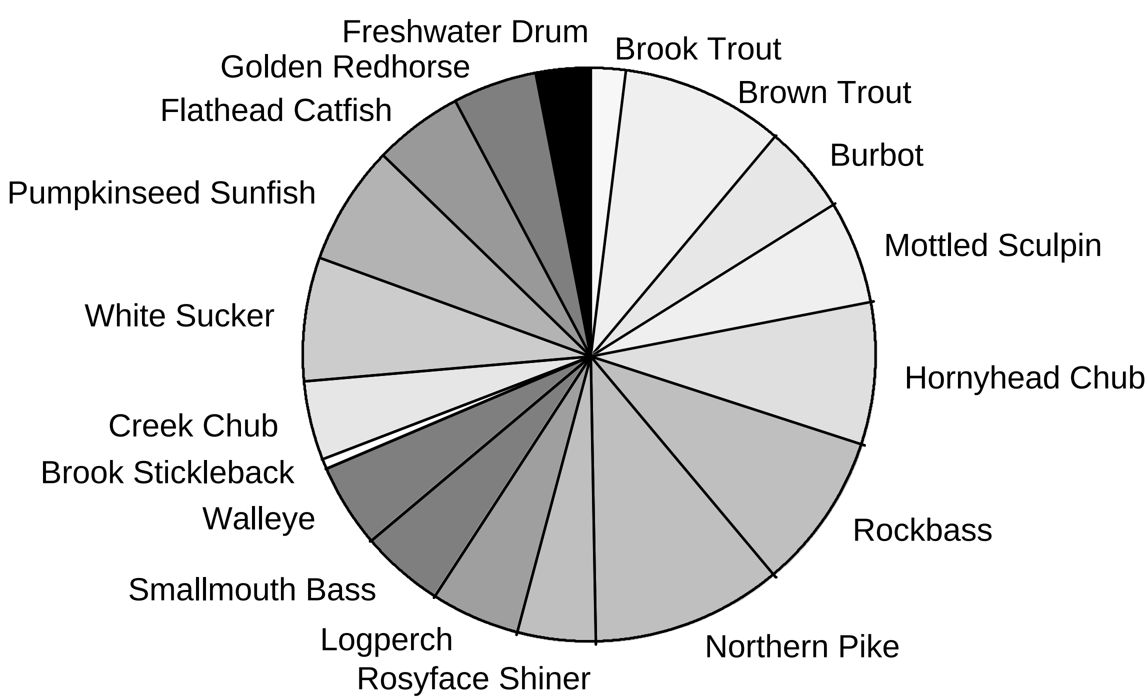
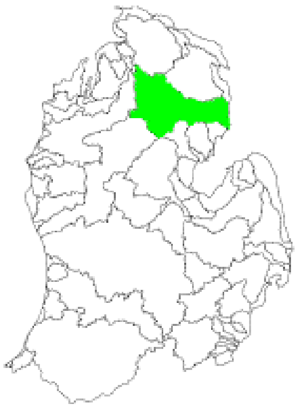


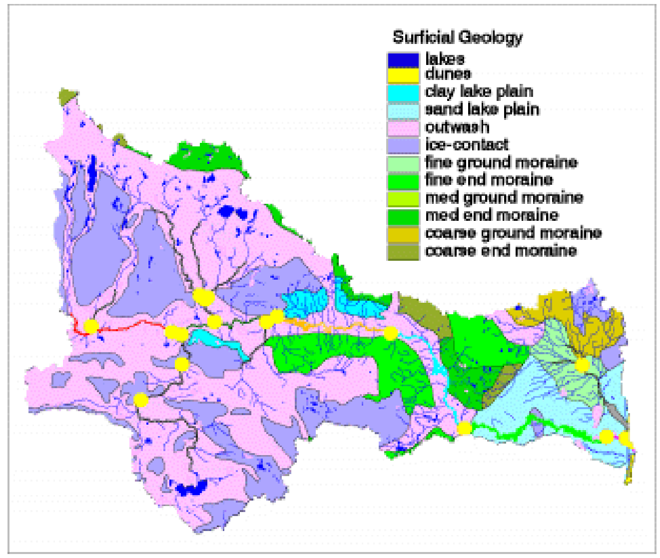
Figure 24.–Percent composition of fish association codings for river valley segments in Lower Michigan. (Species composition of each group is given in Table 4).

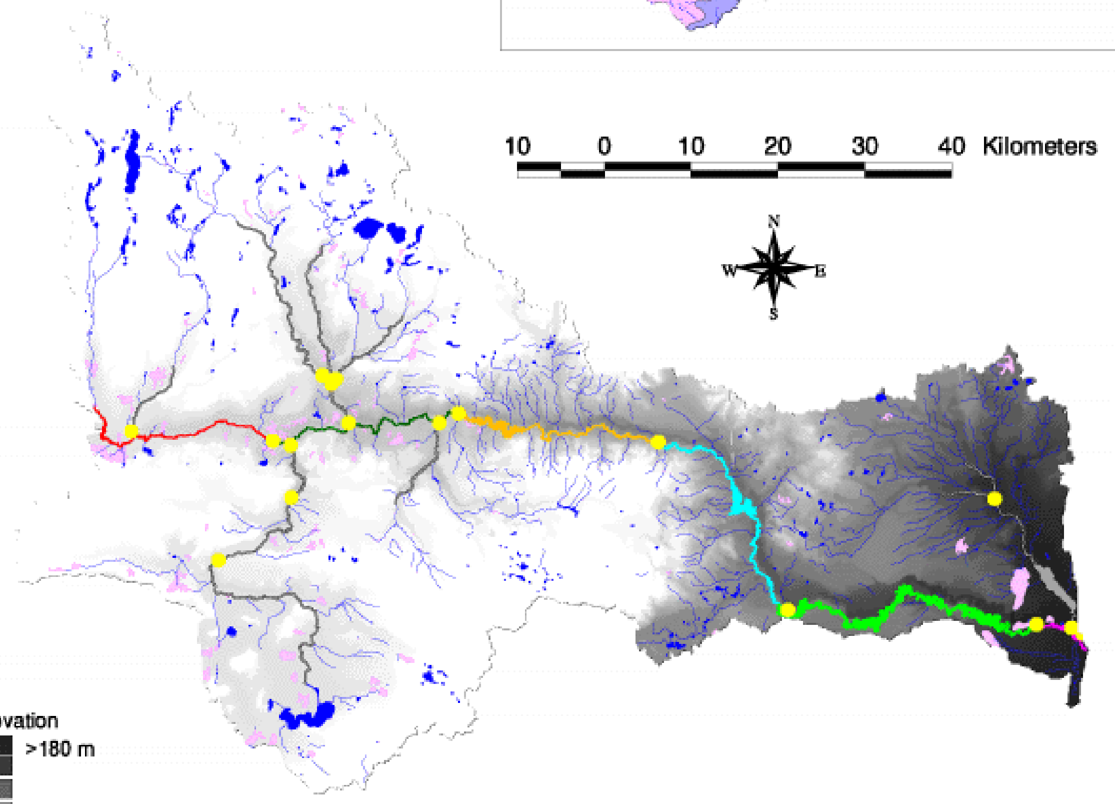
Figure 25.–Examples of VSEC map and table data for mainstem segments of the Au Sable River displayed in ArcView. Table codings are described in the Methods section of this document. The Au Sable River's upper half drains a large, perched outwash (sand) plain that contains ice-contact (sand and gravel) hills. It then cuts sharply down across mixed-textured end moraines and flows across a sandy lake plain to Lake Huron. The river maintains extremely high baseflows throughout its length, with an additional influx of groundwater as it cuts the moraine. Trout associations dominate the upper, coldwater half of the system, but increasing size drives the downstream segments towards cool, stable temperatures and Burbot and Walleye associations. This graphic is best viewed in color and will be available on the Institute for Fisheries Research Internet web site.

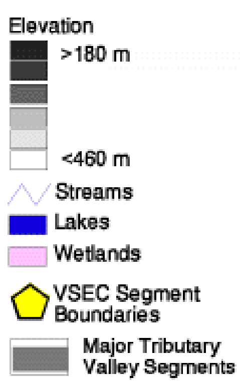
Figure 26.–Examples of VSEC map and table data for mainstem segments of the Grand River displayed in ArcView. Table codings are described in the Methods section of this document. The Grand River begins in an interlobate area of mixed, coarse surficial deposits; dotted with small lakes and wetlands. It then picks its way across alternating, medium-textured end and ground moraines; before dropping into a very large glacial valley about half-way to the mouth. The lower half of the river follows this glacial valley west to Lake Michigan. Fishes typical of lake outlets and small, low-gradient, coolwater rivers are common in the upper segments. Mid sections are steeper and warmer, with abundant smallmouth bass and associated species. The lower river is fairly large (having picked up substantial flows from several large tributary rivers) and flat (running in the glacial valley), and has thermal regimes and fishes typical of larger, warmwater rivers. This graphic is best viewed in color and will be available on the Institute for Fisheries Research Internet web site.

Figure 27.–Examples of VSEC map and table data for mainstem segments of the Raisin River displayed in ArcView. Table codings are described in the Methods section of this document. The Raisin River begins in an area of mixed, coarse, interlobate surficial deposits; dotted with small lakes and wetlands. It drops sharply down across mixed-textured end moraines and then flows across a very large, clay lake plain towards Lake Erie. Its final segment runs down across some protruding limestone deposits to Lake Erie. Fishes typical of lake outlets and small, low-gradient, coolwater rivers are common in the upper segments. Cutting through the moraines, segments are steeper, larger, and warmer, with abundant smallmouth bass and associated species. The large, lake-plain segment is characterized by low gradient, low baseflows, warm waters and fishes typical of larger, warmwater rivers. This graphic is best viewed in color and will be available on the Institute for Fisheries Research Internet web site.



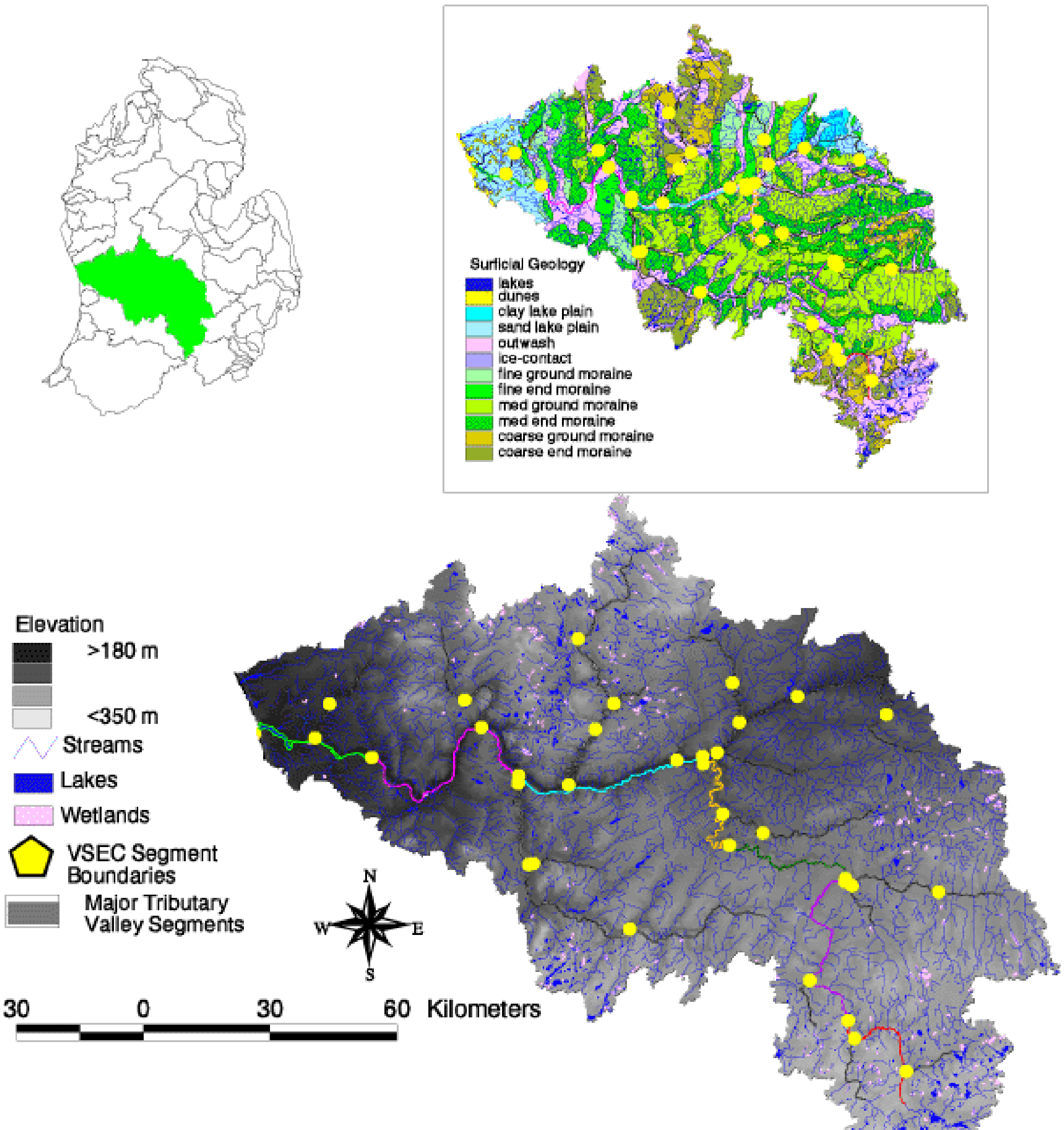






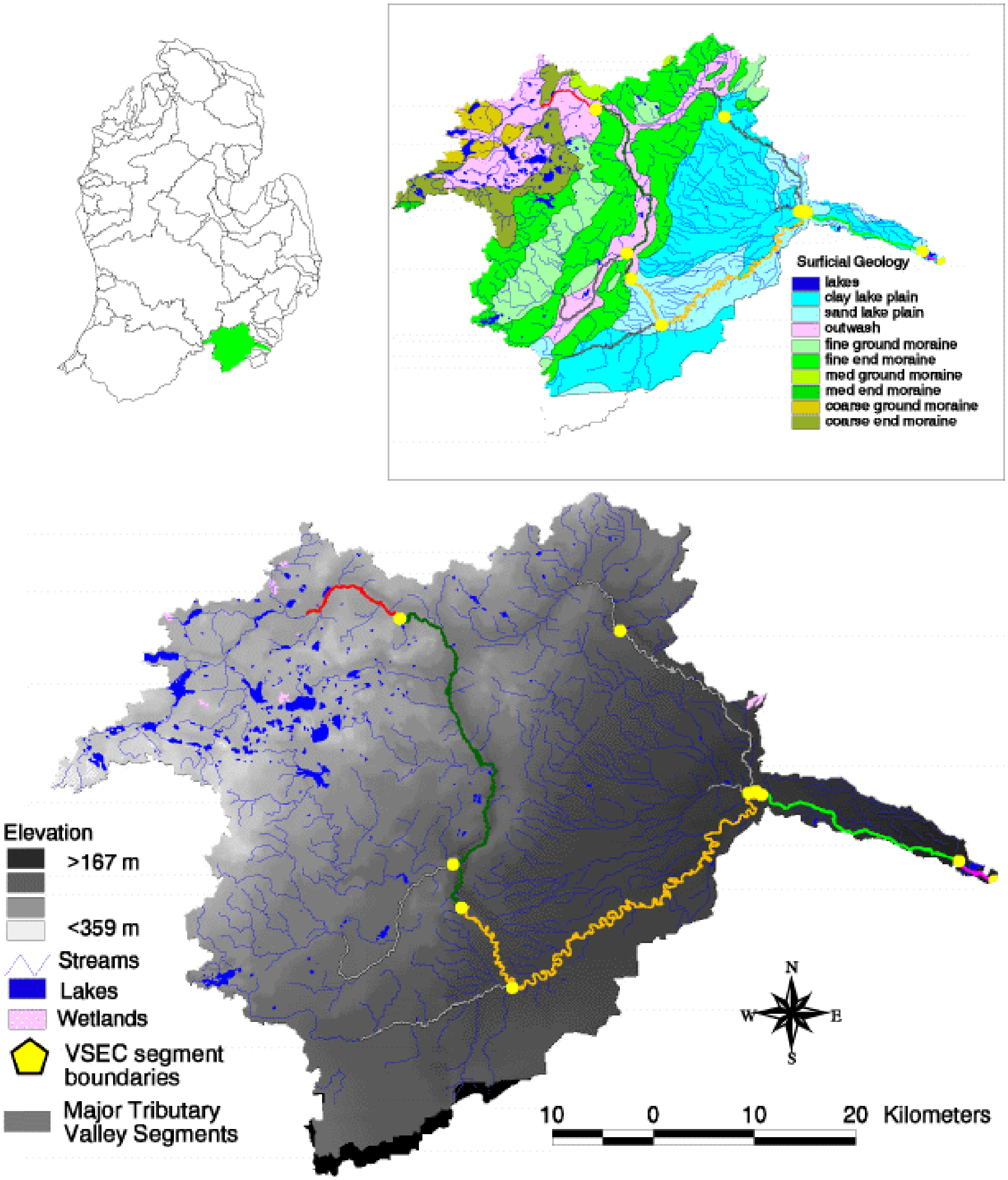
Segment	Link#	D-link#	Grad	Valley	Hydro	Temp	Fish Groups
1	29	66	VL	GS	G1	CM	BrookTr, BrownTr
2	119	133	L	GS	G1	CM	BrownTr
3	139	153	L	GC	G1	KL	Walleye, Burbot
4	161	230	M	GC	G1	KL	Walleye, Burbot
5	171	230	L	GC	G2	KL	Walleye
6	233	4278	VL	AU	G2	KL	Walleye

Figure 25.



Segment	Link#	D-link#	Grad	Valley	Hydro	Temp	Fish Groups
1	150	165	VL	AA	S2	KM	HHChub, WSucker
2	173	246	VL	AA	S2	KM	Rockbass, NPike
3	250	282	VL	AU	S3	WM	SMBass, Logperch, Rockbass
4	285	347	L	GC	S3	WM	SMBass, FlatCat
5	492	555	VL	GC	S3	WL	Walleye, FlatCat, GRedhorse, FDrum
6	615	679	VL	GC	S3	WL	Walleye, FlatCat, FDrum
	679	4278	VL	AC	S3	WL	FDrum, Walleye

Figure 26.



Segment	Link#	D-link#	Grad	Valley	Hydro	Temp	Fish Groups
1	12	14	L	AS	S2	KM	Rockbass, NPike, Rosyface
2	34	43	L	GI	S2	WM	SMBass, Rosyface
3	67	4278	VL	AU	S3	WM	FlatCat, GRedhorse
4	70	4278	L	AU	S3	WM	FlatCat, GRedhorse
5	70	4278	VL	AU	S3	WL	FDrum, GRedhorse

Figure 27.

Table 1.–Examples of key landscape variables interpreted from GIS maps to infer ecological attributes.

Ecological attributes	Key landscape variables	
	Catchment-scale	Local-scale
catchment size	river network pattern	-----
hydrology	catchment slope, percent coarse-textured drifts, percent land cover	local slope, adjacent coarse-textured drifts, connected wetlands
chemistry	inferred hydrology, percent land cover, surficial geology	connected lakes and wetlands, adjacent land cover
summer water temperatures	inferred size and hydrology, percent land cover	local groundwater inputs, adjacent land cover, connected lakes
valley character	-----	landscape slope, surficial geology, glacial-fluvial channels, floodplain wetlands
channel character	-----	planform
fishes	inferred size and hydrology, percent land cover	local groundwater inputs, adjacent land cover, river net position and connectivity

Table 2.–Documentation for map themes of Michigan's Lower Peninsula used in developing MI-VSEC, Version 1.0.

Map description	Source and scale	Format
Quaternary geology	MRI 1996[1], 1:500,000	1 Ha raster
Stream networks	MRI 1996[2], 1:100,000	vector
Digital elevation	USGS, 3-second	1 Ha raster
Land cover	MRI 1996[3], 1:24,000	1 Ha raster
Soil texture	STATSCO	1 Km raster
Groundwater velocity	MRI 1996[4],	1 Km raster

[1] Converted (by Michigan Rivers Inventory project) to raster format from vector-format map obtained from Michigan Natural Features Inventory, Lansing. Based on Farrand and Bell (1984).
[2] Assembled from US Geological Survey Digital Line Graph files.
[3] Converted to raster format from vector-format map obtained from MIRIS, Lansing. Based on 1978-79 color-infrared, aerial photo imagery.
[4] MRI-Derived map of Darcy's Law of groundwater velocity calculated by 1 Km raster, from the Quaternary geology and digital elevation maps.

Table 3.–Great Lake basins and major watershed systems described in the MI-VSEC 1.0 system.

Lake Michigan Basin	Lake Huron Basin	Lake Erie Basin
St. Joseph	Saginaw (lower river)	Raisin
Kalamazoo	Cass	Huron
Grand	Shiawassee	Rouge
Muskegon	Tittabawassee	Clinton
White	Rifle	Black
Pere Marquette	Au Sable	
Manistee	Thunder Bay	
	Cheboygan	

Table 4.–Statistical fish species associations found in lower Michigan rivers (Zorn et al. 1997). Group names are in bold.

creek chub redfin shiner stoneroller minnow common shiner bluntnose minnow Johnny darter	**flathead catfish** white crappie common carp bowfin black crappie tadpole madtom spotted sucker	**smallmouth bass** black redhorse striped shiner river chub northern hog sucker stonecat greenside darter
mottled sculpin blacknose dace	**burbot** longnose dace	**rosyface shiner** yellow perch
white sucker fathead minnow	**pumkinseed sunfish** black bullhead yellow bullhead green sunfish bluegill	**logperch** brook silversides mimic shiner shorthead redhorse sand shiner
brown trout chinook salmon rainbow trout	**hornyhead chub** grass pickerel lake chubsucker	**walleye** channel catfish spotfin shiner
brook trout slimy sculpin coho salmon	**northern pike** golden shiner blackside darter central mudminnow pirate perch	**golden redhorse** greater redhorse silver redhorse
brook stickleback hybrid sunfish northern redbelly dace	**rockbass** brown bullhead longear sunfish largemouth bass rainbow darter	**freshwater drum** quillback carpsucker gizzard shad

Table 5.–Characteristics of common, ecological river valley segment types found in Lower Michigan. Fish associations, which are diagnostic of the overall ecological character of a segment, are emphasized in bold. Types were based on an initial summary of MI-VSEC hydrologic, July thermal, and channel confinement attributes.

Type	Sample size	Hydrologic regime	Thermal regime	Channel confinement	Link number range	Nutrient code	Channel gradient	**Diagnostic fish associations**
#1	N=6	Very high groundwater	Cold & Low daily flux	Confined channel	Links 13-36	Oligotrophic	Low gradient	**Brook trout, Brown trout**
#2	N=6	Very high groundwater	Cold & Low daily flux	Unconfined channel	Links 10-14	Oligotrophic	Very low gradient	**Brown trout**
#3	N=5	Very high groundwater	Cold & Moderate daily flux	Confined channel	Links 23-32	Oligotrophic	Very low/Low gradient	**Brown trout, Mottled sculpin**
#4	N=6	Very high groundwater	Cold & Moderate daily flux	Unconfined channel	Links 12-81	Oligotrophic	Very low/Low gradient	**Brown trout**
#5	N=7	High groundwater	Cold & Moderate daily flux	Confined channel	Links 6-28	Mesotrophic	Low/Moderate gradient	**Brown trout, Mottled sculpin**
#6	N=13	High groundwater	Cold & Moderate daily flux	Unconfined channel	Links 7-28	Mesotrophic	Very low/Low gradient	**Brown trout, Mottled sculpin, Burbot, Hornyhead chub**
#7	N=11	High groundwater	Cool & Moderate daily flux	Unconfined channel	Links 40-113	Mesotrophic	Very low gradient	**Burbot, Logperch, Rosyface shiner, Hornyhead chub**
#8	N=6	Fair groundwater	Cool & Moderate daily flux	Confined channel	Links 9-18	Eutrophic	Low/Moderate gradient	**Mottled sculpin, Hornyhead chub, White sucker**
#9	N=21	Fair groundwater	Cool & Moderate daily flux	Unconfined channel	Links 13-77	Mesotrophic	Very low/Low gradient	**Burbot, Hornyhead chub, Logperch, Rosyface, Rockbass**
#10	N=6	Fair groundwater	Warm & Moderate daily flux	Unconfined channel	Links 36-80	Mesotrophic	Very low/Low gradient	**Smallmouth bass, Rockbass, Rosyface shiner**
#11	N=13	Moderate groundwater	Cool & Moderate daily flux	Confined channel	Links 13-91	Eutrophic	Very low/Low gradient	**Northern pike, Rockbass, Hornyhead chub, White sucker**
#12	N=29	Moderate groundwater	Cool & Moderate daily flux	Unconfined channel	Links 11-54	Eutrophic	Very low/Low gradient	**Northern pike, Rockbass, Hornyhead chub, White sucker**
#13	N=5	Moderate groundwater	Warm & Moderate daily flux	Confined channel	Links 34-97	Eutrophic	Low gradient	**Smallmouth bass, Rockbass, Rosyface shiner**
#14	N=9	Moderate groundwater	Warm & Moderate daily flux	Unconfined channel	Links 14-68	Eutrophic	Very low/Low gradient	**Smallmouth bass, Rockbass, Rosyface shiner, Northern pike**

Table 5.–Continued.

Type	Sample size	Hydrologic regime	Thermal regime	Channel confinement	Link number range	Nutrient code	Channel gradient	**Diagnostic fish associations**
#15	N=6	Low groundwater	Cool & Moderate daily flux	Unconfined channel	Links 8-48	Eutrophic	Very low/Low gradient	**Mottled sculpin, White sucker, Creek chub**
#16	N=11	Low groundwater	Cool & High daily flux	Unconfined channel	Links 7-21	Eutrophic	Very low/Low gradient	**Creek chub, White sucker, Pumpkinseed sunfish**
#17	N=4	Low groundwater	Warm & Low daily flux	Confined channel	Links 468-679	Eutrophic	Very low gradient	**Walleye, Flathead catfish, Freshwater drum, Golden redhorse**
#18	N=7	Low groundwater	Warm & Low daily flux	Unconfined channel	Links 69-195	Eutrophic	Very low gradient	**Walleye, Flathead catfish, Freshwater drum, Golden redhorse**
#19	N=5	Low groundwater	Warm & moderate daily flux	Confined channel	Links 29-115	Eutrophic	Very low/Low gradient	**Smallmouth bass, Northern pike, Golden redhorse**
#20	N=27	Low groundwater	Warm & moderate daily flux	Unconfined channel	Links 12-70	Eutrophic	Very low gradient	**Northern pike, Pumkinseed, Golden redhorse, Flathead catfish**
#21	N=5	Low groundwater	Warm % high daily flux	Unconfined channel	Links 12-21	Eutrophic	Very low gradient	**Creek chub, White sucker, Pumkinseed sunfish**
#22	N=7	Very low groundwater	Warm & high daily flux	Unconfined channel	Links 9-29	Eutrophic	Very low gradient	**Creek chub, Pumkinseed sunfish, Northern pike**

Table 6.–Comparisons of terminology for hierarchical terrestrial classification units used by USFS – National, USEPA, and USFS – Upper Great Lakes States (personal communication, D.A. Albert, Michigan Natural Features Inventory, Lansing). This terminology is still evolving and is not consistent among geographers. Unit names we have adopted are in parentheses; including a breaking of landtype associations into large- and small-scale categories.

USFS – National	USEPA	USFS – Upper GL	Related aquatic unit
Province			
Section	Ecoregion	Region	
Subsection	Subregion	District	
(Sub-subsection)	(Landscape-level ecoregion)	Subdistrict	sub-watershed
Landtype association – (large)	(Landscape-level ecoregion)	Landtype association – (large)	sub-watershed, valley segment
Landtype association – (small)		Landtype association – (small)	valley segment

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