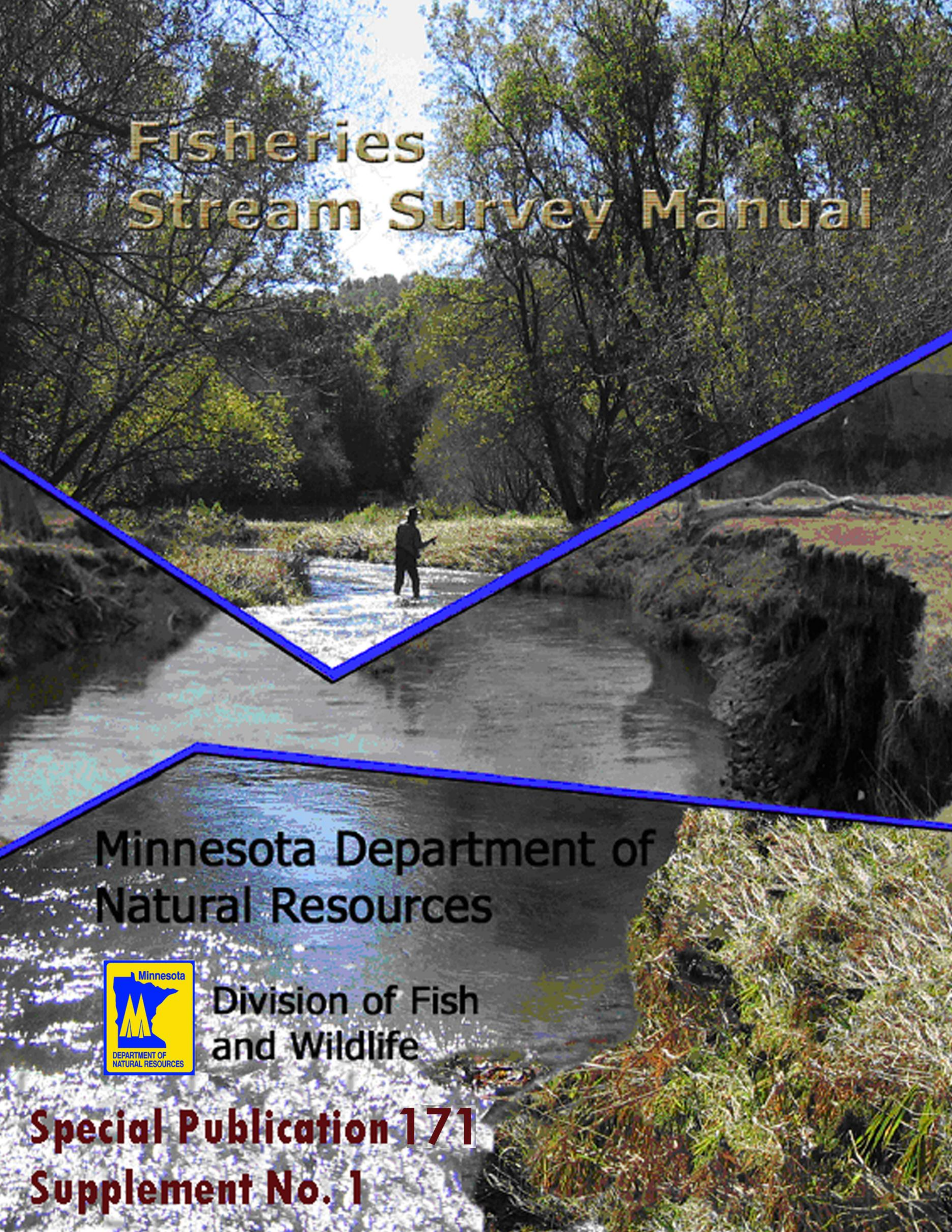

Fisheries Stream Survey Manual

Minnesota Department of Natural Resources

Minnesota
DEPARTMENT OF NATURAL RESOURCES

Division of Fish and Wildlife

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Fisheries Stream Survey Manual

Supplement 1:
Major Components of Stream Systems

Minnesota Department of Natural Resources
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Major Components of Stream Systems

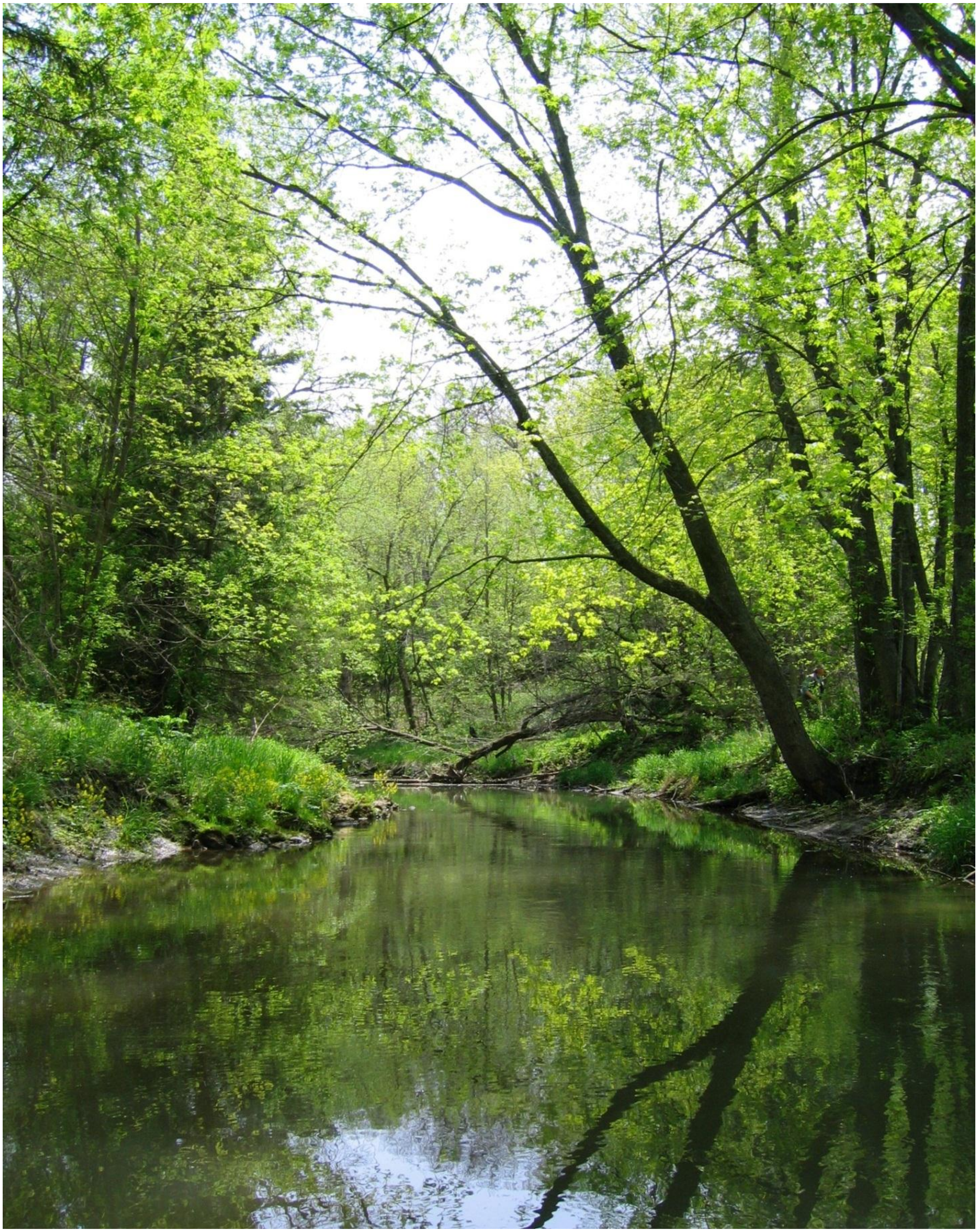


Photo by Rick Nelson

Chapter 1. Hydrology

"Remarkable changes have come about during the last half century in the water supply of the region. Many springs have become entirely dry and others have lost so much in flow as to seriously affect the flow of the streams which they feed, too often becoming entirely dry. That this state of affairs has been brought about by the necessities of civilization is beyond question."

- Thaddeus Surber, 1924, on southeast Minnesota hydrology.

Introduction

Water is essential for all life on earth; it is equally fundamental for humans and ecosystems. Despite the enormous significance of rivers in the development of civilizations and the shaping of landmasses, the amount of water in rivers at any one time is tiny in comparison to other stores **(Figure 1-1)**. Because of the relative scarcity of water in the atmosphere and rivers, the average water molecule cycles through them rapidly, residing only days to weeks, compared with much longer residence times of water in other compartments (Allan 1995).

The hydrologic cycle describes the continuous cycling of water from atmosphere to earth to oceans and back again. Conceptually this cycle can be viewed as a series of storage places and transfer processes, although water in rivers is both a storage place, however temporary, and a transfer between land and sea. The water that flows in streams and rivers comes from precipitation, but only a fraction of the rain or snow that falls actually reaches the channel. Some is immediately evaporated back into the atmosphere from rocks, soil, or vegetation; some enters the soil, where it is taken up by plants and transpired; some is lost into the deep groundwater; and only the remainder enters stream channels as runoff on or through the soil, or as shallow seepage. Climate, vegetation, topography, geology, land use, and soil characteristics determine how much surface runoff occurs compared to other pathways.

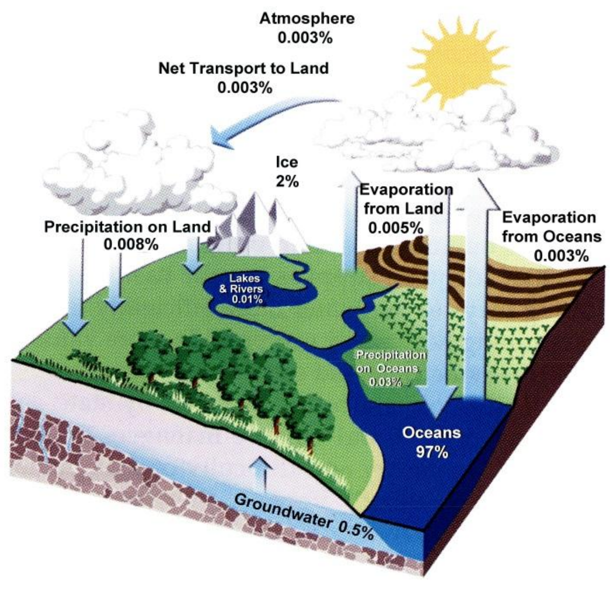


FIGURE 1-1. Groundwater is the second smallest of the four main pools of water on Earth and river flow to the ocean is one of the smallest fluxes. Yet groundwater and surface water are the components of the hydrologic systems that humans use most (Adapted from Schelesinger 1991).

Disturbances to specific hydrologic processes, such as a decrease of infiltration from soil compaction, increase in evaporation from change in vegetative cover type, or changes in runoff from impervious surfaces directly affect the flow regime in the stream channel. Poff et al. (1997) describes five characteristics of a flow regime that influence river ecosystems: magnitude, frequency, duration, timing, and rate of change. Alteration of any characteristic of the flow regime can directly impact physical habitat (e.g., eliminating flood peaks will decrease the streams ability to move sediment) and aquatic organisms (e.g., increasing the rate of change will displace invertebrates and can result in stranding). The naturally variable flow regime creates and maintains the physical habitat in streams and the longitudinal and lateral connectivity (Poff et al. 1997). In addition, species have evolved life histories that depend on the predictable seasonal variation in discharge (Bunn and Arthington 2002).

Various authors (Amoros et al. 1987; Ward 1989) have advanced the notion that there are four dimensions of hydrology: longitudinal (headwater to mouth), lateral (channel to floodplain), vertical (channel bed with groundwater), and chronological. [All four dimensions also apply to stream connectivity (see Connectivity Section on pages 66-77)]. The River Continuum Concept (RCC; Vannote et al. 1980) described the entire fluvial system as a continuously integrating series of physical gradients and associated biotic adjustments as the river flows from headwaters to mouth **(Figure 1-2)**. The flood pulse concept **(Figure 1-3)** applied the RCC to the lateral dimension as a "batch process," operating distinctly from major biota in river-floodplain systems (Junk et al. 1989). Streams interact with groundwater in two basic ways: streams gain water from inflow of groundwater through the streambed; they lose water to groundwater by outflow through the streambed, or they do both—gaining in some reaches and losing in others (Winters et al. 1998). These processes are directly related to the five riverine components.

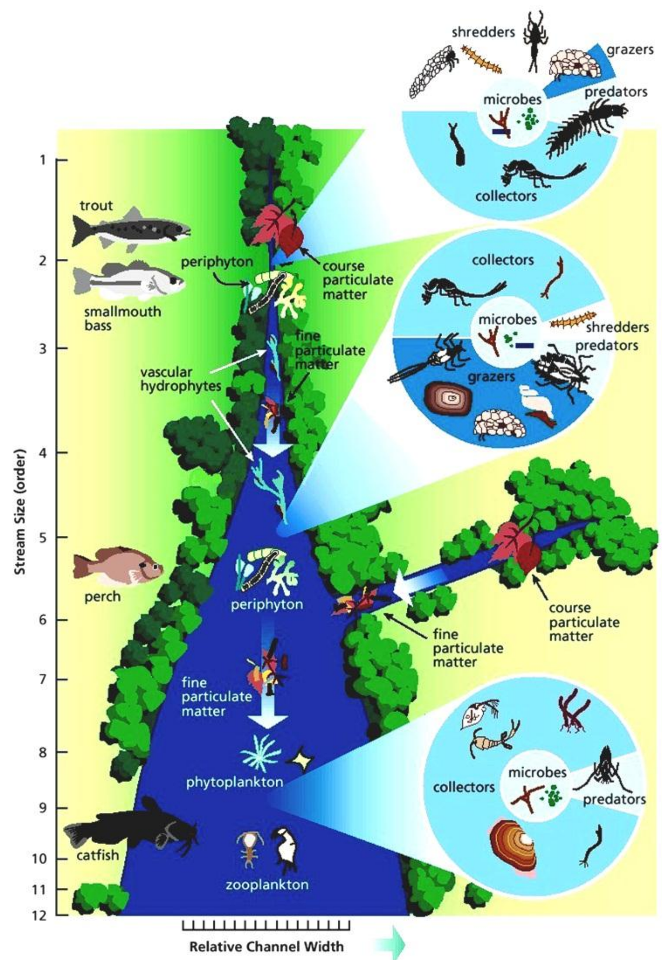


FIGURE 1-2. The River Continuum Concept (RCC) emphasizes the longitudinal dimension of stream ecosystems. The RCC proposes a progressive shift, from headwaters to mouth, of physical gradients and energy inputs and accompanying shift in trophic organization and biological communities. (From Vannote et al. 1980).

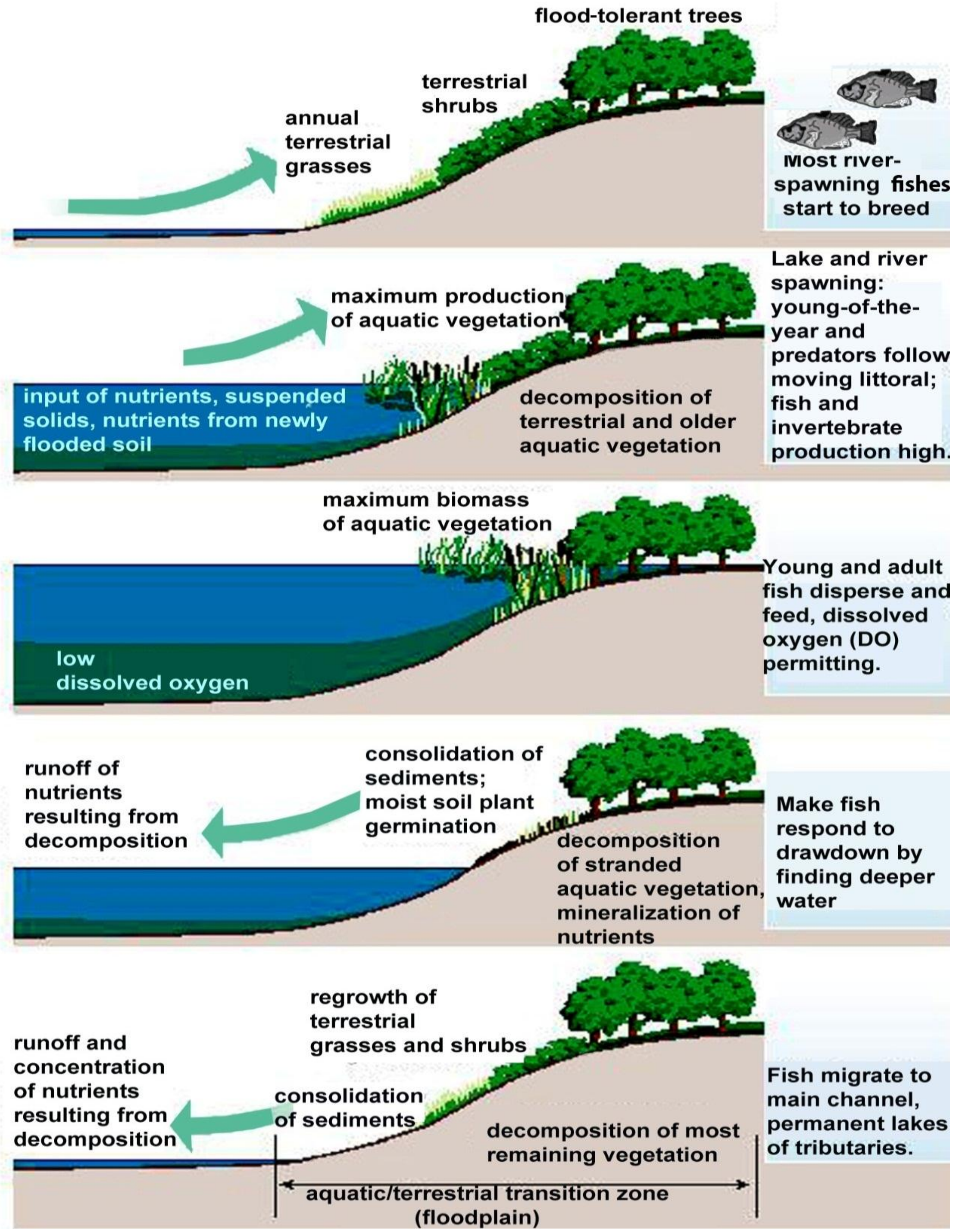


FIGURE 1-3. Floodplain rivers experience seasonal variation in water levels, which sustain riverine processes. Natural patterns of inter- and intra-annual hydrologic variability are needed to match biological requirements (e.g., plant phenology, the life histories of aquatic organisms) and environmental context (e.g., nutrient cycling, temperature regimes, sediment transfer and deposition) (Copyright, American Institute of Biological Sciences 1989).

Hydrologic processes relevant to stream ecosystems, occur at the basic unit of watershed or catchment, and encompass the entire stream network. The interaction of climate, water, and land determines the resulting character, pattern, network, and ultimately biota of a stream. Knowing a stream's watershed characteristics enhances the biologist's ability to understand a stream, and compare among streams both in terms of natural variability and degree of disturbance. Watershed and drainage data provide a basic description of the drainage network (see Gordon et al. 1992 for additional detail).

Hydrologic Data

Precipitation

Precipitation includes all forms of water falling from the atmosphere to the earth's surface. The characteristics of precipitation at a location in a given storm, in terms of intensity, duration, and areal extent, are determined by the source of the water vapor in the atmosphere and the lifting mechanism, which causes precipitation. In particular, convective rainfall typically has higher intensities for shorter durations, and affects a smaller area than cyclonic or frontal rainfall. Variations in these characteristics, and whether the precipitation falls as rain or snow, have a profound effect on the nature and extent of subsequent hydrological processes on and below the land surface. Spatial variability in precipitation, especially rainfall, can dramatically affect the amount and timing of runoff contributed by various parts of the drainage network (a.k.a., variable source concept).

Regional precipitation data are readily available from the State Climatology office or the National Weather Service (http://water.weather.gov/precip/).

Basic measures include:

1. Seasonal patterns (e.g., percent contribution from snow and rain).
2. Mean monthly and annual precipitation (% departure from normal as described by the State Climatology office)

Advanced techniques include:

For example, resolving specific conflicts related to water supply and use may include: analysis of cumulative precipitation and antecedent conditions.

Streamflow

Historic streamflow data are required to develop hydrologic time series and, if needed, water budgets. Streamflow records for gaged streams are available from the U.S. Geological Survey (USGS) and Environment Canada. If streamflow data have not been gathered or if a sufficient period of record is not available, several methods can be used to estimate hydrology (Bovee et al. 1998; Wurbs and Sisson 1999). Hydrologic simulation models (e.g., HEC-HMS, WMS) use information on watershed characteristics, precipitation, and runoff patterns to synthesize or extend a streamflow record **(Figure 1-4)**. Furthermore, if streamflow data are available from gages within a region, runoff patterns for the watershed of interest can be synthesized by establishing statistical relations with similar watersheds. The underlying foundation for accurate synthesis of streamflow records from another river is the similarity of watershed characteristics (e.g., soil, area, topography) and precipitation patterns.

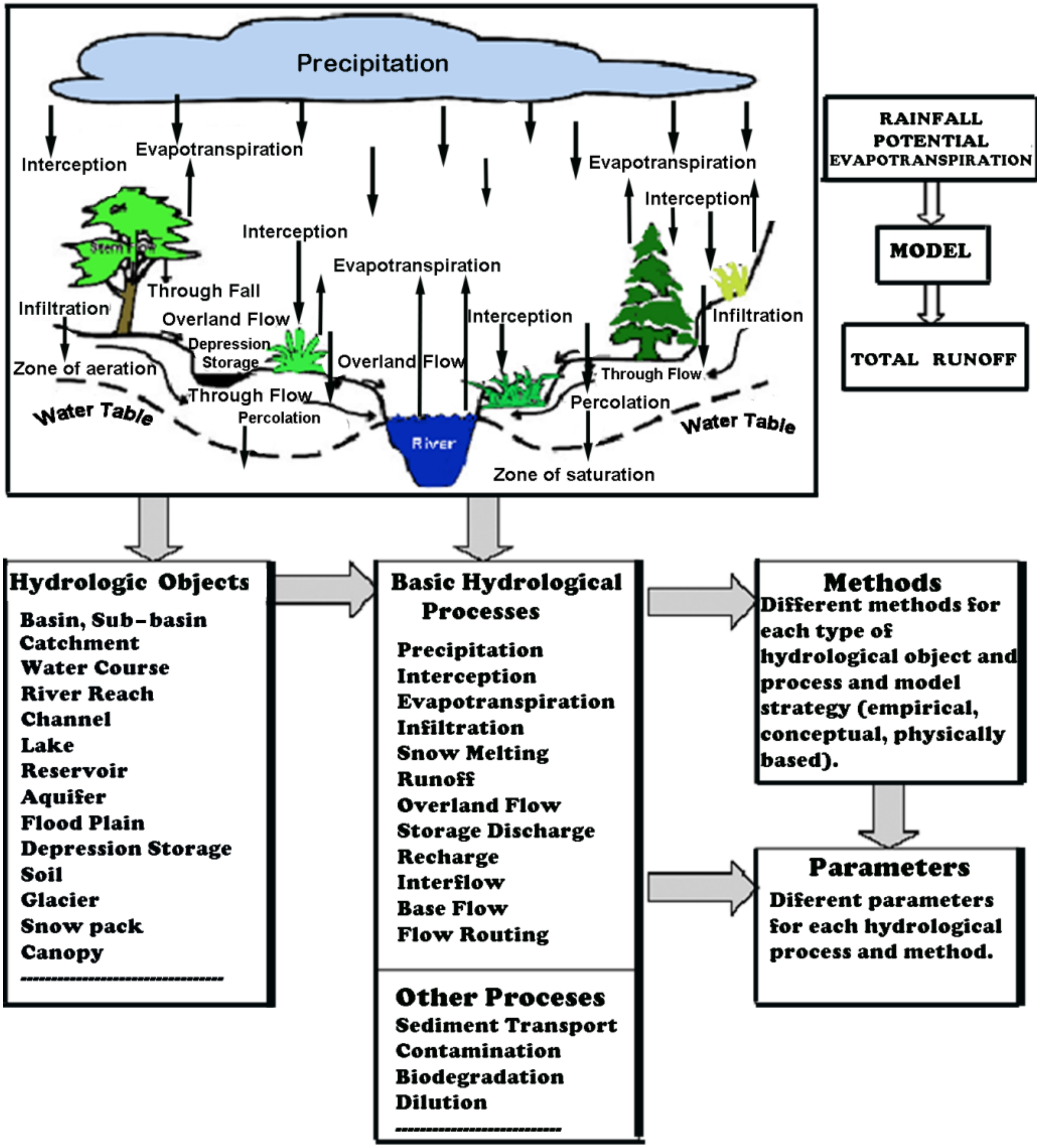


FIGURE 1-4. Hydrologic simulation models (e.g., HEC-HMS, WMS) use information on watershed characteristics, precipitation, and runoff patterns to synthesize or extend a streamflow record.

Hydrologic records are critical for understanding and investigating stream components other than flow. A hydrologic record is needed to assess habitat changes, hydraulic functions, water quality factors, channel maintenance, and riparian and valley-forming processes. For example, an instream flow prescription will most likely include flows with some recurrence interval to maintain alluvial channels. Some geomorphologists have suggested that flows with a 1.5-year recurrence interval are needed—roughly corresponding to bankfull discharge—and others have recommended that bankfull flow should be evaluated for each stream or river (Hill et al. 1991; Rosgen 1996). Either approach requires a hydrologic record.

Basic measures include:

- Seasonal patterns and variability:
  1. Plots of mean daily, monthly, and annual flow over time.
  2. Plots of minimum and maximum daily flows.
  3. Calculation of exceedance values.

- Hydrograph Separation – Direct runoff, baseflow

- Peak flow analysis – Recurrence intervals (based on instantaneous annual peak flow).

Advanced techniques include:

- Analysis using the indicators of hydrologic alteration software, which compares altered and unaltered hydrologic regimes using 32 parameters derived from daily streamflow data.

Indicators of Hydrologic Alteration website:
http://conserveonline.org/workspaces/iha

- Developing synthetic hydrologic data.

Watershed and Drainage Data

A watershed is all land enclosed by a continuous hydrologic drainage divide and lying upslope from a specified point on a stream (Wesche and Isaak 1999). Typically, watershed is synonymous with drainage basin or catchment. A drainage basin is a watershed that collects and discharges its surface streamflow through one outlet or mouth, whereas a catchment is generally considered to be a small drainage basin (Hewlett and Nutter 1969). For simplicity, we use the term "watershed" in this manual when referring to drainage basins of all sizes.

One of the important functions of a watershed is to produce water. We must be concerned not only with the total quantity of water yielded but also with the timing of that yield (flow regime) and its quality. Numerous variables interact within a watershed to control streamflow and the nature of the stream channels that convey the water. In general, these variables can be categorized as climatic, topographic, geologic, and vegetative. One must be aware of the strong interrelations among these controlling factors, their dominant influence on the character of watersheds, and, ultimately, the role they play in regard to the composition and distribution of the stream biota, including fish (Wesche and Isaak 1999) Watershed descriptions should include reference to the rocks and sediments that underlie the drainage basin because geologic characteristics determine the nature and extent of groundwater storage, the type of material available for erosion and transport, and the chemical quality of the water. Ground-bearing formations sufficiently permeable to transmit and yield water are termed aquifers. The most common aquifer materials are unconsolidated sands and gravels that occur in stream valleys, old streambeds, coastal plains, dunes, and glacial deposits. Sandstone, a sedimentary rock, also serves as aquifer material; other sedimentary rocks such as shale and solid limestone do not. Igneous and volcanic materials including basalt can form aquifers if they are highly fractured or porous.

Commonly measured topographic attributes of watersheds are listed in **Table 1-1**. Many of the measures used to describe a watershed are readily computed using data layers that are accessible through the Minnesota Department of Natural Resources (MNDNR) Geographic Information System (GIS). The minimum standard for stream network calculations will be the MNDNR 1:24,000 stream layer and its derivatives, and associated watershed and basin data layers. The basic elements necessary to get to know your watershed, start with first delineating the watershed boundary to a particular point in a stream. This has been done for many minor watersheds in Minnesota. However, at times it may not be available for the particular stream you are interested in and therefore it may be necessary to specifically delineate the watershed. There are several references available for completing this task (Black 1996, Gordon et al. 1992). See Supplement 1, Chapter 6 of this manual for standards on identifying watersheds in Minnesota.

In addition to these measures, maps showing the following features are required:

1. Map of the watershed
2. 24k Stream network
3. Designations as appropriate
4. Shaded relief
5. Geology
6. Soils
7. Land cover / land use
8. Springs, seeps, sinkholes, stream sinks
9. Dams, road crossings, barriers
10. Land ownership / easements

TABLE 1-1. Watershed and stream network measures.

Watershed or basin area - Basin area is the land surface area that drains to a specified point on the stream, usually the mouth.

Basin length – Basin length is estimated as the straight-line distance between the mouth of the basin and the drainage divide nearest to the source of the main stream. Basin length is used to calculate basin shape.

Basin relief - Basin relief is the difference in elevation between the highest and lowest points in the basin. It controls the stream gradient and therefore influences flood patterns and the amount of sediment that can be transported. Sediment load increases exponentially with basin relief (Schumm 1961).

Basin relief ratio – The basin relief ratio index is the basin relief divided by the basin length. It is useful when comparing basins of different sizes because is standardizes the change in elevation over distance.

Basin shape - Two common methods of computing basin shape include:

R_f - An index of basin form is computed as a unitless dimension of drainage area divided by the square of basin length (Horton 1932).

R_e – An index of basin elongation is computed as a unitless dimension of diameter of a circle with the same area as that of the basin divided by the basin length (Schumm 1956). If two basins have the same area, the more elongated one will tend to have smaller flood peaks but longer lasting flood flows (Gregory and Walling 1973). Basin shape is also related to hydrograph shape and response (Black 1996; Gordon et al. 1992).

Basin drainage patterns – Describe drainage patterns, e.g., dendritic, trellis, rectangular, parallel. Pattern is easily obtained from a map of the stream network for the entire watershed, including intermittent and perennial channels.

Stream order – Assign stream order using the Strahler (1952) method, where all the small, often intermittent channels, are designated first order **(Figure 1-5)**. A second-order stream is formed by the junction of any two first-order streams; third-order by the junction of any two second-order streams.

Bifurcation ratio (R_b) – Number of stream segments of a given order divided by number of stream segments of next highest order. The US average for R_b is about 3.5 (Leopold et al. 1964), normally ranging between 2 and 5, and tends to be larger for more elongated basins (Beaumont 1975).

Main stem stream length – Measured from the mouth to the uppermost point of the main stem perennial stream channel.

TABLE 1-1. Watershed and stream network measures (continued).

Total channel length – Total channel length is the sum of the lengths of all perennial and intermittent channels as identified on a 24K stream layer or 7.5-minute quad map.

Mean stream slope – The elevation at the stream source minus the elevation of the stream at its mouth divided by the length of the stream. Main channel slope is an estimate of the typical rate of elevation change along the main channel that drains the basin. This variable is often related to peak flow magnitude and flood volume, and is one of the factors controlling water velocity within the main stem channel.

Longitudinal profile – Plotted as the stream elevation over stream distance. Longitudinal profile is useful for delineating geomorphically similar stream reaches and general trends in elevation change through the basin, and for identifying abrupt change in slope or knick-points, such as waterfalls or changes in bed material.

Drainage density – An index of the length of stream per unit area of basin is calculated by dividing the drainage area by the total stream length. This ratio represents the amount of stream necessary to drain the basin. High drainage density may indicate high water yield and sediment transport, high flood peaks, steep hills, low suitability for agriculture, and high difficulty of access. Drainage density can often increase as a result of roads, increased impervious cover, and change in vegetation type.

Land use and land cover – Existing GIS data layers can be used to determine the percent of each type of land use or preferably land cover in a given watershed. Because they interrupt the longitudinal, vertical, and chronological processes, human activities—such as land use, wetland drainage, channelization, and water withdrawal—alter flow regimes. Land use practices such as removal of permanent cover, grazing, row crop agriculture, and urbanization can accentuate high and low flows and reduce habitat diversity and length of the lateral edge between the terrestrial and aquatic environments (Schlosser 1991). Wetland drainage can increase peak flows and decrease base flows by reducing bank storage (Moore and Larson 1979). Channelizing and diking can increase peak flows (Campbell et al. 1972; Gordon et al. 1992) and accentuate low flows (Karr and Schlosser 1978).

Optional Measures

Aspect – The aspect describes the direction the slope faces with respect to the cardinal compass points. Aspect influences vegetation type, precipitation patterns, wind exposure and snowmelt. Distribution of aspect in a basin is typically plotted as a polar or "rose" diagram (with the aspect shown as an angle 0 to 360 degrees, zero equals North), and percentage area as a distance from the origin. Differences in aspect are often not significant in Minnesota, except in areas with considerable basin relief, such as southeast and northeast Minnesota.

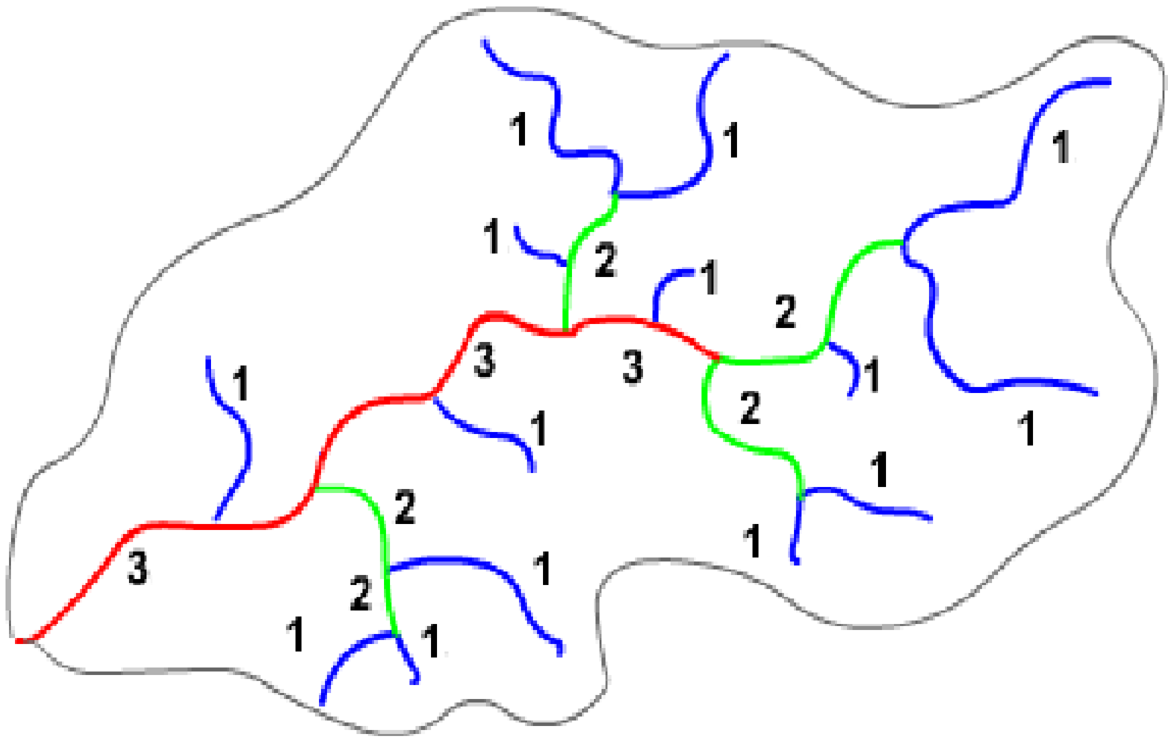


FIGURE 1-5. Strahler's (1952) stream order system is a simple method of classifying stream segments based on the number of tributaries upstream. A stream with no tributaries (headwater stream) is considered a first order stream. A segment downstream of the confluence of two first order streams is a second order stream. Thus, an nth order stream is always located downstream of the confluence of two $(n-1)^{th}$ order streams.

Photo by Rick Nelson

Chapter 2. Geomorphology and Fish Habitat

"The river, then, is the carpenter of its own edifice."
—Luna B. Leopold, 1994, A View of the River

Introduction

A stream's characteristics are determined by the continuous interaction between water and the landscape, and the downstream transfer of water, sediment, nutrients, and organic material (Waters 2000). These interactions and physical changes take place at different spatial and temporal scales, ranging from the individual particle to the drainage network, and from mere seconds to hundreds of years (Frissell et al. 1986; **Figure 2-1**). Such changes can also be viewed and described as a continuous gradient of physical conditions within a stream system that results in a predictable structuring of biological communities (Vannote et al. 1980).

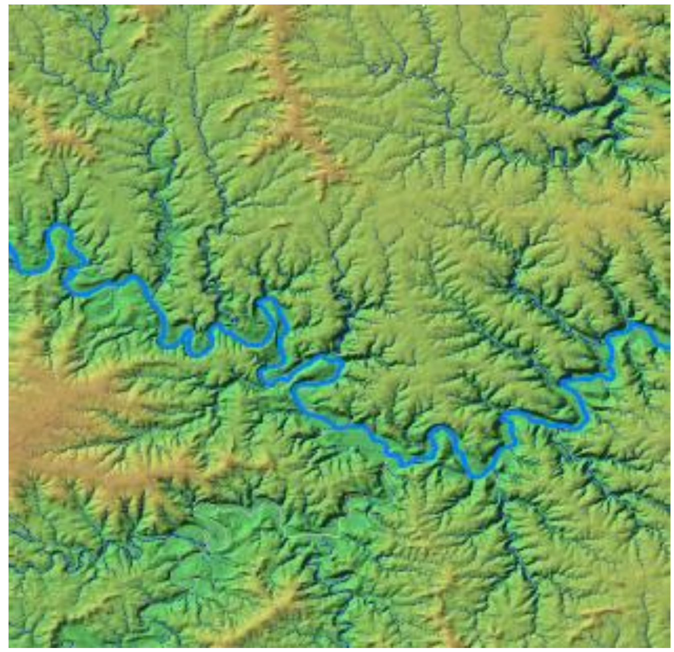


FIGURE 2-1. Interactions between water and landscape, combined with lack of recent glaciation result in a highly dissected and dendritic landscape in southeast Minnesota's Root River basin.

This seemingly intricate arrangement of habitat types exhibits a certain unity of organization, laterally and longitudinally (Leopold 1994; Waters 2000). Meanders scour and deepen the channel along outside bends, providing essential holding and feeding locations for many species of fish and invertebrates **(Figure 2-2)**. Larger particles such as gravel, cobble, and boulders tend to deposit in riffles during floods and high flows. However, during low flows finer particles such as sand and silt, deposit in pools and fine sediment is scoured from riffles. Many aquatic invertebrates rely on these riffle habitats, as do certain species of spawning fish such as walleye, lake sturgeon, trout, darters, and suckers. Similarly, the formation of eddies and deposition of fine sediment on point bars create slack-water habitat used by still other species.

This arrangement and diversity of physical habitat, created by erosion and deposition, has a tendency toward dynamic equilibrium, where the energy of the system is expressed in its dimension (i.e. width and depth), pattern (i.e. meanders), and profile (i.e. stream slope and the vertical undulations often described as pools and riffles) (Leopold 1994; **Figure 2-3)**.

FIGURE 2-2. A broad alluvial valley with gentle gradient showing a meandering stream channel. Scouring and deepening on outside bends form habitat for fish, with riffles between bends providing habitat for juvenile fish and invertebrates.

Leopold (1994) describes this dynamic relationship as follows. "The steady state is an average condition: the hydraulic parameters are constantly adjusting, rapidly and materially, as the water discharge and the sediment it carries varies through time. Low flow is followed by flood followed by low flow, each of different duration depending on the nature and location of the rainfall or snowmelt. To accommodate these various changes the interdependent hydraulic variables will change in any of several combinations of values."

This fact is most obvious where streams flow over beds of unconsolidated sediment. Streambeds comprised largely of bedrock prevent or inhibit the expression of these features. Meanders develop according to fairly consistent patterns, regardless of stream size. Bends form, alternating right to left, with a radius about two to four times stream width. Vary the scale, and an aerial photograph of a small creek would resemble the pattern of a larger river of the same stream type (Leopold 1994).

The eight major variables used to describe these processes include: channel width, depth, velocity, discharge, slope, roughness, sediment load, and sediment size (Leopold et al. 1964). A change in any one of these variables sets up a series of channel adjustments which lead to a change in the others, resulting in alteration of channel patterns (Rosgen 1996; **Figure 2-4)**. An evaluation of fish habitat that includes hydrodynamic and fluvial morphologic variables will provide more precise quantification of habitat characteristics (Heede and Rinne 1990) and help managers identify and address factors limiting the quality and quantity of available fish habitat. Focusing on the processes that create and maintain habitat should help to achieve successful stream habitat management.

Geomorphology

While the largest floods move large amounts of sediment over short periods of time and shape the valleys and floodplain, they are relatively rare. Research over the past 50 to 60 years has increasingly demonstrated the importance of bankfull flows in defining a river's shape (Leopold 1994, Rosgen 1994). The term "bankfull" refers to the water level stage that just

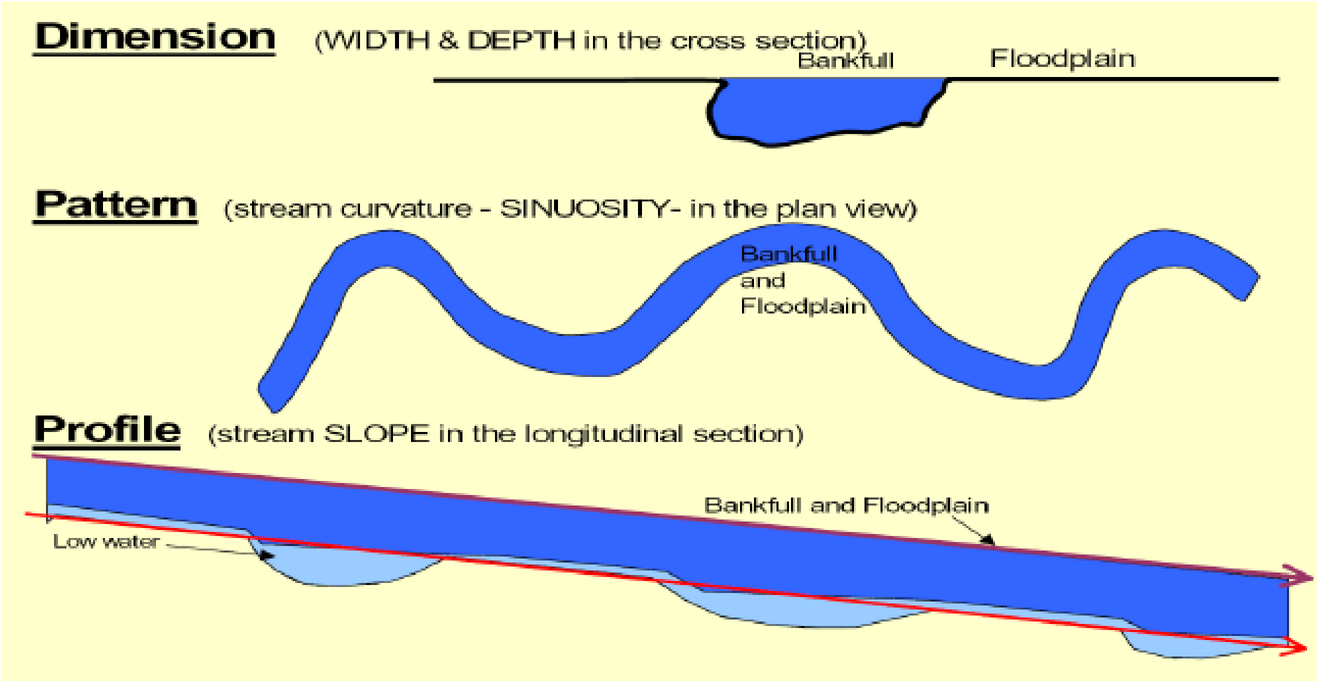


FIGURE 2-3. Stream physical characteristics tend toward dynamic equilibrium at three levels: dimension (width and depth), pattern (meanders), and profile (vertical undulations described as pools and riffles).

begins to spill out of the channel into the floodplain **(Figure 2-5)**. Bankfull flows tend to occur fairly frequently, on the average every two out of three years. Because bankfull floods occur frequently, they move the most sediment over time and shape the stream channel itself. The range of forces—from major floodplain-forming events to recurring bankfull flows—are necessary for healthy river systems.

Long-term changes in the pattern or volume of discharge (tributaries) will change the amount of sediment carried by the river, altering channel width and depth. Disruptions to this natural relationship occur through our land use practices and through direct disruptions to the channel itself. Sediment transport is a function of stream power, which is a function of velocity, depth, slope, and channel roughness. The "roughness" of channel materials provides resistance to flow, the amount of which influences the way that energy is used and dissipated. If at any time the available stress is greater than the resisting force, erosion will occur; if the stress is less, sediment in motion will be deposited. Many alluvial streams (those winding through beds of unconsolidated sediment rather than bedrock) flow in dynamic equilibrium, in which sediment load equals its transport capacity. In other words, healthy streams are able to carry a certain amount of sediment over time in a sustainable balance. With the addition of excessive sediment, such as soil erosion from farmland, the stream will deposit

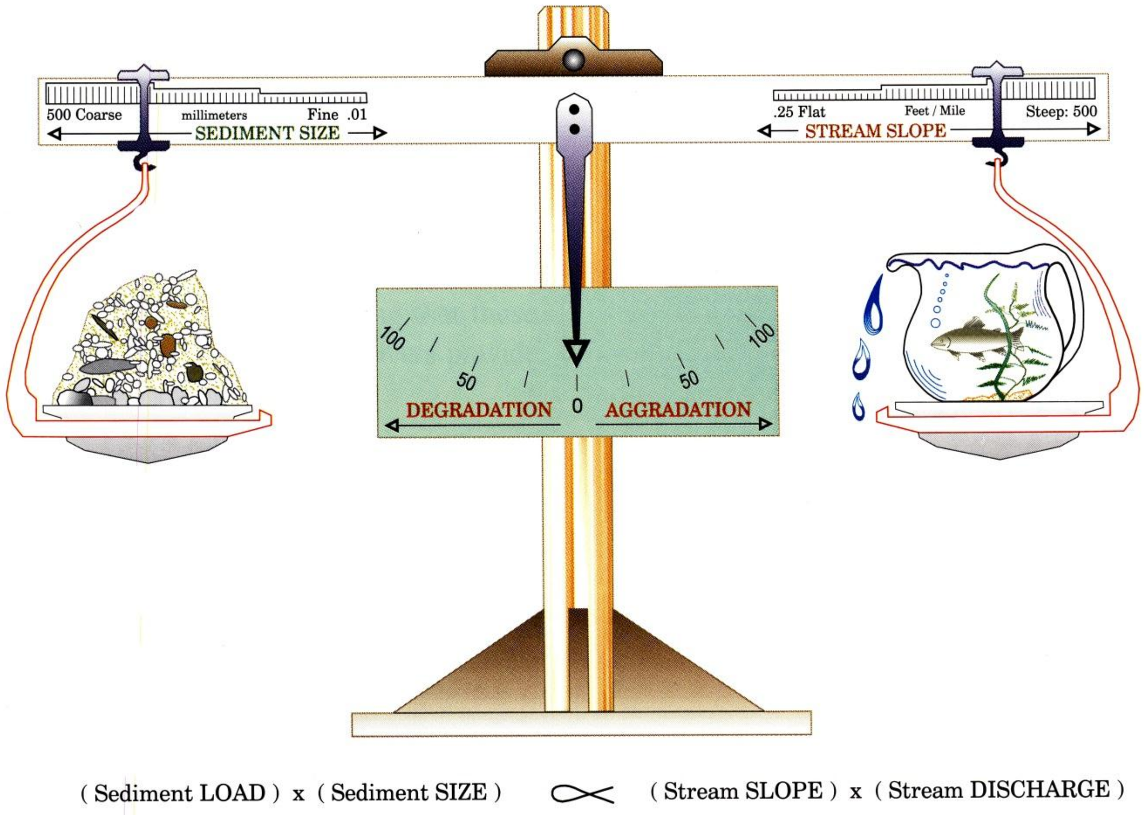


FIGURE 2-4. Lane's Balance Equation has been used to show the concept of stable channel balance and relate sediment load and sediment size to slope and discharge. A change in any one of the parameters will set up a series of adjustments in companion variables and, ultimately, result in changing the river channel. For example, an increase in discharge in a river (e.g., through upstream watershed drainage or urbanization) will adjust channel dimensions and profile, increase the river's capacity for work, and degrade the stream banks and streambed (From Rosgen 1996, adapted from Lane 1955).

excess sediment in the channel as riffles, bars, or islands. A dramatic reduction in sediment, such as construction of a dam that traps sediment, will cause the downstream channel to enlarge by widening and down cutting.

In considering the shape of a river, we must also consider other factors such as geological history and physiographic setting, which impose constraints on river shape and behavior. Rivers are often found meandering through the valley floor where water converges and where the products of erosion, sediment, and organic debris are concentrated. Rivers may flow in valleys that constrain or exert some lateral and vertical control over the channel. Some rivers may be confined or entrenched in narrow valleys, such as the lower stream segments of tributaries to Lake Superior, while others have relatively fewer

FIGURE 2-5. Bankfull discharge (represented by the blue lines) closely corresponds to the effective discharge or flow that maintains the channel. Bankfull elevation usually corresponds to the water surface elevation at which water begins to overtop banks and enter the active floodplain.

constraints on lateral movement as they meander through wide valleys floors (Church 1992), which are common throughout much of Minnesota.

The nature and extent of erosional and deposition processes occurring in the various categories of landforms and valley types produce an array of fluvial and morphological features that can be correlated with stream channel types.

River Morphology and Stream Classification

Over time, a stream continually readjusts its channel, moving sediment, shifting riffles and bends, scouring out new channels, and abandoning old channels as they fill with sediment. Dramatic changes in the variables governing channel formation force rapid changes to the stream channel. These changes can be natural; a landslide may temporarily block the flow of a mountain stream and provide an abundant supply of sediment. More often, dramatic changes in the factors governing channel formation are the result of human activities, such as dam construction or removal, channelization, or clearing of forestland. Given the pervasive influence of humans on the landscape, it is useful to understand how watersheds and stream ecosystems respond to anthropogenic disturbance (Gordon et al. 1992). To do so, requires classification systems and quantitative assessment procedures that permit accurate, repeatable description and convey information about the physical conditions and processes responsible for maintaining a stream system.

One of the ways to better understand streams is through a hierarchical framework developed by David Rosgen (1994, 1996; **Figure 2-6)**. The Rosgen classification system helps us predict the form and shape of a stream when faced with changes in the hydrologic regime and the bankfull discharge, loss of stream length due to straightening, or increases in sediment supply. Rosgen's hierarchal approach is comprised of four inventory or assessment levels that vary from a broad geomorphic characterization down to very detailed-specific description and assessment.

Broad geomorphic classification (Level I) describes the geomorphic characteristics that result from the integration of basin relief, landform, and valley morphology **(Figure 2-7)**. The dimension, pattern, and profile of rivers can be evaluated using aerial photographs and topographic maps and are used to delineate geomorphic types at a coarse scale. Level I stream classifications serve four primary inventory functions:

1. Provide for the initial integration of basin characteristics, valley types, and landforms with stream system morphology.
2. Provide a consistent initial framework for organizing river information and communicating the aspects of river morphology. Mapping of physiographic attributes at Level I can quickly determine location and approximate percentage of river types within a watershed sub-basin, and/or valley type.
3. Assist in the setting of priorities for conducting more detailed assessments and/or companion inventories.
4. Correlate similar general level inventories such as fisheries habitat, river-boating categories, and riparian habitat with companion river inventories.

Morphological (Level II) classification refines the Level I stream types by identifying reaches nested within each of

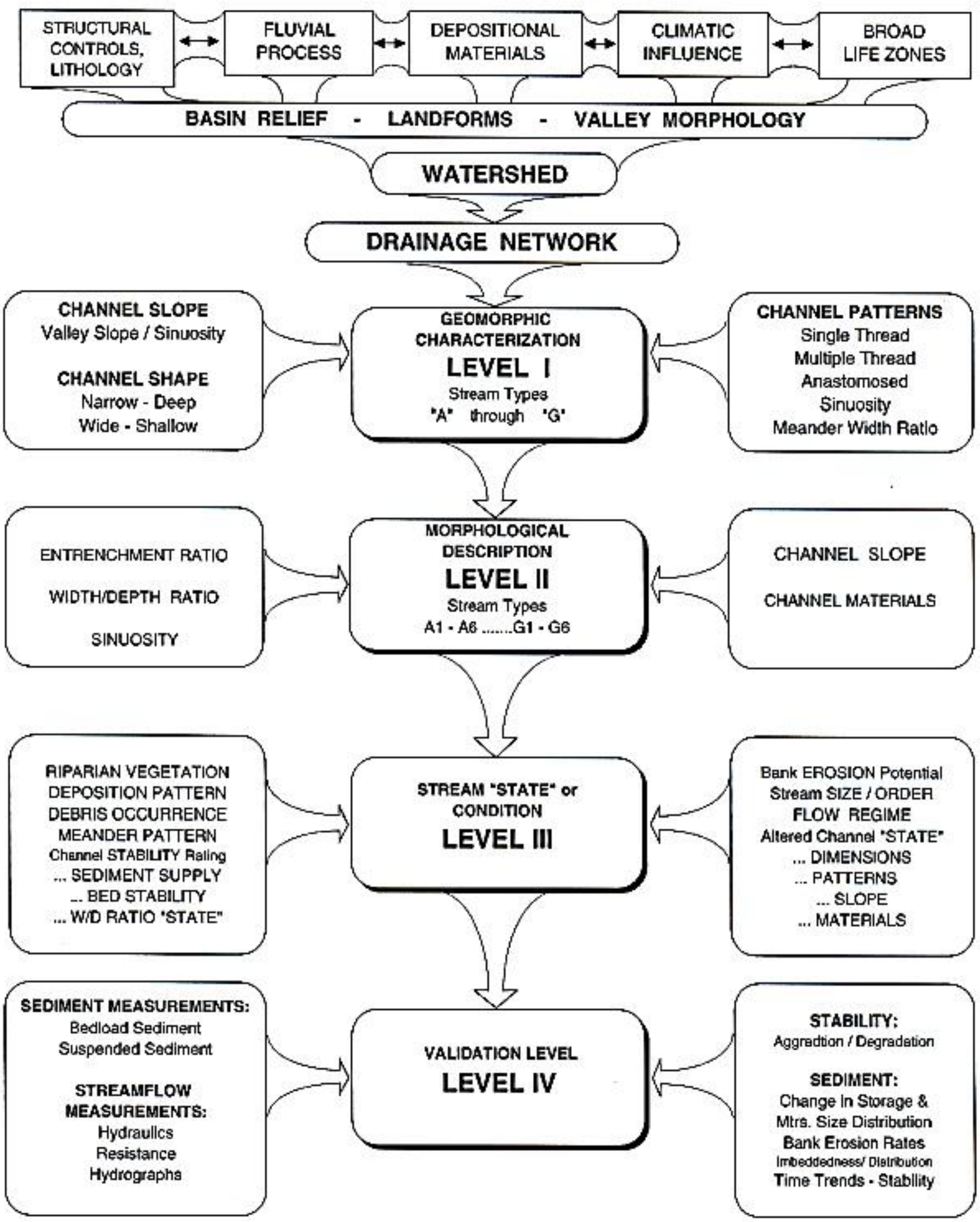
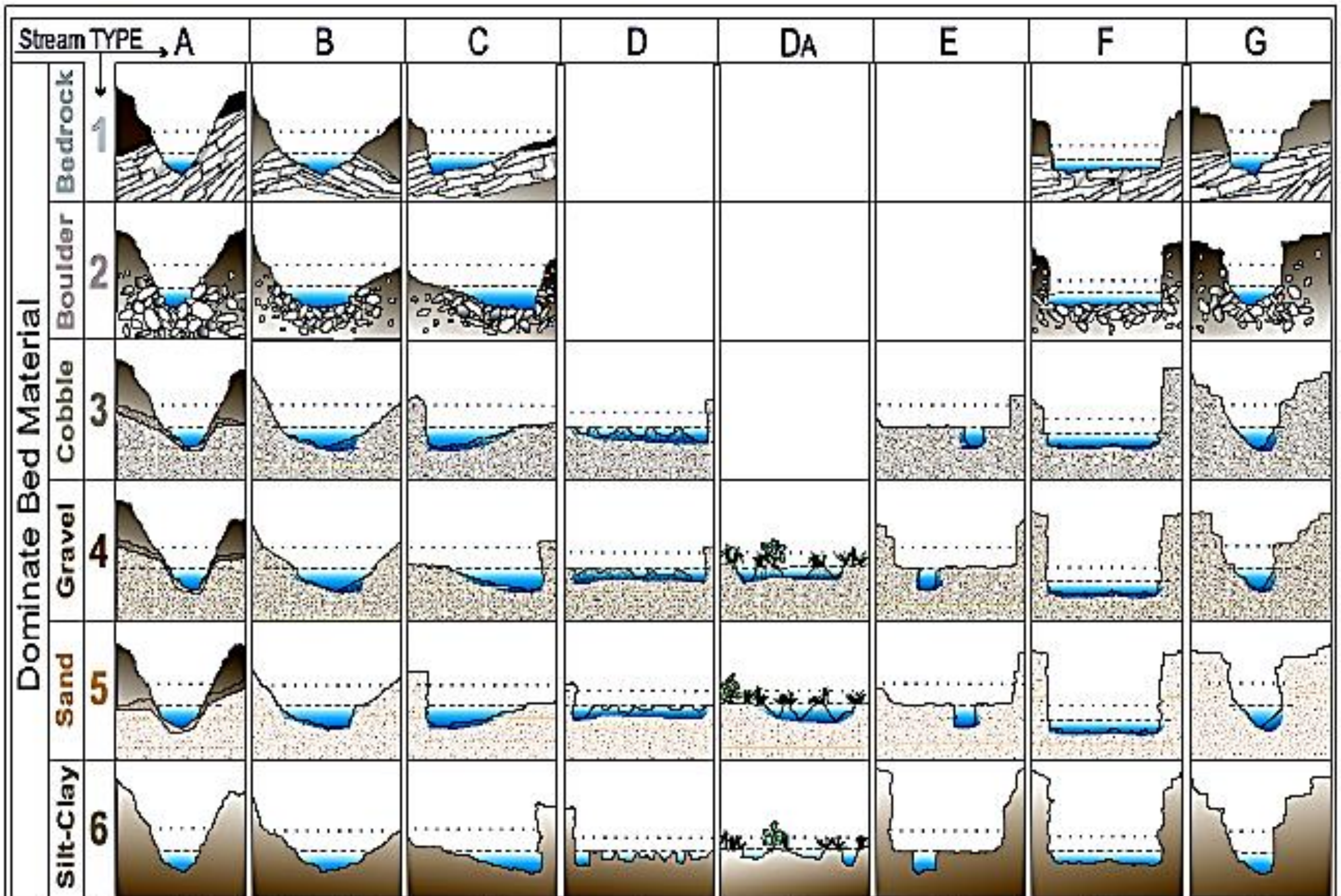


FIGURE 2-6. The hierarchy of river inventory and classification (from Rosgen 1996).



Stream TYPE	A	B	C	D	DA	E	F	G
Entrchmnt.	< 1.4	1.4 - 2.2	> 2.2	n/a	> 4.0	> 2.2	< 1.4	< 1.4
W/D Ratio	< 12	> 12	> 12	> 40	< 40	< 12	> 12	< 12
Sinuosity	1 - 1.2	> 1.2	> 1.2	n/a	variable	> 1.5	> 1.2	> 1.2
H_2O Slope	.04-.099	.02-.039	< .02	< .04	<.005	< .02	< .02	.02-.039

FIGURE 2-7. Level II stream classification representing morphological description (from Rosgen 1996).

the nine Level I categories. Level II classification involves field measurements of bankfull dimensions to determine: entrenchment ratio, width/depth ratio, sinuosity, slope, channel materials, and ultimately stream type **(Figure 2-7)**. The Level II classification processes employ more finely resolved criteria to address questions of sediment supply, stream sensitivity to disturbance, potential for natural recovery, and channel response to changes in flow regime. These processes ultimately influence fish habitat potential and suitability for habitat improvement. These questions require, at a minimum, interpretations based on data and information developed at least to the resolution of a Level II classification.

Assessment of channel condition and factors relating to fish habitat (Level III) results in a description of stream condition as it relates to stream stability, potential, and function **(Figure 2-8)**. The objectives of Level III analyses are to:

1. Develop a quantitative basis for comparing streams having similar morphologies, but which are in different states or condition.
2. Describe the potential natural stability of a stream, as contrasted with its existing condition.
3. Determine the departure of a stream's existing condition from a reference baseline.
4. Provide guidelines for documenting and evaluating additional field parameters that influences stream state (e.g., flow regime, stream size, sediment supply, channel stability, bank erodibility, and direct channel disturbance).
5. Provide a framework for integrating companion studies (e.g., fish habitat indices), and composition and density of riparian vegetation.
6. Develop and/or refine channel stability prediction methods.
7. Provide the basis for efficient Level IV validation sampling and data analyses.

Monitoring and stream inventory (Level IV) analyses are conducted to verify process-based assessments of condition, potential, and stability as predicted from Level II and III. Verification is achieved through reach–specific observation and analysis of sediment condition, stream flow, and stability measurements. After reach conditions have been verified, these data are also used to establish empirical relationships for testing, validating, and improving the prediction of velocity, hydraulic geometry, sediment transport characteristics, bank erosion rates, and channel stability. Such detailed field observations that measure the correct variables can provide data for a better understanding of these complex systems and a basis to answer questions posed.

Sediment is considered to be the major pollutant of streams and rivers in the United States (Waters 1995). Numerous total maximum daily load (TMDL) studies recently conducted by the Minnesota Pollution Control Agency (MPCA) reach the same conclusion for Minnesota streams and rivers. Field measures for quickly determining bank erosion, such as the Bank Erosion Hazard Index (Rosgen 2006), can be applied to this problem. Given the challenge and associated controversy of identifying sources and solutions for sedimentation, what is needed is regional field verification of erosion rates with the associated indices. The Level IV analysis provides the basis for conducting such studies.

Rosgen (1996) provides guidelines for the appropriateness and effectiveness of management activities (e.g., construction of fish habitat improvement structures) based on stream type. A table summarizing each stream type's sensitivity to disturbance, recovery potential, sediment supply, streambank erosion potential, and vegetation controlling influence provides useful information to managers who make decisions about restoration, forestry, mining, or disturbance activities. Information collected about reach properties (e.g., dominant channel materials) can be used to interpret biological function and stability within the river (Rosgen 1994).

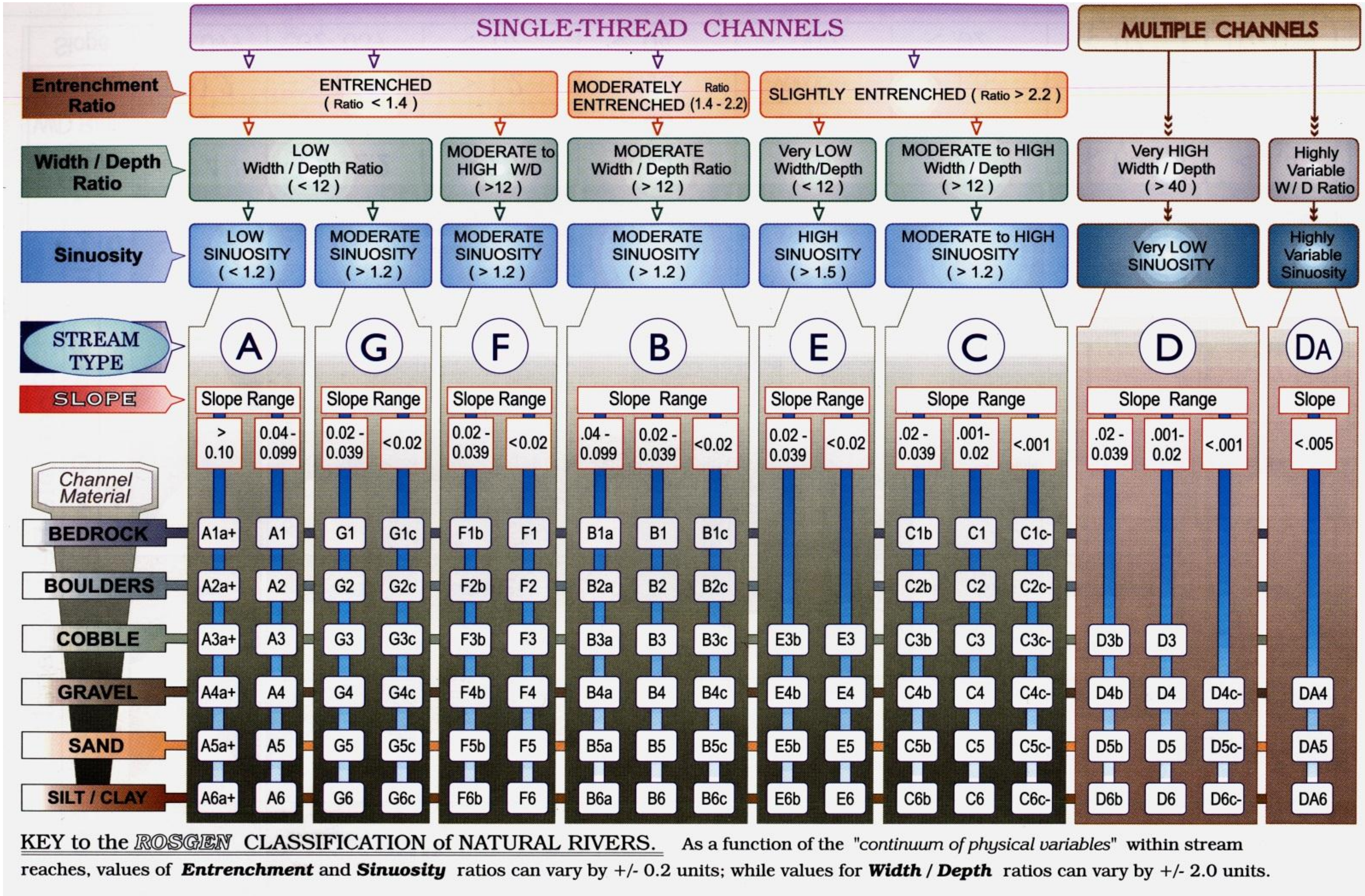


FIGURE 2-8. Level III stream classification representing assessment of stream condition (from Rosgen 1996).

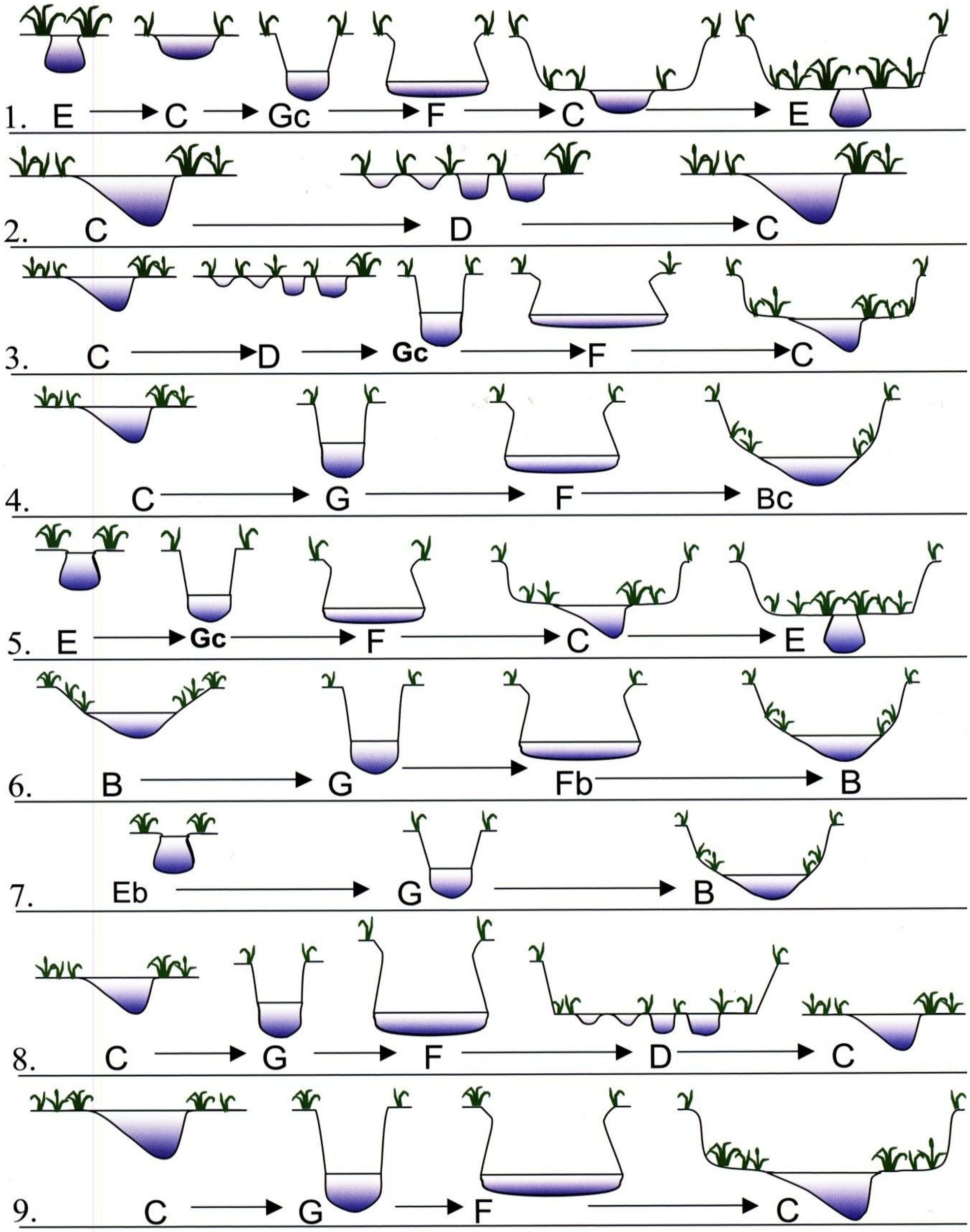


FIGURE 2-9. "Channel evolution" often begins with destabilizing the water-sediment equilibrium, which (depending on initial conditions and the type of disturbance) can result in a variety of scenarios and outcomes (from Rosgen 2006).

Channel Evolution

Streams are considered stable when the dynamic equilibrium of transport of sediment and water through the channel and floodplain is in balance, where the stream neither aggrades nor degrades. Occasionally a disturbance such as a change in the amount, timing, or distribution of water or sediment supply can upset that balance. Changes to water or sediment supply can be brought about by large-scale factors such as precipitation patterns, watershed-scale changes to land use, or localized changes in riparian vegetation or straightening of stream reaches. Isolated events such as large floods can do the same.

Destabilizing the water-sediment equilibrium can set off a process where the stream channel must adjust its dimension, pattern, and profile to accommodate the new regime. These processes are described as "channel evolution." Depending on initial conditions and the type of disturbance, the steps in the evolutionary process can vary greatly. Various channel evolution models **(Figure 2-9)** have been proposed, from the general (Schumm et al. 1984; Simon and Hupp 1986) to more complex models that include a broader mix of scenarios (Rosgen 1996, 2006).

Assessing the stream condition using Rosgen level III or IV methods should not only identify the river's potential (reference) condition, but for unstable reaches identify where the stream is in a channel evolution process. This will allow selection of potential remedies that work with channel processes to reestablish stability, rather than to only treat symptoms such as eroding banks. A more holistic approach will increase the chances of project success, and broader ecologic benefits.

Stream Fish Habitat

Habitat for fishes is a place or set of places in which a fish, a fish population, or a fish assemblage can find the physical and chemical features needed for life, such as suitable water quality, migration routes, spawning areas, feeding sites, resting sites, and shelter from predators and adverse conditions (Orth and White 1999; Hubert and Bergersen 1999). Proper places in which to seek food, escape predators, and contend with competitors are parts of habitat, and a suitable ecosystem for a fish includes habitat for these organisms as well. Habitat quality affects fish abundance and size as well as the species composition (Gorman and Karr 1978; Schlosser 1982; Thorn and Anderson 1999; Aadland 1993; Binns and Eiserman 1979). Habitat influences fish distribution and abundance at all spatial (i.e., global, watershed, stream reach, macrohabitat, mesohabitat, and microhabitat) and temporal scales (Annear et al. 2004). Habitat management is an integral part of an effective stream fish management program (Orth and White 1999). Habitat is the key to managing for ecological integrity and the fish community (Rabeni 1990). A successful fish habitat management program is one that protects, restores, or enhances habitats necessary to maintain or improve target fish populations or communities.

From a fisheries perspective, the goal of a stream habitat inventory and analysis program is to relate habitat conditions with fish production or fish community health. A key product derived from this relationship is the identification of factors that are limiting fish production. By addressing limiting factors, the fisheries manager can increase the probability of formulating successful management plans.

A variety of different habitat types can be found in streams including pools, riffles, runs, and backwaters **(Figure 2-10)**. The physical habitat features described in this section of the manual include: water depth, water velocity, cover components, and substrate composition.

Depth

Depth is one of the most important controlling variables for fishes in streams. Deeper streams generally have higher habitat heterogeneity for fishes, while shallower streams tend to lack habitat for larger fish species and may be subject to extremes in water temperatures in both summer and winter. Mean water volume (3-dimensional) and discharge (4-dimensional, or volume over time) are two of the most critical variables limiting fish abundance in streams.

Velocity

The flow of water directly affects habitat selection by fishes and is a critical component of channel formation and maintenance. Water velocity preference has been shown to vary by fish guild, species, and life stage (Aadland 1993; Leonard and Orth 1988), season, and geography. Stream channels with alternating bends, comprised of inside bends of deposition and outside bends of scour, provide a range of current velocities. Fishes use wood cover, macrophytes, and algae as shelter from currents and predators, as foraging sites, and as spawning locations. Overhead cover, such as undercut banks, overhanging vegetation, and submerged logs across channels provide hiding cover from predators.

Large woody material provides many functions in a healthy stream environment. It is an important source of primary and secondary production (Benke et al. 1984) and physical habitat for fishes. Floods can increase the rate of woody material input by uprooting trees, undercutting banks, or moving loose woody material from the floodplain to the channel. Lodging of these materials within the channel provides habitat for many aquatic organisms by acting as cover, providing substrate for aquatic invertebrates, and shaping channel features by altering currents. Conversely, frequent flooding can dislodge large woody debris and remove it from the channel and onto the floodplain, which could potentially result in habitat loss and/or degradation.

Substrate

Substrate refers to the bottom material of a stream, and is one the most commonly described habitat components. Substrate greatly influences the roughness of stream channels, which has a large influence on channel hydraulics and stream habitat. Certain substrate compositions provide the microhabitat conditions required by many aquatic species. Spawning salmonids require sufficient flow of oxygenated water through substrates to maintain high oxygen levels around buried eggs.

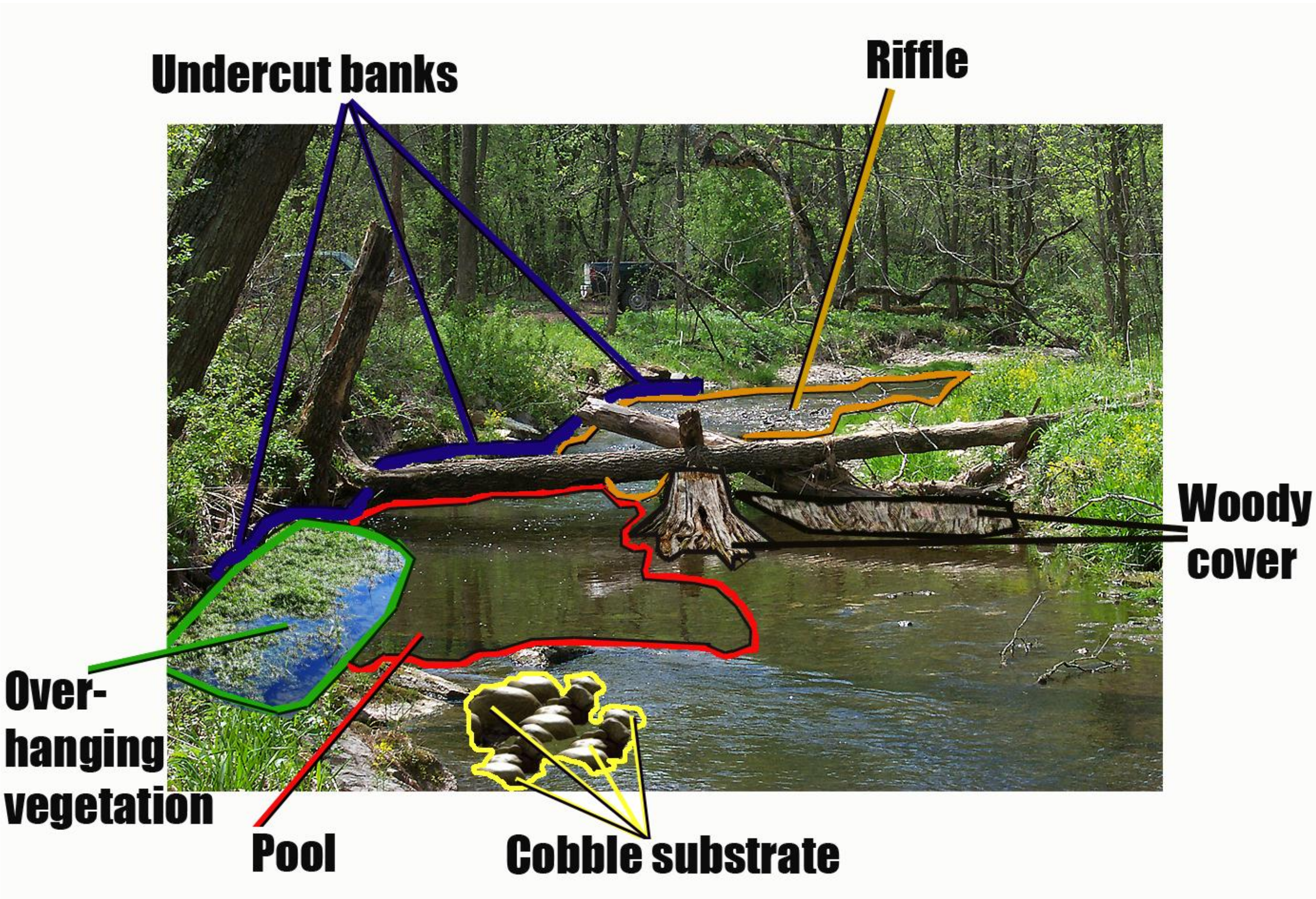


FIGURE 2-10. Stream fish habitat types include pools, riffles, submerged boulders, gravel and cobble substrate, undercut banks, woody cover, and overhanging terrestrial vegetation.

Photo by Rick Nelson

Chapter 3. Water Quality

"The objective of this Act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters."

—Sec. 101(a) of the Clean Water Act, 1972

Introduction

Conditions of life in rivers are largely determined by the properties of water including its physical and chemical stability. These properties make all life possible as it can only exist within a narrow range of conditions. Organisms that live in or use water change the constituents of water. Many of these changes are essential to the existence of the organism. Man also changes water, but many of his changes have not been essential to his existence. Identification of these harmful changes and subsequent corrections allows man to maintain water quality necessary for aquatic life, and, ultimately, his own esthetic and material needs.

The amount of flow is one of several factors that affect maintenance of water quality, including the physical, chemical, and biological attributes of water. Chemical characteristics of a river, such as dissolved oxygen and levels of alkalinity, nitrogen, and pH reflect local geography, land use, climate, and sources of organic matter. These factors ultimately determine the river's biological productivity. Managers seldom look at additive measures to enhance chemical characteristics of river water because the effects are generally short-lived and often unpredictable. However, regulation of point source (e.g., chemical, temperature) and nonpoint source (e.g., sediment) pollutants is an important, on-going effort. Of these, sediment and temperature are the primary physical constituents of water quality assessments for most fishery management-driven actions.

Federal statutes (Clear Water Act; 33U.S.C. § 1251 et seq.) set the basic structure for regulating discharges of pollutants in waters of the United States. The U.S. Environmental Protection Agency (USEPA) retains oversight with many permitting, administrative, and enforcement responsibilities turned over to state governments. In Minnesota, water quality standards are monitored and enforced by the Pollution Control Agency (MPCA) under the state's Water Pollution Control Act (MN Statutes, Chapter 115). Specific standards for water bodies are established under MN Rules, Chapter 7050. Standards for water quality are based on best-usage classifications for each water body **(Table 3-1)**, and all surface waters are protected for multiple uses. Major water bodies have listed classifications within Rule 7050, while all unclassified waters are assigned use classes of 2B, 3C, 4A, 4B, 5, and 6. Standards for each classification include water quality parameters as well as biological standards for fish or invertebrates, and are listed in Rule 7050. Biological standards are assessed using indices of biotic integrity that can be obtained from MPCA biomonitoring staff.

TABLE 3-1. Standards for water quality are based on best usage classifications for each water body, and all surface waters are protected for multiple uses.

Classification	Sub-classification	Description
Class 1. Domestic consumption.	Class 1A.	Meets EPA drinking water standards without treatment.
	Class 1B.	Meets EPA standards with disinfection.
	Class 1C.	Meets EPA standards after sedimentation, filtration, or disinfection.
Class 2. Aquatic life and recreation.	Class 2A.	Supports cold water aquatic life, all types of recreation.
	Class 2Bd.	Cool or warm water community, recreation, and a source of drinking water.
	Class 2B.	Cool or warm water community and recreation.
	Class 2C.	Same as 2b, but with relaxed standards for dissolved oxygen and temperature.
	Class 2D.	Wetlands.
Class 3. Industrial consumption.	Class 3A.	Suitable for industrial use without treatment.
	Class 3B.	Industrial use with moderate treatment.
	Class 3C.	Cooling and materials transport.
	Class 3D.	Industrial use from wetlands.
Class 4. Agricultural and wildlife.	Class 4A.	Suitable for irrigation.
	Class 4B.	Suitable for livestock and wildlife.
	Class 4C.	Livestock and wildlife use of wetlands.
Class 5. Aesthetics and navigation.		Scenery and navigation.
Class 6. Other uses.		Tributaries to other jurisdictions (states, countries).
Class 7. Limited resource value.		Altered water bodies.

If a water body is found not to meet standards, it is listed as impaired and a Total Maximum Daily Load (TMDL) for pollutants is developed to indicate what must be done for the water body to meet standards.

Streams flows (e.g., 7Q10 or the lowest flow present for 7 consecutive days in a 10-year period) specified by Rule 7050 are relevant only for designating the lowest stream flow into which a pollutant discharge can be allowed and should not be approved as the in-stream flow for any other stream management purposes.

Water Quality Monitoring

Water quality monitoring is defined here as the sampling and analysis of water constituents and conditions. These may include:

1. Introduced pollutants, such as pesticides, metals, and oil.
2. Constituents found naturally in water that can nevertheless be affected by human sources, such as dissolved oxygen, bacteria, and nutrients.

The magnitude of their effects can be influenced by properties such as pH and temperature. For example, temperature influences the quantity of dissolved oxygen that water is able to contain, and pH affects the toxicity of ammonia.

Volunteers, as well as state and local water quality professionals, have been monitoring water quality conditions for many years. In fact, until the past decade or so (when biological monitoring protocols were developed and began to take hold), water quality monitoring was generally considered the primary way of identifying water pollution problems. Today, professional water quality specialists and volunteer program coordinators alike are moving toward approaches that combine chemical, physical, and biological monitoring methods to achieve the best picture of water quality conditions.

When planning a stream survey, check with other state and local conservation partners (including Minnesota Pollution Control Agency or Soil and Water Conservation Districts) that may already be monitoring water quality in your stream's watershed. If sufficient information is available, you may not need to collect additional data.

Objectives of water quality monitoring:

1. ***To identify whether waters are meeting designated uses***. All states have established specific criteria (limits on pollutants, MN Rule 7050.0220) identifying what concentrations of chemical pollutants are allowable in their waters. When chemical pollutants exceed maximum or minimum allowable concentrations, waters might no longer be able to support the beneficial uses such as fishing, swimming, and drinking for which they have been designated. Designated uses and the specific criteria that protect them (along with

anti-degradation statements that say waters should not be allowed to deteriorate below existing or anticipated uses) together form water quality standards. State water quality professionals assess water quality by comparing the concentrations of chemical pollutants found in streams to the criteria in the state's standards, and so judge whether streams are meeting their designated uses.

Water quality monitoring, however, might be inadequate for determining whether aquatic life uses are being met in a stream. While some constituents (such as dissolved oxygen and temperature) are important to maintaining healthy fish and aquatic insect populations, other factors, such as the physical structure of the stream and the condition of the habitat, play an equal or greater role. Biological monitoring methods are generally better suited to determining whether aquatic life is supported.

2. ***To identify specific pollutants and sources of pollution.*** Water quality monitoring helps link sources of pollution to a stream quality problem because it identifies specific problem pollutants. Since certain activities tend to generate certain pollutants (e.g., bacteria and nutrients are more likely to come from an animal feedlot than from an automotive repair shop), a tentative link might be made that would warrant further investigation or monitoring.
3. ***To determine trends.*** Chemical constituents that are properly monitored (i.e., consistent time of day and on a regular basis, using consistent methods) can be analyzed for trends over time.
4. ***To screen for impairment.*** Finding excessive levels of one or more chemical constituents can serve as an early warning "screen" of potential pollution problems.

Water Quality Variables

Temperature

Water temperature is one of the most important environmental factors in flowing water, affecting all forms of aquatic life. Temperature influences fish migration, spawning, timing and success of incubation, maturation and growth, inter- and intra-specific competition, proliferation of disease and parasites, and other lethal factors and synergisms (Fry 1947; Armour 1991). Stream temperatures are directly affected by any alteration of flow, shade, and channel morphology.

The rates of biological and chemical processes depend on temperature. Aquatic organisms from microbes to fishes are dependent on certain temperature ranges for their optimal health. Optimal temperatures for fish depend on the species: some survive best in colder water, whereas others prefer warmer water. Benthic macroinvertebrates are also sensitive to temperature and will move in the stream to find their optimal temperature. If temperatures are outside this optimal range for a prolonged period of time, organisms are stressed and can die.

For fishes, there are two kinds of limiting temperatures: (1) the maximum temperature for short exposures and a weekly average temperature that varies according to the time of year, and (2) life cycle stage of the fish species. Reproductive stages (spawning and embryo development) are the most sensitive stages.

Temperature affects the oxygen content of the water (oxygen levels become lower as temperature increases); the rate of photosynthesis by aquatic plants; the metabolic rates of aquatic organisms; and the sensitivity of organisms to toxic wastes, parasites, and diseases.

Causes of temperature change include weather, removal of shading stream bank vegetation, impoundments (a body of water confined by a barrier, such as a dam), discharge of cooling water, urban storm water, and groundwater inflows to the stream. Augmentation, impoundment, or release of flow can change light, temperature, and flow timing, as well as distribution of nutrient and organic inputs, sediment, and biota in downstream reaches (Ward and Stanford 1979; Cummins 1980; Crisp 1987; Newbold 1987; Gilvear 1987). Stratification of reservoirs makes level of flow release at all seasons a significant tool for controlling temperature, nutrient content, and biota downstream (Ploskey 1986).

Alteration of temperature and temperature regimes can have simple and complex effects on river systems. Impoundment behind dams, even small ones, increases surface area and thereby raises thermal input and increases water temperature. Downstream influences, which are affected by temperature change, vary depending on the season, depths, and rates of withdrawal or reservoir release. Downstream waters are generally cooler in the summer and warmer in the winter (Baxter 1977). Such changes in temperature can affect fish at the genotypic level—favoring fish that are more tolerant of an unpredictable discharge schedule. Richmond and Zimmerman (1978) isolated a "coolwater" isozyme in populations of red shiners (*Cyprinella lutrensis*) in tailwater areas significantly influenced by hypolimnial discharges (i.e., within 60 km of the dam). Lower temperatures decrease the viscosity of water and may cause faster settling of some solid particles. Temperature increase causes a decrease in oxygen solubility; at the same time the oxidation rate increases, further depleting the oxygen content. The combination of higher temperature and lower dissolved oxygen (DO) can have significant ecological effects.

Artificially higher water temperature typically leads to less desirable types of algae in water. With the same nutrient levels, green algae tend to become dominant at higher temperatures and diatoms decline, whereas at the highest temperatures blue-green algae thrive and often develop into heavy blooms (Dunne and Leopold 1978). In extreme cases, fish can be killed by wide temperature fluctuations, lethally high temperatures below power plants, or in dewatered reaches. At high temperatures, fish metabolism accelerates and their efficiency of oxygen use decreases. Coldwater species, like trout, may suffer direct mortality whereas other fish species may not be killed outright but suffer increased mortality because some other aspect of their existence becomes unfavorable.

Super-cooled water (<0°C), of which frazil ice is an indicator, can also cause physiological stress in fish. At temperatures less than 7°C, fish gradually lose the ability for ion exchange and the efficiency of normal metabolic processes decreases (Evans 1997). At water temperatures near 0°C, most fish have very limited ability to assimilate oxygen or rid cells of carbon dioxide and other waste products. If fish are forced into an active mode under these thermal conditions (such as to avoid the negative physical effects of frazil ice or if changing hydraulic conditions force them to find areas of more suitable depth or velocity), mortality can occur (Post and Parkinson 2001). The extent of impact is dependent on the magnitude, frequency, and duration of frazil events and the availability (proximity) of alternate escape habitats (Jakober et al. 1998).

The temperature of most North American rivers generally increases toward the mouth, such that in larger river systems the main channel is at or very near mean monthly air temperature (Hynes 1975), although a few exceptions exist. Temperature varies diurnally in streams, depending on water depth, proximity to source, shading, and surface area. Dams can also significantly alter temperature because they disrupt longitudinal linkages in the stream (Ward and Stanford 1983).

pH

pH is the negative logarithm of the hydrogen ion concentration and is used to indicate the alkalinity or acidity of a substance as ranked on a scale from 1.0 to 14.0. Acidity increases as the pH gets lower. pH affects many chemical and biological processes in the water. For example, different organisms flourish within different ranges of pH. The largest variety of aquatic animals prefers a range of 6.5-8.0. pH outside this range reduces the diversity in the stream because it stresses the physiological systems of most organisms and can reduce reproduction. Low pH can also allow toxic elements and compounds to become mobile and "available" for uptake by aquatic plants and animals. This can produce conditions that are toxic to aquatic life, particularly to sensitive species like rainbow trout. Changes in acidity can be caused by atmospheric deposition (acid rain), surrounding rock, and certain wastewater discharges.

The pH scale measures the logarithmic concentration of hydrogen (H^+) and hydroxide (OH^-) ions, which make up water ($H^+ + OH^- = H_2O$). When both types of ions are in equal concentration, the pH is 7.0 or neutral. Below 7.0, the water is acidic (there are more hydrogen ions than hydroxide ions). When the pH is above 7.0, the water is alkaline, or basic (there are more hydroxide ions than hydrogen ions). Since the scale is logarithmic, a drop in the pH by 1.0 unit is equivalent to a 10-fold increase in acidity. So, a water sample with a pH 5.0 is 10 times as acidic as one with a pH 6.0, and pH 4.0 is 100 times as acidic as pH 6.0.

Oxygen

The stream system both produces and consumes oxygen. It gains oxygen from the atmosphere and from plants as a result of photosynthesis. Running water, because of its churning, dissolves more oxygen than still water, such as that in a reservoir behind a dam. Respiration by aquatic animals, decomposition, and various chemical reactions consume oxygen.

Wastewater from sewage treatment plants often contains organic materials that are decomposed by microorganisms, which use oxygen in the process. (The amount of oxygen consumed by these organisms in breaking down the waste is known as the biochemical oxygen demand or BOD.) Other sources of oxygen-consuming waste include stormwater runoff from farmland or urban streets, feedlots, and failing septic systems.

Oxygen is measured in its dissolved form as DO. If more oxygen is consumed than is produced, dissolved oxygen levels decline and some sensitive animals may move away, weaken, or die.

DO levels fluctuate seasonally and over a 24-hour period. They vary with water temperature and altitude. Cold water holds more oxygen than warm water and water holds less oxygen at higher altitudes. Thermal discharges, such as water used to cool machinery in a manufacturing plant or a power plant, raise the temperature of water and lower its oxygen content. Aquatic animals are most vulnerable to lowered DO levels in the early morning on hot summer days when stream flows are low, water temperatures are high, and aquatic plants have not been producing oxygen since sunset.

Conductivity

Conductivity is a measure of the ability of water to pass an electrical current. Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge). Organic compounds like oil, phenol, alcohol, and sugar do not conduct electrical current very well and therefore have a low conductivity when in water. Conductivity is also affected by temperature: the warmer the water, the higher the conductivity. For this reason, conductivity is reported as conductivity at 25 degrees Celsius.

Conductivity in streams and rivers is affected primarily by the geology of the area through which the water flows. Streams that run through areas with granite bedrock tend to have lower conductivity because granite is composed of more inert materials that do not ionize (dissolve into ionic components) when washed into the water. On the other hand, streams that run through areas with clay soils tend to have higher conductivity because of the presence of materials that ionize when washed into the water. Groundwater inflows can have the same effects depending on the bedrock they flow through.

Discharges to streams can change the conductivity depending on their make-up. A failing sewage system would raise the conductivity because of the presence of chloride, phosphate, and nitrate; an oil spill would lower the conductivity.

The basic unit of measurement of conductivity is the mho or siemens. Conductivity is measured in micromhos per centimeter (µmhos/cm) or microsiemens per centimeter (µs/cm). Distilled water has conductivity in the range of 0.5 to 3 µmhos/cm. The conductivity of rivers in the United States generally ranges from 50 to 1500 µmhos/cm. Studies of inland fresh waters indicate that streams supporting good mixed fisheries have a range between 150 and 500 µmhos/cm. Conductivity outside this range could indicate that the water is not suitable for certain species of fish or macroinvertebrates. Industrial waters can range as high as 10,000 µmhos/cm.

Conductivity is useful as a general measure of stream water quality. Each stream tends to have a relatively constant range of conductivity that, once established, can be used as a baseline for comparison with regular conductivity measurements. Significant changes in conductivity could then be an indicator that a discharge or some other source of pollution has entered a stream.

Fine sediment

The amount of fine sediments produced by human activities is significant; sediment is the major pollutant of U.S. waters (Waters 1995; **Figure 3-1)**. The U.S. Fish and Wildlife Service (USFWS) concluded that excessive siltation was the most important factor adversely affecting stream habitat (Judy et al. 1984).

Erosion is a natural watershed and stream-channel process, although erosion rates can be accelerated by human activities. A variety of natural disturbances can account for temporarily increased levels of soil erosion, such as periods following vegetation removal by fire. Natural high flow events can likewise mobilize sediment from the bed and banks of streams. The period of ice-out in temperate regions is also one where sediment mobilization and transport as a function of both hydraulic and physical forces of ice can constitute a significant seasonal pulse in the water quality of some rivers loads (Milburn and Prowse 1996). Water flow, channel morphology, and watershed characteristics—including type of underlying bedrock, soil profile, and vegetation—all affect erosion rate (Leopold et al. 1964). Human activities that increase erosion and sediment production include agriculture, forestry, mining, and urban development (USEPA 1990). Agriculture is by far the biggest cause of sediment pollution—providing over three times the amount of sediment contributed by the next leading source (USEPA 1990). Unstable stream channels are much more prone to erosion of fine sediment, and in some cases channel erosion is the dominant source of sediment in streams.

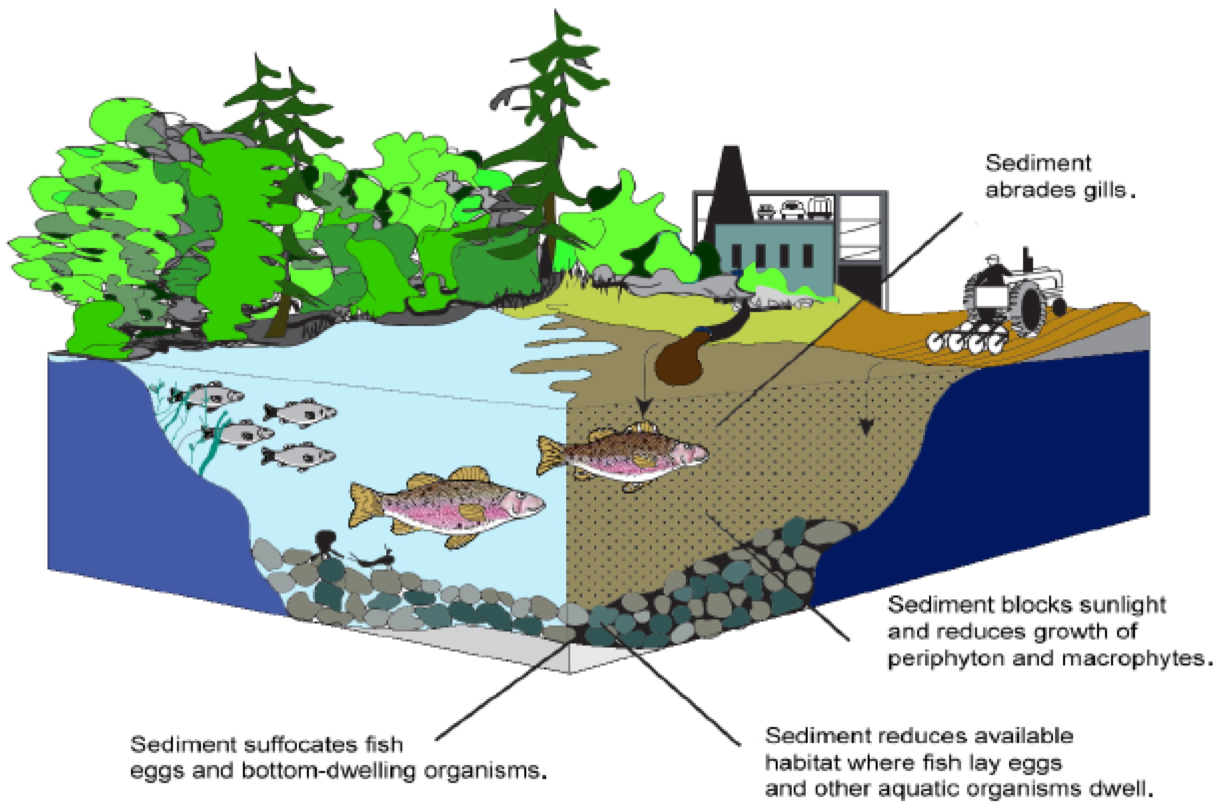


FIGURE 3-1. Sources of sediment include point and nonpoint industrial and agricultural sources. Sediment can impact benthic invertebrates, aquatic plants, and fish at various life-stages.

Sediment arising from the actions of humans can be controlled by prevention, interdiction (e.g., capturing sediment somewhere between source and stream), and restoration (Waters 1995). Prevention is the more preferable option because the cost of intervention—to both the environment and society—increases as the distance from the source increases.

Once excess sediment enters streams, it is transported along the bed of the stream (bedload) or suspended in the water column (suspended solids) and affects stream biota in generally negative ways **(Figure 3-1)**. The transport mode of some particle sizes may change with varying stream flows that change the ability of the stream to mobilize particles.

High suspended solids can interfere with fish behavior and other stream processes, such as reducing the amount of light penetrating the water, which reduces photosynthesis and the production of DO. At high levels, suspended materials can clog fish gills, reducing resistance to disease in fish, lowering growth rates, and affecting egg and larval development. Higher concentrations of suspended solids can also serve as carriers of toxics, which readily cling to suspended particles. This is particularly a concern where pesticides are being used on irrigated crops. Where solids are high, pesticide concentrations may increase well beyond those of the original application as the irrigation water travels down irrigation ditches.

The amount of suspended solids in the water column can be measured directly by expressing the mass of sediment per volume of water, typically milligrams/liter. Indirect measures of transparency and turbidity can also be used, although they are also affected by dissolved materials.

Transparency

Transparency is a measure of water clarity. Transparency of water is affected by a number of factors. Both dissolved and suspended materials can influence water transparency. For most water bodies, the amount of suspended solids in the water is the most important factor as the more suspended materials, the lower the water transparency. In lakes, the majority of suspended solids are algae. In streams and rivers, soil particles (predominantly silts and clays) are a more important influence on transparency as water flows downstream, carrying and depositing sediment with it. A good example of dissolved material that affects transparency is the tea color of some northern, bog-influenced lakes and streams, which is caused by dissolved organic material.

Transparency is measured as the distance one can see through; in lakes it is measured in lakes using a secchi disk, or in rivers using a transparency tube. Transparency is related to another water quality characteristic known as turbidity. By fine-tuning the understanding of the relationship between transparency and turbidity, transparency may be used as a simple meter for identifying exceedances of the turbidity standard, or turbidity impairments.

Turbidity

Turbidity describes how suspended particles (sediment, algae, plankton, and microbes) affect water transparency. Turbidity does not actually measure the concentration of materials in water, but their scattering and shadowing effect on light shining through the water. The 1998 CSMP report described how low transparency readings correspond to high turbidity. This relationship suggests the potential to predict stream turbidity based on transparency-tube measurements. It is important because Minnesota has a water-quality "standard" or limit for turbidity of 25 units for most streams and rivers, or 10 units for designated trout streams.

If turbidity is consistently above the standard (MN Rule 7050.0150 subp.3), a stream is considered "impaired" by MPCA. The relationship between transparency-tube data and turbidity is being developed specific to Minnesota streams. In general, low transparency readings indicate high turbidity.

Total dissolved solids

Total dissolved solids (TDS) consist of calcium, chlorides, nitrate, phosphorus, iron, sulfur, and other ion particles that will pass through a filter with pores of around 2 microns (0.002 cm) in size. The concentration of total dissolved solids affects the water balance in the cells of aquatic organisms. An organism placed in water with a very low level of solids, such as distilled water, will swell up because water will tend to move into its cells, which have a higher concentration of solids. An organism placed in water with a high concentration of solids will shrink somewhat because the water in its cells will tend to move out. This will in turn affect the organism's ability to maintain the proper cell density, making it difficult to keep its position in the water column. It might float up or sink down to a depth to which it is not adapted, and it might not survive.
Sources of total solids include industrial discharges, sewage, fertilizers, road runoff, and soil erosion. Total solids are measured in milligrams per liter (mg/L).

Total alkalinity

Alkalinity is a measure of the capacity of water to neutralize acids (see pH description). Alkaline compounds in the water such as bicarbonates (baking soda is one type), carbonates, and hydroxides remove H^+ ions and lower the acidity of the water (which means increased pH). They usually do this by combining with the H^+ ions to make new compounds. Without this acid-neutralizing capacity, any acid added to a stream would cause an immediate change in the pH. Measuring alkalinity is important in determining a stream's ability to neutralize acidic pollution from rainfall or wastewater. It's one of the best measures of the sensitivity of the stream to acid inputs. Rocks and soils, salts, certain plant activities, and certain industrial wastewater discharges influence alkalinity in streams.

Total alkalinity is measured by measuring the amount of acid (e.g., sulfuric acid) needed to bring the sample to a pH of 4.2. At this pH all the alkaline compounds in the sample are "used up." The result is reported as milligrams per liter of calcium carbonate (mg/L $CaCO_3$).

Phosphorus

Both phosphorus and nitrogen are essential nutrients for the plants and animals that make up the aquatic food web. Since phosphorus is the nutrient in short supply in most fresh waters, even a modest increase in phosphorus can, under the right conditions, set off a whole chain of undesirable events in a stream including accelerated plant growth, algae blooms, low dissolved oxygen, and the death of certain fish, invertebrates, and other aquatic animals.

There are many sources of phosphorus, both natural and human. These include soil and rocks, wastewater treatment plants, runoff from fertilized lawns and cropland, failing septic systems, runoff from animal manure storage areas, disturbed land areas, drained wetlands, water treatment, and commercial cleaning preparations. Phosphorus standards in Minnesota waters are defined in MN Rule 7050.0222, and are defined by water class and ecoregion (total phosphorus, µg/L). Phosphorus effluent limits for point source discharges of sewage, industrial, and other wastes are defined in MN Rule 7053.0255 subp. 3, 4, 5, and 6.

Forms of phosphorus

Phosphorus has a complicated story. Pure, "elemental" phosphorus (P) is rare. In nature, phosphorus usually exists as part of a phosphate molecule (PO_4). Phosphorus in aquatic systems occurs as organic phosphate and inorganic phosphate. Organic phosphate consists of a phosphate molecule associated with a carbon-based molecule, as in plant or animal tissue.

Phosphate that is not associated with organic material is inorganic. Inorganic phosphorus is the form required by plants. Animals can use either organic or inorganic phosphate.

Both organic and inorganic phosphorus can either be dissolved in the water or suspended (attached to particles in the water column). As phosphorus cycles through the environment, it changes its form as it does so. Aquatic plants take in dissolved inorganic phosphorus and convert it to organic phosphorus, as it becomes part of their tissues. Animals get the organic phosphorus they need by eating either aquatic plants or animals.

As plants and animals excrete wastes or die, the organic phosphorus they contain sinks to the bottom, where bacterial decomposition converts it back to inorganic phosphorus, both dissolved and attached to particles. This inorganic phosphorus gets back into the water column when animals, human activity, chemical interactions, or water currents stir up the bottom. Then plants take it up and the cycle begins again.

In a stream system, the phosphorus cycle tends to move phosphorus downstream as the current carries decomposing plant and animal tissue and dissolved phosphorus. It becomes stationary only when it is taken up by plants or is bound to particles that settle to the bottom of pools.

Nitrates

Nitrates are a form of nitrogen, which is found in several different forms in terrestrial and aquatic ecosystems. These forms of nitrogen include ammonia (NH_3), nitrates (NO_3), and nitrites (NO_2). Nitrates are essential plant nutrients, but in excess amounts they can cause significant water quality problems. Together with phosphorus, nitrates in excessive amounts can accelerate eutrophication, causing dramatic increases in aquatic plant growth and changes in the types of plants and animals that live in the stream. This, in turn, affects dissolved oxygen and temperature. Excess nitrates can cause hypoxia (low levels of dissolved oxygen) and can become toxic to warm-blooded animals at higher concentrations (10 mg/L) or higher) under certain conditions. The natural level of ammonia or nitrate in surface water is typically low (less than 1 mg/L); in the effluent of wastewater treatment plants, it can range up to 30 mg/L.

Sources of nitrates include wastewater treatment plants, runoff from fertilized lawns and cropland, failing on-site septic systems, runoff from animal manure storage areas, and industrial discharges that contain corrosion inhibitors.

Fecal bacteria

Members of two bacteria groups, coliforms and fecal streptococci, are used as indicators of possible sewage contamination because they are commonly found in human and animal feces. Although they are generally not harmful themselves, they indicate the possible presence of pathogenic bacteria, viruses, and protozoans that also live in human and animal digestive systems. Therefore, their presence in streams suggests that pathogenic microorganisms might also be present and that swimming and eating shellfish might be a health risk. Since it is difficult, time-consuming, and expensive to test directly for the presence of a large variety of pathogens, water is usually tested for coliforms and fecal streptococci instead. Sources of fecal contamination to surface waters include wastewater treatment plants, septic systems, domestic and wild animal manure, and storm runoff.

In addition to the possible health risk associated with the presence of elevated levels of fecal bacteria, they can also cause cloudy water, unpleasant odors, and an increased BOD.

The most commonly tested fecal bacteria indicators are total coliforms, fecal coliforms, *Escherichia coli*, fecal streptococci, and enterococci. All but *E. coli* are composed of a number of species of bacteria that share common characteristics such as shape, habitat, or behavior; *E. coli* is a single species in the fecal coliform group.

Total coliforms are a group of bacteria that are widespread in nature. All members of the total coliforms group can occur in human feces, but some can also be present in animal manure, soil, and submerged wood and in other places outside the human body. Thus, the usefulness of total coliforms as an indicator of fecal contamination depends on the extent to which the bacteria species found are fecal and human in origin. For recreational waters, total coliforms are no longer recommended as an indicator. For drinking water, total coliforms are still the standard test because their presence indicates contamination of a water supply by an outside source.

Fecal coliforms, a subset of total coliforms bacteria, are more fecal-specific in origin. However, even this group contains a genus, *Klebsiella*, with species that are not necessarily fecal in origin. *Klebsiella* are commonly associated with textile and pulp and paper mill wastes. Therefore, if these sources discharge to your stream, you might wish to consider monitoring more fecal and human-specific bacteria. For recreational waters, this group was the primary bacteria indicator until relatively recently, when EPA began recommending *E. coli* and enterococci as better indicators of health risk from water contact. Fecal coliforms are still being used in many states as the indicator bacteria.

E. coli is a species of fecal coliform bacteria that is specific to fecal material from humans and other warm-blooded animals. EPA recommends *E. coli* as the best indicator of health risk from water contact in recreational waters; some states have changed their water quality standards and are monitoring accordingly.

Fecal streptococci generally occur in the digestive systems of humans and other warm-blooded animals. In the past, fecal streptococci were monitored together with fecal coliforms and a ratio of fecal coliforms to streptococci was calculated. This ratio was used to determine whether the contamination was of human or nonhuman origin. However, this is no longer recommended as a reliable test.

Enterococci are a subgroup within the fecal streptococcus group. Enterococci are distinguished by their ability to survive in salt water, and in this respect they more closely mimic many pathogens than do the other indicators. Enterococci are typically more human-specific than the larger fecal streptococcus group. EPA recommends enterococci as the best indicator of health risk in salt water used for recreation and as a useful indicator in fresh water as well.

Additional parameters

Additional water quality parameters may be important to specific stream situations. See Stream Survey Manual (MNDNR 2007), Water Quality Methods, for specifics on collecting and interpreting these variables. These include BOD, chlorophyll *a*, sulfate, chloride, and methyl mercury.

Photo by Rick Nelson

Chapter 4. Biological Communities

"To preserve river values, our streams must be deliberately managed for diversity – not just for the canoeist, not just for the species of fish that provide sport to the angler, but rather for the myriad life forms that, living interdependently, are unique to flowing waters."

—Tom Waters, 1977, Streams and Rivers of Minnesota.

Introduction

Biological components of stream systems are of obvious importance to stream managers because they include the primary biotic group important to people, fishes; and because other biota are integral to maintaining fisheries as either food sources for higher trophic taxa, decomposers that break down dead materials, or by providing physical habitat, such as instream vegetation. Goldman and Horne (1983) listed eleven primary groups of biota inhabiting aquatic systems: viruses, bacteria, fungi, algae/phytoplankton, macrophytes, protozoans, zooplankton, aquatic invertebrates, worms and mollusks, fishes, amphibians and reptiles. Some bird and mammal species also spend most of their life cycle in aquatic systems and some can have profound influences on habitat and other biota, such as beaver *Castor canadensis* (Naiman et. al. 1988; Schlosser and Kallemeyn 2000). Vegetative communities along stream banks can also be important to instream biota by providing required resources such as allochthonous energy (Hynes 1975), and by modifying stream channel form and instream habitat (Rosgen 1996; Gregory et al. 2003; Sweeney et al. 2004). This chapter will focus survey efforts on aquatic macrophytes, aquatic invertebrates, fishes, and riparian vegetation because these groups most directly influence fishes and their habitat; are logistically feasible to monitor; and may be most amenable to management manipulation.

Stream and riparian biota are often interconnected, with effects on one biota type manifested in other biotic groups. These connections are most often expressed as one of three types: trophic level effects/predation, intra- or inter-specific competition, or parasitism and disease (Moyle and Cech 1996). For example, opossum shrimp, *Mysis relicta*, were introduced into lakes and streams in the upper portion of the Flathead Lake catchment of northwest Montana to promote growth and production of kokanee salmon, *Oncorhynchus nerka* (Spencer et al. 1991). However, the opossum shrimp preyed heavily on the native zooplankton populations, the primary food source for the lake's kokanee prior to shrimp introduction. This resulted in a trophic level collapse as the shrimp competed with the kokanee for the native zooplankton food source, but avoided kokanee predation by using different habitats from the salmon (Spencer et al. 1991). Subsequent declines in kokanee populations and annual spawning runs negatively impacted salmon predators such as grizzly bear and bald eagles as well. Fisheries ecology is replete with other examples of the inter-connectedness of aquatic biota and the riparian zones that surround their environs.

Aquatic ecologists have formulated numerous conceptual frameworks to help explain and understand the dizzying array of interactions among biota in riverine systems (see Lorenz et al. 1997 for a nice summary of lotic concepts). Of primary importance were the River Continuum Concept (Vannote et al. 1980) which stressed upstream-downstream linkages (but see Wiley et al. 1990 for reverse application in agricultural-prairie stream systems), and the flood-pulse concept, which stressed lateral linkages between a river's biota and the terrestrial biota and habitat on its floodplain. Most of these concepts stressed "bottom-up" trophic level interactions whereby biotic and abiotic processes at lower trophic levels effected changes at higher trophic levels (e.g., Peterson et al. 1992); however, "top-down" trophic level interactions exist in some streams as well (e.g., Matthews et al. 1987).

Schlosser (1987) proposed a conceptual framework to better understand the relative influence of biotic and abiotic processes regulating fish communities in small warmwater streams. He proposed that fish communities in smaller more temporally variable headwater streams were regulated primarily by abiotic factors such as flood and droughts, whereas fish communities in larger more stable stream systems were regulated more by biotic interactions, such as predation and competition. This framework might indicate that different management actions are needed for different-sized streams. For example, biotic management actions, such as stocking, might work best in the larger more stable stream systems.

The Riparian Zone

Resource professionals have adopted numerous definitions for riparian zones. The American Fisheries Society adopted the following definition for riparian area, "(1) Of, pertaining to, situated or dwelling on the margin of a river or other water body. (2) Also applies to banks on water bodies where sufficient soil moisture supports the growth of mesic vegetation that requires a moderate amount of moisture" (Armantrout 1998). The National Research Council (NRC) defined the riparian zone as, "the border or banks of a stream. Although this term is sometimes used interchangeably with floodplain, the riparian zone is generally regarded as relatively narrow compared to a floodplain. The duration of flooding is generally much shorter, and the timing less predictable, in a riparian zone than in a river floodplain" (NRC 1992). Ilhardt et al. (2000) reviewed numerous riparian zone definitions used by government agencies from several scientific disciplines and noted that definitions were often dependent on which landscape scales were considered and which legislative mandates or management prescriptions were followed. Following their review, they offered a definition based on the ecosystem function of the riparian zone, "Riparian areas are three-dimensional ecotones of interaction that include terrestrial and aquatic ecosystems, that extend down into the groundwater, up above the canopy, outward across the floodplain, up the near-slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at a variable width" (Ilhardt et al. 2000; **Figure 4-1**). However, none of these definitions is useful for determining where information on riparian zone characteristics should be measured. Ilhardt et al. (2000) also acknowledged the need for delineating a riparian area for measurement purposes as opposed to just defining what a riparian area is.

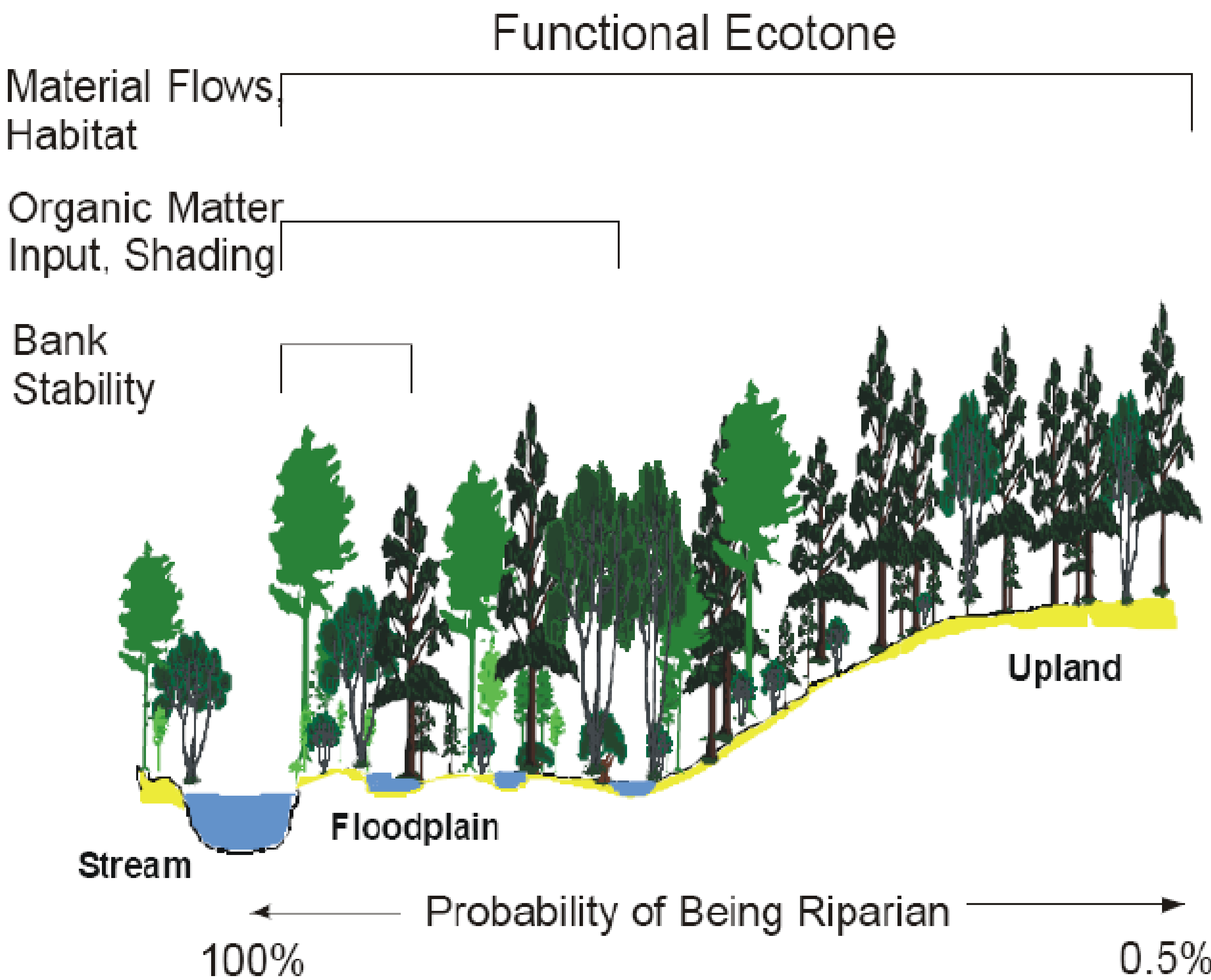


FIGURE 4-1. Defining riparian areas functionally avoids problems associated with assessing whether a terrestrial setting is part of the riparian area based solely on soils, or vegetation, or frequency of flooding. The extent of a riparian area into the terrestrial setting varies with the strength of each function rather than at a fixed distance from the water. The number of functions contributing to riparian and aquatic ecosystem processes decreases with distance from the water ecosystem. In other words, the probability of a function being riparian varies with each function across the riparian ecotone (taken from Ilhart et al. 2000).

The most problematic parameter to estimate when delineating a riparian zone is the width extending outward from the apparent water line. Blann (2000) used a riparian width of 100 m for examining riparian scale influences on stream biota in southeast Minnesota streams. The Wisconsin Department of Natural Resources (WDNR 2002) and Minnesota Pollution Control Agency (MPCA 2004) characterize riparian land use within 100 m of the stream channel also, when measuring stream fish habitat. Large and Petts (1996) provided a review of recommended riparian widths for management to maintain various ecosystem functions, such as fisheries protection, streambank stability, and water quality control. Recommended widths generally ranged from 10 to 150 m. Ilhardt et al. (2000) suggested delineating riparian zone width based on functionality (i.e., by the movement of material and energy between the land and water; **Figure 4-1**). However, this may be somewhat problematic "on-the-ground" as functionality will change as one moves away from the water's edge. Rather, Ilhardt et al. (2000) suggested that geomorphology may provide a surrogate for functionality. Ilhardt et al. (2000) provided a field key to help define riparian area widths in the field based on identification of the floodplain, the terrace, and the slope between them **(Figure 4-2)**.

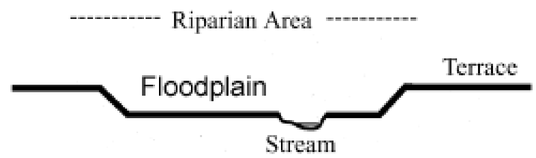
For the scope of this manual, we use the definition put forth by Ilhardt et al. (2000), that the riparian zone is that portion of land extending from the wetted edge of the stream at the time of the survey out beyond the floodplain and terrace plus one tree length.

Riparian land use and vegetation exert strong effects on numerous environmental factors influencing fish communities (Lyons et al. 2000). Riparian zones can modify, incorporate, dilute, or concentrate substances, such as excess nutrients and agricultural chemicals, before they enter the stream (Chauvet and Décamps 1989; Isenhart et al. 1997) and provide fish cover and wildlife migration corridors (Johnson and Ryba 1992; Large and Petts 1996). In small to mid-size streams, riparian zones can moderate temperatures (Blann et al. 2002), reduce sediment inputs (Waters 1995), provide important sources of organic matter (Allan 1995), and stabilize stream banks (Osborne and Kovacic 1993). The riparian corridor provides critical physical and biological linkages between terrestrial and aquatic environments (Gregory et al. 1991). For example, Nerbonne and Vondracek (2001) found that stream sites with grassed riparian zones had lower percent fine substrates, less exposed streambank soil, and more fish cover than sites with wooded or grazed riparian zones in southeast Minnesota. Percent fine substrates were subsequently negatively correlated with indices of fish and macroinvertebrate community health. Blann et al. (2002) found riparian buffers comprised of grasses and forbs provided as much shade and mediated water temperatures as well as wooded buffers in a small southeast Minnesota stream (width<2.5m and low width:depth ratio). However, wooded buffers provided more shade at larger stream sizes.

A. Floodplain & Terrace Slopes Are Identifiable

The Riparian Area consists of:

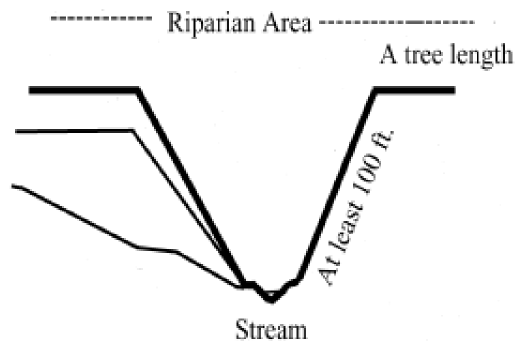
- **–The Stream**
- **–The Floodplain**
- **–The Terrace Slopes adjacent to the floodplain**
- **–One Tree Length on top of each terrace**



AA. Either Floodplain Or Terrace Slopes NOT Identifiable

B. Slopes Steep (>5%) adjacent to stream or floodplain

- **–The Stream**
- **–The Slope to its top**
- **–One Tree Length beyond slope top**



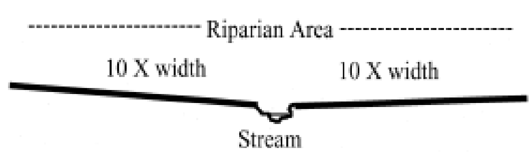
BB. Slopes Gentle (<5%) adjacent to stream or floodplain

C. Streams <10 ft Wide at Bankfull

- **–The Stream**
- **–One Tree Length on each side**

CC. Streams > 10 ft Wide at Bankfull

- **–The Stream**
- **–10 X bankfull width, each side**



(May approach 20 X stream width for E type channels with wide floodplains, see Chapter 6)

FIGURE 4-2 . A dichotomous field key to define riparian areas for streams. The key has two forks: areas where the floodplain and terrace slopes are identifiable; and areas where either the floodplain or terrace slopes are NOT identifiable. Under the second fork, there is a further division based on slope (greater or less than 5%); and where the slope is less than 5%, size of stream is addressed (taken from Ilhart et al. 2000).

Aquatic Plants and Periphyton

Aquatic macrophytes (large plant species, including flowering plants) can be an important component of some stream habitats, primarily by influencing the structure and spatial distribution of benthic invertebrate communities (Ward 1992). Macrophytes increase water depth and change flow patterns, provide shelter and oviposition sites for benthic invertebrates, and substrata for epiphytic algae and invertebrates **(Figure 4-3)**. Macrophytes can also affect trophic relationships. Grazing invertebrates may benefit from epiphytic algae; shredders from decaying plants; and detritivores from fine particulate organic matter that accumulates within plant beds. The abundance and diversity of invertebrates is usually greater in areas covered with macrophytes than in macrophyte-free plots of the same stream.

In lake ecosystems, plants and algae form the basis of primary energy production; however, in stream systems, allochthonous materials (terrestrial-derived plant matter) often provide the majority of energy input. Exceptions include large, slow-moving rivers, impounded streams, and river backwater areas, where aquatic habitats resemble lake rather than stream environments. The running water environment greatly limits the number of species of aquatic plants. Most species found in running water are also found in still-water habitats, but in running water they tend to have smaller leaves, and rarely produce floating leaves. The inhibition of growth appears to be due to current. In running waters only rooted growth forms become established and thus they are usually restricted to areas of sediment deposition. Hynes (1972) stated that no rooted plants show any special adaptation to running water, and the species that occur in streams and rivers have tough, flexible stems or leaves, a creeping growth habit, frequent adventitious roots, and strictly vegetative reproduction.

Aquatic plants in streams can be divided into two primary ecological categories: those attached to rocks and other solid objects, and those that are "rooted" into the substratum. Common attached plants include the mosses and liverworts (Bryophyta), which are often found attached to cobble and rubble near springs. Since mosses cannot metabolize bicarbonate, they are favored in areas where dissolved carbon dioxide is high, usually adjacent to groundwater springs. Rooted plants include:

- Pondweeds (*Potamogeton* sp.)
- Water buttercup(*Ranunculus* sp.)
- Water milfoil (*Myriophyllum* sp.)
- Brooklime (*Veronica* sp.)

Algae grow attached to all kinds of solid objects; they also occur as thin films on mud and silt surfaces. In areas unsuitable for rooted macrophytes, filamentous and microscopic algae often cover these areas, providing food and habitat for invertebrates. Large plants themselves form substrata, which are suitable for epiphytic algae and smaller plants.

Aquatic plants in running water systems tend to be patchy, often covering less than 20% of suitable areas, primarily due to the instability of the plants to scour (Allan 1995). Shifting sediment, and sediment accumulation and subsequent redistribution, all affect the ability of plants to become established.

The presence and development of macrophytes in stream systems can be controlled by the hydrologic regime (frequency of high-velocity flood events; Biggs 1996). In many flowing water situations, the occurrence of floods following heavy rains severely limits the abundance of submersed species due to strong currents. Most of the reduction in macrophyte cover is often where current speeds are the highest (Bilby 1977). Riis and Biggs (2003) found that the abundance and diversity of macrophytes decreased as flood disturbance frequency increased, and that vegetation was absent in streams with more than 13 high-flow disturbances per year. They found the main mechanism for loss was not stem breakage, but uprooting associated with bed sediment erosion. Plants with high propagule production constituted a greater proportion of the vegetation in more flood-disturbed streams than in stable streams, suggesting that this species trait is important for the maintenance of macrophyte communities in flood-prone streams.

FIGURE 4-3. Aquatic vegetation, including watercress and filamentous algae, form substrata for invertebrates and habitat for fish in a small spring creek. Note undercut bank (top) formed by watercress beds.

Differences in hydraulic stability among streams over periods greater than a year may govern whether a stream (or site) is dominated by periphyton, bryophytes, or macrophytes (Biggs 1996). Hydraulic stability over periods of less than a year governs the average periphyton biomass. During steady-state, interspate periods the effect of spatial differences in hydraulics varies depending on the stage of plant development. Periphyton and macrophyte colonization is enhanced by low velocities, and growth rate and organic matter accrual can be enhanced by moderate velocities. However, high velocities retard colonization and organic matter accrual. For mature communities, the peak biomass of periphyton and macrophytes can be negatively correlated with velocity. This is in contrast with bryophytes, which are often restricted to areas of high velocity on stable substrata. Hydraulic habitat suitability curves have yet to be developed for plant communities in streams.

The performance of plant taxa in more stable systems is strongly influenced by local hydraulic conditions (depth/velocity). Riis and Biggs (2003) found velocity, depth, and substrate particle size habitat preferences were displayed by common species study streams. None of the macrophytes showed overlapping preferences for all three habitat variables, suggesting coexisting of the species in streams by physical niche separation.

While macrophytes play a key role in streams by increasing physical heterogeneity, trapping fine sediments, and providing extensive habitat for periphyton, invertebrates, macrophytes can also proliferate and severely impede water flow, degrade water quality (through their effects on pH and dissolved oxygen), and degrade aesthetic/recreational values, especially in disturbed streams. Substantial increases in stream macrophytes can drive physical conditions, periphyton, benthic invertebrates, and thus potentially shape communities (Burkholder 1996; Death 2000).

Stream Benthic Macroinvertebrates

Benthic macroinvertebrates (for example, aquatic insects, crayfish, amphipods; **Figure 4-4**) form the basis of the food chain in many streams, rivers, and other aquatic habitats. As a result of their habitat choice, macroinvertebrates are often regarded as the “benthos,” which refers collectively to organisms which live on, in, or near the bottom. The benthos serves as an important linkage between terrestrial inputs (leaves, woody debris, nutrients) and the fish community **(Figure 4-5)**. Macroinvertebrates have also been used extensively throughout North America as indicators of water quality. Because most or all of their life cycles are spent in the stream, they must be able to tolerate chemical and habitat variations throughout different life stages, or their populations will be eliminated.

Sampling macroinvertebrates can provide baseline data for trend analysis, information on the food base in the system, and can be used to calculate some water quality metrics. Basic level sampling is designed to provide species lists, qualitative assessments of abundances (such as abundant, rare, common), and water

FIGURE 4-4. Invertebrates in running water ecosystems include aquatic insects (shown: caddisflies, mayflies, stoneflies, damselflies, black flies, and hellgrammites), amphipods, clams, and crayfish.

quality metrics such as the Hilsenhoff Biotic Index (HBI) (Hilsenhoff 1987). Quantitative sampling involves different sampling equipment, and will provide species lists, density (#/m^2) and water quality metrics (including the HBI).

Benthic macroinvertebrates are often overlooked or ignored by many biologists working in aquatic habitats. Due to their small size, cryptic habitats, difficulty in collection and sorting, specialized taxonomy and equipment needs, they are either left unrecorded or only mentioned in a cursory fashion (e.g., "crayfish" "mayflies and dragonflies," etc.). Aquatic insects (Class Insecta) often form the greatest majority of the benthic fauna in streams and rivers, but often are only noticed as the adults (e.g., mayfly hatch, dragonflies, and biting black flies). However, benthic macroinvertebrates form a critical component in many lotic systems, particularly in smaller to medium-size streams and rivers.

In smaller streams, trees, shrubs, and other terrestrial vegetation may shade the stream and block sunlight from the stream. Phytoplankton (algae) is very limited, and often rooted aquatic vegetation may be lacking or sparse. Leaf litter, wood pieces, grass, and other terrestrial input provides an important beginning of the food chain. The benthic community is a vital link

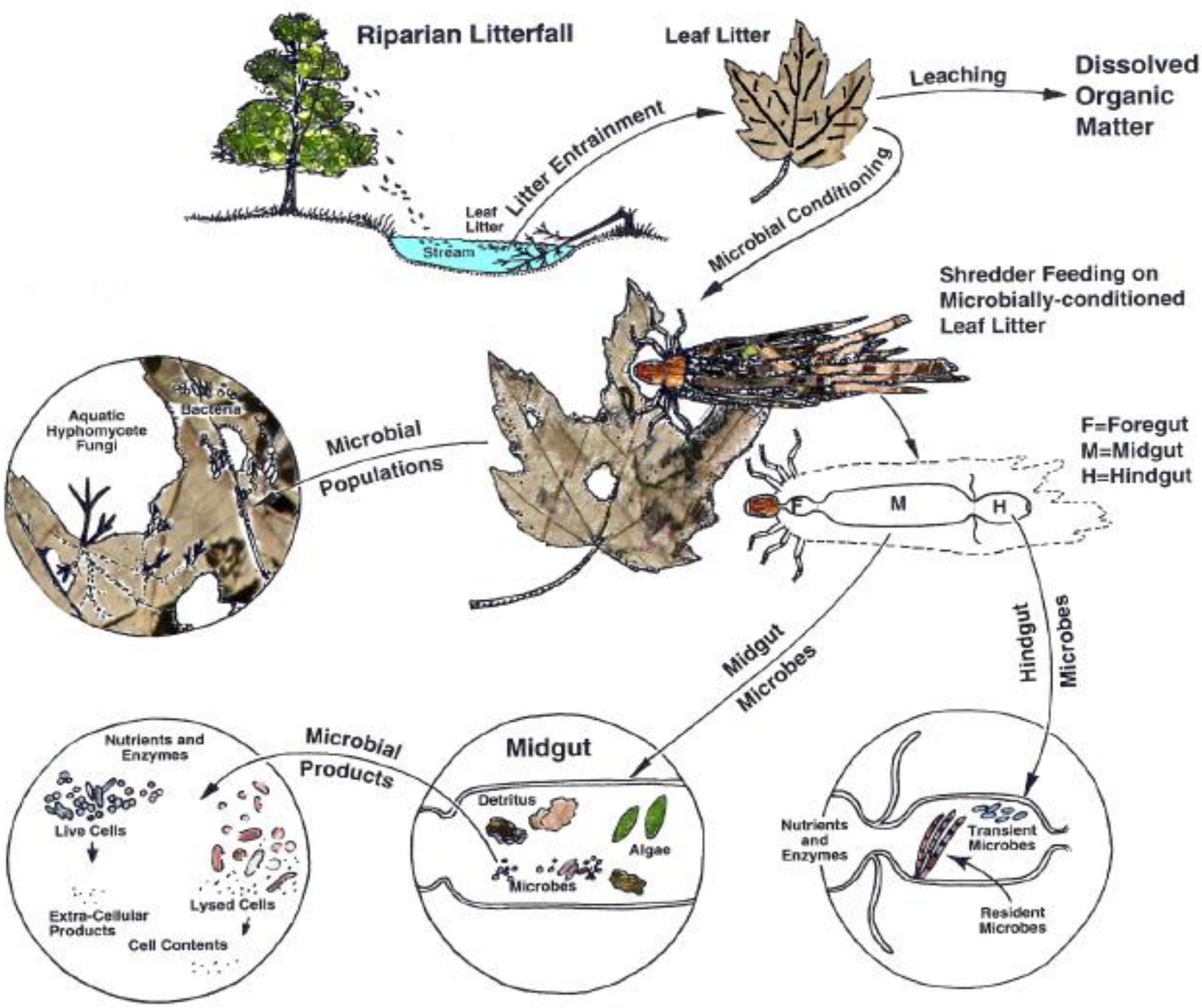


FIGURE 4-5. Some stream invertebrates occupy an essential role in processing riparian energy inputs (leaf litter) into secondary production (microbial and invertebrate biomass). Leaf litter undergoes microbial conditioning, then is fed on by "shredders" (in this case a caddisfly larva). Further microbial decomposition occurs in the invertebrate gut tube, releasing valuable nutrients available for other secondary production. After Merritt and Cummins (1996).

in these smaller systems. It can serve multiple functions; consuming leaf litter and shredding vegetation to smaller particles, filtering these smaller particles for food, boring and consuming woody debris and helping speed the breakdown of coarse organic debris. The benthos takes this plant material and converts it into macroinvertebrate biomass (e.g., mayflies, stoneflies, amphipods, and other organisms), which are important prey items for the fish community. The linkage provided by the benthic community between terrestrial vegetation and the fish community can be very important for some systems (Healey 1984; MNDNR 2004). The emergence of many adult aquatic insects also serves as food not only for the fish community, but also for terrestrial animals associated with the riparian area, such as birds or bats.

In larger streams, the wider channel may allow light penetration to permit more rooted aquatic vegetation and benthic algae. Macroinvertebrates still play a key role in converting small particulate organic matter from upstream into animal biomass through a larger group of filter feeders, varying from black flies to net-spinning caddisflies. Diverse populations of aquatic insects are often found on snags and fallen trees, creating food and cover for fish. Even in larger rivers, high populations of burrowing mayflies turn organic particles that have settled to the bottom to large-bodied animals that must move up through the water column to emerge, creating an easily obtained invertebrate buffet line. Throughout the flowing water system, macroinvertebrates form a part of the food chain linking plant production to fish production.

Benthic macroinvertebrates, particularly insects, are increasingly being used in water quality assessments. Many states and different countries have developed and used indices that examine diversity and density of macroinvertebrates to determine water quality, or to assess impacts from specific actions and perturbations (Barbour et al. 1999; Davis and Simon 1995; Hilsenhoff 1987; Resh and Jackson 1993). The life cycle and habitats of macroinvertebrates make them very useful for water-quality monitoring. Most macroinvertebrates spend the majority of their life in their larval stages, linked to the water and associated parameters in the stream (such as dissolved oxygen, temperature, nutrients), with some adult terrestrial stages being as brief as a day or two. Thus, they are exposed continually to normal water conditions as well as episodic changes in water chemistry. If a specific macroinvertebrate cannot survive the routine conditions, it will be eliminated from a reach or entire stream. Additionally, if a spill or other short-time event occurs, it can eliminate large numbers of different species from an area.

While routine chemical monitoring can easily miss short-duration events, macroinvertebrates cannot avoid exposure to such episodes. The relatively immobile life histories of most macroinvertebrates prevents them from moving during adverse conditions; thus they must be tolerant of water chemistry throughout their long aquatic life cycles or be reduced or eliminated from the benthic community.

Life cycles for different macroinvertebrates vary among taxa, even among related families. Some genera may have several generations a season, while others have life cycles that span more than one year. Many have life cycles that may produce one generation per season. Emergence of the adult forms can occur at varying times over the summer and fall, and a few taxa may even emerge early in spring while ice still covers part of the stream. This constant emergence of different taxa creates a changing mosaic of abundances and presence in the benthic community. Highest diversities and densities are often seen in spring and fall periods.

While there is no one single method that is "correct" for collection of benthic macroinvertebrates, a basic collection with a kick net from some major habitats can provide useful information on the relative abundance and diversity of this community. Not only can this provide a broad picture of the food base in the particular stream or reach, it can provide a snapshot of the water quality for those waters. Establishing such a baseline on the macroinvertebrate fauna and water quality can be useful for long-term monitoring. Additionally, having streams that provide baseline invertebrate information can assist in studies on other waters of a particular region that might have been impacted by a spill, land use change, or other perturbation.

Stream Fishes

Stream fishes serve as valuable resources throughout the state of Minnesota. Coldwater streams in southeast Minnesota provide some of the highest catch rates of trout throughout the United States (Snook and Dieterman 2006). Angling pressure on these trout streams was the highest in Minnesota relative to lake fisheries (Cook and Younk 1998) with an estimated angling pressure of 190,859 angler-hours in 2005 (Snook and Dieterman 2006). Trout anglers spent over 500,000 days fishing coldwater streams in Minnesota in 2001 and generated over 40 million dollars to the state's economy (Gartner et al. 2002).

While trout are a favorite for stream anglers, other species including smallmouth bass, catfish, lake sturgeon, and walleye are also highly sought after **(Figure 4-6)**. Minnesota warmwater streams were found to have moderate to high fishing pressure on a per acre basis when compared to lakes (Cook and Younk 1998). Fishing success was also high, with fish harvest rates averaging 0.44 fish/hr. Hirsch (1986) evaluated fishing on 3.7 miles (87 acres) of the Zumbro River in southern Minnesota. White bass, smallmouth bass, crappie, channel catfish, and carp dominated the harvest. Fishing pressure varied from 61 hours/acre to 1,135 hours/acre, with the higher value representing a tailwater fishery below Lake Zumbro. Hirsch and Peterson (1987) surveyed 83 miles of the Cannon River in southern Minnesota and documented 116,192 angler-hours fishing pressure for a six-month period (April-September 1984). Fish harvest estimates included 27 species of fish, dominated in numbers by black bullhead (84%), black crappie (7%), carp (3%), freshwater drum (2%), and bluegill (1%). Other recreational use estimated included canoeing (39,720 hrs.) and tubing (31,661 hrs.).

FIGURE 4-6. Important game fish species occupying Minnesota streams include channel catfish, smallmouth bass, walleye, brown trout, and brook trout.

Biologists and managers often examine stream fishes with diverse objectives, and stream surveys provide valuable information on fish and fish habitat that assists in making management decisions for streams. Managers collect information to help manage important recreational and commercial species, for compliance with water quality rules, or for general indications of stream quality or, alternatively, degradation. The local significance of the stream and its morphological composition often dictate the objectives of management and research activities (Rabeni and Jacobson 1999).

Stream fishes can be described at two organizational levels useful to the resource manager: fish populations and fish communities. A population is a collective group of organisms of the same species occupying a particular space in time (Odum 1959). Population parameters to describe and manage recreational and commercial fish populations include recruitment, growth, and mortality; ponderal indices, such as relative weight and condition factors; size structure indices; and population size (Ney 1999; Van den Avyle and Hayward 1999). A fish community can be defined as a group of fish populations that live in a common area and interact with one another (Crowder 1990). Various community-level parameters have been proposed and include indicator taxa or guilds; indices of species richness, diversity, evenness, and similarity; and the Index of Biotic Integrity (IBI) (Fausch et al. 1990).

Many factors have been proposed to influence fish community structure and spatial location. All proposed factors can be loosely grouped as either abiotic or biotic drivers. See Matthews (1998) for a more thorough integration of factors into four broad categories: zoogeographic and "deep" evolutionary processes; local phenomena such as floods and drought; ecology of individual species (non-interactive); and biotic interactions. Although fish communities were predominantly influenced by zoogeographic limitations, recent human influence has brought on the introduction of species, construction of barriers, and connection of basins that have spatially altered stream fish communities throughout the world. Abiotic drivers of immediate management concern generally include the other four major components because fishes reflect the ambient conditions of hydrology, geomorphology, water quality, and connectivity. Refer to Chapters 1, 2, 3, and 5 of this document (Fisheries Stream Survey Manual, Supplement 1).

Associations between fish communities and abiotic variables have led to the broad use of fish community indices in determination of environmental degradation and general stream health (Fausch et al. 1990). Of particular importance has been the development of the Index of Biotic Integrity (IBI) (Simon 1999). The IBI is a multimetric index that quantitatively evaluates fish community attributes to produce an overall description of stream quality. The Minnesota Pollution Control Agency (MPCA) has been using fish community IBI data to assess water resource quality since 1994. These assessments are a fundamental part of MPCA's state water quality management program. The Clean Water Act requires all states to assess the quality of surface waters and to report the extent to which waterbodies meet their designated uses and attain state water quality standards. Waterbodies that do not meet their designated uses, such as safely supporting aquatic life, drinking water, swimming, irrigation, or industrial purposes, are placed on the impaired waters list (also known as the Total Maximum Daily Load or TMDL list). Once a waterbody is listed, the state is required to determine the cause of impairment and work to clean up or restore the waterbody.

As of 2006, more than 65% of assessed streams meet water quality standards and designated use criteria; however, only about 8% of stream miles have been assessed. Collection of fish community data by MNDNR in a manner consistent with MPCA protocol could contribute significantly to the assessment process. Biological data are used by the MPCA for other aspects of water resource management, including: long-term condition monitoring (status and trends), problem investigation monitoring, effectiveness monitoring, and permitting. While the main goal of MNDNR fish community sampling may not be the calculation of an IBI score, adherence to standardized IBI sampling protocols can dramatically increase the utility of the data collected.

Primary biotic drivers of fish communities include competition, predation, and symbiotic relationships (Crowder 1990). Competition, and its consequence, resource partitioning, had been considered one of "the" primary driving forces in the structure of fish communities up to about the 1960s (Matthews 1998). Competition was defined as the demand of more than one individual for the same resource that was in limited supply resulting in evidence of mutual negative effects on resource use, individual growth, or some other measure of fitness (Crowder 1990). Competition could occur among individuals within the same population (intra-specific) or among individuals of different species (inter-specific). More recently, other factors have come to be regarded as important drivers of fish community composition, including other biotic interactions of top-down predation and bottom-up trophic effects (Vannote et al. 1980; Matthews et al. 1987). Predation was often characterized by selectivity indices relating prey consumed versus available to determine selection and led to development of optimal foraging theory (Crowder 1990). Predator-prey interactions structured communities by favoring prey species with predator avoidance behaviors and phenotypic traits and through effects of keystone predators (e.g., Paine 1969).

Competition studies were also hindered by the difficulty in definitively demonstrating resource limitation, leading to the corollary "ghost of competition past" argument of Connell (1980). Other ecologists argued that fish community structure simply followed a "null" or "random" pattern and hence were not driven by any organizing principle or abiotic factor (Connor and Simberloff 1984). Finally, many ecologists demonstrated the strong effects of abiotic variables and environmental disturbances such as floods and droughts with excessive intensity and duration and/or erratic timing (Matthews 1998). Together, these arguments served to abolish the competition paradigm as "the" major organizing force in stream fish communities, although competition is still important in some instances.

Schoener (1987) presented seven "axes of controversy" describing competing theories of factors determining ecological communities as applied to stream fishes. Many of his axes could be loosely grouped into the abiotic and biotic categories mentioned above, with abiotic factors generally reflecting variable environmental conditions, such as floods and droughts, which fishes must adapt to or become extirpated, versus biotic factors that tend to occur in a more or less predictable, deterministic manner. Biotic factors are generally believed to be more prevalent in streams characterized by stable, predictable environments, whereas abiotic factors tend to be more important in more variable systems (Schoener 1987; Crowder 1990).

Subsequent thinking has suggested that stream systems are probably not driven primarily by either/or abiotic/biotic factors but are likely more integrated as a continuum of abiotic driven systems to biotic-driven systems. For example, Schlosser (1987) presented a conceptual framework for fish communities in small warmwater streams that represented this continuum integration of ideas. He found small headwater streams to be primarily driven by variable abiotic factors of stream flow and temperature. The smaller, shallower headwater streams exhibited low habitat heterogeneity, were generally shallow, and were thermally more variable than downstream reaches. Headwater fishes were represented by species with smaller body sizes, shorter life spans, and earlier ages of sexual maturity (Schlosser 1987; 1990). Downstream reaches with greater flow volume were more thermally stable, had higher habitat diversity and had fishes that exhibited larger body sizes, longer life spans, and later ages of sexual maturity. The more environmentally stable downstream reaches subsequently permitted biotic interactions, such as predation to become more important in determining community structure (Schlosser 1987; Schlosser and Angermeier 1990). Similar stability-instability gradients in Minnesota likely exist from upstream headwaters to downstream rivers and possibly from northeast to southwest for streamflow.

Spatial and temporal influences on stream fish communities

Most streams arise from small headwater drainages, and increase in size, discharge, and related physical and biological parameters (e.g., habitat, cover, biological productivity). There is a general pattern of a progressive increase in the number of fish species as stream size and complexity increases. This longitudinal zonation of fishes can be influenced or changed by springs, sources of pollution and sedimentation, and other disruptions in connectivity (dams, natural barriers). Stream ecologists refer to this spatial distribution pattern in terms of a "continuum," or in some cases "zonation."

Communities will occur in specific areas over a short time. In stream environments, communities can vary by microhabitat, e.g., pool-riffle complexes in small streams. Various life-stages of stream fishes require different habitats, resulting in movement related to seasonal habitat requirement, spawning requirements, and food and space requirements. Spatial limits based on physical boundaries are less evident in larger streams and rivers. These fish communities can fluctuate from year to year in both species present and abundance; nevertheless, one can return to an area year after year and collect essentially the same fish species in the same relative numbers, barring major anthropomorphic-induced changes (Matthews 1998).

Hydrologic impacts on fish communities

Fish communities in streams can often fluctuate from stable to unstable, with stability directly related to stream physical equilibrium (Schlosser 1990). Changes in hydrology, sedimentation, and resulting channel and habitat changes induce instability that can directly impact fish populations.

Effects of extreme events on fish communities are separable according to species, life stage, and recovery period (Hickey and Salas 1995). Numerous studies have concluded that juvenile life stages are particularly susceptible to heavy losses during extreme floods in high-gradient systems (Elwood and Waters 1969; Hoopes 1975; Jowett and Richardson 1989).

Watersheds and stream fish communities

Fish distribution can vary from microhabitat to stream to watershed. Because landscapes impact stream hydrology, fish habitat, and biological productivity, biologists and managers increasingly are moving to a more "lateral" view of stream management, including the riparian corridor, floodplain, and basin uplands. Factors limiting stability and abundance of fish populations often lie outside the immediate stream channel, and present long-term challenges to resource managers on a larger scale. Hence, the increase in interest in watershed management and restoration (see Williams et al. 1997 for a review of watershed restoration principles and case studies).

Local fish communities are influenced by physical or ecosystem factors within individual drainages or stream reaches. Fish community structure can be related to drainage area, site-specific dimensions (e.g., width, habitat volume, discharge, and depth), habitat heterogeneity, stream physical structure, biotic productivity, longitudinal patterns in streams (Matthews and Robison 1998; Peterson and Rabeni 2001), and the landscape surrounding the water (Osborne and Wiley 1992; Wang et al. 2003). There is a general positive relationship between stream size (order) and fish species richness, which also corresponds to size of drainage area (Vannote et al. 1980; Paller 1994; Fairchild et al. 1998).

Dams and other physical structures impacting flow regime, habitat diversity, and fish migration can cause shifts in fish communities from habitat specialists to habitat generalists (Aadland et al. 2005).

Stream fish cover and habitat

Fishes in streams use actual physical structures such as rock, submerged wood, macrophytes, and algae as shelter from currents and predators, as foraging sites, and as spawning sites. Overhead cover, such as undercut banks, overhanging vegetation, and submerged logs across channels provide hiding cover from predators. The amount of instream habitat can limit the abundance of fish. "Habitat heterogeneity," or the variety of habitat types within a locale is also important, but more difficult to quantify.

Large woody debris in many streams comprises important sources of primary and secondary production (Benke et al. 1984), as well as physical habitat for fishes. Floods can also increase the rate of input of woody debris, uprooting riparian trees or undercutting banks. Lodging of these trees and the resulting scour provide habitat for many organisms including fish. Conversely, frequent flooding can also dislodge large woody debris and remove it from the channel and onto the floodplain, causing habitat loss.

Invasive Species

Invasive species can cause several harmful effects to aquatic systems. They have been implicated as a contributing factor in the decline of large river fishes across the Americas (Hughes et al. 2005) as well as up to 70% of fishes listed as threatened or endangered by the United States government (Li and Moyle 1999). Specific effects vary depending on the species and environmental situation. Of the five components of river systems, aquatic invasive species most often influence biology, as expected. Most common impacts of invasive species on native fauna include: direct predation, competition, as disease vectors, and hybridization (Li and Moyle 1999). Occasionally, invasive species can influence other riverine components such as water quality or geomorphology and fish habitat. For example, metabolic requirements of large populations of zebra mussels *Dreissena polymorpha* can substantially deplete oxygen levels in aquatic systems (e.g., Effler et al. 1998). Alternatively, dense beds of invasive aquatic plants such as Eurasian watermilfoil *Myriophyllum spicatum* and curly-leaf pondweed *Potamogeton crispus* may occasionally provide important cover for small fishes (Valley et al. 2004).

Two ecological models have been proposed to help evaluate the degree of community disturbance an invasive species might elicit: the niche concept and the concept of limiting similarity (Li and Moyle 1999). The niche concept is frequently interpreted, often incorrectly, as a space that is currently open or vacant, which the invasive species enters and exploits. There are likely very few truly "open" niches present in an aquatic ecosystem. A better interpretation is that native species currently inhabit realized niches which are subsets of fundamental niches (*sensu* Hutchinson 1958). Thus, an invasive species may further compress the realized niche of the native species, even if it doesn't have an open niche to inhabit. The concept of limiting similarity suggests that as more and more species enter an ecosystem, they must continually partition the available resources and consequently continually compress their realized niches until no more new species can inhabit the system. At some point, highly diverse assemblages do not have any additional space to allow the invasive species. Thus, diverse native assemblages are resistant to invasion. However, there are likely very few wholly undisturbed ecosystems with a diverse native fauna that can resist invasion. Rather, most aquatic systems represent highly altered environments that have resulted in the loss of certain species, or at least decreased abundances of some native taxa. Thus, the most disturbed ecosystems are often able to support the greatest abundances of invading species.

The MNDNR defines invasive species as any species that are not native to Minnesota AND that cause economic or environmental harm or harm to human health. Both terrestrial and aquatic invasive species are present in Minnesota. For aquatic invasive species, the MNDNR maintains a published list of waterbodies designated as infested by one or more taxa. As of 2012, this list includes the following:

Fishes-
- bighead carp *Hypophthalmichthys nobilis* (22 waterbodies)
- silver carp *Hypophthalmichthys molitrix* (22)
- round goby *Neogobius melanostomus* (1)
- ruffe *Gymnocephalus cernuus* (1),
- white perch *Morone americana* (1)

Invertebrates-
- faucet snail *Bithynia tentaculata* (16)
- New Zealand mudsnail *Potamopyrgus antipodarum* (1)
- spiny water flea *Bythotrephes longimanus* (28)
- zebra mussel *Dreissena polymorpha* (108)

Plants-
- Brazilian elodea *Egeria densa* (1)
- brittle naiad *Najas minor* (2)
- Eurasian watermilfoil (at least 250)
- flowering rush *Butomus umbellatus* (19)

Other-
- Viral hemorrhagic septicemia (VHS) (1)

Specific identification and management options for terrestrial and aquatic invasive taxa are beyond the scope of this chapter but interested resource managers should begin by consulting the MNDNR webpage for additional guidance. For invasive fishes, fisheries managers are also encouraged to consult Wydoski and Wiley (1999), and for bighead and silver carp Kolar et al. (2007).

Photo by Rick Nelson

Chapter 5. Connectivity

"When we try to pick out anything by itself, we find it hitched to everything else in the Universe."

—John Muir, July 27, 1867

"…The one thing that I've learned, or the main thing that I learned in my 40 years as a resource manager is that everything is connected. In order to have good fishing, in order to have clean water you have to have good management of watersheds; you have to have conditions on the watershed that will help maintain the food pyramid, that will help maintain the natural biota."

—Jack Skrypeck, Healthy Rivers: A Water Course, MNDNR (2004)

Introduction

Connectivity of a river system refers to the flow, exchange, and pathways that move organisms, energy, and matter through these systems. These pathways are not always linear. The interrelated components of watershed, hydrology, biology, geomorphology, and water quality, together with climate, determine the flow and distribution of energy and material in river ecosystems. Complexity and interdependence is the hallmark of connectivity. The interaction of primary factors (i.e., water, energy, and matter) creates an extensive physical environment that varies over time. The resulting habitat may be modified by the activities of animals that selectively eat vegetation; burrow, trample, and wallow in soils; and build dams (Naiman and Rogers 1997).

Four Dimensions of Connectivity

As with hydrology, river system connectivity is manifested along four dimensions: longitudinal, lateral, vertical, and time (Ward 1989; **Figure 5-1**). Lateral connectivity is critical to the functioning of large floodplain river ecosystems. Nutrients and organic matter transported from the floodplain to the river encourage the development of aquatic plants, plankton, and benthic invertebrates, and, in turn, provide a rich food source for fish (Junk et al. 1989). Seasonal flooding also brings nutrients and organic matter from terrestrial areas to the river, enriching the river and benefitting the aquatic communities. Bankside vegetation provides habitat and acts as a regulator of water temperature, light, seepage, erosion, and nutrient transfer. Isolation of the main river from its alluvial plain, eliminating access to backwaters, floodplain, lakes, and wetlands, has had a major effect on both the ecological diversity of the highly productive alluvial corridor and riverine fish populations (Petts 1989). The river corridor is especially important for birds and mammals in high-latitude watersheds (Nilsson and Dynesius 1994) and in arid lands (Brown et al. 1977). The seasonal flooding of an unregulated river maintains a variety of successional vegetation stages, thus creating excellent conditions for an

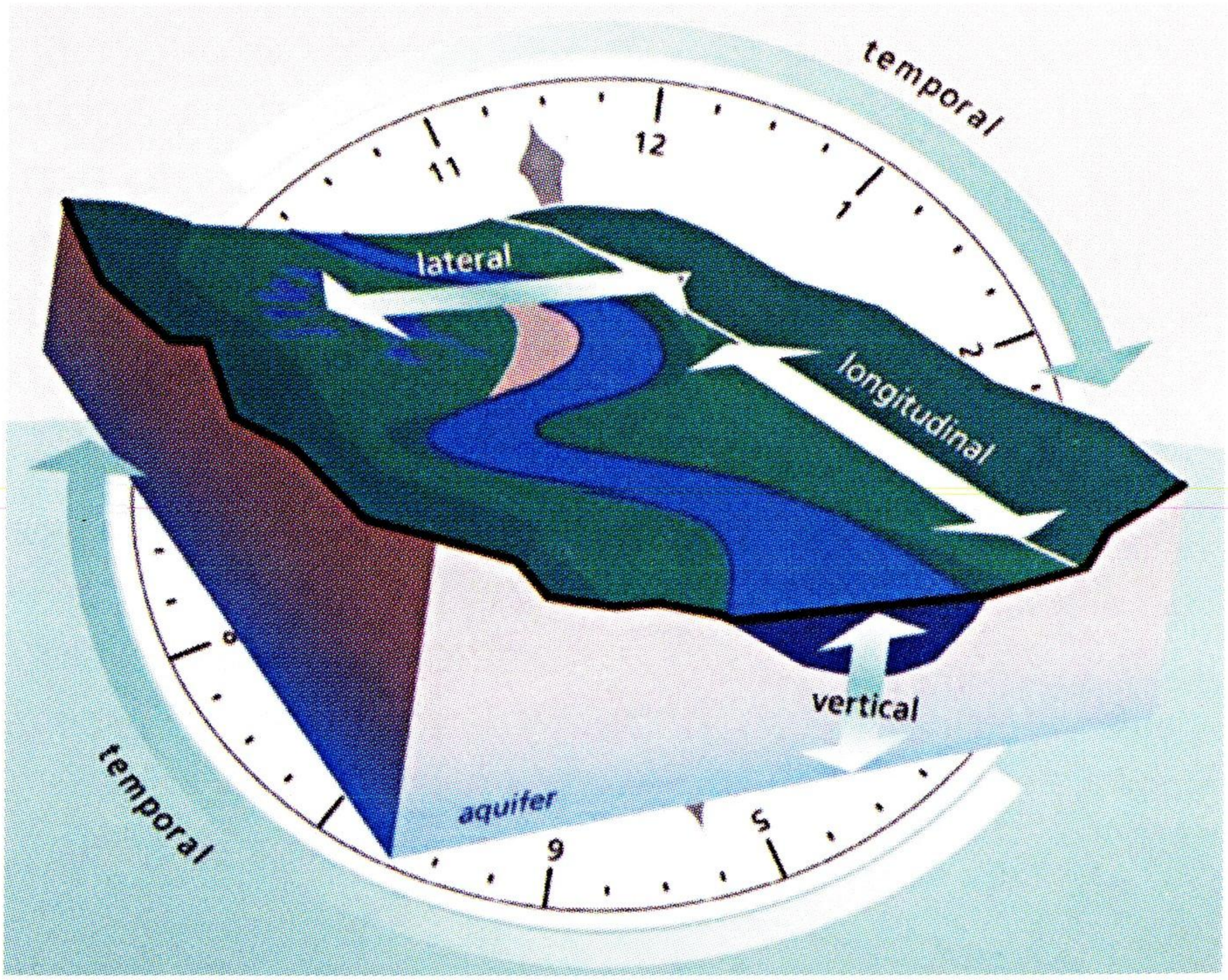


FIGURE 5-1. Rivers are connected in four dimensions – longitudinally from headwaters to their mouth, laterally from channel to floodplain and valley, vertically from their bed to the groundwater, and through time. Rivers are shaped and characterized by movements of water through the longitudinal, lateral, and vertical dimensions, which transfer materials, energy, and organisms. The time dimension (duration and rate of change) is also a critically important consideration in establishing instream flow prescriptions because of the dynamic nature of the riverine components (from Ward 1989).

abundant and diverse wildlife community (Nilsson and Dynesius 1994). Flooding also creates and maintains diverse species of vegetation (Nilsson et al. 1989), which in turn favors animal diversity.

Assessing Connectivity on Streams

When developing river management prescriptions, practitioners must account for the presence of physical, chemical, and even biological barriers to connectivity. Examples include an assessment of dams, including their position in the watershed; dam operation (hydrology); effects on water quality (e.g., DO, mercury methylization); sediment and thermal regimes; natural history of fishes in the area; and effect on aquatic communities (i.e., lacustrine or exotic species, predator concentrations), including their position in the watershed; dam operation (hydrology); effects on water quality (e.g., DO, mercury methylization); sediment and thermal regimes; natural history of fishes in the area; disruption including physical (e.g., dams), biological (e.g., exotic species introductions or extinction of native biota), hydrological (e.g., dewatering of aquifers), and water quality (e.g., endocrine disruption, thermal, chemical, or sediment pollution). Vaughan (2002) suggested that culverts and other barriers in stream channels can have negative effects on the upstream movement of some invertebrates.

Although not as well studied as longitudinal connectivity, examinations of vertical connectivity have led to remarkable observations documenting the extensive biomass of riverine invertebrates living within the hyporheic zone. Stanford and Ward (1988) found stoneflies in 10-m deep wells in the floodplain of the Flathead River, Montana, as far as 2 km from the river channel and concluded that the biomass in the hyporheic zone may exceed the benthic biomass of the river.

Nutrient Cycling and Energy Pathways

River corridors are linear systems, at least in part, in which a gradient of physical, chemical, and biological change occurs from source to mouth. The River Continuum Concept (RCC) described biotic adjustments and organic matter processing along a river's length in response to the downstream gradient of physical conditions. Food relations usually play a large role in determining the structure and function of stream communities. Disruption of the physical and hydrologic connectivity will change the biological structure (Vannote et al. 1980; **Figure 5-2**).

Continuity of upstream and downstream reaches is a critical aspect of the river system. Nutrient spiraling (i.e., the downstream transport of organic matter and its coincident cycling—uptake, use, and release—by the instream biota) is the mechanism of energy transfer in headwater streams (Elwood et al. 1983). A stream and its watershed are critically linked (Hynes 1975; Likens et al. 1977); stream invertebrates are key components in the energy cycling dynamics of stream systems, directly breaking down terrestrial plant inputs or linking the processing of primary producers to higher trophic levels. Invertebrate consumers are important in regulating energy flow and nutrient cycling in stream ecosystems (see Brock 1967; Wallace et al. 1977; Elwood et al. 1983). The rate of spiraling and cycling nutrients and organic matter is influenced by the interaction of flow and channel form. Thus, physical retention of terrestrial inputs and macroinvertebrate processing are important mechanisms, along with microbial action,

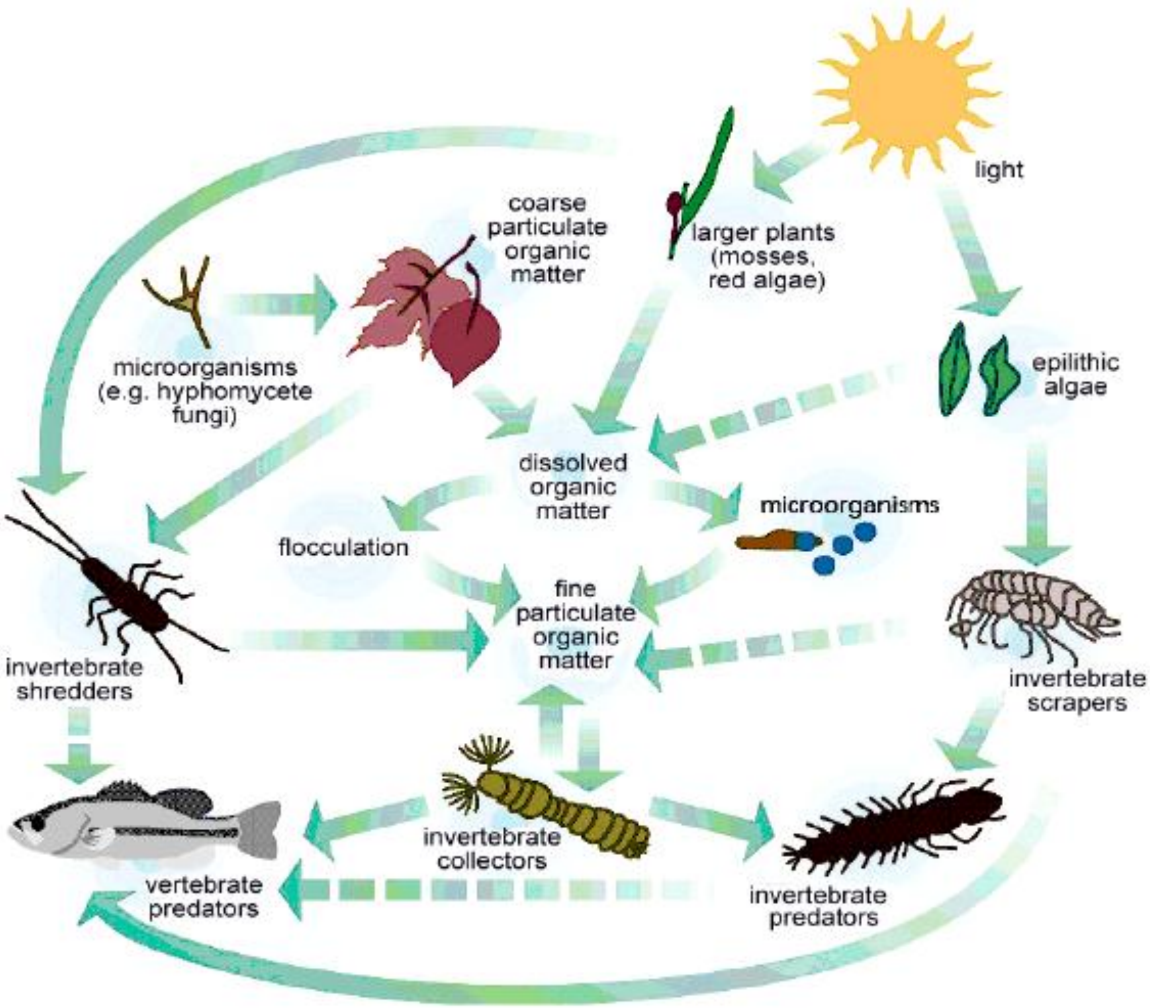


FIGURE 5-2. Energy transfer in river systems can be very complex. Interactions between one level can affect the energy amount and type available for subsequent levels, thereby influencing trophic level competition and, ultimately, the species composition of aquatic communities (Source: Federal Interagency Stream Restoration Working Group 1998).

for closing or tightening the recycling process in streams and preventing the rapid throughput of materials (Minshall et al. 1985). In essence, the diversity and productivity of lower trophic levels (i.e., microbial and invertebrate populations and productivity) determine the diversity and productivity of higher trophic levels along the stream gradient. Fish species are particularly sensitive to discontinuity in bio-energetic processes associated with changes in the thermal regime below dams.

The concept of serial discontinuity explains the effect of dams, which displace aquatic communities along the river continuum (Ward and Stanford 1983; **Figure 5-3**). Modifying thermal and flow regimes by impoundment were considered to be "major disruptions of continuum processes." Changes in flow regime, water temperature, oxygen, turbidity, and the quality and quantity of food particles in the river downstream of impoundments shift the upstream-downstream patterns of biotic structure and function predicted by the RCC. The serial discontinuity concept predicts the way dams shift the expected continuum. The reach immediately downstream of the dam may be reset as measured by 16 variables, including the ratio of coarse particulate to fine particulate organic matter, relation of substrate size to biodiversity, and environmental heterogeneity. A dam may result in some conditions being more like those of the headwaters (an upstream shift), while other conditions become more like those of downstream segments (a downstream shift; Ward and Stanford 1983). Other characteristics may not fit either paradigm (Annear and Neuhold 1983). Moreover, dams and reservoirs create lentic environments where production is based on plankton rather than the benthic algae and allochthonous material on which lotic production is usually based. When reservoir water is released to a stream, it carries with it the plankton that would otherwise be scarce in streams. The stream management practitioner must consider these potential changes and document the rationale used to arrive at decisions pertaining to quantification of instream flow needs.

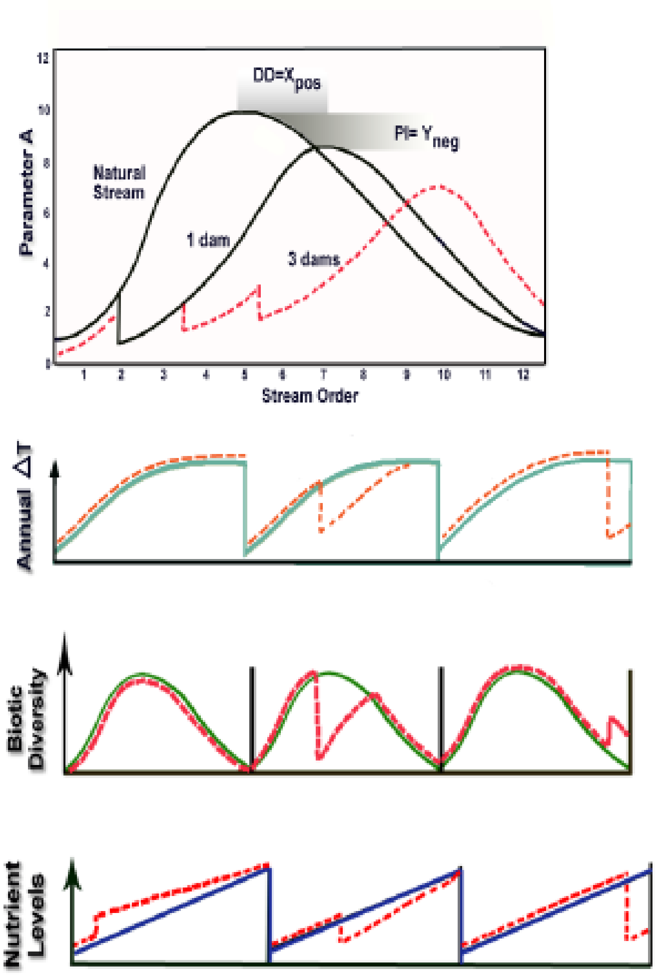


FIGURE 5-3. Theoretical framework for conceptualizing the impact of dams on selected ecological parameters. The relative influence of one and three dams is shown in the upper graph. Discontinuity distance (DD) is the positive downstream or negative upstream shift of a parameter a given distance (X) due to stream regulation. The change in parameter intensity (PI) is also defined. The relative changes in three of many potentially affected parameters as a function of stream order and postulated effects of locating a dam at different points on the continuum are shown in the lower three graphs (From Ward and Stanford 1983).

Riverine connectivity is inextricably linked to hydrology and operates on several scales. For example, each watershed has a drainage network that is related to its shape, geology, geographic position, and climate. Drainage density and pattern are used to describe the drainage network and have been related to flood flows. According to laboratory studies on watershed models, drainage pattern (e.g., dendritic, trellis, radial, palmate) is more important than drainage density in influencing peak flows and lag times (Black 1972). Intensifying the drainage network, through tiling, channelization, and wetland draining, modifies the natural hydrograph and results in several potential costs, including channel instability, increased bank erosion, bed degradation or aggradation, and simplification or modification of riparian or instream biota (Dunne and Leopold 1978). Urbanization and creation of impervious surfaces (watershed hardening) have similar effects **(Figure 5-4)**.

Although riverine food webs are highly sensitive to the natural history attributes of the biota, discharge is the "master variable" that limits and resets river populations through entire drainage networks (Power et al. 1995; **Figure 5-5**). Trophic pathways on floodplains of southeastern rivers consist of dry and wet systems (Wharton et al. 1982). Flows can affect migration of fishes from lake or ocean into streams; these migratory fishes redistribute nutrients and energy in the course of their migrations. Ponding (i.e., the creation of natural or artificial pools) can change the aquatic ecosystem from an allochthonous-based food chain to an autochthonous-based food chain; the relation between flow and pond volume can influence where on the allochthonous-autochthonous continuum the system will be. Flows can affect the transport of terrestrial nutrients into a channel or stream nutrients into the floodplain.

In examining a stream in eastern Canada, Halyk and Balon (1983) concluded that the growth rate of some species of young fish that were spawned in the stream is controlled by the duration of the stream's connection to the floodplain. Oxbow lakes can be very productive fish habitats, supporting high densities of species that are highly sought after by humans (Lambou 1959; Beecher et al. 1973). On the Danube River floodplain, fish yield per-unit-area increased substantially from short inundation to long (half-year) inundation (Stankovic and Jankovic 1971). Fishes were also shown to move onto the floodplain in a North Carolina Stream (Walker 1980).

Fragmentation and its Effects on Fish Movement

Fragmentation of river systems by dams is pervasive and affects 77% of the total water discharge in the northern third of the world (Dynesius and Nilsson 1994). Introduction of barriers, especially to migrant spawning fishes, has had a widespread impact that is not solely confined to the large dams of the mid-1900s. The most visible effects are those occurring to salmon production as a result of the damming of the river systems in the Pacific Northwest (Goldman and Horne 1983). Atlantic salmon (*Salmo salar*) disappeared from the Dordogne River, France, soon after the first dams were built on the lower reaches between 1842 and

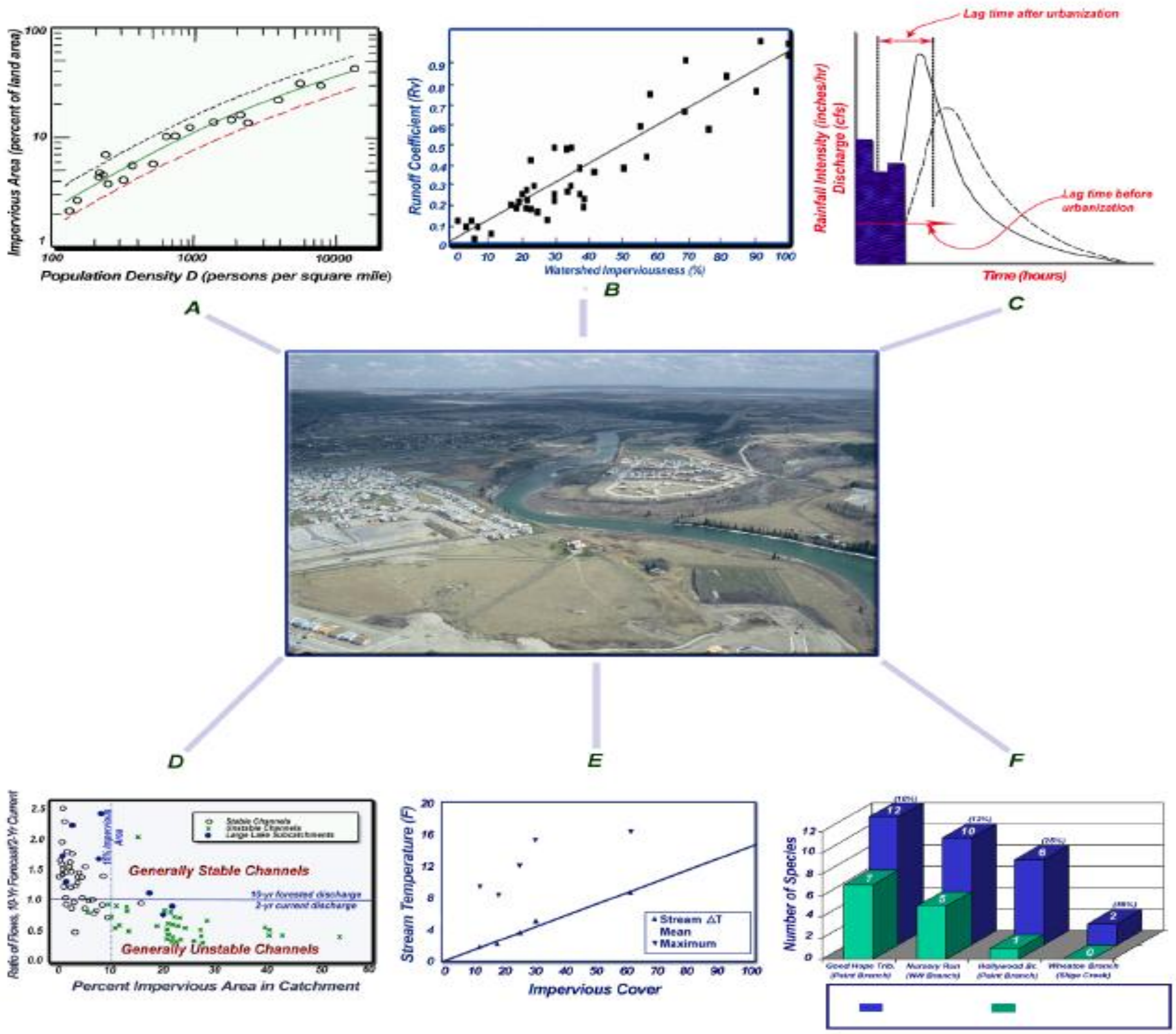


FIGURE 5-4. Impervious areas associated with urban communities—as shown in this photo of Cochrane, Alberta—are powerful influences on stream ecosystems. Increases in human population are likely to result in increases in the impervious area (A). As the percent of impervious area in a watershed increases, the amount of runoff increases (B), and changes in runoff amount and pattern will often change the shape of the hydrograph (C). Channel stability is also inversely related to the percent of impervious area in the watershed (D). The physical effect of an increase in impervious area can also affect water quality and biological processes. Percent of impervious area has been shown to increase stream temperatures (E), and was found to be inversely related to fish diversity (F), presumably as a result of the changes in the hydrograph (e.g., increased runoff and disassociation of peak flows with temperature cues), alteration of channel stability (and increases in channel sediment), and increases in stream temperature (Source: Figures A and B from Stankowski 1972; figure C from Leopold 1968; figure D from Booth et al. 2003; figure E from Galli 1990; figure F from Schueler and Galli 1992. Photograph courtesy of Lorne Fitch, Alberta Sustainable Resource Development, Fish and Wildlife Division).

FIGURE 5-5. Stream management should address the entire range of flows that the watershed provides to the river. The Yellow Medicine River, southwestern Minnesota, is shown at four flow levels: 5,390 cfs (*upper left*) constitutes a flood flow for this river and forms the channel and floodplain, providing floodplain habitat (visible in the foreground of the picture); 292 cfs (*upper right*) is a typical spring flow and provides good spawning habitat for walleye (*Sander vitreus)* and other riffle spawners; 112 cfs (*lower left*) provides sufficient flow for all types of fish habitat (fast and slow riffles, runs, and deep, medium, and shallow pools) as measured through Physical Habitat Simulation study; and 2 cfs (*lower right*) characterizes severe drought conditions in a channel dominated by shallow pool habitat, which provides diminished habitat area and low habitat diversity. Under high water demand, setting “minimum flow” protection levels at 2 cfs would fail to address the functions and processes that accompany the higher flow levels and would lead to degradation of the river system (Source: Luther Aadland, Stream Habitat Program, Ecological Services Division, Minnesota Department of Natural Resources).

1904 (Decamps et al. 1979). Delayed up- and downstream migrations related to fish movement through reservoirs can adversely affect the survival and reproduction of migratory species. This observation seems valid irrespective of dam height (Raymond 1979). Aadland et al. (2005) document the loss of lake sturgeon *Acipenser fulvescens* from the Red River of the North basin, a 287,000 km^2 area of the upper Midwestern United States and south-central Canada. In addition to overfishing, over 500 dams blocked access to critical spawning habitat in the basin starting in the late 1800s; during the mid-1900's, many of the tributaries were channelized, resulting in loss of several thousand stream kilometers. Additional localized extirpations of channel catfish *Ictalurus punctatus*, several redhorse *Moxostoma* species, sauger *Sander canadensis*, and other migratory fishes have occurred upstream of dams on several tributaries. While dam removal is the preferred alternative, fishways (**Figure 5-6**) can help mitigate fish migration disconnectivity.

Disconnections Caused by Changes in Water Quality

There is increasing concern about the effects of chemicals in our environment and on the endocrine systems of fishes, wildlife, and humans (Folmar et al. 1996; Harries et al. 1996; Jobling et al. 1998; Colborn and Thayer 2000). At least 45 chemicals have been identified as potential endocrine-disrupting contaminants (Colborn et al. 1993). The chemicals in question—including pesticides, PCB's, plasticizers, and petrochemicals—have been known to cause sex changes in fish. Decreased fertility (fewer gametes), hatchability, viability (less robust gametes), altered sex ratios in gametes, and altered sexual development and behavior are among the reproductive injuries reported to date (Colborn and Clement 1992). The endocrine disruptors enter rivers concentrated in point-source discharges or more diffusely in nonpoint source runoff (Harries et al. 1996).

Temporal discontinuity may also be occurring between generations of fishes. For example, fish affected by endocrine disruption from organic contaminants may be unable to interact with older fishes that are not affected. Downstream of large cities, sewage treatment effluent containing detergent metabolites (i.e., nonylphenols and surfactants), alkylphenols ethoxylates (APE's), and human estrogen and birth control pills (17a-ethynylestradiol) have been implicated in endrocrine disruption in fishes (Purdom et al. 1994; Jobling et al. 1998; Barber et al. 2000). Biomarkers, like the protein vitellogenin (a precursor protein of egg yolk normally in the blood or hemolymph of female fishes), are being used to determine if fishes (male and female) are affected by water quality changes traceable to endocrine disruptors such as steroid hormones, 17B-estradiol-female, and 11-ketotesterone. The use of these and other biomarkers of potential endocrine disruption will be important for detecting and monitoring adverse effects of environmental contaminants on aquatic organisms (Goodbred et al. 1997).

The tie between contaminant levels, the occurrence of endocrine disruption, and water discharge has important implications for river managers, particularly those who work on river systems with large municipal

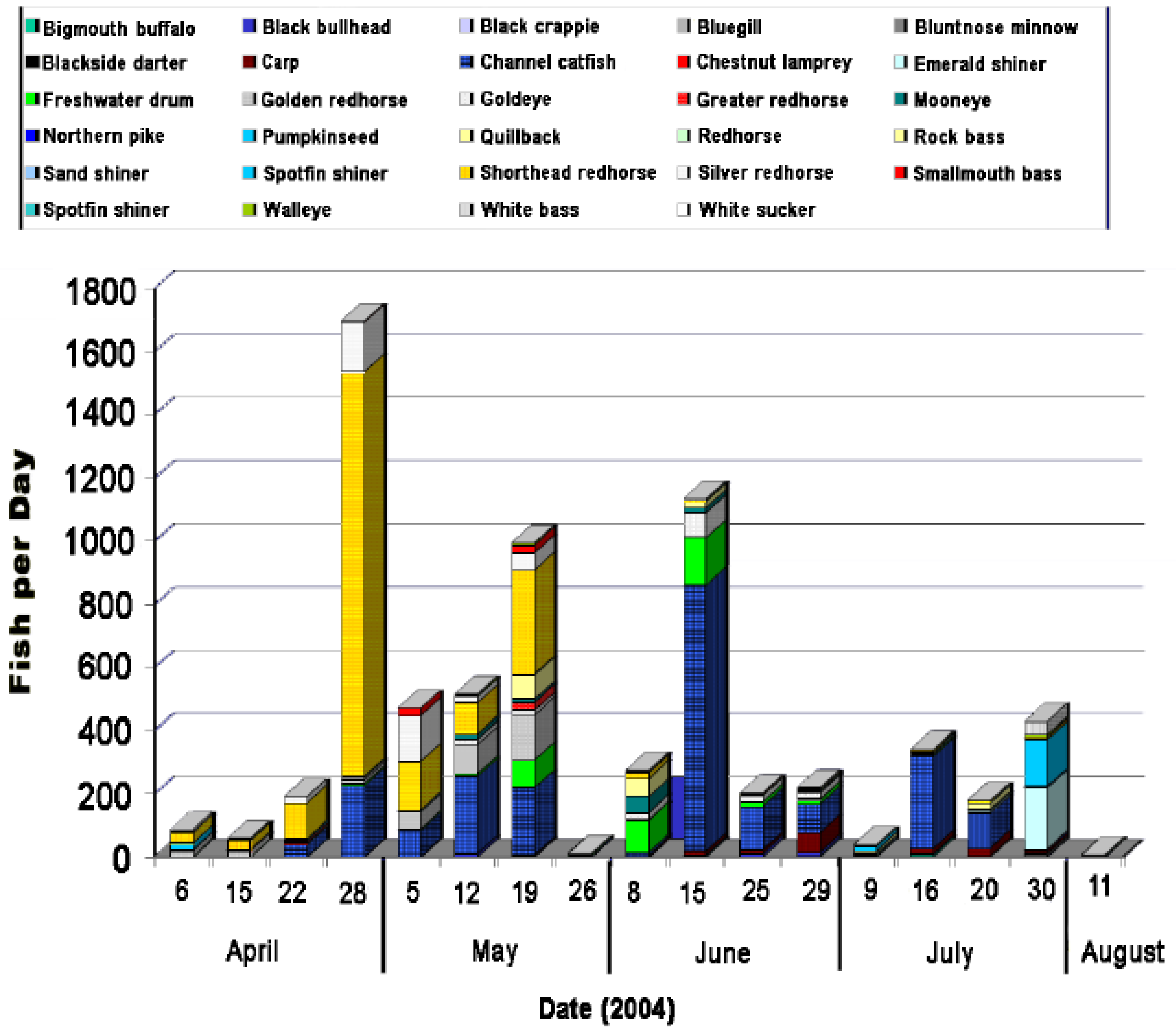


FIGURE 5-6. Construction of a fishway at the Breckenridge dam on the Ottertail River (Red River drainage basin, Minnesota) documented fish passage of 28 species of fish from April to August 2004. Significant temporal variation in migration patterns by species were also seen (Source: Luther Aadland, MNDNR, unpublished data).

wastewater treatment facilities. Organic contaminants released from treated municipal wastewater systems may effectively disconnect different segments of the river system spatially by segregating populations according to water quality and the physiological health of the aquatic community. Dilution of treated sewage effluent through increases in discharge has been offered as an explanation for a reduced effect of exogenous estrogens on trout held in cages at increasing distances below the plant outflow (Harries et al. 1996). Still the problem is likely to be widespread: reconnaissance assessment of carp from U.S. streams indicates that fish in some streams within all regions studied may be experiencing some degree of endocrine disruption (Goodbred et al. 1997).

The degree of dilution and disconnectivity is a function of flow. Increasing flows to provide dilution can transport pollutants downstream and ultimately lead to deposition and impacts elsewhere. Practitioners must realize that flow recommendations for water quality that traditionally focused on assimilation of sewage, now must also account for the presence of estrogenic chemicals. Because these chemicals are very persistent, their removal is not accomplished solely by increased flow and is unlikely to occur for some time. Prescriptions must be made in the context of what is currently possible. Because national standards for endocrine-disrupting chemicals are not currently in place, the practitioner is relegated to considering dilution as the only available solution. Still, walking away from a problem after prescribing a flow regime does not ensure successful natural resource management; in fact, it may lead to failure to fulfill public stewardship responsibilities if the other elements are ignored.

Considering Connectivity and Invasive Species

Despite the many stated reasons why maintaining connectivity is beneficial for aquatic systems, managers sometimes choose to erect barriers to prevent invasive species from having access to portions of a watershed. This is done in situations where the undesirable impacts of invasive species are considered greater than the impacts to native species and the broader aquatic habitat, from a loss of connectivity. Examples include barriers to prevent migration of common carp into shallow lakes, to exclude brown trout from streams being managed for brook trout, or to prevent Asian carp from expanding their range in Minnesota. Managers must assess the tradeoffs of interrupting connectivity when considering invasive species barriers. There may be situations where they are beneficial and justified, while at other times the impacts to native species from a loss of connectivity may be worse than those caused by the invasive species. The detail of such an assessment will vary depending on the potential for impact on native species or aquatic habitat.

Communication with the public regarding invasive species and connectivity is critical. Misunderstandings may arise when barriers are constructed in some places to benefit native species, but removed in other situations. Because of the high-profile status of some invasive species such as Asian carp, this issue is likely to come up with almost any fish passage project.

Editor's note*: The majority of the preceding section, 'Connectivity' was excerpted with permission from "Annear, T., I. Chisholm, H. Beecher, A. Locke, and 12 other authors. 2004. Instream flows for riverine resource stewardship, revised edition. Instream Flow Council, Cheyenne, Wyoming." Some editorial changes were made to focus on upper midwestern streams.*

Chapter 6. Considerations for Sampling Minnesota Streams

"Facts are facts and cannot be denied by any rational being. Facts, however, may also be highly scale dependent—and the perceptions of one world may have no validity or expression in the domain of another.

—Stephen J. Gould, The Lying Stones of Marrakech (2001), p. 355

Introduction

The five riverine components (hydrology, geomorphology, water quality, biological communities, and connectivity) help resource managers address the whole ecosystem when making stream management prescriptions. Assessment methods and sampling designs must be matched to appropriate spatial and temporal scales in order to meet survey objectives, and develop and evaluate management plans.

Spatial Scales

A management or study reach is that part of a stream system where stream surveys and management occurs. It is the point of reference for geographic scale discussion. Spatial scales range from global to micro. River scale is a nested hierarchy; the smaller spatial scales, including micro-, meso-, and macrohabitats, are nested within larger landscape features, such as reach, stream segment, watershed basin, and major drainage. The relative importance of controlling factors changes with the spatial scale, as does a manager's ability to influence those factors uniquely; however, to be effective, managers must be aware of regional and global trends **(Figure 6-1)**.

Global scale

For migratory fishes—such as white sturgeon (*Acipenser transmontana*), American eel (*Anguilla rostrata*), American shad (*Alosa sapidissima*), chinook salmon (*Oncorhynchus tshawytscha*), and many others, including those with less extensive migration areas—a spatial scale larger than the watershed should be considered. Fish species previously considered relatively sedentary (e.g., nonanadromous stream salmonids, cyprinids) have been shown to move more than previously thought (Crook 2004). Even fishes that spend their entire lives in a single pool can in some way be affected by global changes. Hydrology, water temperature, and aquatic ecosystem functions can all be influenced by climate change (Jager et al. 1999). For example, Kling et. al (2003) project global climate changes will impact the Great Lakes Region substantially within the next century. A warmer, drier climate will impact hydrology by causing earlier ice-out dates, low water levels, diminished groundwater recharge, and more frequent flooding due to land use changes and increases in heavy rainfalls. River water temperatures are projected to increase, while the amount of habitat available to aquatic organisms is projected to diminish due to the shrinking of aquatic refugia in streams and wetlands. Distribution of fishes is likely to change with

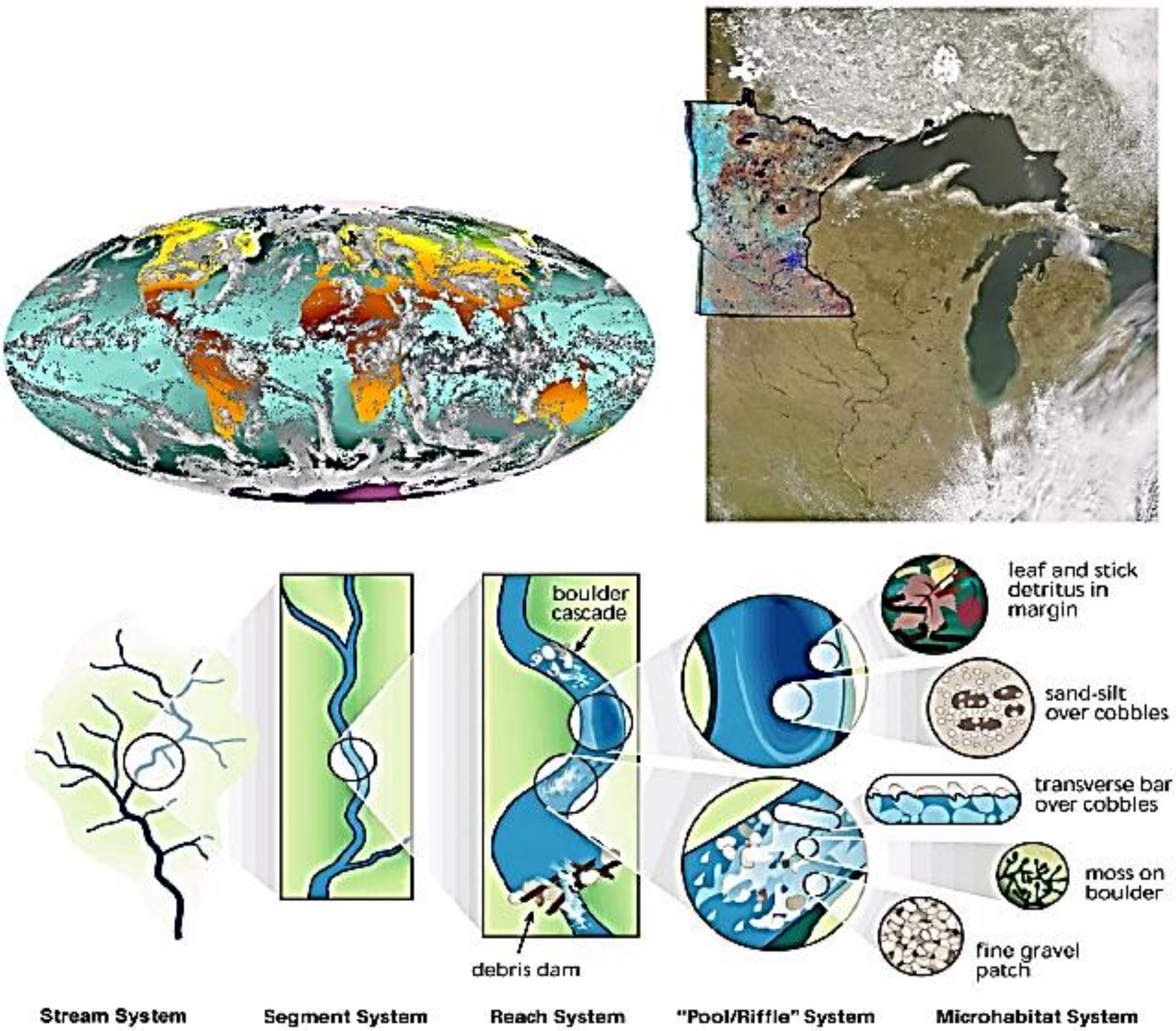


FIGURE 6-1. River system scale is a nested hierarchy; the smaller spatial scales are nested within larger landscape features, such as reach, stream segment, region and, ultimately, the globe (Adapted from Frissell et al. 1986).

the northward expansion of cool and warmwater species, while coldwater species' northern distribution limits will retreat. Localized populations of stream salmonids may shrink or be lost.

For these reasons, even resource agencies that have little ability to influence global scale phenomena should consider global trends when making management decisions. Important questions to ask are whether stream management prescriptions will be adequate to meet objectives if climate changes the timing or magnitude of flows in the system, and if water will maintain an acceptable temperature if the air temperature increases.

The watershed scale

Watershed or river basin refers to a scale at which state and federal agencies have more management control. For major watersheds, it may be more practical to address issues on a sub-basin scale, because river management decisions generally influence a sub-basin scale watershed more directly and information at this scale is more easily understood. For example, the Snake River watershed in east-central Minnesota is large, encompassing 1,008 mi^2 **(Figure 6-2)**. By looking at river management issues at the subbasins scale (75 sub-basins in this case), complex management issues can be identified more easily.

Conditions of a watershed directly affect the channel form and the timing and magnitude of flow in the management reach (Hill et al. 1991). Watershed interacts with climate, topography, and geology to influence vegetation, stream channel, groundwater, and streamflow. Vegetation influences the channel through erosion and deposition patterns and rates. The effects of fire illustrate the connection of watershed, stream, and fish populations (Gresswell 1999). That connection is evident in the way that land use activities—such as urban or suburban development, road building, agriculture, and forestry—modify vegetation, erosion, and sedimentation, as well as the temporal relation between precipitation and streamflow. Watershed conditions such as migration barriers may limit movement of fish into or out of a management reach. Watersheds that contain lakes and wetlands modify hydrology and store and release water somewhat more gradually than in watersheds without lakes (Leopold 1994).

The macrohabitat scale

Geomorphologists have coined the term "hydraulic biotope" to describe the flow-dependent abiotic environment of a community or species assemblage (Wadeson and Rowntree 1998). These occur at different levels such as macro-, meso-, and microhabitat. Macrohabitat includes many reach and larger scale phenomena, primarily dealing with abiotic habitat conditions (such as channel morphology and chemical or physical properties of water) that control the longitudinal distribution of aquatic organisms. The mix of mesohabitats (see p. 85), such as the ratio of pools to riffles, is determined by macrohabitat. Macrohabitat is determined by long-term geological setting, climate interaction with geology, vegetation, and the shorter term influence of land use superimposed on the preceding processes. It includes such factors as net rate of sediment transport and type of sediments transported, as well as abundance and distribution of sediment, large woody debris, and boulders. Infrequent high flows are also a major influence on macrohabitat. Flows that form channels, floodplains, and valleys were discussed by Hill et al. (1991) and Whiting (1998).

The mesohabitat scale

Mesohabitat refers to a combination of pool and off-channel habitats within a reach (Bisson et al. 1988;Kershner and Snider1992;Hawkins et al. 1993; Vadas and Orth 1998). At least at low flows, certain

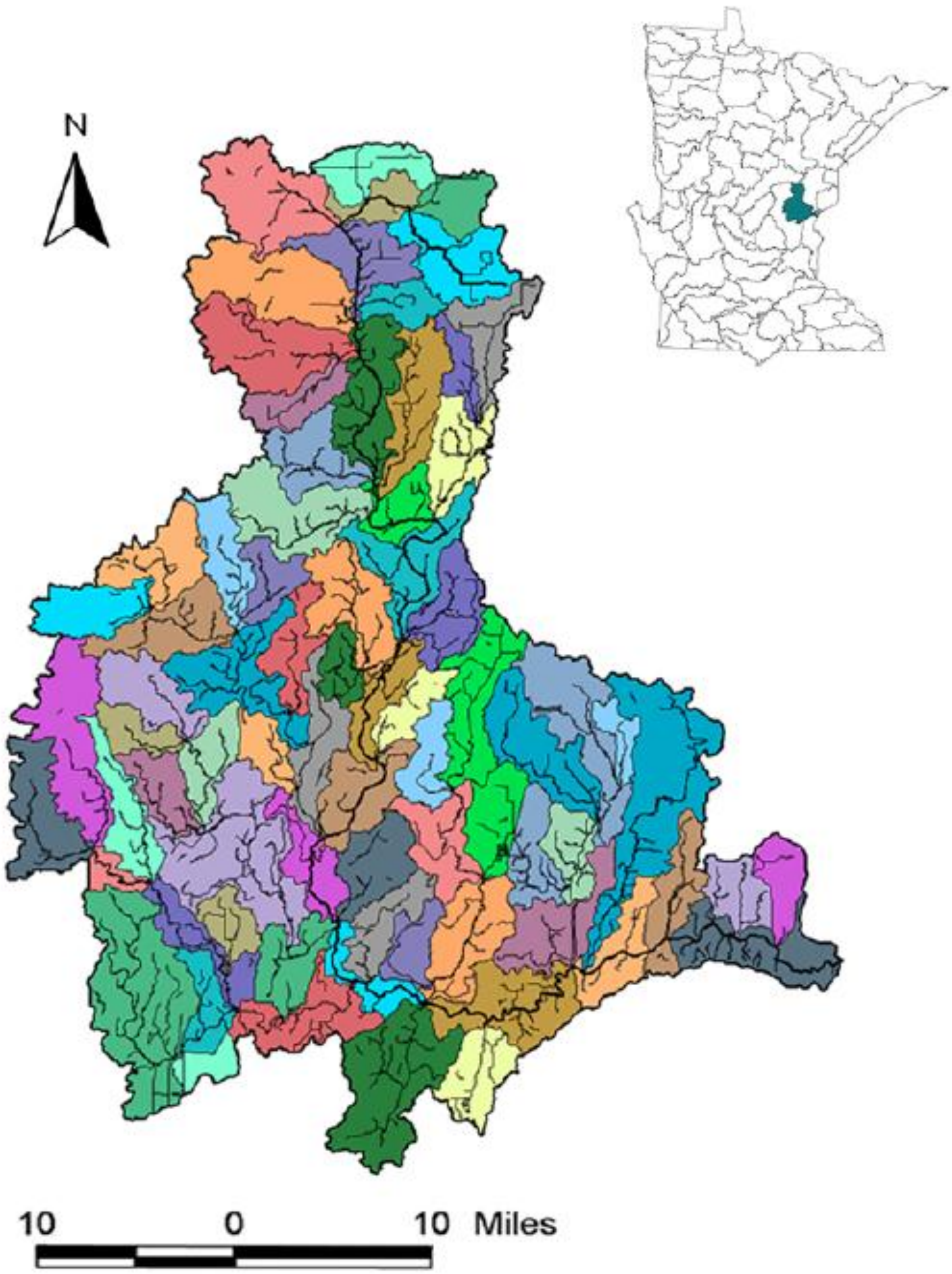


FIGURE 6-2. Managing large, complex stream systems requires data analysis and remedies at the proper scale. For example, the Snake River system in east-central Minnesota encompasses 1,008 square miles, and has been delineated into 75 subbasins.

combinations and ranges of depth and velocity are associated with different mesohabitats (Vadas and Orth 1998). Relative proportions of different mesohabitats appear to vary with flow as depth and velocity distributions change (Vadas and Orth 1998; Hildebrand et al. 1999). However, work by others (Rowntree and Wadeson 1998; Wadeson and Rowntree 1998) suggested that geomorphic-defined units do not change with discharge (when the stream and its watershed are in "dynamic equilibrium"). Certain life stages of certain fish species are associated with particular mesohabitats (Bisson et al. 1988).

The connectivity among mesohabitats is often flow-dependent. A connection among habitats at certain times is critical to the life history of some fishes. Passage through or around migration barriers—such as shallow riffles, cascades, and waterfalls—and access to the floodplain depends on flow (Smith 1973; Powers and Orsborn 1985).

The microhabitat scale

Microhabitat refers to the hydraulic features determined by the unique combination of depth, velocity, substrate, and cover at specific points in a stream (Bovee 1982). Many commonly used instream flow methods focus on the hydraulics of microhabitat. One commonly used tool is the PHABSIM component of the Instream Flow Incremental Methology (IFIM), which allows analysis of the distribution of hydraulic habitat at different flows (Bovee and Milhous 1978; Bovee 1982; Bovee et al. 1998). The microhabitat variables provide a reasonable within-reach description of hydraulic features selected and avoided by fish at different flows within a reach (Orth and Maughan 1982; Beecher et al. 1993, 1995; Shuler and Nehring 1993; Thomas and Bovee 1993; Shuler et al. 1994; Gallagher and Gard 1999).

Although PHABSIM results are useful for identifying how the hydraulic features of microhabitat vary with flow, units of microhabitat must be sufficiently large or contiguous to support the species and life stages of interest (Gallagher and Gard 1999).

Temporal Scales

Streams are dynamic systems, changing over time. Yet a fundamental problem in the development of a general model of system response to river alteration is the failure to consider changes within an appropriate time-scale (Petts 1984). When data collection and analysis take several months or even years, the channel form must be described anew if and when its geometric characteristics change significantly. Seasonal and flow-related changes impact fish community composition (Matthews and Hill 1980); variations in fish communities have even been found to vary by the time of day (Starret 1950).

The present status of a watershed reflects its history, as expressed in the volume, stratification, and slope of deposits—all of which affect the present dynamics of the channel. Moreover, as climate, discharge, and sediment change, the geomorphic characteristic of a river also changes (Amoros et al. 1987) and different components of the system respond at different rates (Petts 1987). In watersheds undisturbed by human activity, all these factors usually operate in a dynamic equilibrium. Human actions can change process rates by several orders of magnitude, disrupting the equilibrium. The minimum time required for system adjustment to a new set of conditions is dependent on those variables that require the longest time to achieve a stable structure. The relative importance of these factors changes with the spatial scale, which is inversely related to the time scale of potential persistence. Microhabitats may change daily; mesohabitats may change annually; stream reaches may change with the occurrence of landslides, log inputs or washouts, dam building, and the like; and the watershed may change through tectonic uplift, subsidence, glaciation, or climate shifts (Frissell et al. 1986; **Figure 6-3**).

Identifying Minnesota Stream Watersheds, Watercourses, and Reaches

Any stream survey and monitoring program must account for the unique identification of watersheds, streams, stream segments, and reaches. The development of future information systems will rely on unique identifiers for watersheds, stream networks, and reaches. Multiple standards and terminology in identifying and naming watersheds and watercourses have resulted in confusion. The Hydrography Committee for the Minnesota Governor's Council on Geographic Information has developed identification and naming standards for Minnesota governmental agencies to promote data integration across state lines and with national data sets (Minnesota Dept. of Admin. 2006).

Watershed identification

Minnesota has four major drainages **(Figure 6-4)**, the Mississippi River, Red River, Lake Superior, and Sioux River. Management at this scale is complex, involving five other states and the province of Ontario, Canada. River management is more feasible on a watershed level. Minnesota's 4 drainages can be further subdivided into 81 "major" watersheds (**Figure 6-4**, **Figure 6-5**).

Minnesota Statutes define watersheds most frequently in terms of the "State of Minnesota Watershed Boundaries – 1979 Mapping Project." This project by the MNDNR represented a major effort to develop official, systematic, detailed height-of-land boundary maps for all watersheds of the state. The Watershed Mapping Project identified and delineated what has become known as the 81 MNDNR Major Watersheds and approximately 5,600 MNDNR Minor Watersheds. In 1995, the MNDNR Division of Waters developed GIS coverages for the Major and Minor watersheds in Minnesota. These data were originally developed from the original U.S.G.S. 7½ Minute Quadrangles, based on 20-foot contours.

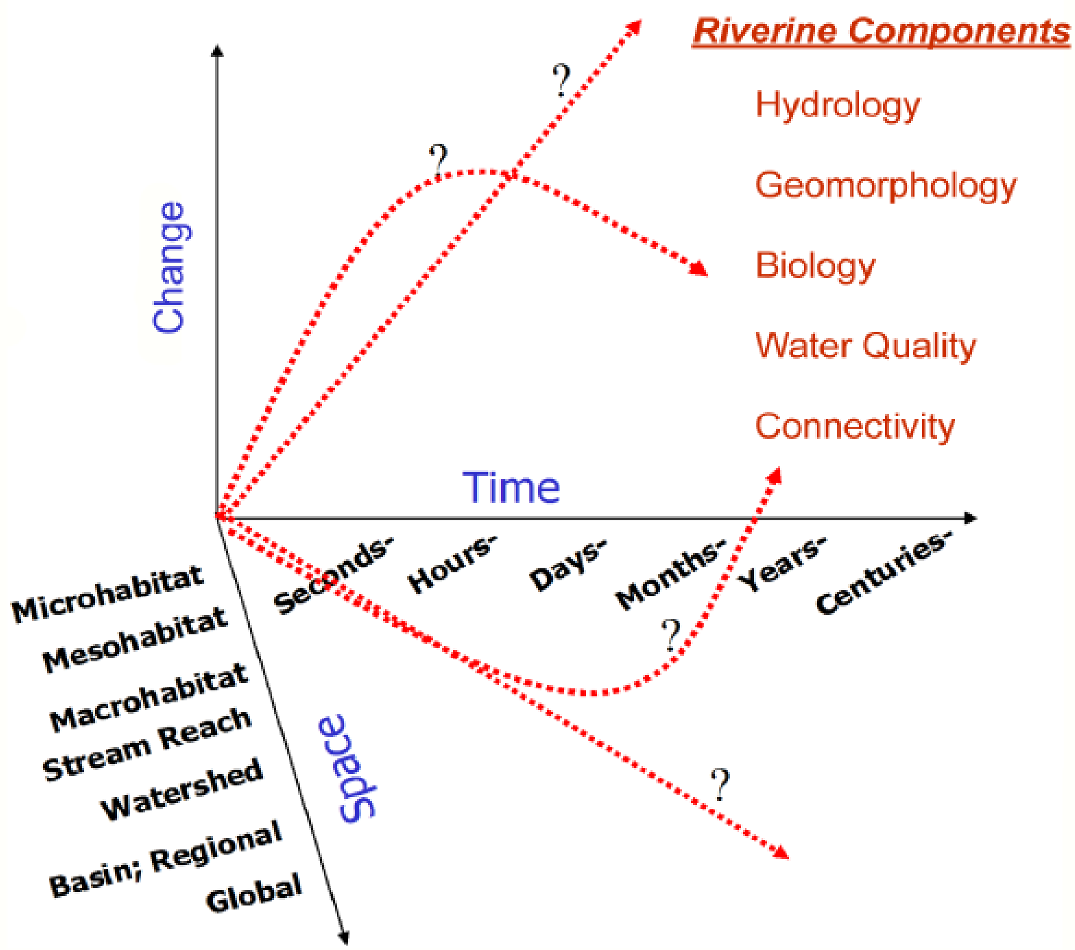


FIGURE 6-3. Each riverine component functions over the full range of spatial and temporal scales (e.g., microhabitat to global and seconds to centuries and beyond). The riverine components respond to natural and human-induced perturbations at different rates. Those system variables that require the longest time to reach equilibrium determine the time of adjustment (adapted from Frissell et al. 1986).

The MNDNR Major Watersheds were designed to be consistent with the Federal U.S.G.S. Level-4 or 8-digit Hydrologic Unit Code (HUC). This system was developed according to standards referred to the national Watershed Boundary Dataset. Delineation, naming, and numbering of these hydrologic units is described in Federal Geographic Data Committee Proposal Version 1.0, Federal Standards for Delineation of Hydrologic Unit Boundaries – March 1, 2002.

The objective of the Minnesota Hydrography standards is to synthesize state and federal standards and bridge data development efforts. The MNDNR Lakeshed Project currently underway uses

FIGURE 6-4. Minnesota has four major drainage basins, the Upper Mississippi River, Souris-Red-Rainy River, Great Lakes, and Missouri River.

the Watershed Boundary Dataset standards, thereby making this synthesis possible. A translation table has been developed to bridge U.S.G.S Hydrologic Units and MNDNR Major Watersheds (Stream Survey Manual, Appendix 2, MNDNR 2007). To view the MN Governor's Council on Geographic Information Watershed Naming and Numbering Standard, see MN Dept. Admin. (2006).

Stream (watercourse) identification

The Minnesota Stream Identification System (MSIS), or Kittle Code, was originally developed by the MNDNR Section of Fisheries in the 1970s (MNDNR 1978) and adopted by the MNDNR in 1979 as part of the Minnesota Watershed Mapping Project (MN Planning 1981). The MN Hydrography Committee of the Governor's Council on Geographic Information has adopted the MSIS as Minnesota's standard for watercourse identification (see Stream Survey Manual Part 2, Appendix 3, MNDNR 2007).

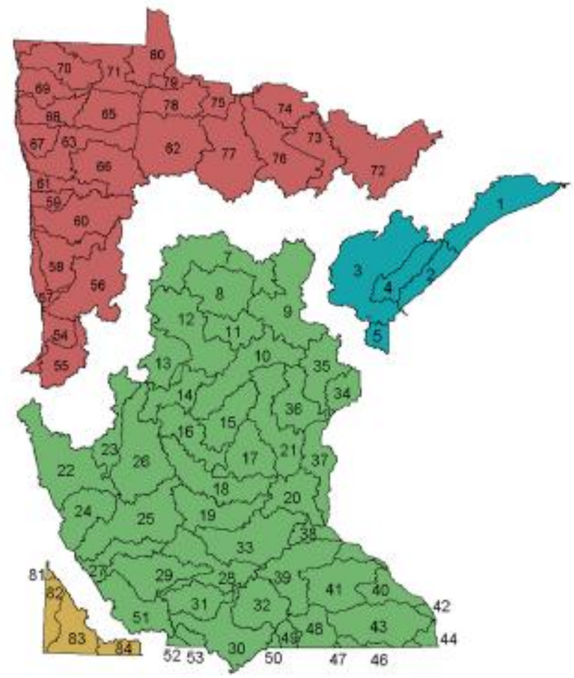


FIGURE 6-5. Minnesota's four drainage basins can be further subdivided into 81 "major" watersheds or subbasins.

The U.S.G.S. Watercourse designation in the National Hydrography Dataset (NHD; U.S.G.S. 2000) uses the federal watercourse identifier standard, which is the GNIS_ID, from the USGS Geographic Names Information System (GNIS) data set. The GNIS_ID is an 8-digit number. This code is available as an identifier to bridge to the U.S.G.S NHD. The NHD is a comprehensive set of digital spatial data that encodes information about naturally occurring and constructed bodies of water, paths through which water flows, and related entities. The information encoded about these features includes classification and other characteristics, delineation, geographic name, position and related measures, a "reach code" through which other information can be related to the NHD, and the direction of water flow. In addition to this geographic information, the dataset contains metadata and information that supports the exchange of future updates and improvements to the data. The NHD is the culmination of cooperative efforts of the U.S. Environmental Protection Agency (EPA) and the U.S. Geological Survey (USGS 2000).

Numbers assigned by the MSIS are commonly referred to as "Kittle Codes" or "Tributary numbers." Kittle Codes are based on the concept of a "watercourse," which in this context defined a named flowpath of a stream drainage, usually from its source to mouth. A watercourse can be composed of multiple stream segments or reaches.

A Kittle Code is a compound identifier consisting of up to 10 parts, each designating another level of tributary. All stream numbers begin with a letter prefix indicating the main drainage basin into which they flow:

M = Mississippi River
S = St. Lawrence (Great Lakes)
H = Hudson Bay (Souris-Red-Rainy Rivers)
I = Iowa

Within each of these major hydrologic systems, rivers were numbered, with each upstream tributary represented as an additional number, separated by a dash. For example, Minnesota tributaries to the Mississippi River are numbered from the south boundary of the state upstream. The Mississippi itself is designated as "M".

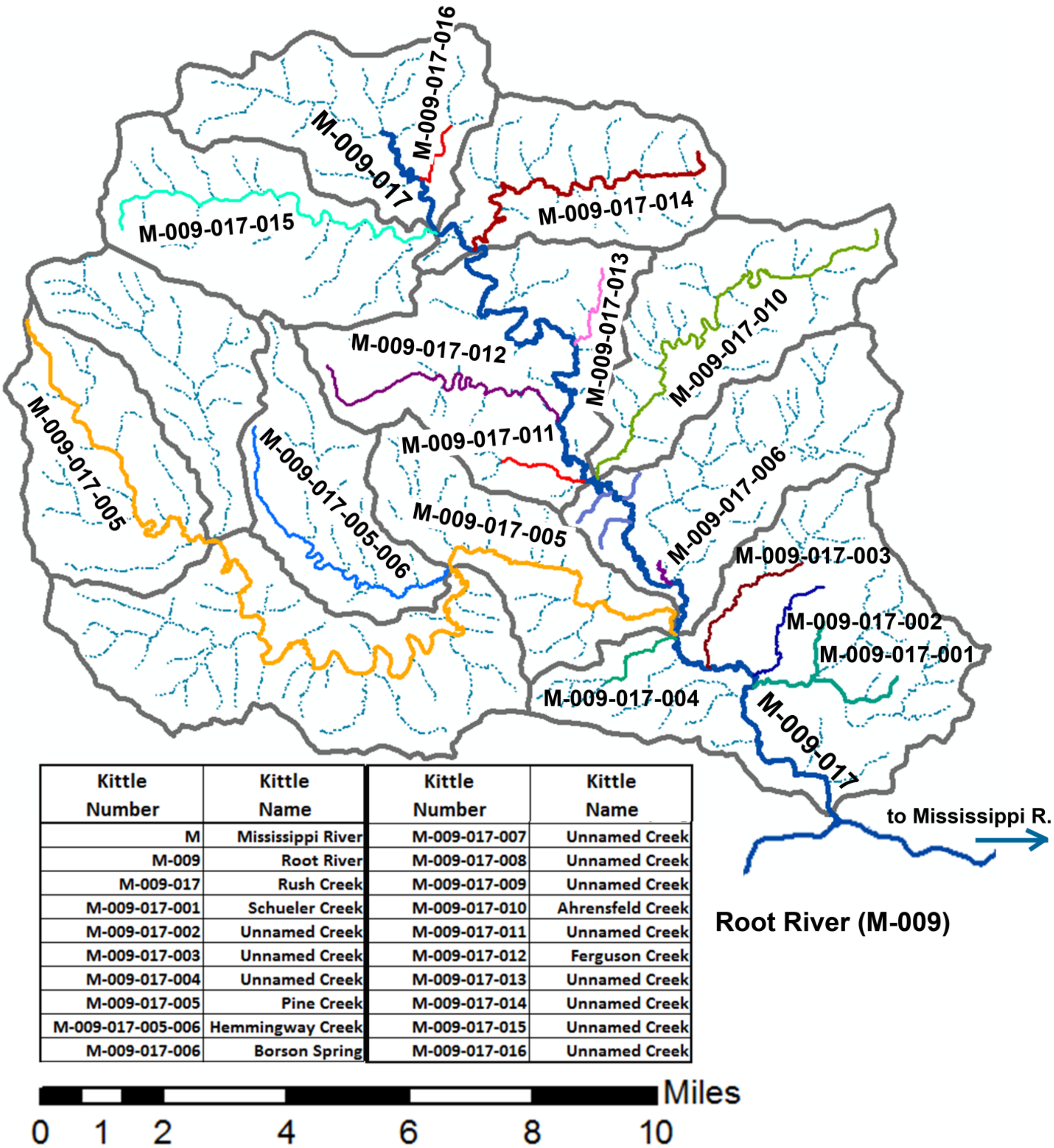
Example:

River Name	*Kittle Code*
Mississippi River	M
Minnesota River	M-055
Blue Earth River	M-055-076
Watonwan River	M-055-076-003

The Kittle Code thus contains information about upstream/downstream relationships between watercourses **(Figure 6-6)**. For standards to assign Kittle Codes, refer to MNDNR (1978) and Stream Survey Manual Part 2, Appendix 3 (MNDNR 2007).

Stream segments and reaches

A stream reach is defined as a segment of a stream, river, or ditch, generally defined from confluence to confluence, or by some other distinguishing hydrologic feature (LMIC 2004). Reach is often used interchangeably with segment, although the term "segment" is better described as a longitudinal section of stream bound by any downstream and upstream point; it usually doesn't carry any hydrologic significance unless stated. Reaches and segments have been commonly defined based on river miles, or distances from a confluence (e.g., 3.3 to 6.4 miles from mouth). While river miles have been useful references in the past, and still retain usefulness in quick references to stream locations, Global Position System (GPS) coordinates are needed for all stream data



Kittle Number	Kittle Name	Kittle Number	Kittle Name
M	Mississippi River	M-009-017-007	Unnamed Creek
M-009	Root River	M-009-017-008	Unnamed Creek
M-009-017	Rush Creek	M-009-017-009	Unnamed Creek
M-009-017-001	Schueler Creek	M-009-017-010	Ahrensfeld Creek
M-009-017-002	Unnamed Creek	M-009-017-011	Unnamed Creek
M-009-017-003	Unnamed Creek	M-009-017-012	Ferguson Creek
M-009-017-004	Unnamed Creek	M-009-017-013	Unnamed Creek
M-009-017-005	Pine Creek	M-009-017-014	Unnamed Creek
M-009-017-005-006	Hemmingway Creek	M-009-017-015	Unnamed Creek
M-009-017-006	Borson Spring	M-009-017-016	Unnamed Creek

FIGURE 6-6. The Minnesota Stream Identification System (MSIS), or Kittle System, preserves stream connectivity information through its hierarchical numbering system. The Rush Creek watershed (above), tributary to the Root River system (M-009) in southeast Minnesota illustrates these linkages. (Note that because some numbered tributaries are extremely small, they do not appear on the map, or they may not be numbered).

to retain geographic meaning as stream channels change, thus changing river mile references.

The National Hydrologic Dataset (NHD) has adopted the NHD Reach as the primary unit of waterbody designation, as defined above. The NHD Reach Code is a unique 14 digit number defined in two parts; the first 8 digits are the federal hydrologic unit code; the last 6 digits are assigned arbitrarily to reaches, and cannot be reused. The NHD Reach Code has been adopted by the Minnesota Governor's Council on Geographic Information's Hydrography Committee as the primary standard for defining stream reaches for Minnesota streams. For a complete document on the federal National Hydrography Dataset, refer to http://nhd.usgs.gov/.

DNR Fisheries similar reach

DNR Fisheries has used a reach designator as a basis for stream management, the "similar reach." The term similar reach (sometimes used synonymously with "sector") refers to a defined stream segment used as a functional unit of stream planning and management **(Figure 6-7)**. While no formal definition was documented, MNDNR (1978) used two characteristics to delineate similar reaches on a watercourse, gradient and sinuosity. Since no formal methodology for defining similar reaches was defined, the designation of similar reaches could vary with opinion, especially by the tendency of the designee to lump or split, and incorporating other variables, including riparian corridor condition, disconnectivity (dams, dredging, etc.), and major changes in water quality (tributaries and major springs). While many past similar reach designations have involved some subjectivity, most appear to have been based on both hydrologic and biological criteria. This is evident in the ecological classification of stream similar reaches based on the suitability of conditions for a fish species or combination of species. With these limitations, the use of similar reach designations has been useful to stream planning and management for MNDNR Section of Fisheries, and is expected to be used. Defining stream reaches or segments based on management objectives or other needs are not limited to NHD Reach Codes or Similar Reach. Any segment of stream bound by an upstream and downstream boundary (segment XY) can be defined with current mapping and GIS technologies. Examples include stream habitat improvement projects, special fishing regulations, political boundaries (counties, watershed districts), or management units.

Considerations for Sampling Fishes in Streams

Stream fish communities are composed of species that vary substantially in population size, both spatially and temporally, resulting in high natural variability. Fish management in streams benefits from understanding natural variation due to seasonal, annual, and longer time scale variation as compared to variation attributed to changes in biotic and abiotic factors including sedimentation, water quality, hydrology, instream habitat, and watershed impacts associated with human activities.

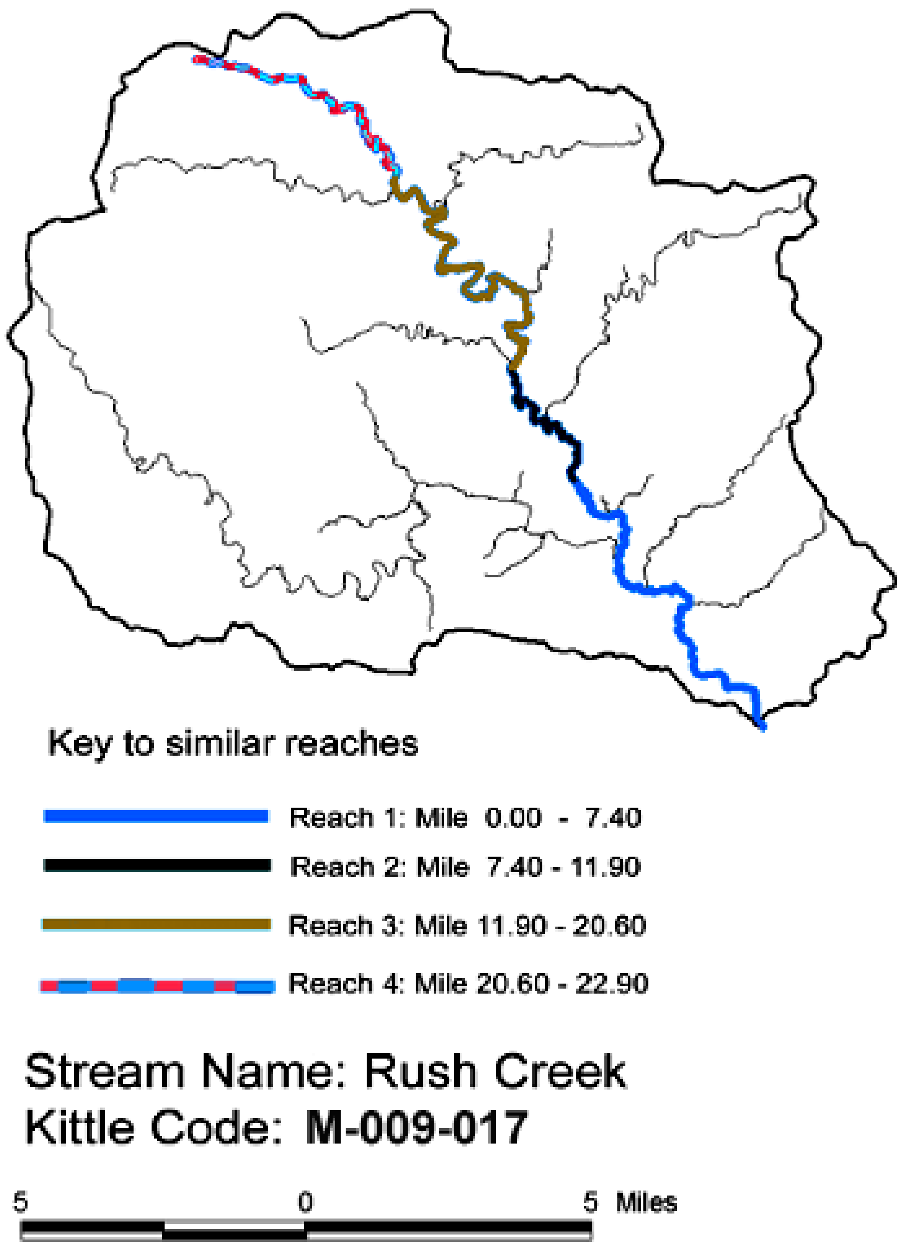


FIGURE 6-7. The 1998 stream survey of Rush Creek (M-009-017, Fillmore and Winona counties) identified four similar reaches, based primarily on gradient and sinuosity, but also reflected differences in the fish community. Reach boundaries are identified in this table by stream miles from the mouth. GPS coordinates should also be assigned for delineating similar reaches.

Because the stream environment, and associated fish communities, are inherently variable, especially in disturbed ecosystems, sampling methods must account for this high natural variability through stratified sampling and increased size and frequency of samples where required.

Fish community sampling methods must be matched closely to objectives. As objectives move from basic to more complex (e.g., fish presence-absence to relative abundance; catch per unit effort to estimated population density; and finally to trends in population metrics over time), methods must be adjusted. To document fish presence-absence, smaller sample sizes with less quantitative gear can yield basic information. Documenting spatial and temporal distribution requires sampling more representative reaches, and more often over time. Various microhabitats (riffles, pools, undercut banks, runs) must also be representatively sampled.

Time-series information can be used to document the persistence of a species of fish (whether a species remains in specific areas or habitats over time). In long-term sampling where species disappear, there are often one or more anthropogenic effects that can be linked to the declines (Burr and Burr 1991). Presence-absence data can adequately document an increase or decrease in the number of species, but cannot document changes in relative abundance.

There is a need for long-term data sets to document changes in fish communities, and to use these as a potential gauge of future changes that may be associated with anthropogenic effects. In measuring the stability of fish populations, it is important to have more quantitative data, such as estimates of numbers and biomass of target species, along with associated estimates of variation.

Designing and Implementing a Stream Monitoring Program

The objective of a stream survey is to deduce a representation of a stream as accurately as possible, without sampling it in its entirety (Bain and Stevenson 1999). By designating reaches as hydrologic and biologically meaningful units, and sampling stations within these reaches, an accurate picture of stream conditions and status can be drawn. Methods for standard stream reconnaissance surveys, basic surveys, and full surveys are covered in the stream survey manual (MNDNR 2007). To develop stream management plans on Minnesota streams, refer to the Fisheries Management Planning Guide for Streams and Rivers (MNDNR 2013).

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