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Identifying and Protecting Healthy Watersheds

Chapter 2. Key Concepts and Assessment Approaches

February 2012

2. Key Concepts and Assessment Approaches

1

Introduction

This chapter introduces the Healthy Watersheds Initiative, discusses the characteristics of a healthy watershed, and reviews the benefits of protecting healthy watersheds. This chapter also describes the purpose, target audience, and intended use of this document.

Overview of Key Concepts

This chapter describes the healthy watersheds conceptual framework. It then discusses, in detail, each of the six assessment components – landscape condition, habitat, hydrology, geomorphology, water quality, and biological condition. A sound understanding of these concepts is necessary for the appropriate application of the methods described in later chapters. This chapter concludes with a discussion of watershed resilience.

3

Examples of Assessment Approaches

This chapter summarizes a range of assessment approaches currently being used to assess the health of watersheds. This is not meant to be an exhaustive list of all possible approaches, nor is this a critical review of the approaches included. These are provided solely as examples of different assessment methods that can be used as part of a healthy watersheds integrated assessment. Discussions of how the assessments were applied are provided for some approaches. Table 3-1 lists all of the assessment approaches included in this chapter.

4

Healthy Watersheds Integrated Assessments

This chapter presents two examples for conducting screening level healthy watersheds integrated assessments. The first example relies on the results of a national assessment. The second example demonstrates a methodology using state-specific data for Vermont. This chapter also includes examples of state efforts to move towards integrated assessments.

5

Management Approaches

This chapter includes examples of state healthy watersheds programs and summarizes a variety of management approaches for protecting healthy watersheds at different geographic scales. The chapter also includes a brief discussion of restoration strategies, with focus on targeting restoration towards degraded systems that have high ecological capacity for recovery. The results of healthy watersheds integrated assessments can be used to guide decisions on protection strategies and inform priorities for restoration.

2.1 A Systems Approach to Watershed Protection

The healthy watersheds conceptual framework is based on a holistic systems approach to watershed assessment and protection that recognizes the dynamics and interconnectedness of aquatic ecosystems. Maintenance of aquatic ecological integrity requires that we understand not only the biological, chemical, and physical condition of water bodies, but also landscape condition and critical watershed attributes and functions, such as hydrology, geomorphology, and natural disturbance patterns.

Watersheds provide a useful context for managing aquatic ecosystems. Rivers, lakes, wetlands, and ground water are sinks into which water and materials from the surrounding landscape drain (U.S. EPA Science Advisory Board, 2002). Landform, hydrology, and geomorphic processes generate and maintain freshwater ecosystem characteristics, including stream channel habitat structure, organic matter inputs, riparian soils, productivity, and invertebrate community composition (Montgomery & Buffington, 1998; Vannote, Minshall, Cummins, Sedell, & Cushing, 1980). Consequently, the ecosystem protection approaches described in this document focus on assessing and managing landscape conditions, including connectivity, and key functional processes in the watershed of which the aquatic ecosystem is a part and cannot function without. These processes are hierarchically nested and occur at multiple spatiotemporal scales (Beechie et al., 2010) (Figure 2-1). Therefore, assessment and management must also occur at multiple spatial and temporal scales.

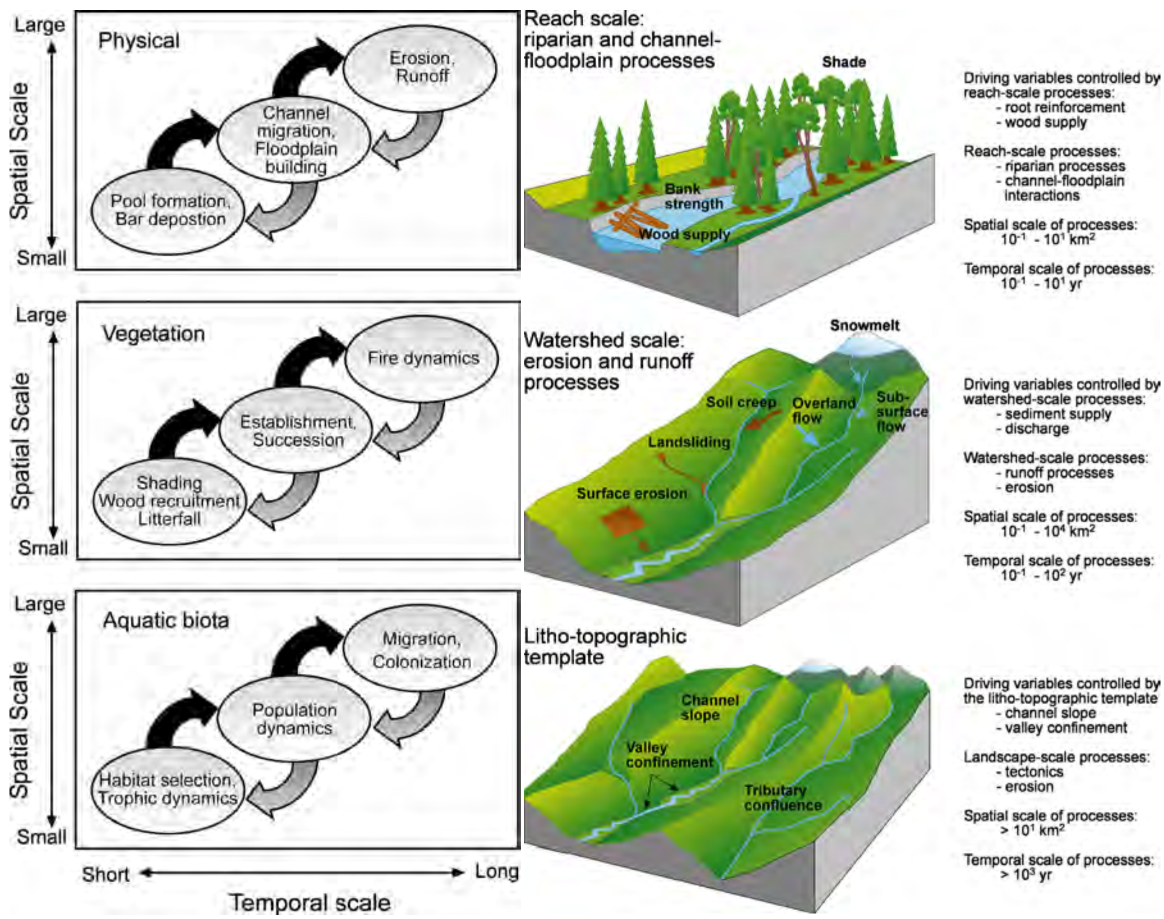


Figure 2-1 Spatial and temporal scales of watershed processes. Watershed and ecosystem processes operate at a variety of spatial and temporal scales, with processes operating at larger spatial scales generally influencing processes operating at smaller scales. In some instances, processes operating at smaller scales may also influence processes operating at larger spatial scales. This is perhaps best illustrated in fishes, where processes such as habitat selection and competition influence survival of individuals, which influences population dynamics at the next larger space and time scale (Beechie et al., 2010). Reprinted with permission of University of California Press.

Although EPA's watershed approach has traditionally focused primarily on the management of the chemical, physical, and some biological aspects of water quality, the importance of pattern, connectivity, and process for integrated management of watershed health is emerging (e.g., California's Healthy Streams Partnership and Virginia's Healthy Waters Program). Assessments of landscape condition, hydrology, geomorphic condition, and natural disturbance regimes provide complementary information to the chemical, physical, and biological parameters commonly measured by water quality monitoring programs. Integrating the results of all of these assessment approaches can help to provide a more comprehensive understanding of aquatic ecosystem health.

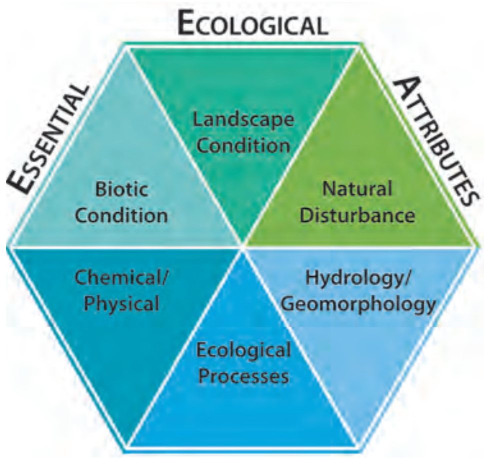


Figure 2-3 Essential ecological attributes (U.S. EPA Science Advisory Board, 2002).

The healthy watersheds conceptual framework is consistent with recommendations by EPA's Science Advisory Board (SAB) (U.S. EPA Science Advisory Board, 2002). Building on previous work to describe aquatic resource integrity (Figure 2-2), the EPA SAB identified six essential ecological attributes (EEAs) to describe factors that support healthy ecosystems (Figure 2-3). These include landscape condition, biotic condition, chemical and physical characteristics, ecological

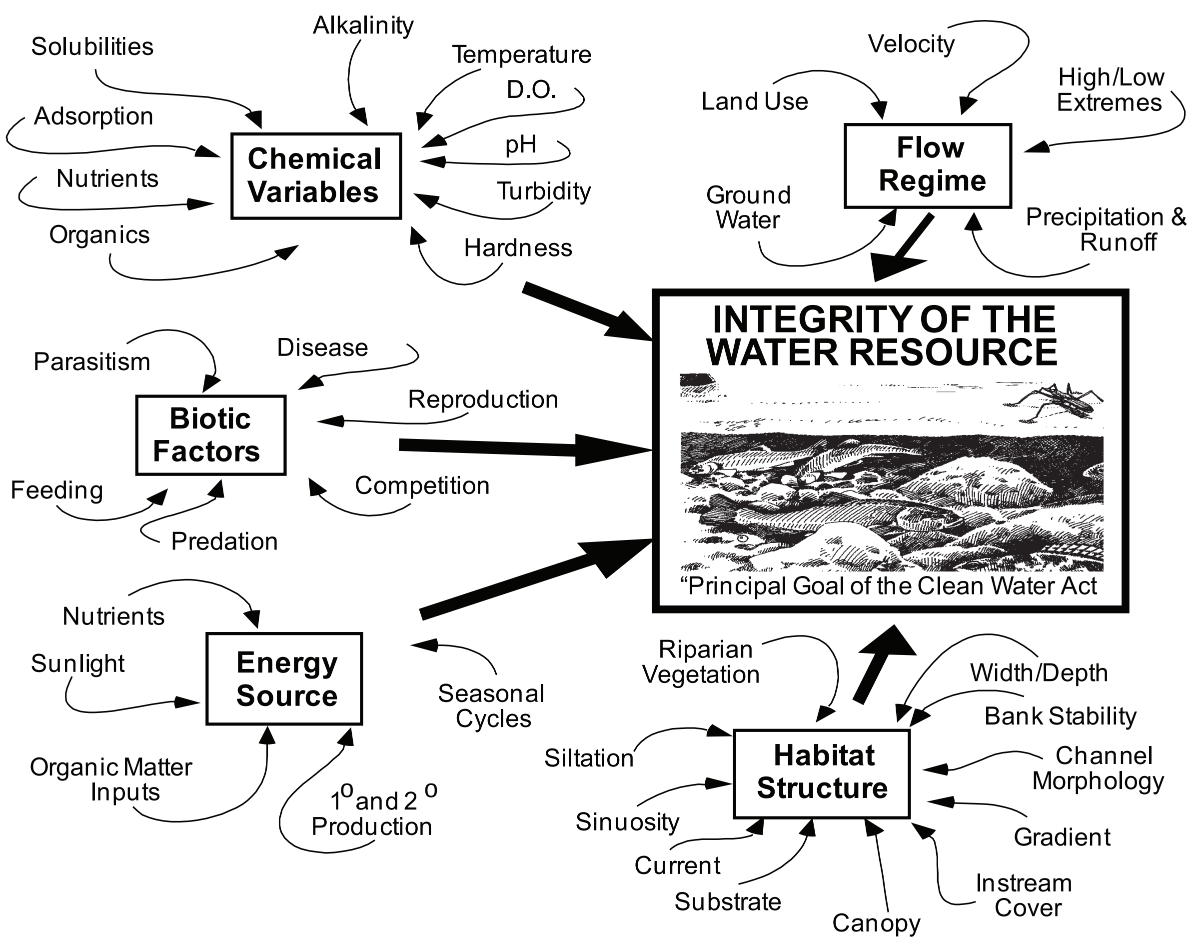


Figure 2-2 The five major factors that determine integrity of the aquatic resource (modified from Karr, Fausch, Angermeier, Yant, & Schlosser, 1986).

elements (e.g., energy and material flow), hydrologic and geomorphic condition, and natural disturbance regimes. The healthy watersheds concept views watersheds as integral systems that can be understood through the dynamics of these essential ecological attributes.

The systems approach to healthy watersheds assessment and protection is based on an integrated evaluation of: 1) Landscape Condition, 2) Habitat, 3) Hydrology, 4) Geomorphology, 5) Water Quality, and 6) Biological Condition (Figure 2-4). Ecological processes and natural disturbance regimes are addressed in the context of these six components. Background information on each of these components is provided in the pages that follow.

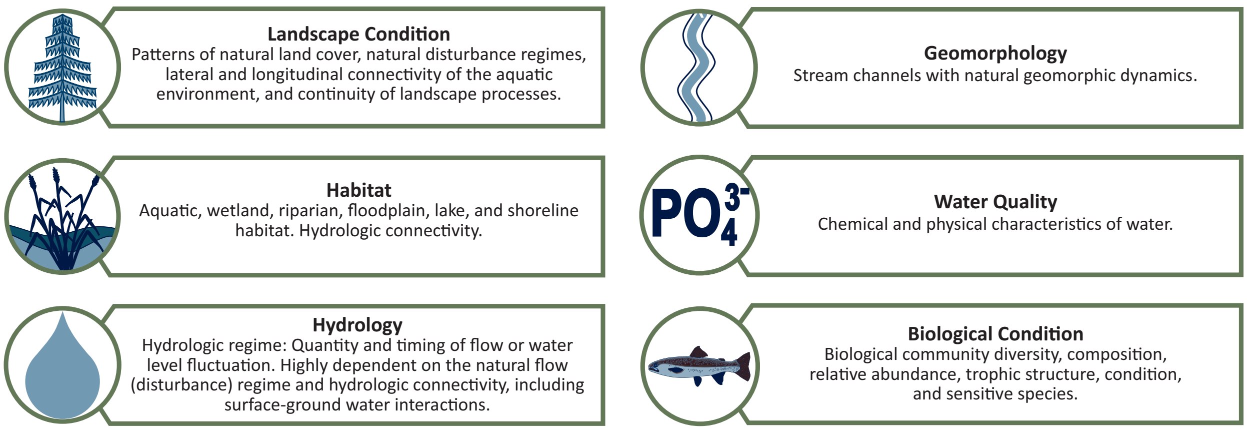


Figure 2-4 Healthy watersheds assessment components.

2.2 Landscape Condition

Natural vegetative cover stabilizes soil, regulates watershed hydrology, and provides habitat to terrestrial and riparian species. The type, quantity, and structure of the natural vegetation within a watershed have important influences on aquatic habitats. Land cover is a driving factor in determining the hydrologic and chemical characteristics of a water body. Vegetated landscapes cycle nutrients, retain sediments, and regulate surface and ground water hydrology. Riparian forests regulate temperature, shading, and input of organic matter to headwater streams (Committee on Hydrologic Impacts of Forest Management, National Research Council, 2008). Conversely, agricultural and urban landscapes serve as net exporters of sediment and nutrients, while increasing surface runoff and decreasing infiltration to ground water stores.

Recognition of these landscape influences has shaped previous aquatic ecosystem management efforts. Adequate protection of a range of aquatic ecosystem types is a widely accepted conservation approach (Noss, LaRoe III, & Scott, 1995). The Center for Watershed Protection (2008c) recommends conservation of multiple landscape areas: 1) critical habitats; 2) aquatic corridors; 3) undeveloped areas, such as forests, which help maintain the pre-development hydrologic response of a watershed; 4) buffers to separate water pollution hazards from aquatic resources; and 5) cultural areas that sustain both aquatic and terrestrial ecosystems.

It is important that forest patches, wetlands, and riparian zones are of sufficient size, quantity, and quality to sustain ecological communities and processes. Interconnections among habitat patches are also important. For many species, an isolated forest patch is not a high quality habitat. However, a number of forest patches interconnected by forested corridors can provide outstanding habitat for a number of species. This is because species need to migrate, feed, reproduce, and ensure genetic diversification. Native habitat in the landscape provides a variety of benefits for aquatic ecological integrity, including maintenance of the natural watershed hydrology, soil and nutrient retention, preservation of habitat for both aquatic and terrestrial species, and the prevention of other adverse impacts associated with development. The photos in Figure 2-5 illustrate the difference between intact habitat in the landscape and fragmented habitat.

Figure 2-5 These photos provide an example of intact landscape condition (on the left) and fragmented landscape condition (on the right).

2.2.1 Green Infrastructure

The concept of linked landscape elements and ecological networks has evolved into the green infrastructure movement in land conservation. Green infrastructure is "an interconnected network of natural areas and other open spaces that conserves natural ecosystem values and functions, sustains clean air and water, and provides a wide array of benefits to people and wildlife" (Benedict & McMahon, 2006). The natural areas are typically referred to as "hubs," and the connections, or links, between the hubs are termed "corridors" (Figure 2-6). The green infrastructure movement is rooted in: 1) Frederick Law Olmsted's idea of linking parks for the benefit of people (e.g., Boston's famous Emerald Necklace) and 2) the recognition by wildlife biologists and ecologists that interconnected habitat patches are essential for maintaining viable ecological communities (Benedict & McMahon, 2002). The evolution of the green infrastructure movement has coincided with the development of geographic information system (GIS) technology and conceptual developments in landscape ecology and conservation biology.

The green infrastructure approach considers open and green space as a system to be managed to meet the needs of both ecosystems and humans. It can provide information to assist community planning, and to identify and prioritize conservation opportunities. It can be mapped as a network of key ecological areas, or hubs, and corridors connecting them. For example, the Green Infrastructure Vision of Chicago Wilderness identifies 1.8 million acres of potential areas for protection and restoration throughout the region (Figure 2-7; Chicago Wilderness, 2009).

The greenways movement, an evolution of Olmsted's idea, has influenced green infrastructure considerably, linking people with their landscape through recreational activities. Greenways are recreational and alternative transportation corridors surrounded by vegetation. An example of a popular greenway approach is the Rails-to-Trails Conservancy's acquisition of abandoned railways to create bike paths for local transportation and recreation. Green infrastructure is different from greenways in that green infrastructure emphasizes ecology over recreation. Further, green infrastructure focuses on large, ecologically important hubs and planning for growth around the green infrastructure, as opposed to "fitting"

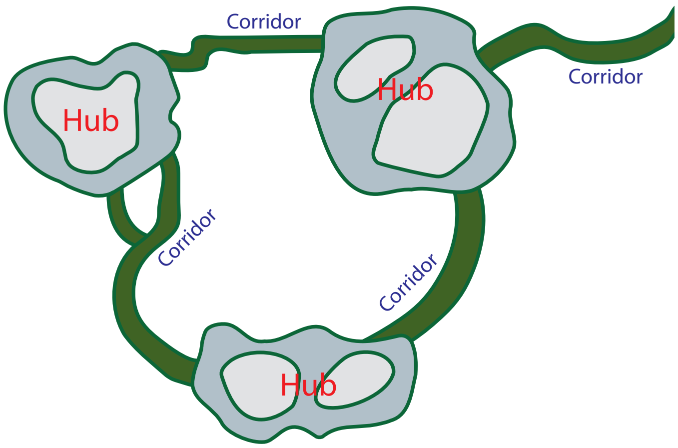


Figure 2-6 Green infrastructure network design (modified from Maryland Department of Natural Resources, 2011).

Figure 2-7 Map of the Chicagoland area showing land cover and currently protected areas (Chicago Wilderness, 2009).

conservation areas into developed landscapes (Benedict & McMahon, 2002). Identification of hubs in a green infrastructure program typically involves a land cover and human infrastructure assessment to identify interior habitat patches, which are areas of forest or wetland that have not been fragmented by roads or other development. These hubs often serve as core habitat for a number of species. The links, or corridors, between these hubs provide opportunities for movement of fauna and flora between the habitat patches, thus allowing for dispersal and genetic diversity, which are essential for ecological integrity.

The 1990s saw the development of a number of green infrastructure programs, the most notable of which were in Florida and Maryland (Benedict & McMahon, 2006). Ecologists Larry Harris and Reed Noss at the University of Florida conceptualized an integrated habitat conservation system to address the fragmentation of natural areas that they saw as the primary cause of biodiversity decline across the state (Benedict & McMahon, 2006). This vision led to the development of Florida's Ecological Network Project and, later, the Southeastern Ecological Framework Project, the first regionally-based green infrastructure study (John Richardson, EPA Region 4, Personal Communication). Maryland's green infrastructure assessment built off of the success of these pioneering programs (John Richardson, EPA Region 4, Personal Communication). These programs also drew upon work by The Nature Conservancy on an ecoregional approach to selecting wildlife reserves (Benedict & McMahon, 2006). The original green infrastructure approaches contain five basic steps, as outlined by Benedict and McMahon (2006):

1. Develop network design goals and identify desired features.
2. Gather and process data on landscape types.
3. Identify and connect network elements.
4. Set priorities for conservation action.
5. Seek review and input.

Green infrastructure assessments utilize a weighted overlay technique in GIS that identifies the most ecologically valuable lands based on co-occurrence of multiple ecological attributes. For example, creating a map that overlays the state's road network with land cover data allows one to identify those areas with remaining natural land cover that contain the fewest road crossings. Additional data layers can be added to this analysis, with each layer weighted according to the importance of its features for ecological integrity. The final result is a map that shows the areas with the highest priority for conservation. This approach has been replicated and modified for use in a number of states, local communities, and regions throughout the United States.

2.2.2 Rivers as Landscape Elements

Although the term landscape implies a focus on terrestrial features, aquatic systems are just as much landscape elements as forested patches and corridors (Wiens, 2002). Rivers interact with other landscape elements over time through their natural floodplains, migrating meander belts, and riparian wetlands (Smith, Schiff, Olivero, & MacBroom, 2008). Natural hydrology provides connectivity among aquatic habitats and between terrestrial and aquatic elements. Many aquatic organisms depend on being able to move through connected systems to habitats in response to variable environmental conditions. Forested riparian zones are often some of the best remaining green infrastructure links, or corridors, for connecting hubs on the landscape. Furthermore, maintenance of natural land cover protects aquatic ecosystems from nonpoint sources of pollution, including urban and agricultural runoff.

Recognizing the importance of connectivity, The Nature Conservancy advocates a systems approach to river protection, exemplified by the Active River Area (Figure 2-8), which includes not only the river channel but also floodplains, riparian wetlands, and other parts of the river corridor where key habitats and processes occur (Smith et al., 2008). The Active River Area concept can be applied at different scales, from basin to catchment or reach. For example, identification of intact riparian areas and headwaters in the Connecticut River Basin was accomplished using standard GIS techniques, available models, and national datasets (Smith et al., 2008). A more detailed analysis, using techniques such as Vermont's Stream Geomorphic Assessment protocols (see Chapter 3), can then be used to identify specific conservation priorities on a subwatershed scale.

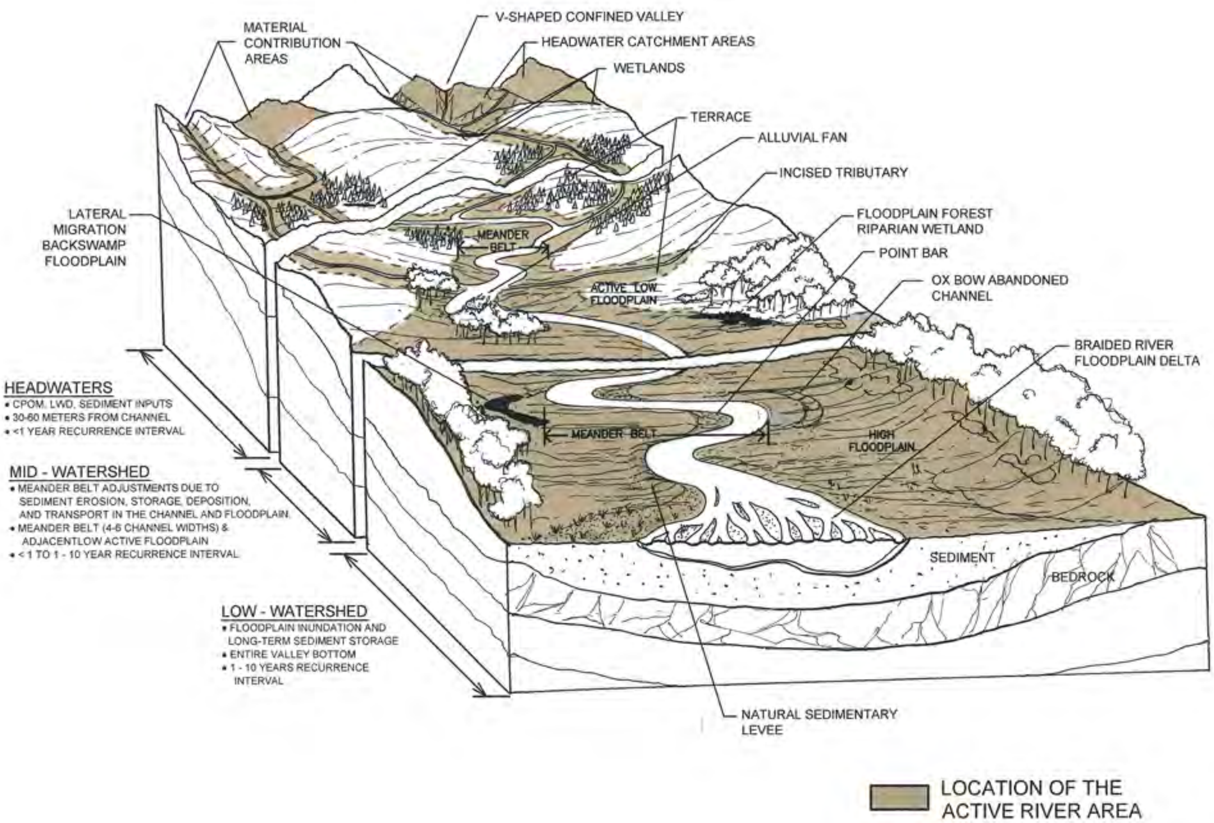


Figure 2-8 Components and dominant processes of the Active River Area (Smith et al., 2008).

Active River Areas, in their natural state, maintain the ecological integrity of rivers, streams, and riparian areas and the connection of those areas to the local ground water system. They also provide a variety of ecosystem services, such as flood prevention and hazard avoidance, recreation and open space, and other habitat values. The Active River Area is essential to healthy and productive fish populations. Preserving riparian wetlands and a river channel's connection with its floodplain provides surface and subsurface floodwater storage and reduces stream power during flood events. This is especially important in temperate regions, where increases in average annual precipitation and frequency of extreme storm events have been observed and are expected to continue as a result of climate change (IPCC, 2007). Also, warming temperatures will increase the importance of these undeveloped areas as zones of ground water discharge provide refugia for coldwater aquatic species. Maintaining natural vegetation in the entire Active River Area and in the wider watershed provides water quality improvements through reduced surface runoff and increased opportunity for ground water infiltration and storage.

2.2.3 Natural Disturbance

The natural disturbance regime is an important consideration in assessment and management of landscape condition. Ecosystems are naturally dynamic and depend on recurrent disturbances to maintain their health. Natural disturbance events that affect watershed ecosystems include fires, floods, droughts, landslides, and debris flows. The frequency, intensity, extent, and duration of the events are collectively referred to as the disturbance regime (U.S. EPA Science Advisory Board, 2002). The natural fire regime, particularly in some regions of the United States (e.g., longleaf pine/flatwoods ecosystems of the southeast), helps to maintain healthy landscape condition through a process of ecological renewal that creates opportunities for some species while scaling back the prevalence of others. Fire dependant ecosystems require this periodic disturbance to maintain their natural state and composition. Suppression of the natural fire regime may cause an excessive build-up of nutrients on the forest floor due to decomposition of organic matter (Miller et al., 2006). These nutrients can then be transported to aquatic ecosystems during rainfall/runoff events, causing eutrophic conditions. Fire disturbances of natural frequency and intensity remove the excess organic matter causing the nutrient build-up and may actually improve long-term water quality, although water quality will be temporarily worsened immediately following a fire (Miller et al., 2006). The Fire Regime Condition Class methodology is an example of a landscape condition assessment that focuses on the natural disturbance regime (see Chapter 3). This approach assesses a landscape's degree of departure from the natural fire regime and suggests management approaches for emulating that regime.

2.2.4 Connectivity and Redundancy

Connectivity of landscape elements, including aquatic ecosystems, provides organisms with access to the habitats and resources necessary for the different stages of their life cycle (e.g., breeding, feeding, nesting). It also helps to ensure that ecosystems and species have the ability to recover and recolonize following disturbance (Poiani, Richter, Anderson, & Richter, 2000). Lateral (floodplain access), vertical (hyporheic exchange), and longitudinal (stream flow) connectivity are equally important for supporting these processes. Physical barriers, such as dams and levees, isolate aquatic populations and prevent dispersal of organisms (Frissel, Poff, & Jensen, 2001). Further, these barriers prevent the flow of water, sediment, nutrients, and heat loads that support ecosystem processes (Frissel, Poff, & Jensen, 2001). As a result, non-native species are often better able to compete with native species (Frissel, Poff, & Jensen, 2001). Connectivity is therefore critical to ensuring the persistence of native species by providing habitat refugia and recolonization access. Redundancy refers to the presence of multiple examples of functionally similar habitat and ecosystem types that help to "spread the risk" of species loss following major ecological disturbances. This can allow populations of the same species to persist in the presence of disturbance or environmental change.

2.3 Habitat

Habitat extent is directly related to hydrologic and geomorphic processes. The number and distribution of different habitat types, or patches, and their connectivity influence species population health (Committee on Hydrologic Impacts of Forest Management, National Research Council, 2008). Habitat quality is also affected by the physical and chemical characteristics of water (e.g., water temperature). Water quality and geomorphic and hydrologic processes are all affected by landscape condition, which also shapes riparian and terrestrial habitat. Thus, habitat condition serves as an integrating indicator of other watershed variables, upon which biological condition is highly dependent.

Protection efforts must consider a variety of habitat types that serve different needs of an ecosystem, such as cool water rivers for trout foraging (Figure 2-9), riffles in cold headwater streams for breeding, and springs for thermal refuge during low water conditions (Montgomery & Buffington, 1998). In addition, natural variability within a habitat patch provides opportunities for species with different requirements and tolerances (Aber et al., 2000).

Figure 2-9 Cool water rivers provide important trout foraging habitat.

2.3.1 Fluvial Habitat

Hydrologic and geomorphic processes create the physical habitat template that supports aquatic communities in fluvial systems. As described by the River Continuum Concept (RCC), physical habitat variables can change predictably along the longitudinal gradient of the riverine system (Figure 2-10) (Vannote et al., 1980). Changes in biological communities generally correspond with this physical gradient. For example, a characteristic community of macroinvertebrates (dominated by shredders and collectors) is typically found in headwater

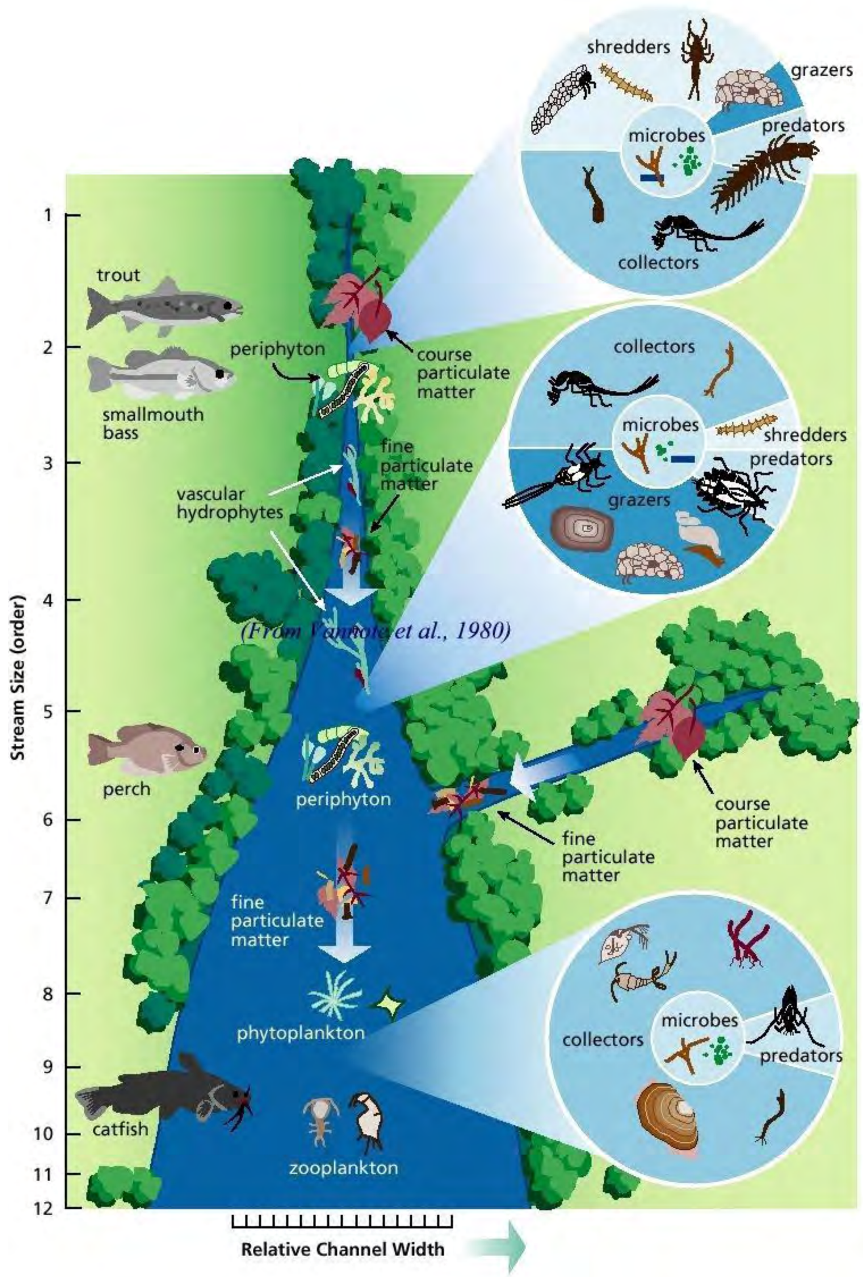


Figure 2-10 The River Continuum Concept (Vannote et al., 1980). © 2008 NRC Canada.

streams. These species are dependent on sufficient shade and inputs of terrestrial vegetation (e.g., large woody debris) from riparian areas. As a stream channel widens, allowing more sunlight to penetrate into the open water, algae and rooted vascular plants become the primary sources of energy input, and the macroinvertebrate community reflects this transition (dominated by collectors and grazers). As a river becomes larger and wider, fine particulate matter from upstream becomes more important as an energy source for the macroinvertebrate community (dominated by collectors).

This predictable change in community structure has been shown to be generally true at broad scales. However, the influence of tributary confluences and watershed disturbances on aquatic habitat must be understood to explain the many deviations from the habitat type and expected biological community predicted by the River Continuum Concept. Inputs of sediment and large woody debris at river confluences create habitat heterogeneity, allowing for the existence of communities that would not otherwise be expected to occur in a given stream order. Additionally, flood pulses and other aspects of the natural flow regime create a lateral and temporal gradient of habitat from the stream channel and out on to the floodplain. Ground water input in the hyporheic zone also creates unique habitats that cannot be explained from a purely longitudinal perspective of riverine habitat. This inherent complexity of riverine ecosystems is responsible for the diversity of aquatic habitats and resultant biological communities found within them.

Understanding riverine ecosystems in a landscape context can help to elucidate the complex relationships that define aquatic habitat. The RCC conceptual model has been improved upon in recent years to include not only the longitudinal dimension of river systems, but also the lateral (floodplain and riparian zone), vertical (hyporheic zone), and temporal (flow regime) dimensions (Thorp, Thoms, & DeLong, 2006). The Riverine Ecosystem Synthesis (RES) (Thorp, Thoms, & Delong, 2008) builds on the RCC and other leading concepts in river ecology to explain the spatial and temporal distribution of species, communities, and ecosystem processes as a function of hydrogeomorphic differences in the riverine landscape. Heterogeneous patches of habitat result from unique combinations of hydrologic and geomorphic processes, including the dynamics of watershed disturbance and the structure of the river network within a watershed. The geomorphic, hydrologic, and ecological processes that form these patches operate at a variety of scales. Thus, hydrogeomorphic patches exist at multiple spatial and temporal scales, such as drainage basins or watersheds, functional process zones (FPZ), reaches, functional units, and individual habitats (Thorp, Thoms, & DeLong, 2006) (Figure 2-11). Hierarchically-organized units, such as watersheds, are most affected by the scale immediately below that of interest and the scale immediately above it (Thorp, Thoms, & Delong, 2008). As FPZs are the level immediately below watersheds or basins, they are an appropriate scale for integrated watershed assessments and receive special attention in the RES. These FPZs are not necessarily distributed in a manner predictable by longitudinal theories of river ecology, such as the RCC (Figure 2-12). Rather, all four dimensions of the riverine system influence their distribution.

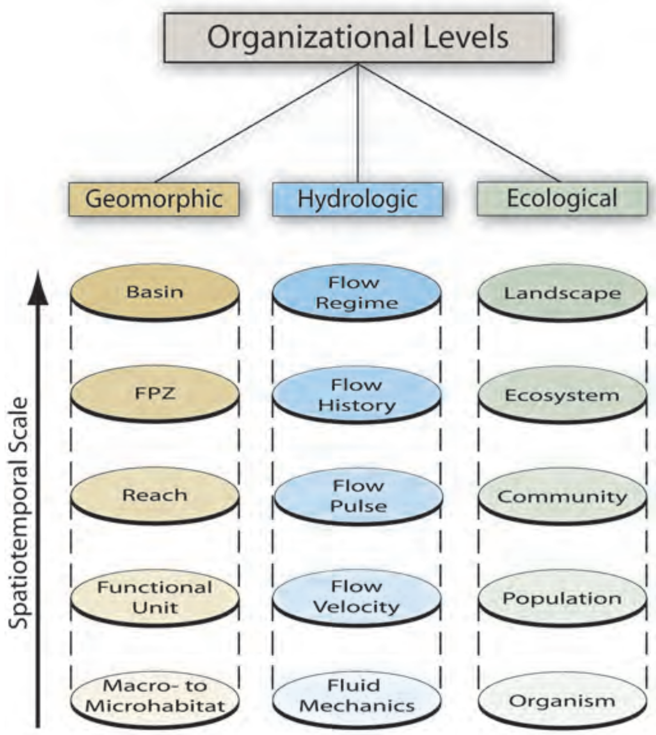


Figure 2-11 Hierarchy defining spatiotemporal scales of hydrogeomorphic patches (Thorp, Thoms, & Delong, 2008). Reprinted with permission of Elsevier.

Through a collaborative effort, EPA and the University of Kansas developed a computer program that statistically delineates FPZs using precipitation, geology, elevation, and remote sensing data. The program extracts 14 hydrogeomorphic variables from these datasets and uses multivariate cluster analysis to identify the distinct FPZ types. This approach minimizes human bias in the classification. See Figure 2-13 for an example of the various FPZs delineated in the Kanawha River Basin of West Virginia.

Stratifying a field sampling program based on FPZs can be a useful method for ensuring that scale is adequately considered in the data collection process. Data can be collected at reaches within each FPZ and averaged to get a condition score for the FPZ. FPZs can then be compared across the watershed to understand watershed condition. Important habitat variables at the reach scale (and smaller) include substrate composition and riparian vegetation, both of which are dependent on processes operating at larger scales.

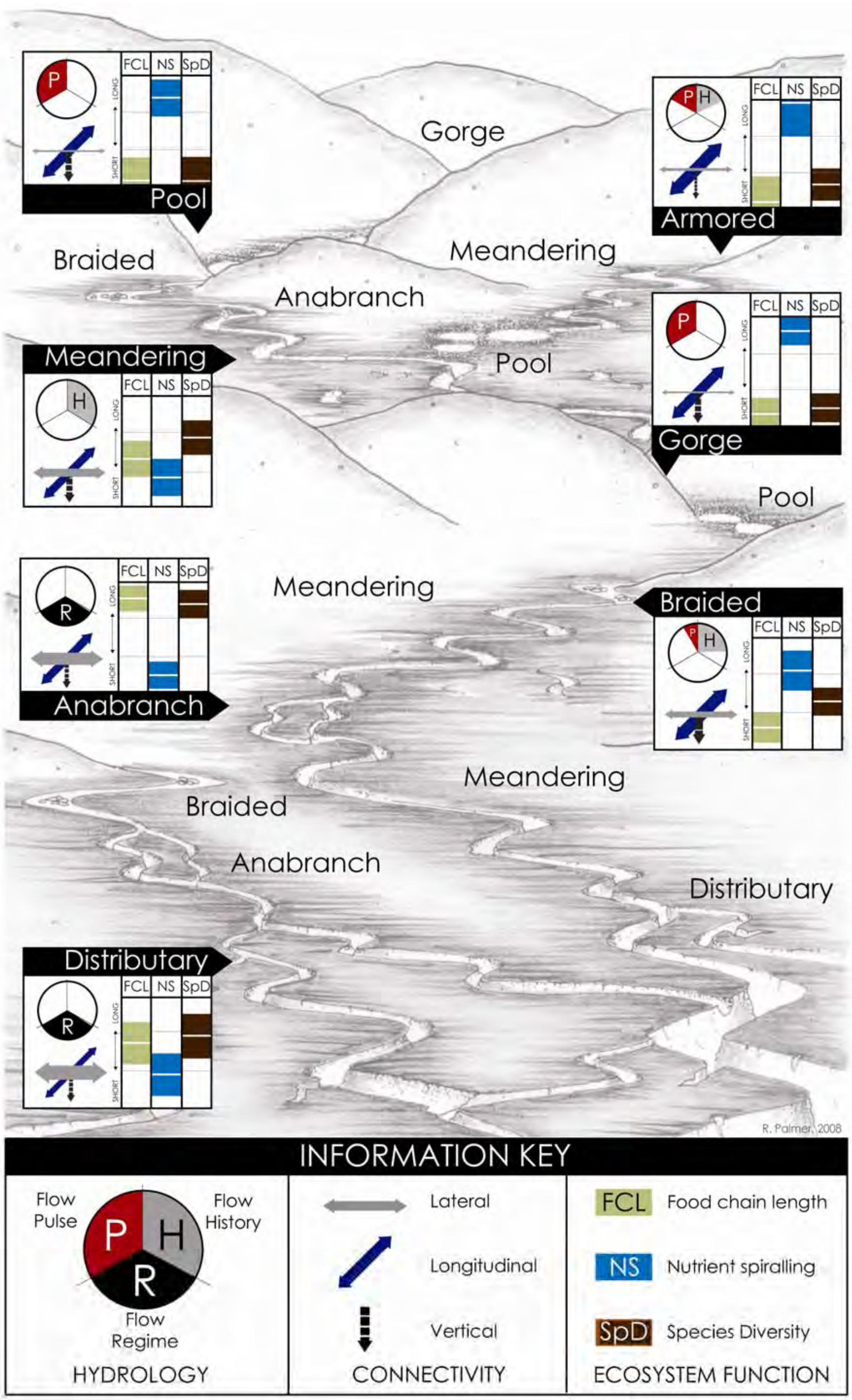


Figure 2-12 A conceptual riverine landscape is shown depicting various functional process zones (FPZ) and their possible arrangement in the longitudinal dimension. Note that FPZs are repeatable and only partially predictable in location (corrected copy from Thorp, Thoms, & Delong, 2008). Reprinted with permission of Elsevier.

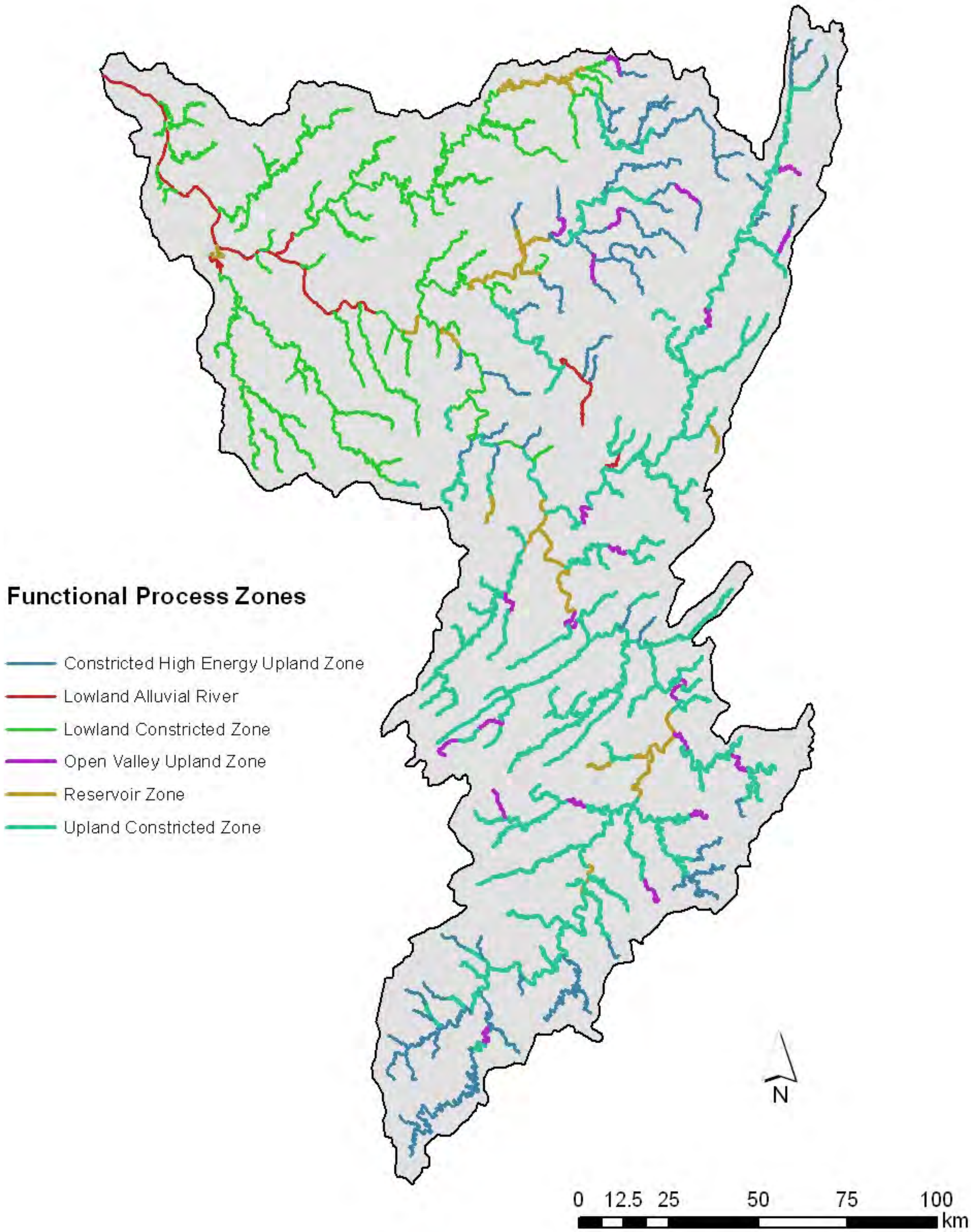


Figure 2-13 Distribution of the various Functional Process Zones in the Kanawha River, West Virginia (from in-review manuscript by J.H. Thorp, J.E. Flotemersch, B.S. Williams, and L.A. Gabanski entitled "Critical role for hierarchical geospatial analyses in the design of fluvial research, assessment, and management").

Headwater streams represent more than half of the nation's stream miles and are fundamental to a healthy watershed. Properly functioning headwater streams are one of the primary determinants of downstream flow, water quality, and biological communities (Cohen, 1997). Headwater streams provide sediment, nutrient, and flood control and help to maintain base flow in larger rivers downstream. They support macroinvertebrate, amphibian, and plant populations that contribute to regional and local biodiversity.

Riparian zones are strongly influenced by the flow regime of a river, as well as the geomorphology of the river network, including the river banks and floodplain elevations. Riparian zones provide organic material as input to the riverine system, providing both energy and habitat to stream dwelling organisms. Riparian vegetation stabilizes the banks of the river channel and provides important nutrient and mineral cycling functions (Mitsch & Gosselink, 2007). Riparian habitats support diverse plant and animal species that provide important ecological functions and also regulate inputs to the aquatic system. These unique habitats require hydrologic connectivity with the river channel to be maintained.

Substrate composition is a physical habitat variable that is highly dependent on flow, geomorphic stability, and sediment inputs from the watershed. Many macroinvertebrates and aquatic plants require specific substrates for attachment and anchoring, while fish use cobble and boulders for shelter from currents and predators. Some fish species lay their eggs, which require unrestricted flow of well-oxygenated water, in gravel substrates. When these gravel substrates become embedded in finer sediment, the eggs do not have access to sufficient oxygen and die.

2.3.2 Lake Habitat

Lakeshores also have riparian zones that serve as a source of organic material to the lake's aquatic habitat and stabilize the lake's perimeter. Lakeshore vegetation creates stable habitat conditions in the peripheral waters of a lake by buffering it from exposure to environmental elements such as wind and sunlight. EPA's National Lakes Assessment (NLA) indentified poor lakeshore habitat as the most prominent stressor to the biological health of lakes (U.S. Environmental Protection Agency, 2009a).

Lakes are typically thought of as having three habitat zones: the littoral zone, the limnetic zone, and the benthic zone (Figure 2-14). The littoral zone is the nearshore area where sufficient sunlight reaches the substrate, allowing aquatic plants to grow. This zone provides habitat for fish, invertebrates, and other aquatic organisms. The limnetic zone is the open water area where light does not penetrate to the substrate. Although rooted aquatic plants cannot live in this zone, plankton and nekton are found here and serve as sources of food for many fish species. Habitat in the benthic zone (the lake bottom) consists of mostly mud and sand, which can support diverse invertebrate and algal communities, which in turn serve as primary food sources for many fish and other vertebrates.

The three lake habitat zones are tightly coupled, with organic matter from the limnetic zone serving as an important food source for animals in the benthic zone and many organisms spending different parts of their life cycles in different zones. Many fish species, for example, spend their time in the limnetic zone as juveniles, taking advantage of the abundant plankton found there. As they grow, they shift to feeding in the benthic zone and may spend their nights in the littoral zone, while other species may spend the day in the near shore zone and the night in the limnetic zone.

Lakes with greater, and more varied, shallow water habitat are able to more effectively support aquatic life (U.S. Environmental Protection Agency, 2009). Lakeshore habitat is strongly influenced by natural fluctuations in lake levels, with characteristic plant communities existing in the transition zone where the water rises and recedes. The natural fluctuation helps to prevent establishment of invasive species that are not adapted to such fluctuations and provides seasonal cues for reproduction of native species. Lake level fluctuation is influenced by ground water inputs, precipitation, evaporation, and runoff from storm events or snowmelt. Like riverine habitats, the physical and chemical characteristics of the water also contribute to the quality of a lake's aquatic habitat.

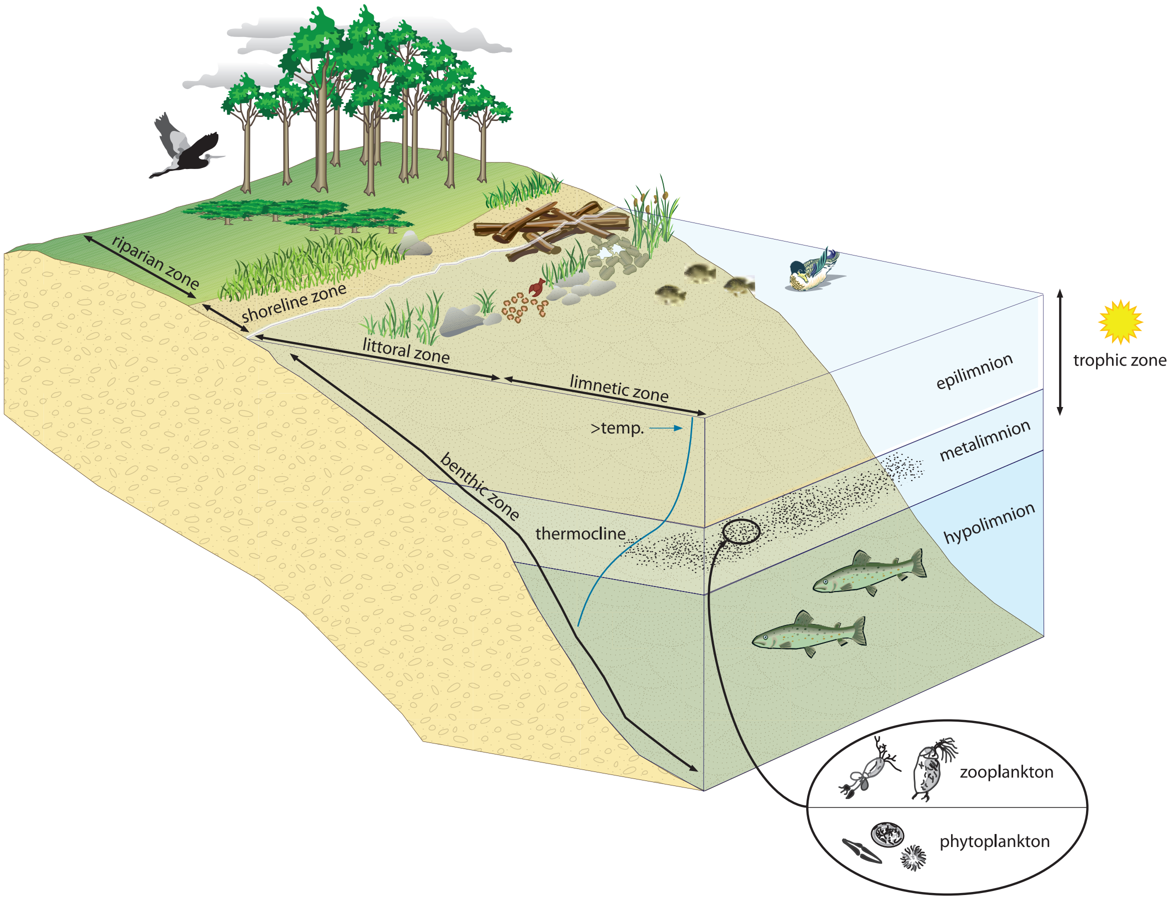


Figure 2-14 Schematic of a lakeshore and the three habitat zones of a typical lake (U.S. Environmental Protection Agency, 2009a).

2.3.3 Wetland Habitat

Wetland habitat characteristics are largely affected by their hydrologic connectivity to surrounding landscape features. The hydrogeomorphic wetland classification and assessment approach defines seven types of wetlands based on their geomorphic setting and dominant water sources: *riverine* wetlands primarily receive overbank flow from the stream channel, *depressional* wetlands receive return inflow from ground water and interflow, *slope* wetlands receive return inflow from ground water, *mineral soil flats* and *organic soil flats* primarily receive inputs from precipitation, *estuarine fringe* wetlands receive their water from overbank flows from the estuary, and *lacustrine fringe* wetlands receive their water primarily from overbank flows from lakes (Smith, Ammann, Bartoldus, and Brinson, 1995).

The biological communities that occur in wetlands are uniquely adapted to their environmental conditions because wetland habitats offer essential resources in limited forms and quantities. Soil saturation reduces the availability of oxygen to plants, and nutrient availability is low in some wetland types because decomposition rates are slowed in these low-oxygen conditions. Bogs, in particular, are characterized by their low nutrient concentrations. In other wetlands, the combination of shallow water, high levels of nutrients, and primary productivity is ideal for the development of organisms that form the base of the food web and feed many species of fish, amphibians, shellfish, and insects. Many species of birds and mammals also rely on wetlands for food, water, and shelter, especially during migration and breeding. Variations in the biological communities of different wetland types provide unique habitat structures. For example, swamp communities are dominated by woody vegetation, whereas marshes are dominated by herbaceous vegetation. More than one third of the United States' threatened and endangered species live only in wetlands, and nearly half use wetlands at some point in their lives (U.S. Environmental Protection Agency, 1995).

2.4 Hydrology

Watershed hydrology is driven by climatic processes; surface and subsurface characteristics, such as topography, vegetation, and geology; and human processes, such as water and land use. A watershed can be thought of as a surface catchment (drainage basin) plus a subsurface catchment. A drainage basin can be defined as the surface area that, on the basis of topography, contributes all the runoff that passes through a given cross section of a stream (Dingham, 2002). Drainage that occurs via subsurface flow, controlled by hydrogeology, is called the subsurface catchment (Kraemer et al., 2000). Precipitation that falls within the watershed can be stored on the land surface (e.g., lakes or wetlands), infiltrate to the subsurface, move as overland flow to stream channels, or be lost to evapotranspiration. Ground water can also enter and exit a watershed via inflow and outflow through aquifers that extend beyond the surface catchment. Rain and snowmelt produce runoff that moves through a variety of surface and subsurface pathways as it flows through the drainage network, eventually exiting the watershed via stream or ground water flow.

An important conceptual framework for understanding and evaluating watershed structure and function is the water budget (see Appendix A). A water budget can be developed for any hydrologic feature and accounts for all water inputs and outputs. A watershed scale water budget includes the following components:

$$P + Gin - (Q + ET + Gout) = \Delta S,$$

where P is precipitation, G_{in} is ground water inflow to the watershed, Q is stream outflow, ET is evapotranspiration, G_{out} is ground water outflow from the watershed and ΔS is change in storage over time.

Spatial and temporal variation in evapotranspiration, infiltration, and overland flow is determined by the size of the watershed, the surface topography and vegetation, the underlying geology, climatic conditions, and water and land uses. Small watersheds are more dynamic than large watersheds, responding more rapidly to inputs from precipitation. Hydrographs for streams dominated by snowmelt and base flow follow a more predictable pattern than those for streams dominated by surface runoff (Healy, Winter, LaBaugh, & Franke, 2007). Surface and ground water interact in a variety of ways. Overland flow to surface waters results from both saturation-excess and infiltration-excess runoff processes. Water that infiltrates to the subsurface can discharge to a nearby stream as interflow or move vertically to the water table providing aquifer recharge. Water that recharges aquifers flows through the subsurface to discharge areas, such as springs, seeps, wetlands, fens, streams, and lakes.

Stream flow can be affected by surface runoff, interflow discharge, and base flow discharge. The contribution of ground water to stream flow varies significantly, but is estimated to be 40% to 50% in small- to medium-sized streams (Alley, Reilly, & Franke, 1999). A given reach of stream can be perennial, intermittent, or ephemeral (Figure 2-15) and the ground water contribution can vary over an annual hydrograph.

2.4.1 Hydroecology

Hydroecology is a new discipline that examines the relationship of hydrology and ecology. Although hydroecology as a distinct discipline is new, this interdisciplinary field has, at its roots, the applied science of instream flows. With increasingly large withdrawals from surface and ground water, protection of sufficient instream flow became a major concern during the middle of the last century. The difficulty in determining ecologically relevant instream flow requirements initially led to the development of "rule of thumb" hydrologic statistics serving as the basis of minimum flows requirements (Annear, et al., 2004). The 7Q10 rule is an example of this kind of thinking. 7Q10 refers to the lowest 7-day average flow that occurs on average once every 10 years. It is calculated based on historic flows and does not necessarily "protect" because it is unrelated to any explicit biological needs or thresholds. Increased knowledge of aquatic ecosystems and access to computers led to more sophisticated techniques for assessing instream flow requirements in the 1970s and 1980s (Annear, et al., 2004). The National Biological Service published its Instream Flow Incremental Methodology (IFIM) in 1995. The IFIM uses a suite of models to evaluate physical habitat availability in riverine systems based on recent historical stream flows (Stalnaker, Lamb, Henriksen, Bovee, & Bartholow, 1995). It was developed in response to the National Environmental Policy Act's mandate that all federal water

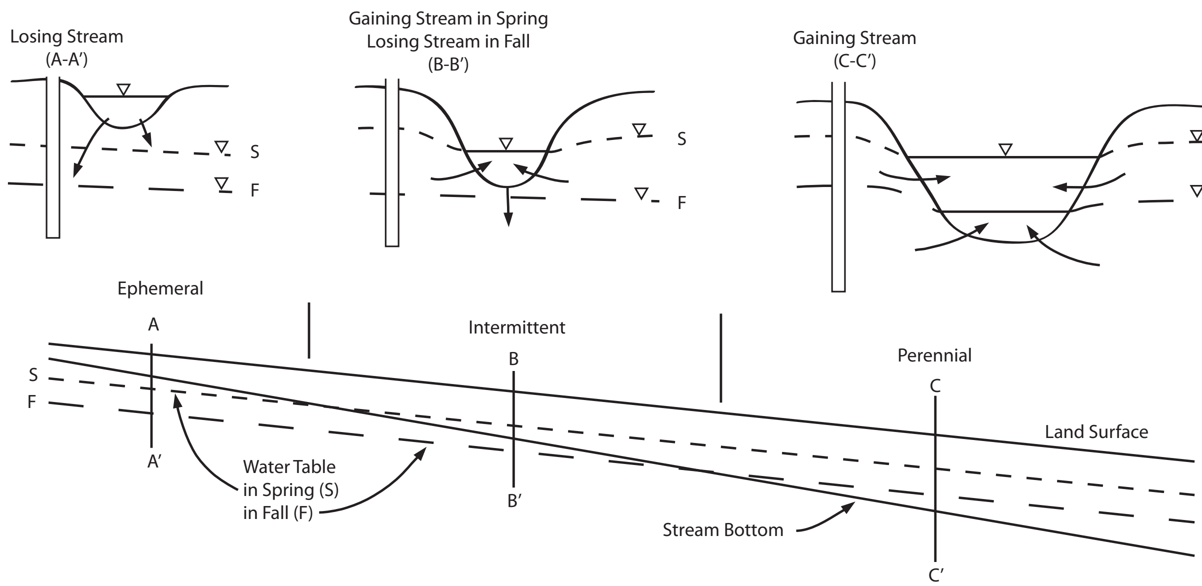


Figure 2-15 Relation between water table and stream type (U.S. Environmental Protection Agency, 1987).

resource management agencies consider alternative water development and management schemes (Stalnaker et al., 1995). IFIM was designed to predict the flow/habitat relationships for different species and lifestages, evaluate flow management alternatives, and reach agreement on preferred flow regime(s). This method is data intensive, requiring substantial fieldwork and multidisciplinary expertise.

Ecosystems are naturally dynamic and depend on recurrent natural disturbances to maintain their health. The publication of *The Natural Flow Regime* (Poff, et al., 1997) contributed greatly to the understanding that a dynamic river is a healthy river. Natural flow regimes are composed of seasonally varying environmental flow components (Matthews & Richter, 2007), including high flows, base flows, pulses, and floods. Each flow component serves critical ecological functions such as creating habitat and providing cues for spawning and migration during discrete times of the year (Figure 2-16 and Figure 2-17). Environmental flow components can be characterized in terms of their magnitude, frequency, duration, timing, and rate of change. The Indicators of Hydrologic Alteration (IHA) (Richter et al., 1996) quantifies these characteristics of environmental flow components, as well as other ecologically relevant stream flow statistics, based on daily stream flow data. IHA can also calculate the degree to which flow components have been altered from a reference condition. The Hydroecological Integrity Assessment Process (Henriksen, Heasley, Kennen, & Nieswand, 2006) also calculates stream flow statistics, and uses them to classify streams into regional hydrologic types. The Ecological Limits of Hydrologic Alteration (Poff, et al., 2010) is a framework that relates hydrologic alteration to ecological response to support the

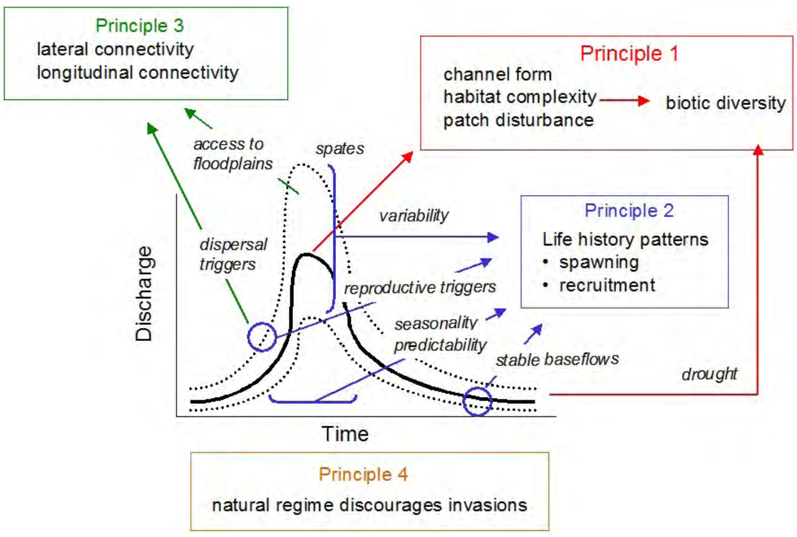


Figure 2-16 Different components of the natural flow regime support different ecological processes and functions (Bunn & Arthington, 2002). Reprinted with permission of Springer Science and Business Media B.V.

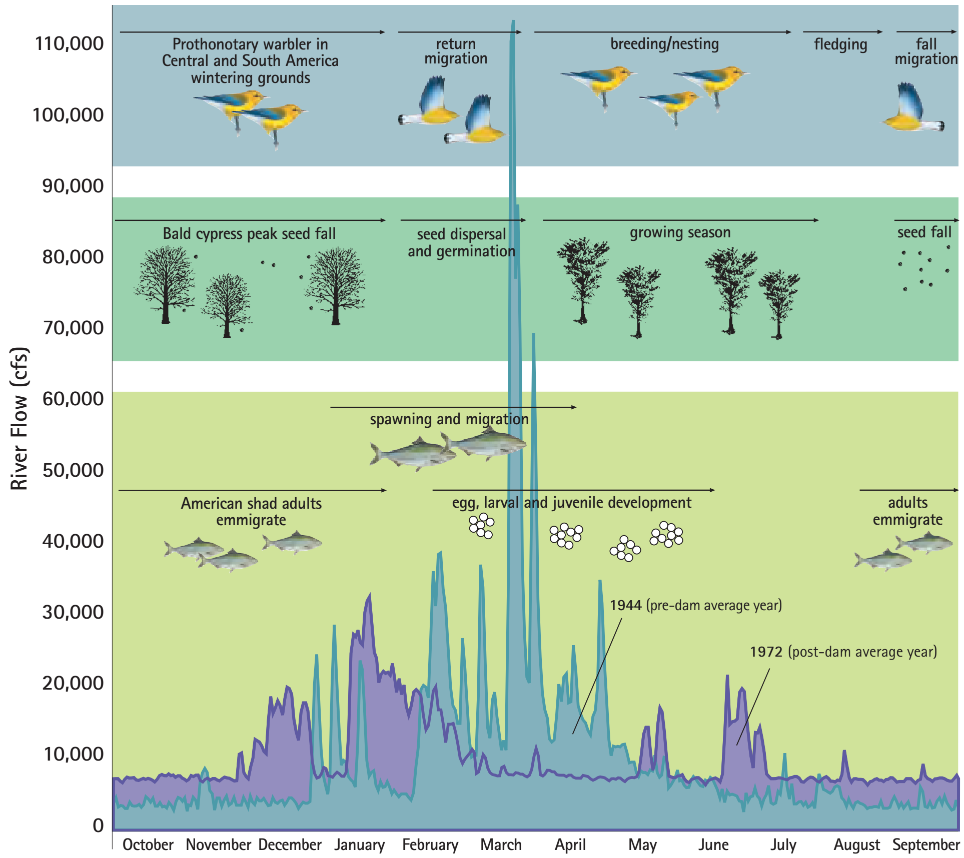


Figure 2-17 Ecological model of the Savannah River, Georgia illustrating the ecological importance of the natural flow regime. Note the loss of high and low flows during critical bioperiods for the post-dam hydrograph (The Nature Conservancy). Illustrations from the National Audubon Society: Sibley Guide to Birds, by David Allen Sibley, published by Alfred A. Knopf, Inc. Copyright © 2000 by Andrew Stewart Publishing, Inc. All rights reserved. Reproduced with permission of the copyright holder.

determination of environmental flow standards or targets. Recognition of the role that flow variability and disturbance play on the health of aquatic and riparian species initially led to flow prescriptions focused on one or a few species (Richter, Baumgartner, Powell, & Braun, 1996). More recent, holistic assessment methods (Tharme, 2003) focus on maintaining the natural flow regime, or the flow variation that existed prior to human modification, by relating flow statistics to a variety of biological community metrics (Richter et al., 1996).

The natural disturbance regime is a vital component of instream flow assessments. Holistic assessments determine the flow variability and magnitude necessary to maintain aquatic and riparian communities over time (Figure 2-18). In the higher order reaches of large river/floodplain systems, aquatic biota have adapted their life history strategies to cope with, and even take advantage of, the predictable flood regime. For example, a gradient of plant species exists along the aquatic/terrestrial transition zone as a result of seasonal degrees of inundation, nutrients, and light (Bayley, 1995). The littoral zone in rivers is a moving zone of alternating flooding and drying as the water level rises and falls. This zone provides excellent nursing grounds for many fish species, which have adapted their life histories to spawn just before or during the rising, flooding phase. During the drawdown phase, nutrient runoff from the littoral zone increases primary production of algae, which in turn increases production of aquatic invertebrates that feed on these algae. Not only does periodic flooding affect biological communities directly, but it also affects the distribution of habitat patches through sediment deposition and scouring. In order for this natural regime of flood disturbance to effectively influence riparian biodiversity, it is essential that the river channel maintain lateral connectivity with its floodplain (Junk & Wantzen, 2004).

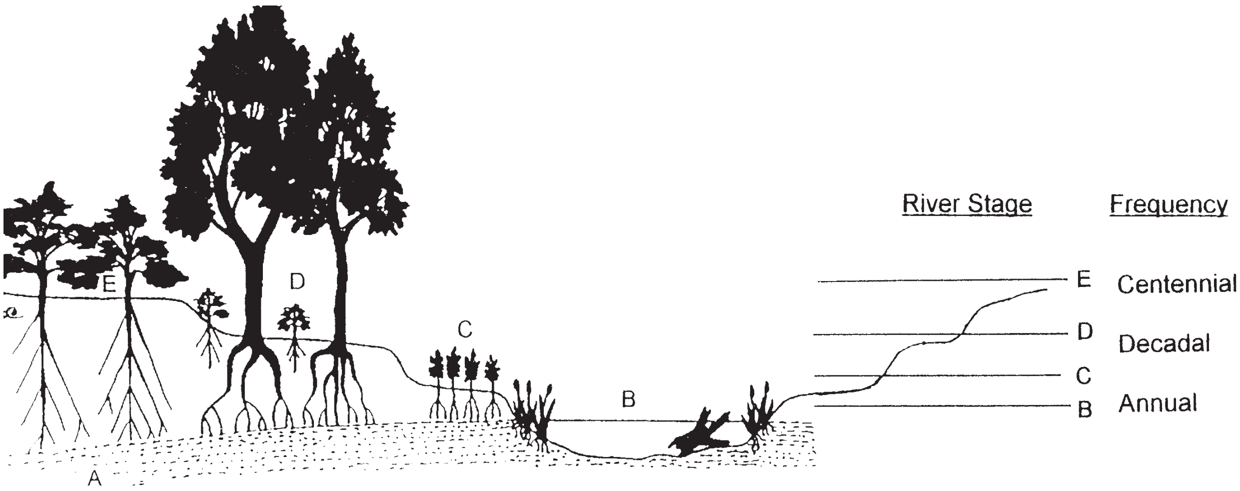


Figure 2-18 Geomorphic and ecological functions provided by different levels of flow. Water tables that sustain riparian vegetation and that delineate in-channel baseflow habitat are maintained by ground water inflow and flood recharge (A). Floods of varying size and timing are needed to maintain a diversity of riparian plant species and aquatic habitat. Small floods occur frequently and transport fine sediments, maintaining high benthic productivity and creating spawning habitat for fishes (B). Intermediate-sized floods inundate low-lying floodplains and deposit entrained sediment, allowing for the establishment of pioneer species (C). These floods also import accumulated organic material into the channel and help to maintain the characteristic form of the active stream channel. Larger floods that recur on the order of decades inundate the aggregated floodplain terraces, where later successional species establish (D). Rare, large floods can uproot mature riparian trees and deposit them in the channel, creating high-quality habitat for many aquatic species (E) (Poff et al., 1997). Reprinted with permission of University of California Press.

2.4.2 Ground Water Hydrology

It is estimated that ground water represents about 97% of all the liquid freshwater on earth (Dunne & Leopold, 1978). Water stored in rivers, lakes, and as soil moisture accounts for less than 1% of the planet's freshwater. Ground water is an important source of water for meeting human needs, including drinking water, irrigation, and industrial use. In the United States, approximately 50% of the drinking water supply comes from ground water; in rural areas, 99% of the population relies on ground water to meet their drinking water needs (Kenny et al., 2009). Ground water is equally important to conservation of aquatic and terrestrial ecosystems and species. Many aquatic, riparian, and wetland ecosystems rely on ground water to meet their water needs. Ground water is also important for maintaining the water temperature and chemical conditions required by these ecosystems and the plants and animals they support. Describing the link between ground water and ecosystems, understanding and documenting the key processes and functions that ground water provides, and identifying the critical threats are key components of a healthy watersheds assessment.

Spatial and temporal distribution of ground water recharge is influenced significantly by geomorphic landforms, soil conditions, vegetation patterns, and land use. Direct recharge occurs when precipitation infiltrates to the water table at or near the point of impact and does not run off. Direct recharge, more common in humid areas, is controlled by soil moisture, plant communities, and landform type. Indirect recharge occurs when precipitation flows as surface runoff and infiltrates to the water table at some distance from its original point of impact. More common in semi-arid regions, indirect recharge can occur in two ways: 1) infiltration of overland flow into fractures, joints, faults, and macropores; and 2) seepage through the beds and banks of recognizable streams, lakes, or wetlands (Younger, 2006). This happens in beds of ephemeral streams during flood flow and through multiple channel beds in alluvial fans along mountain fronts. Recharge to regional aquifers underlying a watershed may also occur by ground water inflow from aquifers outside the boundaries of the surface catchment. Adequate recharge is fundamental to ensuring that sufficient ground water is available to support ecosystems.

Ground water flows from areas of recharge to locations of discharge. Depending on the size and geology of a watershed, multiple aquifers may be found within the boundaries of a surface catchment. Conversely, a single aquifer may underlie multiple watersheds. Watersheds of moderate to large size and significant relief typically contain multiple ground water flow systems of different scales (Figure 2-19). Flow system boundaries are controlled by topography, type, and distribution of geomorphic land forms within the watershed, and the underlying geology. Ground water discharge is dynamic and occurs at a variety of locations within a watershed, including springs and seeps, streams, wetlands, and lakes. Discharge from local and intermediate ground water flow systems is likely to fluctuate over an annual hydrograph while discharge from deeper, regional aquifers is likely to be more stable. Travel times from ground water recharge areas to ground water discharge areas can vary greatly, from days to millennia.

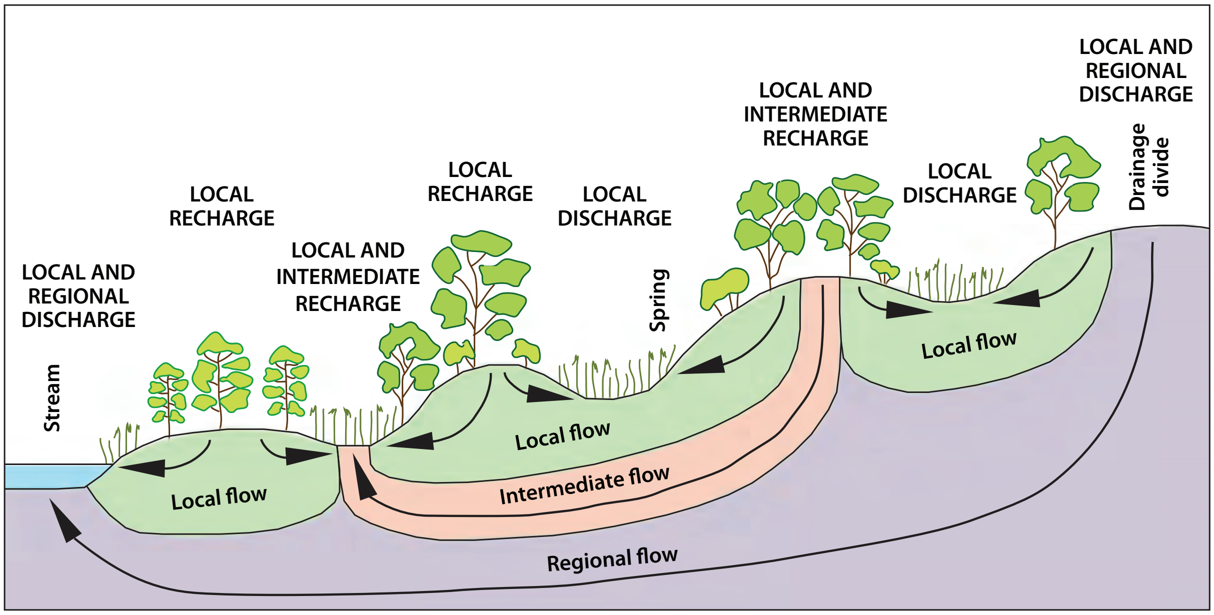


Figure 2-19 Different scales of ground water flow systems (modified from U.S. Geological Survey, 1999).

Discharge to Springs

Springs are focused points of ground water discharge. The locations of springs within a watershed are controlled primarily by topography and geology. Springs are the principal type of natural discharge for confined aquifers and are also important discharge features in unconfined aquifers. Springs can be divided into four types: 1) *depression springs* occur where the water table intersects the land surface; 2) *contact springs* occur along the geologic contact between an aquifer and a confining layer, usually at the lowest point where the confining layer intersects the land surface; 3) *fault springs* occur where faulting has brought an aquifer in contact with a confining layer; and 4) *sinkhole springs* occur in karst terrains where natural vertical shafts connect the land surface to underlying, confined karst aquifers. In watersheds underlain by consolidated bedrock, springs often occur where preferential flow paths composed of fractures and joints intersect the land surface. In semi-arid regions underlain by extensive bedrock formations, regional springs are critical for sustaining important ecological resources.

Discharge to Streams

Ground water discharges to streams via seepage faces above the channel and by direct inflow through the streambed. Streams can also lose water to underlying aquifers. Temporal and spatial distribution of ground water discharge can vary over the annual hydrograph. Perennial flow in most streams is due to base flow provided by ground water discharge. In arid areas or areas where aquifer water levels have been significantly lowered due to pumping, streams can be disconnected from the underlying aquifer.

An important hydrologic process affecting the chemical and biological conditions within a stream system is hyporheic flow (Figure 2-20). In streams with coarse bed sediments, there is strong mixing between ground water and stream water within the bed sediment in response to local head conditions. Within the hyporheic zone: 1) water in the channel can flow into the coarse bed sediment and back into the channel a short distance later; 2) ground water discharge can flow upwards through the bed sediment and into the channel; and 3) water from the open channel can flow downward though the bed sediment and infiltrate into the underlying aquifer.

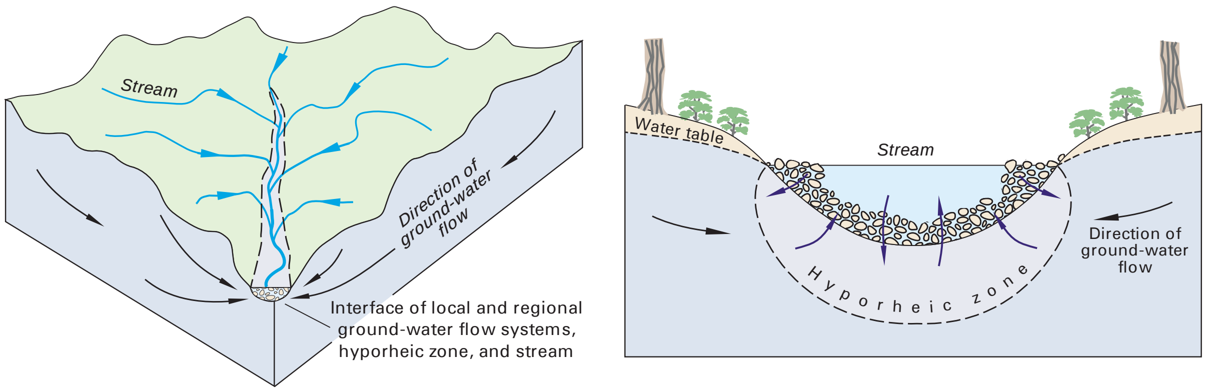


Figure 2-20 Streambeds and banks are unique environments because they are found where ground water that drains much of the subsurface of landscapes interacts with surface water that drains much of the surface of landscapes (Winter, Harvey, Franke, & Alley, 1998).

Discharge to Wetlands

Wetlands generally occur where hydrologic and geologic/topographic settings facilitate the retention of soil water and/or surface water. Wetlands commonly occur in topographic depressions and flat lying lowlands. However, wetlands can also occur on slopes and topographic high points. Sources of water to wetlands include rainfall, surface water inflow, and ground water discharge. Many wetlands occur where there is a perennial ground water discharge. Ground water supports wetlands by either focused discharge at the ground's surface or discharge from an underlying aquifer.

Discharge to Lakes and Ponds

Ground water discharge to lakes and ponds occurs primarily by preferential or diffuse inflow through the lakebed sediments in the littoral zone, and less commonly from seepage faces or springs above or below the water line. In humid, temperate areas there are typically four types of lake-ground water relationships (Younger, 2006): 1) lakes that receive most inflow from ground water and all outflow is to surface water, 2) lakes that receive most inflow from surface water and most outflow is to ground water, 3) lakes that receive most inflow from ground water and all outflow goes back to ground water (through-flow lakes), and 4) lakes that receive inflow from ground water and surface water and outflow is to ground water.

Ground Water Dependent Ecosystems

Ecosystems and species that depend on ground water to sustain their ecological structure and function are termed Ground Water Dependent Ecosystems, or GDEs (Murray, Hose, Eamus, & Licari, 2006). GDEs often harbor high species richness for their overall size, contributing significantly to the ecological diversity of a region. GDEs often contain endangered, threatened, or rare plants and animals. In addition, GDEs can act as natural reservoirs, storing water during wet periods and releasing it during dry periods, and can function as refugia during periods of environmental stress. In some circumstances, the flora and fauna of GDEs can help clean up contaminants and sediments.

Eamus and Froend (2006) identified six ecosystems that depend on ground water: springs, wetlands, rivers, lakes, phreatophytes, and subterranean systems. These ecosystems can be classified as either obligately ground water dependent or facultatively ground water dependent. Obligately ground water dependent ecosystems are found only in association with ground water. Facultatively ground water dependent ecosystems may receive some or all of their water supply from ground water, depending on the hydrogeologic setting.

Springs, including seeps, are ecosystems where ground water discharges at the surface. Thus, they are obligately ground water dependent by definition. The water supply of springs comes solely from ground water, and often this water has chemical or temperature characteristics that support uncommon communities or species (Sada et al., 2001; Williams & Williams, 1998). With some exceptions (e.g., arid regions), wetlands are generally facultative GDEs that, depending on their setting, may rely on ground water to create specific hydroperiods or chemical conditions, which govern wetland structure and function (Wheeler, Gowing, Shaw, Mountford, & Money, 2004; Mitsch & Gosselink, 2007). Some types of wetlands are obligately ground water dependent, such as fens, which receive their water supply almost exclusively from ground water (Bedford & Godwin, 2003). In some ecosystems, such as calcareous fens, the influx of ground water creates unusual water chemistry (Almendinger & Leete, 1998).

In general, rivers, lakes, and areas of phreatophytic plants are facultatively ground water dependent. However, perennial rivers and streams are often obligately dependent on ground water to maintain late-season base flow, maintain moderate temperature regimes, create certain water chemistry conditions, or produce thermal refugia for fish and other species during temperature extremes (Power, Brown, & Imhof, 1999). Lakes can receive significant inputs of ground water during certain times of the year under specific hydrologic, geologic, and topographic conditions (Grimm et al., 2003; Riera, Magnuson, Kratz, & Webster, 2000; Winter, 1978; Winter, 1995). Phreatophytic plants have deep roots that can access water in the capillary fringe, immediately above the water table; if these plants use this deep water at some point during the year or the plant life cycle, they are considered to be ground water dependent (Zencich & Froend, 2001). These species have been identified in arid climates, and recent work in more humid climates suggests this phenomenon may be more widespread than is generally acknowledged (Brooks, Meinzer, Coulombe, & Gregg, 2002).

Subterranean GDEs consist of aquatic ecosystems that are found in the free water of caves and karst systems, and within aquifers themselves (Gilbert, Danielopol, & Stanford, 1998). Aquifer ecosystems represent the most extended array of freshwater ecosystems across the entire planet (Gilbert, 1996). Their fauna largely consists of invertebrates and microbes (Humphreys, 2006). The ecological importance of subterranean ecosystems has only recently emerged in the scientific literature (Tomlinson & Boulton, 2008; Goldscheider et al., 2007; Hancock, Boulton, & Humphreys, 2005).

The type and location of GDEs depends on the hydrogeologic setting of the ecosystem in the watershed and its climate context. The hydrogeologic setting is defined by factors that control the flow of surface water and ground water to ecosystems. These factors include: elevation and slope of the land surface; composition, stratigraphy, and structure of subsurface geological materials in the watershed and underlying the GDE; and position of the GDE in the landscape (Winter, Labaugh, & Rosenberry, 1988; Komor, 1994; Bedford, 1999). Some common locations for GDEs to occur are landscape depressions, breaks in slope, and areas of stratigraphic change (Figure 2-21).

In general, there are three ecological attributes related to ground water that can be important to GDEs:

1. Water quantity: This includes timing, location, and duration of ground water discharge. In rivers and streams, ground water provides the base flow component of the hydrograph. In wetlands, ground water may partly or fully control the hydroperiod, or water table fluctuation. Shallow ground water can support terrestrial and riparian vegetation, either permanently or seasonally. Healthy watershed assessments and actions need to consider the relationship of ground water quantity to aquatic ecosystems.

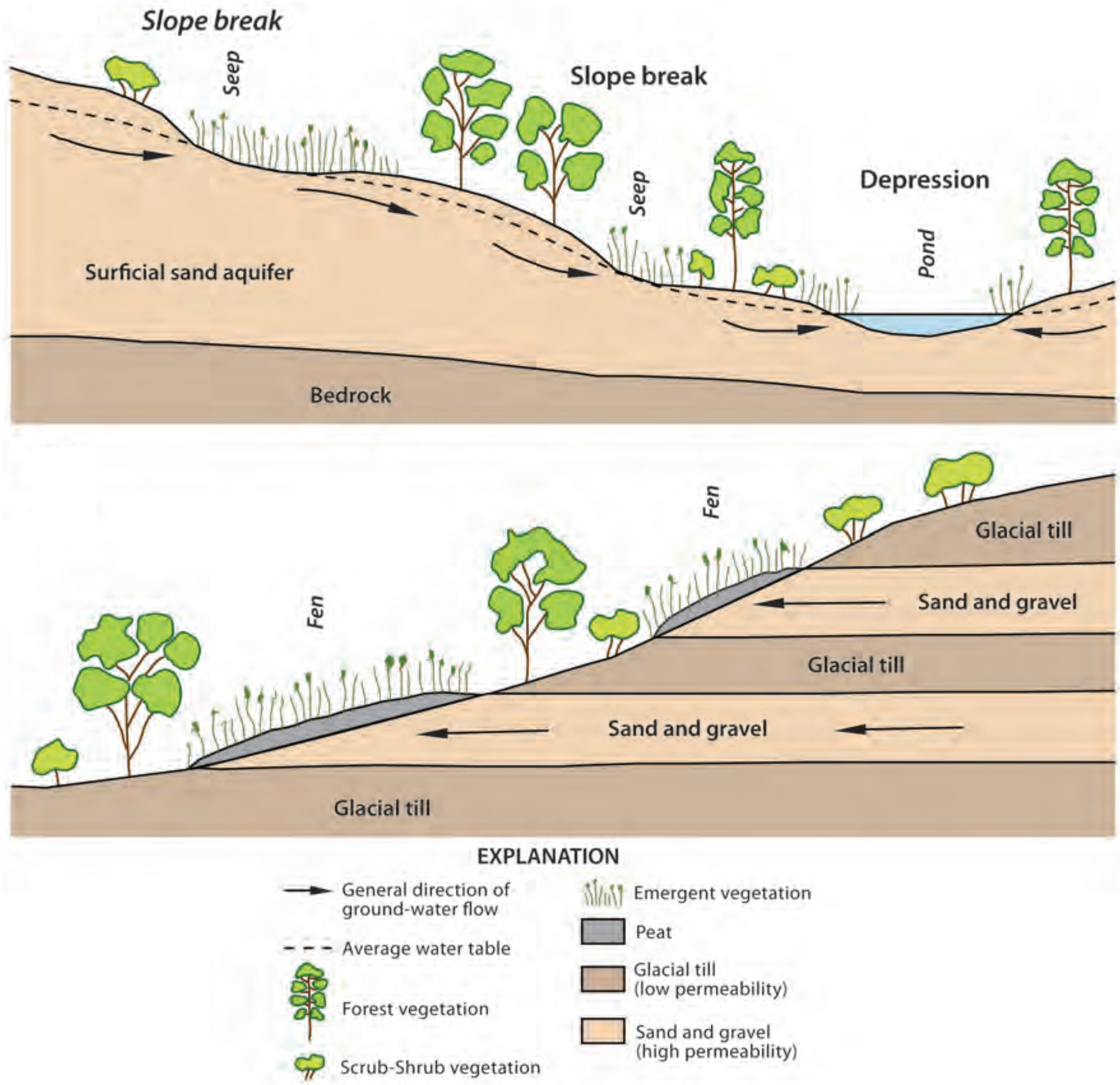


Figure 2-21 Common locations for ground water dependent ecosystems to occur include landscape depressions, breaks in slope, and areas of stratigraphic change (modified from U.S. Geological Survey, 1999).

2. Water chemistry: When ground water discharges at the surface, its chemical composition represents a mixture affected by the quality of the recharge water and the interaction of ground water with the geologic materials through which it flows. Many ground water fed wetlands (e.g., calcareous fens) have chemical compositions that support a unique suite of flora and fauna. In some settings, ground water can be the principal source of dissolved chemicals to a lake, even in cases where ground water is a small component of the lake's water budget (Striegl & Michmerhuizen, 1998).
3. Water temperature: Ground water emerging at the surface often maintains a fairly constant temperature year round. This low variability can be important as ground water dependent species can be adapted to these stable conditions. Localized areas of ground water discharge often provide areas of thermal refugia for fish in both winter and summer (Hayashi & Rosenberry, 2002). This is particularly important for species such as salmonids, including bull trout, which have specific temperature requirements for spawning and egg incubation (U.S. Fish & Wildlife Service, 2002; King County Department of Natural Resources, 2000). In some settings, ground water emerges at the surface as hot springs, which support a unique set of flora and fauna (Springer, Stevens, Anderson, Parnell, Kreamer, & Flora, 2008).

2.5 Geomorphology

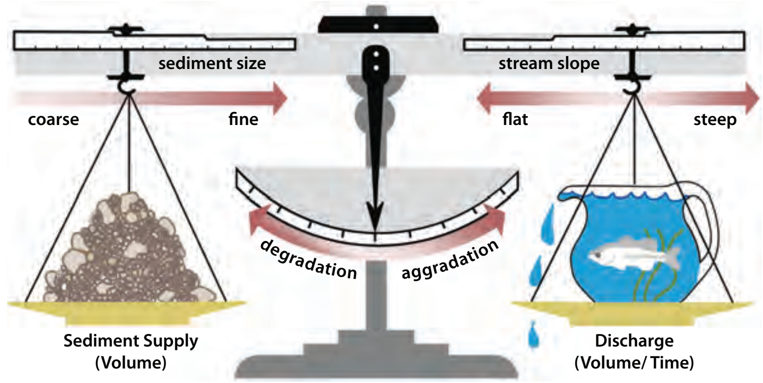


Figure 2-22 Lane's Balance (1955). Modified from Rosgen (1996). Reprinted with permission of American Society of Civil Engineers.

Fluvial geomorphology seeks to explain river forms and processes through an understanding of landscape characteristics, water movement, and sediment transport (Leopold, Wolman, & Miller, 1964). Watershed inputs (water, sediment, and organic matter) and valley characteristics (valley slope and width, bedrock and surficial geology, soils, and vegetation) determine a river channel's form (pattern, profile, and dimension) (Vermont Department of Environmental Conservation, 2007). Although watershed inputs and channel form vary over time, they are often considered to be balanced in natural systems. This natural balance is termed "dynamic equilibrium" and is illustrated by Lane's Balance (Figure 2-22), where sediment size and volume are in balance with stream slope and discharge. Any time one of these variables changes, the other variables will respond to bring the stream back to a dynamic equilibrium. Disturbances such as floods or forest fires are natural, episodic events that cause a stream to become unbalanced. After such disturbances, the stream will "seek" equilibrium conditions through adjustment of the components of Lane's Balance until the stream is once again in a form that allows it to efficiently perform its functions of water and sediment discharge. This form may or may not be the same as the pre-disturbance form. There are instances where a threshold is crossed, pushing the stream into a new, metastable state (Hugget, 2011). Periodic disturbances, of natural intensity and frequency, can increase aquatic biodiversity by creating opportunities for some species and scaling back the prevalence of others.

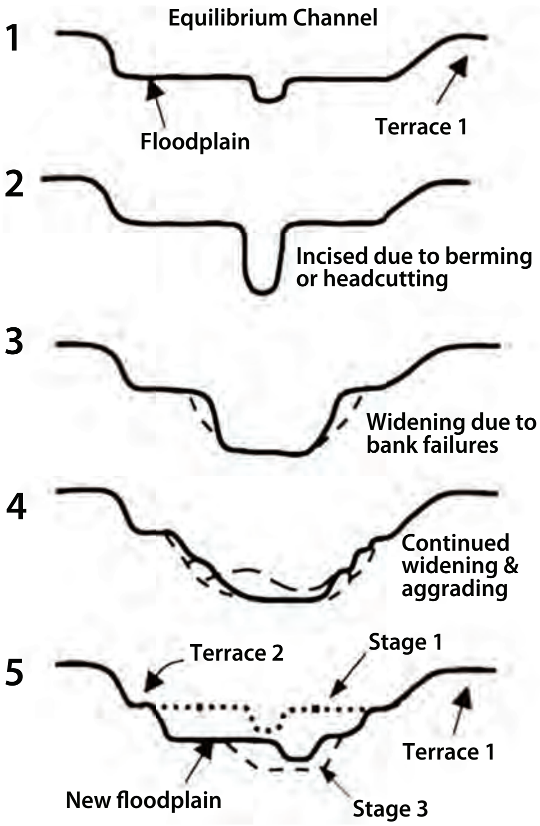


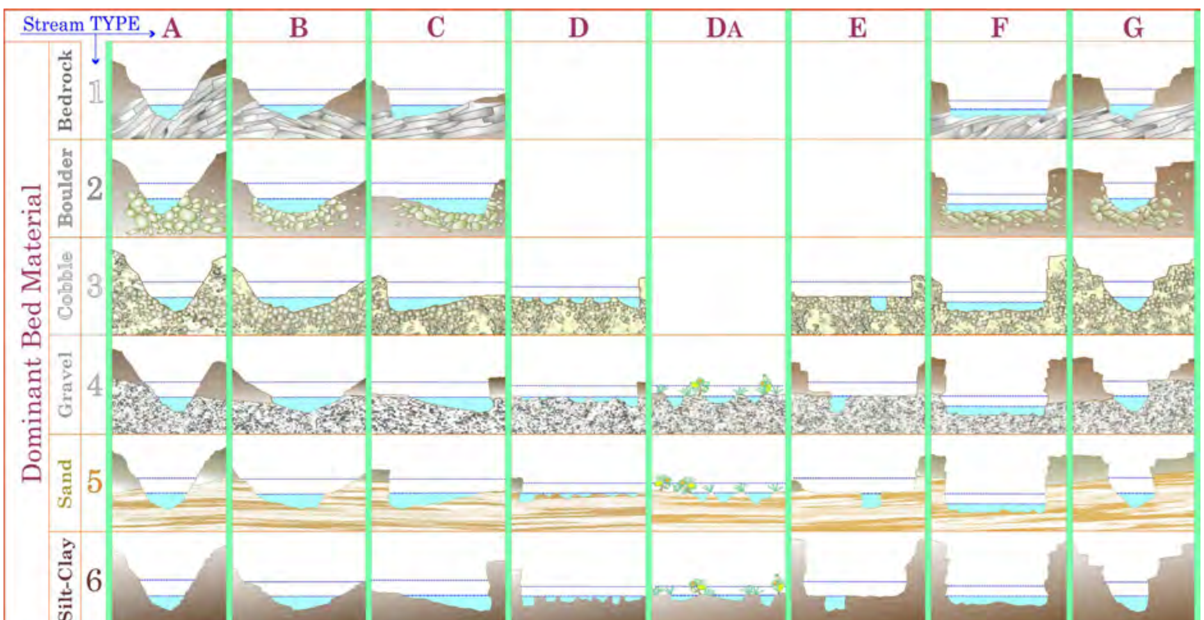
Figure 2-23 This channel evolution model shows the stages of channel adjustment due to a disturbance (modified from Schumm, 1977).

As a result of its watershed inputs and valley characteristics, a stream will typically have a predictable and characteristic form. When watershed inputs or valley characteristics change, or when disturbances are of extreme intensity or frequency, as many human disturbances are, a stream channel will undergo adjustment to a new form. Assessing a stream's watershed inputs and valley characteristics allows the resource manager to determine the predicted form of the stream channel. If the existing channel does not match the predicted form, it is likely undergoing adjustment to a new form, which will be evidenced by head cuts or channel incision (bed degradation), sedimentation or deposition (bed aggradation), or channel widening (Figure 2-23). The channel may also have already undergone adjustment and be in a stable new form. Factors that may initiate channel adjustment include changes in land use/cover (e.g., urbanization or agriculture), channel and floodplain encroachment (e.g., bank armoring and riverside development), and flow alteration (e.g., dam construction or large municipal withdrawals) (Vermont Department of Environmental Conservation, 2007).

Before the publication of *Fluvial Processes in Geomorphology* (Leopold, Wolman, & Miller, 1964), the field was primarily descriptive. The new quantitative focus drew the interest of engineers, which resulted in the development of engineered approaches to river restoration over the next few decades. David Rosgen's 1996 publication *Applied River Morphology* is one of the most influential in modern river restoration practice. His ideas built off of Luna Leopold's classification and Stanley Schumm's concept of channel evolution. Rosgen developed a classification system for describing channel form and sequences of adjustment in disturbed channels. The underlying principles in Rosgen's *Applied River Morphology* have been used by a number of states in their own river protection programs. The following are the objectives of the Rosgen stream classification system:

- Predict a river's behavior from its appearance.
- Develop specific hydraulic and sediment relationships for a given stream type and its state.
- Provide a mechanism to extrapolate site-specific data to stream reaches having similar characteristics.
- Provide a consistent frame of reference for communicating stream morphology and condition among a variety of disciplines.

This four-level, descriptive classification system is analogous to the Linnaean classification system in biology, in which each species receives one Latin name for its genus and one for its species. Level I of the Rosgen system classifies a channel as one of seven letters (A through G) based on channel slope, entrenchment, width/depth ratio, and sinuosity. The width/depth ratio and entrenchment refer to the amount of erosion that has shaped the stream channel and relate to the stream's power. There are then six numerical categories based on the dominant bed material (Rosgen, D., 1994) (Figure 2-24). An A3 stream, for example, is one in which the dominant substrate is cobble, the slope is steep, does not have much sinuosity (the channel is relatively straight), has a low width/depth ratio, and is well entrenched. These streams are typically found in mountainous headwater areas. Level II classifies stream types to a finer level of detail based on slope ranges. Levels III and IV then assess



Stream TYPE	A	B	C	D	DA	E	F	G
Entrenchment Ratio (W_{fpa}/W_{bkf})	<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 2-24 Rosgen stream types (Rosgen, D., 1996).

the stream's condition and validate the predictions based on field measurements. The Rosgen classification system is a valuable tool for communicating stream characteristics to others. However, it has been criticized for focusing too heavily on form without sufficient regard to variation in the processes affecting streams, such as flow hydraulics, sediment transport, and bank stability (Simon et al., 2007).

The mechanisms by which streams adjust to altered inputs of energy (stream slope and discharge) and materials (sediment size and volume) are just as important as the form of the channel. Quantitative linkages between sediment transport (the combination of energy and materials) and the driving and resisting forces (flow hydraulics and bank stability) acting on the stream channel can enhance the understanding of processes controlling channel form (Simon et al., 2007). For example, three streams with the same original morphology and similar altered sediment transport scenarios may adjust to different morphologies because of differences in bank materials (e.g., clay vs. silt vs. sand) (Simon et al., 2007).

2.6 Water Quality

Aquatic ecosystems are substantially affected by the quality of their water, but also by the chemical and physical characteristics of the air, surrounding watershed soils, and sediment transported through the aquatic system. EPA and states have established water quality criteria for freshwater ecosystems that address important ecological constituents. Chemical and physical constituents include: (1) concentrations of organic and inorganic constituents, such as nutrients, trace metals, and dissolved organic matter; (2) additional chemical parameters indicative of habitat suitability, such as pH and dissolved oxygen; and (3) physical parameters, including water temperature and turbidity. Many of these constituents are dynamic and related to natural watershed hydrology. For example, dissolved oxygen fluctuations in streams are related to watershed nutrient loading, biotic activity, stream flow, and temperature. Monitoring methods for many of these parameters are well established and should be part of an ecosystem assessment and management approach (MacDonald, Smart, & Wissmar, 1991).

Physical and chemical water quality is strongly influenced by hydrology, geomorphology, and landscape condition. Forested landscapes cycle nutrients and retain sediments, while riparian forests regulate temperature, shading, and input of organic matter to headwater streams (Committee on Hydrologic Impacts of Forest Management, National Research Council, 2008). Natural quantities of suspended and bedded sediments (SABS) transport nutrients, detritus, and other organic matter, which are critical to the health of a water body. Natural quantities of SABS also replenish sediment bed loads and create valuable microhabitats, such as pools and sand bars.

Material flows, such as the cycling of organic matter and nutrients, are very important ecosystem functions. As described in *The River Continuum Concept* (Vannote et al., 1980), the flow of energy and materials is closely linked by downstream transport of biomass created by primary productivity in headwater streams. These areas contain unique assemblages of organisms that begin the processing of coarse particulate organic matter, providing the nutrients required by other assemblages of organisms downstream.

Chemical and physical water quality parameters are common in water quality monitoring programs. The ecological information derived from chemical/physical monitoring will become more valuable as more sophisticated monitoring designs, sampling instruments, modeling tools, and analytical procedures are developed. Chemical and physical assessment information has been well integrated into assessments of biological condition, hydrology, geomorphology, and the importance of vegetative cover.

2.7 Biological Condition

Ecosystem protection efforts are often driven by concerns over biodiversity. Though originally defined simply as the number of species in a given region, the term biodiversity is now commonly used to refer to the diversity of life at all levels (from genes to ecosystems). Biological condition is defined here as the ability to support and maintain a balanced, integrated, and adaptive community with a biological diversity, composition, and functional organization comparable to those of natural aquatic ecosystems in the region (Frey, 1977; Karr & Dudley, 1981; Karr, Fausch, Angermeier, Yant, & Schlosser, 1986). Thus, biodiversity is one aspect of biological condition.

Large river basins that contain a distinct assemblage of aquatic communities and species are referred to as freshwater ecoregions. Freshwater ecoregions are a useful organizational unit for conducting biodiversity assessments, as a given ecoregion contains similar species, ecosystem processes, and environmental conditions. Freshwater ecoregional assessments identify the suite of places that collectively best represent the biodiversity and environmental processes of a large river basin. Efforts to protect "enough of everything" (The Nature Conservancy, 2011a) should consider ecoregional patterns and processes when assessing and prioritizing areas for ecosystem protection actions.

Biological condition can refer to individual organisms, species, or entire communities. The health of individuals may provide an indication of future trends affecting an entire population or supporting ecological process (e.g., the spread of a virus in fish populations). Species are a common focus because they may be endangered or game species, or because they exert an important influence on an ecosystem (e.g., indicator species or keystone species). Measures of species health include population size and genetic diversity. The condition of an entire ecological community depends upon species composition, trophic structure, and habitat extent and pattern. A balanced ecological community, as naturally occurs, reflects good water quality and a naturally expected hydrologic regime. Habitat variables such as substrate and vegetative cover also impact the biological health of aquatic ecosystems. Moreover, landscape conditions in the watershed will affect aquatic habitat through the dynamic linkage of terrestrial and aquatic elements that defines a watershed. Biology and habitat are intricately entwined, with habitat structural elements often composed of biotic components themselves. For example, certain invertebrate communities live out their lives on the leaves of wetland vegetation. If it were not for the existence of the wetland vegetation, which has its own habitat requirements, these invertebrate communities would likely not exist.

Biological assessments typically rely on bioindicators (U.S. Environmental Protection Agency, 2011b). Bioindicators are groups of organisms used to assess environmental condition. Fish, invertebrates, periphyton, and macrophytes can all be used as bioindicators. Species within these groups are used to calculate metrics, such as percent Ephemeroptera, Plecoptera, Trichoptera (EPT) or an Index of Biotic Integrity (IBI), which convey important information on the state of a water body. Bioindicators are useful measurements of environmental condition because they integrate multiple effects over time. An assessment of biotic organisms can often detect ecosystem degradation from unmeasured stressors and unknown sources of stressors. Many biological assessments rely on the concept of reference conditions to determine the relative biological health of a given water body. Reference conditions are the expected conditions of aquatic biological communities in the absence of human disturbance and pollution. Reference conditions may be modeled or determined through an assessment of minimally-impacted sites that represent characteristic stream types in a given ecoregion. Identifying reference conditions provides some of the information for the biological condition assessment component of a healthy watersheds assessment.

The Biological Condition Gradient (BCG) is a conceptual, scientific model for interpreting biological response to increasing levels of stressors. It has been shown to assist with more accurate assessments of aquatic resource condition, a primary objective of the CWA (Davies & Jackson, 2006). The BCG (Figure 2-25) describes six different levels of biological condition along a generalized stressor gradient ranging from biological conditions found at no or low stress (level 1) to those found at high levels of stress (level 6). This generalized stressor gradient consists of the sum of all aquatic resource stressors, including chemical, hydrologic, and geomorphic alterations. Biological condition can be evaluated through the use of new or existing biological assessment methods that have been calibrated to the BCG, such as an IBI, the River Invertebrate Prediction and Classification System (RIVPACS), or Threshold Indicator Taxa Analysis (TITAN).

The BCG is characterized by a description of how 10 attributes of aquatic ecosystems change in response to increasing levels of anthropogenic stress. The attributes include several aspects of community structure, organism condition, ecosystem function, spatial and temporal attributes of stream size, and connectivity (Davies & Jackson, 2006). A BCG can be used in conjunction with biological assessments to more precisely define designated aquatic life uses, establish biological criteria, and measure the effectiveness of controls and management actions aimed at protecting the aquatic biota (U.S. Environmental Protection Agency, 2011b). This approach, often called tiered aquatic life uses, when applied to water quality standards (WQS), consists of bioassessment-based statements of expected biological condition in specific water bodies and is based on the following concepts:

- Surface waters and the biological communities they support are predictably and consistently different in different parts of the country (classification along a natural gradient, ecological region concept);
- Within the same ecological regions, different types of water bodies (e.g., headwaters, streams, rivers, wetlands) support predictably different biological communities (water body classification);
- Within a given class of water bodies, observed biological condition in a specific water body is a function of the level of stress (natural and anthropogenic) that the water body has experienced (the biological condition gradient);
- Similar stressors at similar intensities produce predictable and consistent biological responses in waters within a class, and those responses can be detected and quantified in terms of deviation from an expected condition (reference condition); and
- Water bodies exposed to higher levels of stress will have lower biological performance compared to the reference condition than those waters experiencing lower levels of stress (the biological condition and stressor gradients).

The results of biological assessments based on the BCG approach can be used in state healthy watersheds assessments to identify high quality biological condition (e.g., BCG levels I and II) (Figure 2-26).

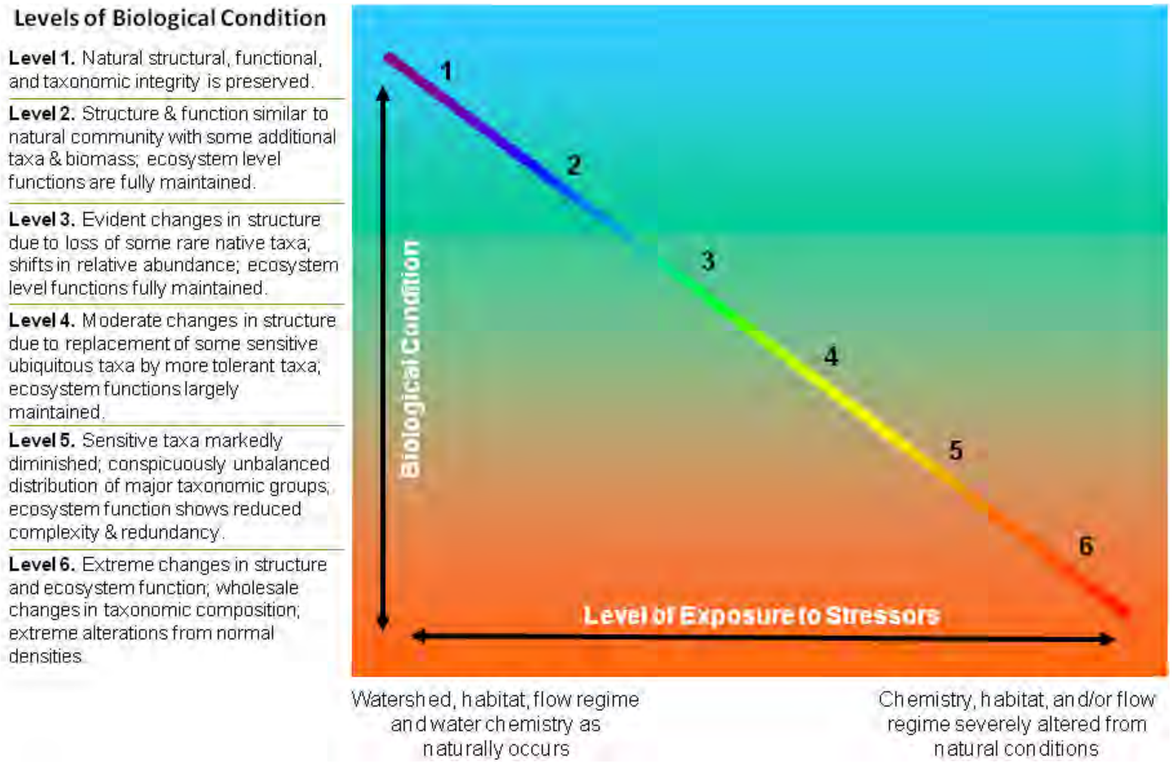


Figure 2-25 Conceptual model of the Biological Condition Gradient (U.S. Environmental Protection Agency, 2011c).

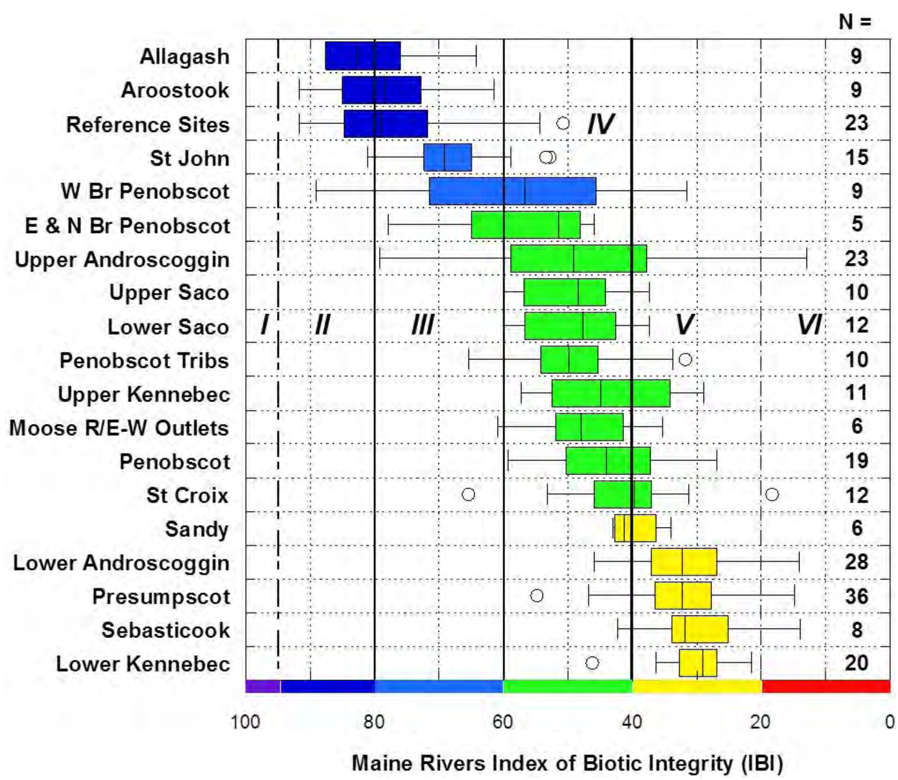


Figure 2-26 Box-and-whisker plots of Maine Index of Biotic Integrity (IBI) scores arranged, and color coded, according to the six Biological Condition Gradient (BCG) tiers (Chris Yoder, Midwest Biodiversity Institute, Personal Communication). The dark blue watersheds can be considered the healthy watersheds.

2.8 Watershed Resilience

A key component of watershed health is the ability to withstand, recover from, or adapt to disturbances, such as fires, floods, and droughts. Healthy ecosystems are naturally dynamic and often depend on recurrent natural disturbances to maintain their health. However, natural disturbance regimes have been severely altered in many watersheds due to dam construction, fire suppression, surface and ground water withdrawals, and land use change (Figure 2-27). This can increase a watershed's vulnerability to future disturbance events, whether natural or anthropogenic. Anthropogenic disturbances may take years to be recognized and can persist for decades or centuries (Committee on Hydrologic Impacts of Forest Management, National Research Council, 2008).

Figure 2-27 Sprawling development results in significant land use change, which can alter natural disturbance regimes.

Broadly speaking, stressors from human activity can be classified into two categories: 1) changes in the natural variability of ecological attributes; and 2) introduction of pollutants or species that interfere with ecological processes (Center for Watershed Protection, 2008c). The former can include urbanization impacts on the magnitude and frequency of stormwater runoff events, habitat conversion and fragmentation, climate change, and over-harvesting. If perturbations are large enough to reach a threshold, ecosystems can change rapidly to a new state (e.g., fishery collapse), and these changes are typically difficult to reverse (Noss, LaRoe III, & Scott, 1995). Pollutants that disrupt ecosystem function can be physical (e.g., sediment from construction sites) or chemical (e.g., pesticides). Salt Cedar, an example of a biological stressor, is an invasive tree that has spread throughout the western United States and uses long taproots to take advantage of deep water tables. Its invasion not only disrupts the native vegetative community, but also disrupts the natural hydrology of the area, affecting aquatic habitat as well.

The impact of climate change and other stressors on different ecosystems and regions of the United States depends on the vulnerability of those systems and their ability to adapt to the changes imposed on them. As temperature and precipitation regimes change, so too will the ecological processes that are driven by these regimes. These processes are assumed to have a natural range of variability that may be exceeded when disturbances, changes, and shocks occur to a system. In such cases, the system may still recover because its adaptive capacity has not been exceeded, or it could pass a threshold and change into another ecosystem state. Although some ecosystems can rely on their size for *resistance* to climate change, other ecosystems will need to rely on *resilient processes*. Resistance is distinguished from resilience in that resistant systems persist and remain relatively stable when faced with stresses, whereas resilient systems are affected by stresses, but are able to recover from the impacts of stress and adapt to new conditions. Increasing a system's resilience to pressures includes ensuring that watersheds have adaptive attributes such as meander belts, riparian wetlands, floodplains, terraces, and material contribution areas. For example, a disturbance may lead to changes in the timing, volume, or duration of flow that are outside the natural range of variability. In a healthy, resilient watershed, these perturbations would not cause a permanent change because riparian areas and floodplains would help to absorb some of the disturbance. Managing to optimize resilience includes both minimizing threats and protecting the most essential or sensitive areas.

An example of managing for resilience is the Massachusetts Division of Fisheries and Wildlife's process for identifying and prioritizing land protection and stewardship actions needed for long-term conservation of the state's biodiversity, and for climate adaptation (Massachusetts Department of Fish & Game and The Nature Conservancy, 2010):

1. **Prioritize habitats, natural communities, and ecosystems of sufficient size.** Larger ecosystems are more likely to provide the tracts of intact habitat and functioning ecosystem processes needed to support larger numbers of organisms and a broader diversity of native species. Climate refugia, which organisms can use to endure extreme conditions, are likely to be more prevalent in larger ecosystems than they are in smaller ecosystems as well.
2. **Select habitats, natural communities, and ecosystems that support ecological processes.** Healthy functioning of ecological processes allows an ecosystem to persist through conditions of environmental stress or adapt to the stresses imposed on it. Natural flow regime is an ecological process that is particularly important to healthy watersheds. Ecosystems that have the least potential to be disturbed by anthropogenic influences often have the greatest potential to maintain functioning processes in the long term and are thus most likely to have the resilience needed to recover from climate change impacts.
3. **Build connectivity into habitats and ecosystems.** Connectivity is a conservation priority for the same reason that large ecosystems are a conservation priority: it maximizes the accessibility of resources populations can use to survive periods of environmental stress. Many species representing diverse classes of organisms, including amphibians, aquatic insects, and anadramous and catadramous fish require multiple habitat types to carry out their life cycles. In addition to connectivity to other habitat sources, wildlife populations need connectivity to other populations of their own species in order to maintain levels of genetic diversity sufficient to sustain viable populations.
4. **Represent a diversity of species, natural communities, ecosystems, and ecological settings.** Conserving a representative set of species and habitats creates a diversified "savings bank" of physical and genetic resources that provides the greatest chances for successful ecosystem adaptation and recovery. In addition, protecting a variety of habitat conditions provides a coarse filter for protecting the diversity of biota these conditions support.