Watersheds

Introduction

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This training module introduces watershed ecology. Understanding watershed structure and natural processes is crucial to grasping how human activities can degrade or improve the condition of a watershed, including its water quality, its fish and wildlife, its forests and other vegetation, and the quality of community life for people who live there. Knowing these watershed structural and functional characteristics and how people can affect them, sets the stage for effective watershed management.

After completing this training, the participant should know the basic biotic and abiotic components of watersheds, the basic natural processes and interrelationships occurring in watersheds, and how watershed structure and functions may vary in time and space. Some background in the life sciences is helpful for comprehending this material, but not required.

Watershed Ecology

Watershed ecology is essential knowledge for watershed managers because it teaches us that watersheds have structural and functional characteristics that can influence how human and natural communities coexist within them. The gross structure of a watershed -- its headwaters area, side slopes, valley floor, and water body, as well as its soils, minerals, native plants and animals -- are, in one sense, raw material for all the human activities that may potentially occur there. The watershed's natural processes -- rainfall runoff, groundwater recharge, sediment transport, plant succession, and many others -- provide beneficial services when functioning properly, but may cause disasters when misunderstood and disrupted. It is crucial for people to understand watersheds and how they work before they make decisions or take actions that may affect important watershed structural or functional characteristics.

Definitions
Watershed: An area of land that drains water, sediment and dissolved materials to a common receiving body or outlet. The term is not restricted to surface water runoff and includes interactions with subsurface water. Watersheds vary from the largest river basins to just acres or less in size.
Watershed Ecology: The study of watersheds as ecosystems, primarily the analysis of interacting biotic and abiotic components within a watershed's boundaries.
Ecosystem: A functioning natural unit with interacting biotic and abiotic components in a system whose boundaries are determined by the cycles and flux of energy, materials and organisms. It is valid to describe different ecosystems with different, overlapping sets of boundaries in the same geographic area (e.g. forest ecosystems, watershed ecosystems and wetland ecosystems). A watershed is just one of many types of ecosystems.

Watershed Ecology Topics

This module introduces watershed ecology by covering the following five topics:

Major landscape-defining processes: the physical template. This section covers the physical processes which are shaping forces of ecosystems. Climate, hydrology, and geomorphology provide the template upon which all life is ultimately based.

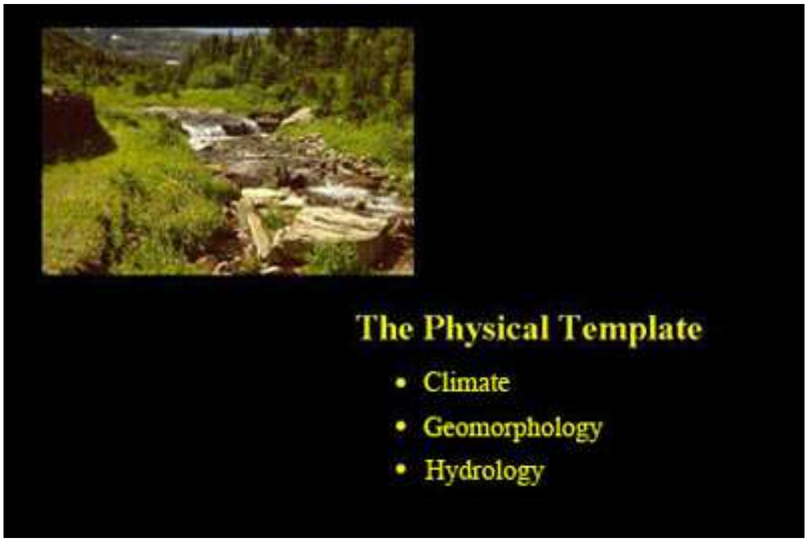
The biological setting. This section discusses the terms and concepts associated with ecosystem science as it relates to living plant and animal communities.

Natural systems concept. This section discusses how watersheds behave as natural systems and describes how different-sized watersheds operate on various spatial and temporal scales. This section also introduces structure and function, two vital concepts for understanding and managing watersheds and ecosystems.

Watershed structure. This section defines the various patterns of physical structure formed by both the living and non-living watershed components.

Watershed functions. This section covers watershed functions and processes -- vital cyclic events necessary to the continuation of life in aquatic and terrestrial systems, and the source of substantial ecological services and benefits to our human communities as well.

The Physical Template



Within the watershed, various forms of matter, including water, are in constant cyclic flow. Through these processes, an abiotic (non-living) template of air, water, and soil is formed, upon which life can exist. The physical template of watershed structure is ultimately determined by varying combinations of climatic, geomorphic, and hydrologic processes.

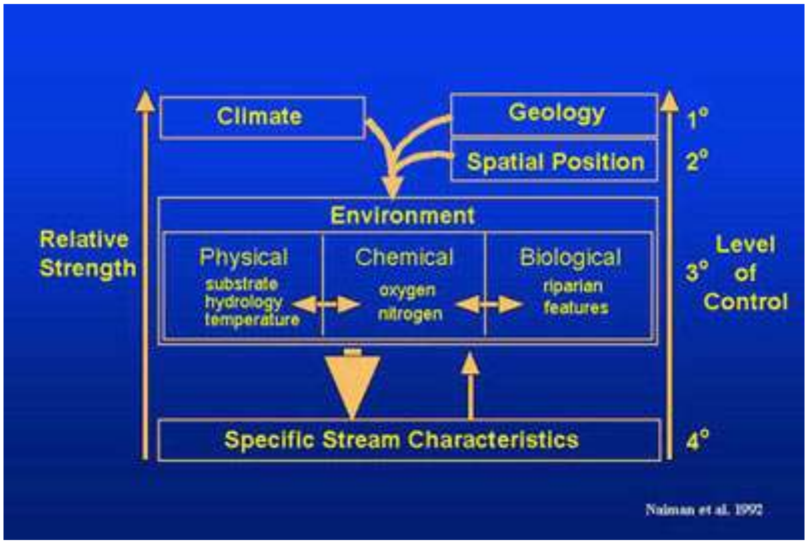
Climatology, the science of climate and its causes, becomes important in understanding regional issues in watershed science. Though sometimes used synonymously with weather, climate is actually a distinct term with important ecological ramifications. Climate refers to an aggregate of both average and extreme conditions of temperature, humidity, and precipitation (including type and amount), winds, and cloud cover, measured over an extended period of time. Weather refers to present-day environmental conditions; current temperatures and meteorological events make up weather, not climate. Long-term weather trends establish averages which become climatic regimes. Climate heavily influences watershed vegetation communities, streamflow magnitude and timing, water temperature, and many other key watershed characteristics.

Geology is defined as the science centered around the study of various earth structures, processes, compositions, characteristics, and histories. **Geomorphology**, however, refers specifically to the study of the landforms on the earth and the processes that change them over time. Fluvial geomorphology, referring to structure and dynamics of stream and river corridors, is especially important to understanding the formation and alteration of the stream or river channel as well as the flood plain and associated upland transitional zone; this is a critical discipline for effective, long-term watershed management.

One of the life-sustaining cycles we are most familiar with is the hydrologic cycle. This cycle is a natural, solar-driven process of evaporation, condensation, precipitation, and runoff.

Hydrology is the science of water, as it relates to the hydrologic cycle. More specifically, it is the science of water in all its forms (liquid, gas, and solid) on, in and over the land areas of the earth, including its distribution, circulation and behavior, its chemical and physical properties, together with the reaction of the environment (including all living things) on water itself. The global water budget adds further insight into the water resources of our planet.

Watershed Structure and Composition



The three elements of the physical template and other factors also interact significantly in determining the structure and composition of a watershed and its biotic communities. **In this**

diagram, the strength of influence on the watershed is represented in two ways: the relative size of the arrows, and the level of control indicated at the right side of the diagram.

As a result of different combinations of these formative processes, different types of watersheds are created. Here are some examples that show how different from one another watersheds of different origin and physical template conditions can be.

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The Biological Setting

Concepts of basic ecology provide us with the vocabulary to understand and describe the biological setting of watersheds and the interaction of biotic components with the physical template just described. It is important to have a working knowledge of the following basic ecological terms: ecology, species, population, community, habitat, niche, ecosystem, ecotone, and biosphere. Beyond these basic definitions it is also important to understand the following ecological concepts: life history strategies, carrying capacity, competition, and symbiosis. You should become familiar with these basic definitions and key concepts before we discuss specific areas of ecology that are particularly relevant to watersheds.

Soil Ecology

Soil is a complex mixture of inorganic materials (sand, silt, and clay), decaying organic matter, water, air, and a great array of organisms. Because of its abundance of living organisms, soil is discussed here along with other "biological setting" components, even though soil is sometimes incorrectly described as a physical, non-living entity.

Soil has three basic properties which aid in its identification and taxonomy: color, structure, and texture. Soils often vary substantially from place to place within a watershed, and among different watersheds. To describe their differences, soils are classified into soil orders. Knowing the basic differences among types of soils can be useful for understanding why they vary in their suitability for supporting different land uses and ecological communities. Histosols, for instance, are poorly drained with a high organic content. These, essentially, are wetland soils -- soils where a constant presence of water allows for the growth of water-tolerant plants, but breakdown of organic matter is slow due to the anaerobic condition of the soil. Oxisols, on the other hand, occur throughout the tropics -- these soils are low in nutrients because most available nutrients are being utilized. The extremely high turnover rate (of matter and particularly nutrients) in the tropics makes these soils, when taken alone, highly infertile. This is one of the key reasons why deforestation in tropical watersheds creates a serious dilemma: once the vegetative cover is removed, there is little capacity for the site to self-restore.

Food Webs and Trophic Ecology

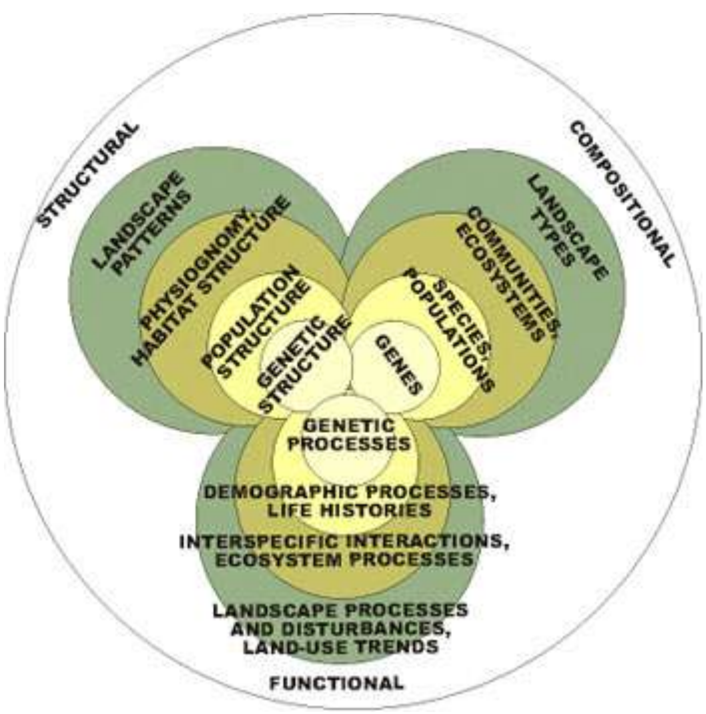
Terrestrial and aquatic ecosystems have characteristic trophic (feeding) patterns that organize the flow of energy into, through, and out of the watershed ecosystem and support the growth of organisms within the system. Food "chains" are rarely linear, hence the term **food web**, often used to describe the trophic interactions of organisms within an ecosystem.

Within a food web, organisms interact and, in the process, may directly or indirectly affect other organisms. The example pictured is a simple, aquatic-only food web; when the whole watershed's terrestrial components are also considered, food webs can be very complex with numerous interactions among land-based and water-based species. Food webs also often recognize the different roles species play by terming them **producers** (organisms that generate food, primarily through photosynthesis), **consumers** (first-order consumers are vegetarians, second-order consumers feed on first-order, etc.), and **decomposers** (which feed on dead tissue and return nutrients and energy to other parts of the cycle), among other terms.

Species with especially far-reaching effects on an ecosystem are called **keystone species**. These species differ from dominant (i.e. abundant) species in that their effects are much larger than would be predicted from their abundance. They have a disproportionate effect on the composition of communities and ecosystem function. A keystone species' presence is often the lone reason for the presence of other organisms and/or the maintenance of unique ecological areas. The effects of keystone species are context-dependent, meaning that a species is not always a dominant controlling agent across its entire range, through all stages of its life cycle, or at all times of the year. The American Alligator is an example: it is not the most common species in southern swamplands and bayous, but it is an important predator that also modifies aquatic habitat structure by creating `gator wallows'.

Indicator species are species whose presence or absence indicates an environmental change. 19th-Century coal miners used to keep a caged canary with them in the mine shaft; the especially-sensitive canary would signal the presence of dangerous, flammable gases by ceasing to sing, and dying. The ever-cognizant miners could evacuate upon noticing the death of the pet bird. This is the concept behind an indicator species: they are modern-day canaries-in-a-coal mine. Watershed canaries in a coal mine include several types of aquatic invertebrates that are labeled "intolerant" of poor water quality, and amphibians such as frogs and salamanders.

Biodiversity (Genetic, Population, Species, Habitat)



Biodiversity is a contemporary term which has several subcategories. In general, the term applies to the relative amount of biological elements existing within a given area. The accompanying image illustrates the complexity and importance of biodiversity at different levels from the genetic to the landscape scale, noting how biodiversity influences and helps define the structural, functional and compositional nature of our environment.

Genetic biodiversity refers to the total number of genotypes available within a given population. For example, whooping cranes were driven to the brink of extinction; at one point the total global population stood at 14 individuals. Today, the population has returned to a more comfortable level. Still, the current population is limited to the genetic material which was contained within those 14 birds, and it will take eons and many, many generations for genetic diversity to build up again. Populations with low genetic biodiversity may be more susceptible to certain diseases given the limited amount of genetic resistance potentially available. A "genetic bottleneck" refers to the loss of valuable survival traits from a population that has shrunk to a low level and then re-expanded.

Population biodiversity refers to the total amount of populations a given species has, worldwide. For instance, Pacific salmon are anadromous, meaning that they are born in freshwater, spend their adult life in the ocean, and then return to the fresh water from whence they originally came to reproduce and then expire. These fish rarely stray to other river systems, migrating in distinct populations from river to sea and then back to the same river. While the total number of pink salmon may be "healthy", given the number of fish surviving in Alaska, population biodiversity may suffer if several rivers in southern British Columbia suddenly experience the loss of the runs of these fish.

Species biodiversity is the total number of species found within a given area. In natural systems, as an example, species biodiversity is considered quite high in the tropical regions of the world, while the number may be quite moderate in temperate zones. In the woodlands of Pennsylvania, for instance, it is not uncommon to count on one hand the total number of tree species within an acre of land. In the tropics, the number of tree species found within an acre of land may be over 250.

Habitat or **ecological biodiversity** refers to the number of different habitats or ecotypes found within a given region. In the Pacific Northwest, industrial forestry has reduced entire landscapes to monocultural tree plantations with a simple, homogeneous forest structure. On the other hand, in the region's natural systems there exists a much higher level of ecological diversity, given the various natural processes (e.g., wind, fire, flooding, disease, succession, competition) which create a mosaic of habitat types.

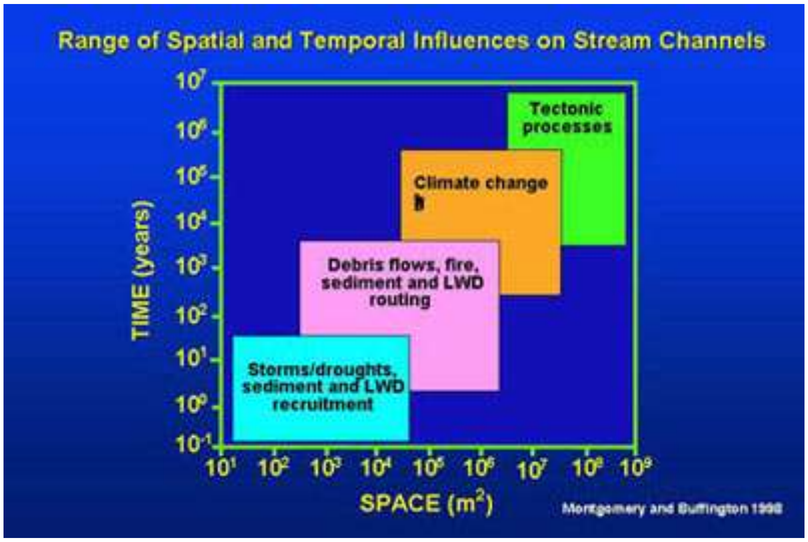
The Natural Systems Concept

Thus far, you have been introduced to the physical template from which watersheds develop, and the biological setting which then becomes established upon and integrated with the physical template. The interactions and natural processes that link these abiotic and biotic components of watersheds (note here the similarity to the definition of ecosystem) exhibit what can be called **system-like behavior**.

The dictionary defines a **system** as "a group of interrelated, interacting, or interdependent constituents forming a complex whole." We have seen that natural systems such as watersheds have interacting components that together perform work (e.g., transport sediment, water, and energy) and generate products (e.g., form new physical structures like floodplains or channels, and form biological communities and new energy outputs). In a natural system, interactions make the whole greater than the sum of its parts -- each of the physical and biological components of watersheds if they existed separately would not be capable of generating the work and the products that the intact watershed system can generate.

The natural systems concept is key to watershed management because it emphasizes that a watershed, as a natural system, is more than just a variety of natural resources coincidentally occurring in one place. Severely degraded watersheds may have lost several of their components and functions and provide fewer benefits to human and natural communities as a result. Thus it is clear that **recognizing the natural system** and **working toward protecting the system's critical components and functions** are key to sustainable watershed management. Other ecological concepts and theories help explain the idea of natural systems. These include **spatial and temporal scale, disturbance theory, and the river continuum concept**, all discussed below

Spatial and Temporal Scale



Spatial and temporal scales are important parts of the natural systems concept. The spatial scale at which a system operates is an important factor in recognizing the system's key components, and in turn, the kind of management practices that may be appropriate. In the diagram, note the general tendency for systems at a larger spatial scale to have natural processes that operate on longer time frames.

Disturbance Theory

Whereas natural systems have a certain degree of organization and order, they also exhibit constant change and disturbance at varying levels. Disturbance ecology often centers around a concept known as the intermediate disturbance hypothesis. This hypothesis explains why diversity is often highest in systems with intermediate levels of disturbance. Few species are capable of colonizing an area that either experiences high frequency or intensity of disturbance (e.g. frequent or intense flooding). In areas of low or infrequent disturbance, a small number of species optimally suited to local conditions establish themselves and outcompete other potential colonizers, so here too diversity tends to be lower.

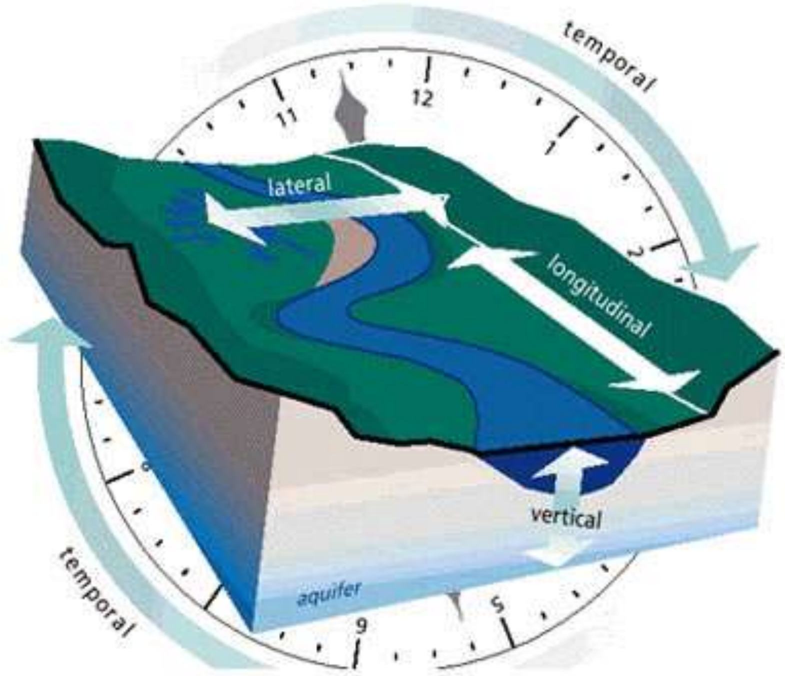
The importance of natural disturbances in shaping landscapes and influencing ecosystems is well-documented in the scientific literature. Ecologists generally distinguish between relatively small, frequent disturbances and large, infrequent, so-called "catastrophic" disturbances. Much has been recently learned of the former, while a relative paucity of data exists on the latter. Examples of small, frequent disturbances include seasonal floods, periodic grassland fires, and mild to moderate storms which periodically influence the landscape (e.g., wind-created forest canopy gaps). Examples of the large, infrequent disturbances include volcanic eruptions, hurricanes, and major wildfires. Recent examples of these include the 1988 Yellowstone fires (which charred over 1,500 mi^2 of predominantly forested National Park land), Hurricanes Hugo and Mitch (which flattened trees and created landslides in Puerto Rico and Honduras, respectively), and Mount St. Helens, which erupted in May 1980 and affected more than 250 mi^2 within the affected landscape, including areas of pyroclastic flow, debris avalanche, mudflow, blowdown, singe, and ash deposition.

The River Continuum Concept
This concept (Vannote et al. 1980) is a generalization of the physical and biological patterns often seen in different zones of rivers from source to mouth. Conceptually, from headwaters to outlet, there exists in a river a gradient of physical conditions width, depth, velocity, flow volume, temperature, and other factors. Geomorphologists have shown that lotic (flowing water) systems show patterns, or adjustments, in the relationship of a number of physical characteristics (e.g., stream width, depth, velocity, bedload) along their entire length. Biotic characteristics in each zone reflect the influence of the physical influences they exist under; in other words, similar natural systems often develop under similar conditions. And as we move from the headwaters to a downstream reach, we see a continuum of physical conditions and a subsequent response in expected biota within these aquatic systems.

Watershed Structure

Now that you have reviewed the physical and biological components of watersheds and considered that together they comprise organized, functional systems, the discussion now will briefly cover **watershed structure**. Basically, this includes structure of **flowing waters** (mainly rivers and streams with associated riverine wetlands and riparian zones), **still waters** (lakes and associated basin-type wetlands and shorelands), and **upland areas** of watersheds. Note that other existing and planned Watershed Academy Web modules cover the structure and classification of streams and stream corridors and upland landscape patterns in greater detail than the brief introduction presented here.

Flowing (Lotic) Systems



The US has more than 3.5 million miles of flowing water systems, which include springs and seeps, rivers, streams, creeks, brooks and side channels.

At left, the **Four-Dimensional Concept** (Ward 1989) recognizes that lotic systems' structure exists in a four-dimensional framework, as below:

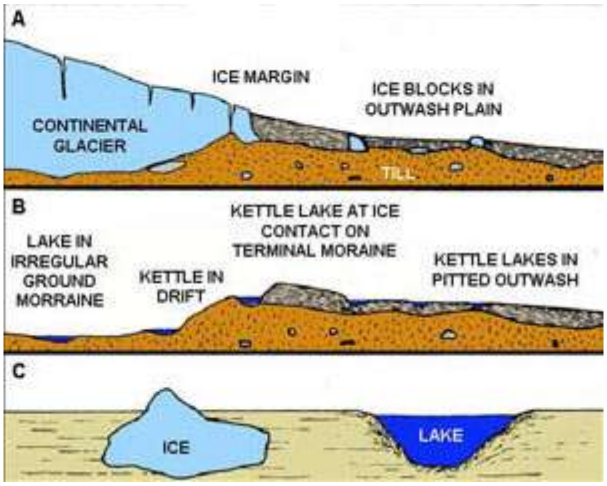
> **Longitudinal** (in an upstream and downstream direction) - Flowing water systems commonly go through structural changes en route from their source to mouth. Three zones are usually recognized - **headwaters**, where flow is usually lowest of any where along the system, slope is often steepest, and erosion is greater than sediment deposition; **transfer zone**, the middle range of the stream where slope usually flattens somewhat, more flow appears, and deposition and erosion are both significant processes; and the downstream end's **depositional zone**, where flow is highest but slope is minimal and deposition of sediment significantly exceeds erosion most of the time.
>
> **Lateral** (across the channel, floodplains and hillslopes) - Again, significant variation occurs among stream types, but a common pattern includes the channel, the deepest part of which is called the **thalweg**; **low floodplains** that a re flooded frequently, and higher floodplains (e.g., the 100-year or 500-year) that are rarely inundated; **terraces**, which are former floodplains that a downcutting stream no longer floods; and **hillslopes** or other upland areas extending up-gradient to the watershed boundary.
>
> **Vertical** (surface waters, ground water and their interactions) - It is always important to recognize that water bodies are not purely surface features; rivers and streams constantly interact with groundwater aquifers and exchange water, chemicals, and even organisms.

Over its entire length, a stream often varies between influent reaches where surface water leaks downward into the aquifer, and effluent reaches where the stream receives additional water from the aquifer.

Temporal (through time, from temporary response to evolutionary change) - The dimension of time is important because rivers and streams are perpetually changing. Structure as described in the other three dimensions above should never be considered permanent, and watershed managers should always think of structure not just as what is there now, but in terms of the structural changes in progress and their rates of occurrence.

Recognition of different types of streams and rivers is mostly reliant on channel form and function. For more on stream and river categories see **classification of stream types**.

"Still" (Lentic) Waters



Lentic systems generally include lakes and ponds. A lake's structure has a significant impact on its biological, chemical, and physical features. Some lentic systems may be fresh water bodies, while others have varying levels of salinity (e.g., Great Salt Lake). Most basin-type wetlands are also generally grouped within lentic systems; these are areas of constant soil saturation or inundation with distinct vegetative and faunal communities. Lakes and ponds are almost always connected with streams in the same watershed, but the reverse is not nearly as often true.

The method of lake formation is the basis for classifying **different lake types**. Natural processes of formation most commonly include glacial, volcanic, and tectonic forces while human constructed lakes are created by dams or excavation of basins. In his classic review of lake types, Hutchinson (1957) describes 76 different types of lakes. **Of the processes that form these lakes, glacial activity has been the most important mechanism for their formation in North America.** Although on human time scales we may think of lakes as permanent, they are ephemeral features on the landscape. They are found in depressions in the earth's surface in regions where water is available to fill the basin. Over time, lakes fill with sediments and organic material while outlets tend to erode the lake rim away.

Areas referred to as lake districts contain lakes created by similar processes. While the individual lakes in a lake district often share similar geologic features, the lakes themselves are often quite unique. In Northern Wisconsin and Minnesota for example many of the lakes were formed by the same glacial processes, but the individual biological, chemical, and physical characteristics of lakes even just a few miles apart can be dramatically different. In these lakes, landscape position of the basin, characteristics of the watershed, and morphometry of the basin are usually more important than method of basin formation for describing the biological features of a lake.

Basic Functional Differences Between Streams and Lakes

Functional Differences

Lakes

- Water retained for days/months/years
- Energy fixed primarily in lake
- Most organisms suspended in the water column

Streams

- Water in transit almost immediately
- Energy fixed primarily in watershed
- Most organisms near/on or in substrate

Differences between lake and stream dynamics are largely the result of differences in the location of energy fixation and the water residence time. Streams are primarily heterotrophic systems with energy fixed in the terrestrial environment rather than the stream itself and they are much more dependent on their watershed. Energy fixation and decomposition are spatially separated from each other. Although lakes are also dependent on their watersheds largely as the source of nutrients, most of the activity occurs in the water. In a lake, energy fixation and utilization of that energy by other organisms are not as spatially separated. Organisms in lakes and streams also tend to differ, due to the fact that stream organisms experience flowing water currents. The majority of primary producers and consumers in streams are benthic organisms that spend much of their time closely associated with the substrate. Because many lakes stratify, and have bottom waters that are limited in light and nutrients, the main challenge for organisms in many lakes is to remain suspended in the water column.

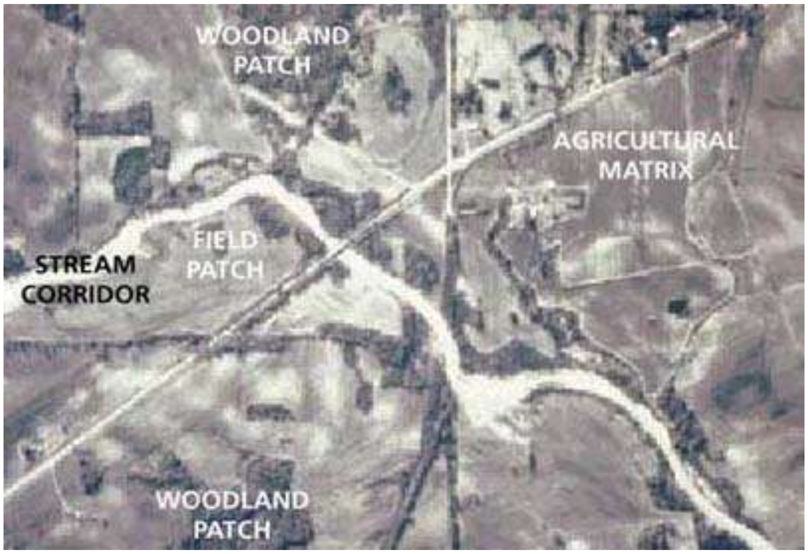
Structure in Upland Areas of Watersheds

The physical form of the uplands in watersheds can vary greatly, in ways beyond the scope of this discussion. Here we focus only on the distribution of and variations in vegetation and land use, which together create the element of watershed structure called **landscape pattern**. Vegetation and land use patterns in watersheds are known to have many significant influences on the condition of the water bodies they drain into; this topic is explored in greater detail in the Watershed Academy Web module on Watershed Change.

Landscape patterns
Landscape ecology offers a simple set of concepts and terms for identifying basic landscape patterns: **matrix**, **patch**, and **mosaic**. The ecological term **matrix** refers to the dominant (> 60%) land cover, while a **patch** is a non-linear area that is less abundant and different from the matrix. A **mosaic** is a collection of different patches comprising an area where there is no dominant matrix. Various patch types have been described. Basically, the most obvious landscape patterns are formed by combinations of native vegetation communities, unvegetated areas, and land use patterns.

Landscape pattern change. The individual patches in a landscape can change, and so can the entire landscape change in pattern and/or composition. Disturbances and various landscape processes maintain a constant dynamic, referred to as a shifting mosaic. Some landscapes remain in a "dynamic equilibrium" and, although changing steadily from place to place, retain an important quality called **mosaic stability**. A well-managed forestry operation, for example, would exhibit over the long term a constantly shifting set of locations where mature forest occurred, but at the same time sustains the relative proportions of forested and nonforested land in the area. Or, a landscape may evolve toward a new type of pattern and composition (e.g., via timber clearcutting, suburban sprawl, abandonment and succession of agricultural lands back to forest, or landscape change due to disease, fire, or climate change). It is always important, when analyzing landscape pattern and landscape change, to remember that the spatial resolution of your information (how small a landscape feature you can detect) **may or may not be sufficient** to detect all the landscape changes of possible significance that may be occurring.

Vegetation and Land-Use Patterns



Vegetational patterns
Upland vegetation structure varies spatially, following various biogeographical patterns based on climate, physiography, soils, disturbance regimes, and their interactions.

Vegetation communities are areas where a few species of plants dominate and establish a characteristic form or structure, within which a potentially large number of less abundant organisms also exist. Nationwide, there are hundreds of vegetation community types; the Society of American Foresters recognizes over 80 forest types alone (SAF, 1980). As a first step in analyzing vegetational patterns, it is easier to recognize a few generalized upland vegetation types based on their growth form, including:

- Forests (deciduous, evergreen and mixed)
- Shrublands
- Grasslands
- Forbs (broad-leaved herbs)

These categories are commonly found on land cover maps likely to be available in the GIS data for most watersheds, and can be consulted to give a general sense of vegetation patterns in the watershed.

Human activity has carved up and fragmented many of the natural vegetation patterns that formerly covered our watersheds. Without human influence, however, vegetation patterns would not be uniform due to different vegetation communities arising from different environmental conditions (e.g. variations in moisture and temperature due to slope and aspect) and events (e.g., fire, pest outbreak). In the West, the "rain shadow" is a common, basic example of how vegetation varies with physical position. Sierra Nevada example

Land-use patterns
Increasingly, the landscape structure and pattern we see is the result of widespread human

activity. In all fields of environmental management including watershed management, analysis of land use types, patterns, and trends is commonplace. Because multiple uses occur in many locations and some land uses are not in themselves a visible landscape feature, mappers often use term **land cover** to describe the delineation of landscape structure and pattern formed by the dominant land uses and remaining vegetation communities. Some common land cover categories (indicating land uses within the areas) include:

- urban land (residential, commercial, industrial, mixed)
- agriculture (row crops, field crops, pasture)
- transportation (roads, railroads, airports)
- rangelands
- silviculture
- mining/extractive areas

Like vegetation patterns, the land use patterns in a watershed can be studied through GIS data or maps. Human-dominated landscapes, just as natural landscapes, are shifting mosaics that often progress through a series of changes in what is dominant. Rural upstate New York example.

Watershed Functions

Most of this training module has been spent describing the basic building blocks of watersheds, their structure and pattern. Now, the module concludes with a discussion of a few of the essential functions that occur in most healthy watersheds. These include:

- Transport and storage
- Cycling and transformation
- Ecological succession

As this module has gradually added layers upon layers of information about watersheds, this final category is the most complex. As you follow these materials, recall the elements of the physical template, the biological setting, the characteristics of natural systems, and the discussion of watershed structure and appreciate why watersheds as natural systems are capable of performing many complex functions.

Transport and Storage of Water, Energy, Organisms, Sediments, and Other Materials

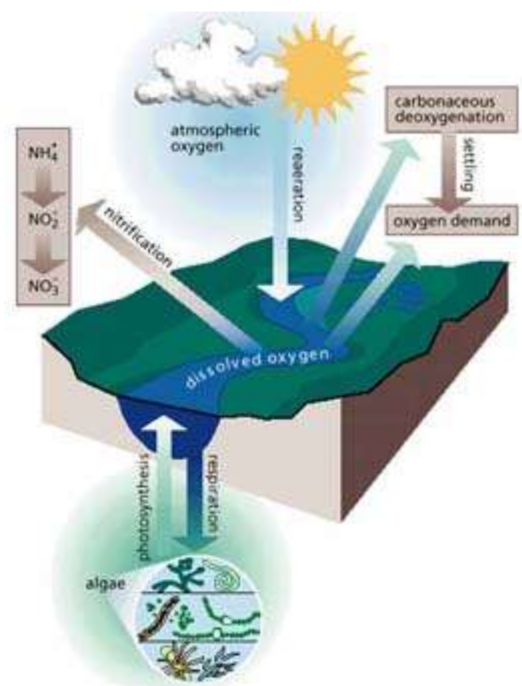
Because a watershed is an area that drains to a common body of water, one of its main functions is to temporarily store and transport water from the land surface to the water body and ultimately (for most watersheds) onward to the ocean. But, in addition to moving the water, watersheds and their water bodies also transport sediment and other materials (including pollutants), energy, and many types of organisms. It is important when recognizing the **transport** function to also recognize temporary retention or **storage** at different locations in the watershed.

Concepts: Transport and Storage. As matter physically moves through the watershed, there are a number of terms which arise relative to various stages of cycling. **Availability** refers not just to the presence of an element in a system, but also speaks to the usability of a given agent. For instance, nitrogen gas may be plentiful in and around dam spillways, but N2 is not a usable form for most aquatic organisms, and thus the availability of nitrogen is compromised. **Detachment** refers to the release of matter from an anchoring point, and its subsequent movement. **Transport**, a process most evident in stream channels, involves the movement of a material through a system. **Deposition** refers to a given endpoint within a cycle. **Integration** refers to the assimilation of matter into a site or organism following depositional processes (see Naiman and Bilby 1998). (Example using these terms)

Transport and storage of water. One can view a watershed as an enormous precipitation collecting and routing device, but transportation and storage of water actually involves a complicated mix of many smaller processes (which are **bolded** in the following text). Even before **precipitation** reaches the ground, it interacts with vegetation. Trees and other vegetation are responsible for **interception** and **detention** of some of the rainfall, leading to some **evaporation** and also slowing the amount reaching the ground via **throughfall** and giving it time for better **infiltration** to groundwater (one form of **storage**). **Saturation** of soils, occurring when precipitation exceeds infiltration, leads to **overland flow** and, over longer time frames, **drainage network development**. The consistent flow of water in channels affects and shapes **channel development and morphology** in ways that seek dynamic equilibrium with the job to be done (moving water downstream). Recall also this module's earlier discussion of the **longitudinal profile development** of rivers and streams, and how upper, middle and lower zones of streams generally have very different forms to handle very different sets of functions, many related to transport and storage of water.

Transport and storage of sediments. Watersheds also collect and transport sediments as a major function. Sediment transport and storage is a complex network of smaller watershed processes, like the water processes described above, and actually is inseparable from water transport and storage. Sediment related processes mostly involve **erosion** and **deposition**, but sediment transport and storage also play a longer-term role in **soil development**. The **drainage network development** and **channel development** discussed above appears to be dominated by erosion at first glance, but the redeposition of sediments on floodplains is an important function that rejuvenates soils and influences the productivity and diversity of stream corridor ecosystems.

Cycling and Transformation



Cycling and transformation are another broad class of natural functions in watersheds. Various elements and materials (including water) are in constant cycle through watersheds, and their interactions drive countless other watershed functions. The figure at left, for example, illustrates interactions of the carbon and nitrogen cycles with stream biota and the resulting influence on dissolved oxygen. Elements like carbon, nitrogen, and phosphorus comprise the watershed's most important biogeochemical cycles. Cycling involves an element of interest's transport and storage, change in form, chemical transformation and adsorption.

Nutrient Spiraling. The flow of energy and nutrients in ecosystems are cyclic, but open-ended. True systems, in both an environmental and energetic context, are either "open" (meaning that there is some external input and/or output to the cyclic loop) or "closed" (meaning that the system is self-contained). In watersheds, streams and rivers represent an open-system situation where energy and matter cycles, but due to the unidirectional flow, the matter does not return to the spot from whence it came. Also, nutrients "spiral" back and forth among the water column, the bodies of terrestrial and aquatic organisms, and the soil in the stream corridor en route downstream. Hence, the concept of nutrient "spiraling" implies both movement downstream and multiple exchanges between terrestrial and aquatic environment, as well as between biotic and abiotic components of the watershed.

The Cycling of Carbon and Energy. In food webs, carbon and the subsequent synthesized energy is cycled through trophic (food web) levels. Energy transfer is considered inefficient, with less than 1% of the usable solar radiation reaching a green plant being typically synthesized by consumers, and a mere 10% of energy being typically converted from trophic level to trophic level by consumers.

Nitrogen (N). N_2 (gaseous state) is not usable by plants and most algae. N-fixing bacteria or blue-green algae transform it into nitrite (NO_2) or ammonia (NH_4). N-fixation, precipitation, surface water runoff, and groundwater are all sources of nitrogen. Under aerobic conditions, NH_4+ is oxidized to NO_3- (nitrate) in the **nitrification** process. Losses of N occur with stream outflow, denitrification of nitrate (NO_3) to N_2 by bacteria, and deposition in sediments. Unlike P, inorganic N ions are highly soluble in water and readily leach out of soils into streams. NH_4+ (ammonium) is the primary end-product of decomposition.

Phosphorus (P). Phosphorus in unpolluted watersheds is imported through dust in precipitation, or via the weathering of rock. Phosphorus is normally present in watersheds in extremely small amounts; usually existing dissolved as inorganic orthophosphate, suspended as organic colloids, adsorbed onto particulate organic and inorganic sediment, or contained in organic water. Soluble reactive phosphorus (consisting of ionic orthophosphates) is the only significant form available to plants and algae and constitutes less than 5% of the total phosphorus in most natural waters. Phosphorus tends to exist in waters of a pH of 6-7. At a low pH (<6), P tends to combine readily with manganese, aluminum, and iron. At a higher pH (>7), P becomes associated with calcium as apatite and phosphate minerals. It is normally retained in aquatic systems by algae, bacteria and fungi.

Nitrogen and Phosphorus limitation. Most watershed systems (both the aquatic and terrestrial realms) are either N or P limited, in that these are the required elements which are at the lowest availability. As a general rule, the N:P ratio should be 15:1. A lower ratio would indicate that N is limiting, a higher ratio places P in that role. Commonly P is the limiting factor. Often, the slightest increase in P can trigger growth, as in algal blooms in an aquatic setting. In N and P limited systems, an input of either element above and beyond normal, "natural" levels may lead to eutrophication.

The stream corridor is often a mediator of upland-terrestrial nutrient exchanges. As N and P move down through subsurface flow, riparian root systems often filter and utilize N and P, leaving less to reach the stream. This has a positive influence on those already nutrient-overloaded bodies of water, but would not necessarily be a positive influence on organisms struggling to find food in very clean, nutrient-limited headwaters streams. Microbes also denitrify significant amounts of N to the atmosphere. Still, N-fixers, like alder, may serve as sources of N for the stream channel, and groundwater pathways between the stream and the streamside forest may provide significant quantities of nitrogen.

Decomposition. Decomposition involves the reduction of energy-rich organic matter (detritus), mostly by microorganisms (fungi, bacteria, and protozoa) to CO2, H2O and inorganic nutrients. Through this process they both release nutrients available for other organisms and transform organic material into energy usable by other organisms. In lakes, much of the decomposition occurs in the waters prior to sedimentation. In the headwater reaches of streams, external sources of carbon from upland forests are a particularly important source of organic material for organisms and decomposition of microscopic particles occurs very rapidly. The bacteria and fungi modify the organic material through decomposition and make it an important food source for invertebrate and vertebrate detritivores, thereby reinserting these nutrients and materials into the watershed's aquatic and terrestrial food webs.

Decomposition is influenced by moisture, temperature, exposure, type of microbial substrate, vegetation, etc. Specifically, temperature and moisture affect the metabolic activity on the decomposing substrate. Nutritional value (as well as palatability) of the decomposing structure will also affect the time involved in complete breakdown and mineralization. Decomposition involves the following processes:

- The leaching of soluble compounds from dead organic matter
- Fragmentation
- Bacterial and fungal breakdown
- Consumption of bacterial and fungal organisms by animals
- Excretion of organic and inorganic compounds by animals
- Clustering of colloidal organic matter into larger particles

The process of death and consumption, along with the leaching of soluble nutrients from the decomposing substrate, release minerals contained in the microbial and detrital biomass. This process is known as mineralization.

Ecological Succession

The classical ecological definition of plant succession involves a predictable set of vegetative changes through a series of discrete stages (seres). Recent challenges to the original succession concept suggest that succession does not necessarily involve a "climax" stage (after which additional changes in dominant species and structure do not normally occur). Within the watershed, succession may vary with spatial scale, elevation, and topography. Modern successional theories view the landscape as being in a sort of dynamic equilibrium, in that various patches make up a shifting mosaic of various successional stages.

In watershed terms, succession is a process that circulates significant amounts of the watershed's energy, water and materials from the abiotic environment back into the biotic, and from one set of predominant organisms on to a subsequent set of dominant organisms. Characteristic forms of succession may be typical of specific parts of the watershed (see examples below). Succession builds and gradually changes vegetational structure that serves many critical functions such as maintaining varied habitat (recall the earlier discussion of the highest biodiversity often being found in areas of intermediate disturbance) and reestablishing renewable resources for human use, like woodlots.

Terrestrial Forest Succession

Much of the western slope of the Sierra-Nevada Range is generally classified as a mixed-conifer forest. Timber species like ponderosa pine, white fir, and incense-cedar occur in varying proportions across the landscape continuum. Historically, wildland fires burned in relatively frequency, maintaining the forest in varying stages of growth, development, and species composition. The fire-resistant pines would dominate in areas of relatively frequent fire disturbances; fir and cedar would dominate in areas where fire was somehow excluded. High intensity disturbances (e.g., the so-called stand-replacing events), like large fires, might destroy the majority of trees, thereby reverting the landscape to a grassland or chaparral community. A simple view of Sierra-Nevada forest succession is as follows:

> **Early successional stage:** Following a catastrophic fire, Sierran wildlands are usually chaparral or grassland communities. This is also referred to in a forest development context as the "stand initiation stage."

Mid-successional stage: The brush and grass sere is gradually overtaken by shade-intolerant pines, which prefer growth in areas of open sunlight. Also known as the "stem exclusion stage."

Mid- to Late- successional stage: If fire is excluded, shade-tolerant fir and cedar begin to occupy the pine understory. This corresponds to the "understory reinitiation stage."

Late-successional stage: Also known in forest development circles as the "old growth stage", this sere involves the dominance of fir and cedar, with the occasional old-growth pine.

The California gold discovery of 1848 created a massive immigration into the region, and many of the Sierran forests were felled for building construction, firewood, and mine timbers. As a result, many Sierran forestlands quickly became chaparral and grassland communities. These clearcuts, coupled with the exclusion of fire beginning with the establishment of the U.S. Forest Service, are the reasons much of the Sierra is currently a second-growth forest of shade-tolerant forests dominated by white fir. Today, management plans in the Sierra center around re-establishing forest structure based on natural succession.

Riparian Forest Succession

Along the stream, riparian vegetation is subjected to periodic spates of flooding, erosion and redeposition. As such, the life history patterns and physiological adaptations of different tree, shrub and herbaceous species will enable them to dominate in different stages of riparian succession. The following are some common plant strategies for survival in the riparian corridor:

Invaders, for instance, are typically the first trees to establish themselves following a landscape disturbance such as a flood or landslide. Examples of invaders are alder and aspen.

Resisters are those species which are adapted to resist the stress of their environment. In riparian corridors, these are species which can withstand the force of intense floods. The flexible, "whippy" stems of willow serve as an example of a resister-like adaptation.

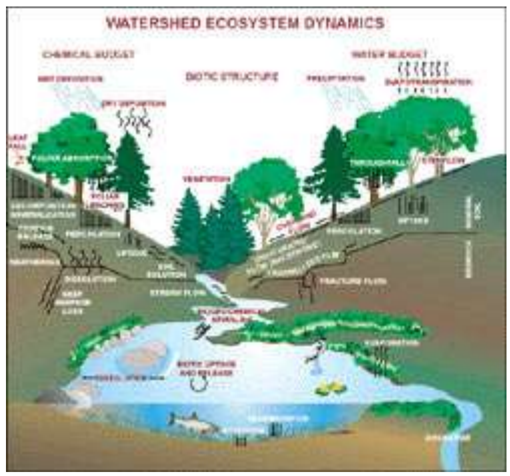
Endurers are species which endure floods by timing or mode of reproduction. Cottonwood, willow, dogwood, and alder may reproduce by sprouting from a severed and deposited branch. Another example of an endurer would be the coast redwood which has the ability to sprout adventitious roots to withstand the effects of periodic burial.

Evaders reproductively "wait out" the process of disturbance by producing seeds which are capable of experiencing dormancy through the given disturbance. Riparian trees do not exhibit this strategy, but many riparian understory species do.

Avoiders find a way to survive disturbances by simply not growing in regions of frequent perturbation. In general, conifers take root and exist in riparian systems only in areas where the intensity and frequency of disturbances are low.

What results is a mosaic of patch types on a small scale within the riparian zone. Protected areas mixed with areas of frequent erosion and deposition create a patchwork of various soil types and successional stages within the stream corridor. Woody debris, large enough and decay-resistant enough to withstand fluvial processes, can create "islands" of refuge where conifers may eventually be able to take root again near the stream channel. This "process loop" between woody debris deposition, alder establishment, and eventually leading to conifer establishment (and the prospect of recurring woody debris deposition) represents an example of a riparian successional process.

Summary



In this Watershed Ecology module, you have been introduced to the most basic features of an exceedingly complex type of natural system -- the physical template, the biological setting, the traits and behavior of natural systems, and watershed structure and function. In closing, examine the graphic of watershed dynamics at left (you may click to enlarge it to full screen size after reading this) and think particularly about all the interactions occurring even in this simplified example. It is truly important for watershed managers to appreciate the natural processes at work, and how they are beneficial to our communities as well as our ecosystems. Even more, it is crucial to recognize how change affects watersheds and can jeopardize these benefits in very costly ways, when a normal change becomes great enough to be a change of concern. For more on this topic, please visit the Watershed Academy Web module on **Watershed Change**.

Self-Test for Watershed Ecology Module

Acknowledgments

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Slides 2, 3d, 7b, 7c, 10c, 12, 15b, 16a, 18b, 18c, 18d, 19a, 19b, 19c, 20a:
from *Federal Interagency Stream Restoration Working Group, 1998. Stream Corridor*

Restoration: Principles, Processes and Practices. U.S. Government Printing Office, Washington, DC.

Slide 8: from *Noss, R. 1990. Indicators for monitoring biodiversity: a hierarchical approach. Cons. Biol. 4(4): 355-364.*

Slide 21: from Johnson and Van Hook, 1989. *Analysis of biogeochemical cycling processes in Walker Branch Watershed.*

References Cited

Federal Interagency Stream Restoration Working Group, 1998. Stream Corridor Restoration: Principles, Processes and Practices. U.S. Government Printing Office, Washington, DC.

Hutchinson, G.E. 1957. A treatise on limnology. v. 1. Geography, physics, and chemistry. Wiley, New York.

Johnson and Van Hook, 1989. Analysis of biogeochemical cycling processes in Walker Branch Watershed. Springer-Verlag, New York.

Montgomery, D.R. and J.M. Buffington. 1993. Channel classification, prediction of channel response and assessment of channel condition. Report TFW-SH10-93-002, U of Washington, Seattle.

Naiman, R.J. (ed.) 1992. Watershed Management: Balancing Sustainability and Environmental Change. Springer-Verlag.

Naiman, R.J. and R. Bilby (eds.) 1998. River Ecology and Management: Lessons from the Pacific Northwest Coastal Ecoregion. Springer-Verlag.

Noss, R. 1990. Indicators for monitoring biodiversity: a hierarchical approach. Cons. Biol. 4(4): 355-364.

Rosgen, D. L. 1994. A classification of natural rivers. In: Catena 22(1994): 169-199.

Rosgen, D.L. 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, CO.

Society of American Foresters. 1980. Forest cover types of the Conterminous United States. Society of American Foresters, Washington, DC.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130-137.

Ward, J.V. 1989. The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society 8(1):2-8.

http://cfpub.epa.gov/watertrain/moduleFrame.cfm?parent_object_id=603