Assessment of Landscape Characterization and Classification Methods

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Table of Contents

Executive Summary

The absence of a hierarchical approach to classification that integrates landscape and riverine ecological theory hampers scientific and regulatory endeavors to define natural resource management strategies protective of watershed dynamics. It is my intent to review existing aquatic and landscape classification methodologies and measures of ecosystem condition and to develop a synthesis paper that first describes the components and uses of existing methods, and that evaluates the strengths and weaknesses of existing approaches. Finally, a suggested template for "riverscape" classification based on the assessment of existing systems and a suggested case study applying the classification template will be presented. Additional basic research supporting hierarchical classification will be outlined.

Classification systems often focus solely on ecosystem structure, ignoring ecosystem processes and patch dynamics responsible for establishing system heterogeneity and driving resource distribution. Structural classification systems have stemmed from the classic work conducted by Bailey (1976) and Omernik (1987). Rohm et al. (1987) and Whittier et al. (1988) found that the approaches used by Bailey (1976) and Omernik (1987) could serve as a geographic framework for classifying streams. However, ecoregions alone were insufficient to classify fish assemblages, predict resource pattern, and diagnose biotic impairment (Hughes et al. 1994, Boulton 1999, Meixler and Bain 1999). Classification systems based solely on ecosystem structure omit ecological concepts important in predicting resource distribution and pattern such as disturbance and recovery processes (Naiman et al. 1992, Reeves et al. 1995), hierarchy theory (Frissell et al. 1986, O'Neill et al. 1986, Pringle at al. 1988, Wu and Loucks 1995), stream connectivity (Ward 1989, Stanford and Ward 1992, Townsend 1996, Poole 2002), and patch dynamics (Pringle et al. 1988, Kotliar and Wiens 1990, Schlosser 1991, Dunning et al. 1992, Schlosser 1995, Wu and Loucks 1995). With few exceptions (e.g., Whiting and Bradley 1993, Poff 1997, Montgomery 1999), classification systems focus on the physical characteristics (structure) of landscapes without attempting to explicitly classify and map types and rates of critical ecosystem processes across multiple scales. As such, existing stream classification systems are often arbitrary, developed by creating classes out of a continuum of channel form. Owing to the discontinuous, patchy nature of stream networks, classification approaches omitting a process-based hierarchical framework are limited in their utility.

To accurately partition ecosystem variability, infer system structure and function across landscapes, predict watershed response to disturbance, diagnose lotic system impairment, and design effective recovery strategies, a classification approach embracing the fundamental tenets of hierarchical patch dynamics (HPD) theory is needed – an approach emphasizing the nested, discontinuous hierarchies of patch mosaics and the centrality of pattern, process, and scale. The discontinuum view central to the HPD theory recognizes general trends and trend reversals in habitat characteristics along the longitudinal profile of the stream network, and serves as a framework to understand the ecological importance of the unique habitat patterns created by processes and structures varying along the stream network (Poole 2002). Finally, a new model for classification, the generic process hierarchy (GPH), is presented.

The GPH is a general protocol for the *hierarchical classification of landscape processes* that influence materials flux within watersheds. As biotic populations respond to both ecosystem patterns and processes, the GPH protocol combines classification of landscape processes and structures to improve assessment of ecosystem integrity and vulnerability. Classification of watershed processes using the GPH protocol may be applied at any spatio-temporal scale, but

always incorporates the scale immediately above and below that scale where the response of interest can be measured (i.e., observation scale). At the coarser scale (i.e., encompassing scale), the GPH classifies land use trajectories and other processes influencing materials availability. At the observation scale, the GPH classifies rates and means of materials delivery to streams. At the finer scale (i.e., component scale), the GPH classifies materials transport and storage within the stream. Finally, a proposed case study in the Umpqua Basin, Oregon is developed. In this case study the GPH protocol is applied to basin-wide hydrological processes and patterns affecting stream network thermal dynamics. Ultimately, the composite picture of thermal processes and patterns across stream reaches developed by application of the hydrological process hierarchy would be related to salmonid distribution and biological impairment.

Management Implications

In this age of information, hierarchical landscape classification can provide the conceptual framework necessary to organize, interpret, and apply data to resolving complex ecological and social issues. In so doing, we will improve our knowledge of landscapes and the complexities associated with variability and scale (Frissell et al. 1986; Poole 2002), facilitate our ability to make inferences within and across landscapes (Poff 1997; Townsend 1996; Urban et al. 1987), and ultimately improve our ability to define standards of ecosystem protection and recovery, so important in land management. Specifically, hierarchical landscape classification yields testable hypotheses regarding watershed responses to disturbance (Bisson and Montgomery 1996; Hunsaker and Levine 1995; Montgomery et al. 1995, Ralph and Poole 2003), assists in the design of efficient and effective trans-scale monitoring programs (Ralph and Poole 2003), promotes realistic and effective recovery strategies including risk identification, protection, and recovery prioritization (Frissell et al. 1993), and provides a conceptual framework to integrate ecological theory and to test hypotheses concerning watershed dynamics (Naiman et al. 1992, Schlosser 1995). Additionally, measures of ecosystem condition tied to contemporary riverine ecological theory and descriptive of the processes, structures, and patterns relevant to landscape dynamics are necessary components of hierarchical classification both as a driver of classification as well as a diagnostic of landscape condition. Classification systems and quantitative procedures that permit accurate, repeatable description, and convey information about biophysical processes provide a foundation for effective and efficient monitoring, protection, and recovery strategies (Bisson and Montgomery 1996).

Introduction

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Objectives

The absence of a hierarchical approach to classification that integrates landscape and riverine ecological theory hampers scientific and regulatory endeavors to define natural resource management strategies protective of watershed dynamics. It is my intent to review existing aquatic and landscape classification methodologies and measures of ecosystem condition and to develop a synthesis paper that first describes the components and uses of existing methods, and that evaluates the strengths and weaknesses of existing approaches. Finally, a suggested template for "riverscape" classification based on the assessment of existing systems and a suggested case study applying the classification template will be presented. Additional basic research supporting hierarchical classification will be outlined.

Background: Classification and Ecological Theory

The stream network is inextricably tied to catchment features including geomorphology, soils, climatic gradients and hydrologic patterns, spatial and temporal scales of natural and anthropogenic disturbances, and the extent and diversity of biotic patterns (Naiman et al. 1992, Allan and Johnson 1997). Landscape variability in catchment features drives abiotic and biotic patterns of structure and process over a range of spatial and temporal scales (Allan and Johnson 1997). In turn, biotic dynamics and interactions are intimately linked to variation in abiotic factors across multiple scales (Hynes 1975, Power et al. 1988, Schlosser 1991, Allan and Johnson 1997). It is the longitudinal, lateral, and vertical connectivity between system components as well as spatial and temporal dynamics across scales that drive system heterogeneity, and hence biotic distribution and pattern (Minshall 1988, Ward 1989, Naiman et al. 1992, Wu and Loucks 1995, Schlosser 1995, Poff 1997, Montgomery 1999).

Ecological patches are the distinct, relatively homogenous abiotic and biotic "units" created by catchment dynamics. For a given ecological system, structural and process patches at different scales form a nested, interactive hierarchy (Frissell et al. 1986, Pringle at al. 1988, Kotliar and Wiens 1990, Wu and Loucks 1995). The resulting patch dynamics and patch geometry play a critical role in the distribution of biota (den Boer 1968, Pringle et al. 1988, Schlosser 1991, Wu and Loucks 1995, Yahner and Mahan 1997, Cohen et al. 1998, Crook et al. 2001). It is this association between physical and chemical structures and processes and biotic pattern and assemblage composition that allows for predictive capabilities within lotic systems.

Through the identification of landscape structural components, landscape classification has been applied to assess relative ecosystem capacity, partition ecosystem variability, and determine watershed responses to disturbance (Power et al. 1988, Frissell et al.1986, Naiman et al. 1992, Montgomery 1999, EPA 2000). Traditionally, a stratification of structural landscape components has occurred to differentiate distinct biophysical classes across a landscape (Albert et al. 1986, Richards et al. 1996, Lunetta et al. 1997, Abell et al. 1998, Cohen et al. 1998, Higgins et al. 1998, Staus and Strittholt 2001, Jensen et al. 2001). These biophysical classes are assumed to be the template upon which processes and patterns regulate the flow of energy and materials (Quigley et al. 1996). As such, distinct biophysical classes should share commonalities regarding available successional pathways and response and rate of recovery to disturbance. Assumptions regarding the behavior of biophysical classes as well as the ability of structural classification to capture important elements of ecosystem function have not been validated. Additionally, the capacity of existing classification systems to yield predictive models of ecosystem dynamics, so important in designing management systems; trans-scale monitoring frameworks; or realistic and effective recovery strategies requires examination. It is these omissions and shortcomings that this report will address.

Key Classification Components Based on Riverine Ecological Theory

The process of identifying and delineating unique landscape classes i.e., landscape classification, is essentially the process of developing conceptual models of watershed dynamics and linkages across scales. For a model to be an accurate representation of watershed dynamics the rules of classification must be based on riverine ecological theory. Ignoring or selectively drawing from theories will impart inaccuracies to the classification system. Ecological theory provides a framework for classification as well as aids in the identification of important measures of ecosystem condition. Therefore, it is important to review key components of riverine ecological theory prior to identifying critical components of a classification system.

Critical elements of classification can be drawn from the evolution of riverine ecological theory beginning with the importance of catchment setting introduced by Hynes (1975) to the explicit linkage of scale and heterogeneity advanced in the hierarchical patch dynamics paradigm codified by Wu and Loucks (1995) and further developed by Poole (2002). Hynes (1975) illustrates the importance of stream context and observed that "every stream is likely to be an individual" and "in every respect, the valley rules the stream." This tight coupling of water and land espoused by Hynes opened the discipline of fluvial ecology to a more holistic, systems-based view of riverine ecosystems. Theories put forth subsequent to Hynes focused on the direction and magnitude of the connections between river and landscape. The River Continuum Concept (Vannote et al. 1980) described the longitudinal structure of river systems. By distinguishing a continuum of habitats arranged from headwater to mouth, Vannote et al. (1980) described productivity and species distribution as a function of stream network position and catchment context. The Serial Discontinuity Concept developed by Ward and Stanford (1983, 1995) identified "discontinuities" such as dams (as well as tributaries and lateral inputs; see Rice et al. 2001) and geomorphically discontinuous stream reaches that disrupt the predicted outcome of continuous habitats put forth in the River Continuum Concept. Lateral connectivity between a river and its floodplain was the focus of the Flood Pulse Concept (Junk et al. 1989, Tockner et al. 2000). Strong lateral connectivity associated with some unconstrained reaches alters the continuum of habitats outlined by Vannote et al. (1980). The Hyporheic Corridor Concept (Stanford and Ward 1993) also focused on one vector of connectivity over time, the vertical interaction between the stream and hyporheos and its role in altering the progression of habitats from headwater to mouth.

The above ecological concepts begin with a basic acknowledgement of the importance of riverine context and expand to describe the importance of Ward's (1989) connectivity vectors - longitudinal, lateral, vertical, and temporal. As the strength of connectivity vectors varies along a stream network, discontinuities in the river continuum appear (Townsend 1996, Poole 2002). Ultimately, it is the downstream variation in stream segment structure that determines the pattern and strength of longitudinal, lateral, and vertical connectivity along the river (Townsend 1996, Poole 2002). This variation in connectivity vectors drives resource patterns and creates heterogeneous resource patch structure varying spatially and temporally. Patch structure reflects the configuration of patches each with unique internal process and structure characteristics. It is this patch structure occurring across multiple spatial and temporal scales that determines stream dynamics. Wu and Loucks (1995) embrace the concept of discontinuity and move forward the concept of hierarchical patch dynamics keying in on the importance of nested hierarchies of patch mosaics; ecosystem dynamics as a composite of patch temporal and spatial changes; and the pattern-process-scale perspective (Wu and Loucks 1995). As each stream network is composed of patches in a unique structure, it would follow that stream dynamics differ between stream networks (Wu and Loucks 1995, Poole 2002). Hence, we come full circle to Hynes' (1975) statement that "every stream is likely to be an individual." For a classification system to be predictive of ecosystem responses and to be diagnostic of ecosystem health, it must be responsive to the scale-dependent drivers of abiotic and biotic patch structure unique to each stream network.

An examination of modern riverine ecological theory points to several components necessary for classification to be predictive and diagnostic across variable landscapes. These components include (a) catchment influences on stream network structure and resource dynamics; (b) disturbance and recovery process influence on connectivity vector strengths, resource dynamics, and biotic pattern; and (c) hierarchy, scale, and patch dynamic influences on energy and materials flow through the system. These key components, described below, will be used as evaluation parameters to assess existing classification systems and to develop a proposed classification system model (Table 1).

Evaluation Parameters	
	Catchment influences on stream structure and resource dynamics
	Disturbance and recovery processes
	Patch dynamics and hierarchy

Table 1: Evaluation parameters

A) Catchment Influences on Stream Structure and Resource Dynamics

The stream network is tied to an array of catchment features exerting distinct influences on stream network structure and patch configuration (Hynes 1975, Naiman et al. 1992). Catchment context along with catchment-specific geomorphic and disturbance processes profoundly influence ecosystem dynamics across multiple spatial and temporal scales (Whiting and Bradley 1993, Montgomery 1999, Winter 2001, Church 2002). Catchments characterized by their geomorphic processes, disturbance regimes, response potential, and recovery time have ecological significance reflected in unique patterns of scale-dependent resource distribution (Frissell et al. 1986, Paustian et al. 1992, Whiting and Bradley 1993, Grant and Swanson 1995, Montgomery 1999).

Catchment properties shape resource dynamics associated with the availability and delivery of materials (sediment, water, nutrients, pollutants, etc.) to the stream network and the routing (transport and processing) of these materials within the network. As biotic distribution is associated with resource availability across multiples scales, resource patch structure (i.e., patch composition and configuration) drives biotic pattern (Naiman et al. 1992, Poff 1997, Poole 2002). Power et al. (1988) emphasize investigating the processes that establish these resource patches at different scales to better understand biotic/abiotic interactions in lotic ecosystems.

Resource patch structure is a reflection of both emergent system properties (i.e., internal or component patch structure), as well as constraints imposed by patch context (i.e., external or encompassing patch structure). In other words, large-scale factors constrain the structure and function of systems at smaller-scales and small-scale factors shape the structure and function of systems at larger –scales (Wu and Loucks 1995, Cohen et al. 1998, Poole 2002). For example, ecological disturbances (e.g., flood, fire, wind) are large-scale factors that influence patch structure and dynamics at smaller scales while small-scale factors such as the upriver expansion of habitat generalists influence biotic patch structure and dynamics at larger scales. It is the emergent properties of systems as well as contextual constraints that contemporary ecological theory attempts to capture and that ecologically relevant classification systems must address to (a) provide accurate, repeatable descriptions of distinct landscape classes, (b) predict biotic pattern and distribution, and (c) diagnose system impairment (Fausch et al. 2002).

B) Disturbance and Recovery Processes

Channel response to disturbance is a fundamental component driving stream network structure and affecting a) connectivity vector strength, b) resource dynamics, and c) biotic distribution and pattern. Disturbance shapes the structural and process patch mosaic unique to a stream network. This mosaic repeated at different scales forms a nested hierarchy (Frissell et al. 1986, Pringle et al. 1988, Kotliar and Wiens 1990, Wu and Loucks 1995). An important reason for the existence of patch hierarchies is that disturbances over different spatio-temporal scales are common structuring forces in ecological systems (Wu and Locks 1995, Montgomery 1999). The resulting patch dynamics and patch geometry play a critical role in the distribution of abiotic and biota resources (den Boer 1968, Pringle et al. 1988, Schlosser 1991, Wu and Loucks 1995, Yahner and Mahan 1997, Cohen et al. 1998, Crook et al. 2001, Poole 2002).

Abiotic resource patterns reflect natural disturbance regimes unique to a catchment. Anthropogenic actions leading to alterations in natural disturbance processes can alter the relationship and linkages between patches as well as resource dynamics including the availability, delivery, transport, and processing of materials fundamental to biotic communities (Schlosser 1991, Naiman et al. 1992, Rice et al. 2001, Poole 2002). For instance, biotic response to disturbance is mediated by physiological and behavioral adaptations of the organism. One behavioral adaptation to broad-based or localized disturbance is movement away from habitat exposed to disturbance to a refuge environment. As such, redundancy in patch type and pattern at many scales may be critical to aquatic organisms responding to environmental stochasticity (den Boer 1968, Pringle et al. 1988, Wu and Loucks 1995, Yahner and Mahan 1997). To increase the likelihood of species/population persistence, the connection among spatially diverse and temporally dynamic habitats and populations is a critical factor to the persistence and integrity of aquatic communities (Sedell et al. 1990, Quigley 1997, Ward et al. 1999, Schmutz and Jungwirth 1999, Dunham and Rieman 1999, Snyder and Stanford 2001). Ultimately, classification must capture disturbance and recovery processes to (a) understand connectivity vector strength, (b) understand the catchment-specific hierarchy of patch mosaics, (c) predict system change over time and rate of recovery, (c) understand resource dynamics, and (d) understand biotic pattern.

C) Patch Dynamics and Hierarchy

In aquatic and landscape ecology, patches are important spatial components that contribute to the heterogeneity of a system. The degree of heterogeneity in a landscape plays a crucial role in determining biotic distribution and pattern, as well as the abiotic functioning of the landscape. Patches represent distinct structural and process units and result in the heterogeneous distribution in space or time of environmental resources – abiotic and biotic (Forman and Godron 1986). Patches vary widely in size, shape, type, heterogeneity, and boundary characteristics (i.e., patch composition and configuration) that in turn influence the flow of materials through the system (Kotliar and Wiens 1990). This patch diversity is driven by variation in resource dynamics arising from landscape variability across scales (e.g., climate, geology, vegetation, land form). Key to understanding patch heterogeneity, are the concepts of scale and hierarchy.

Patch structure (i.e., configuration) is scale-and context-dependent with patch mosaics forming nested hierarchies (Wu and Loucks 1995). The fact that patch structure varies according to the scale of observation is biologically relevant. Patch hierarchies are structured or constrained based on how organisms respond to heterogeneity (Pringle et al. 1988, Kotliar and Wiens 1990). For instance, a patch at one scale may provide suitable resources for one species, but may prove to be a barrier or conversely insignificant to another species (Wiens 1989). Absent coarse-grain continuous sampling, there is no *a priori* method to determine which scales are relevant to questions of interest (Fausch et al. 2002). Predicting species distribution at local reaches based on catchment characteristics may be no more useful for elucidating and evaluating multiple scale relationships than relying solely on local habitat features (Fausch et al. 2002). Both emergent system properties as well as constraints imposed at larger scales are important to understanding resource dynamics and patterns (Poff 1997, Bult et al. 1998, Poole 2002).

Because ecological systems operate at multiple scales, understanding the spatial configuration and temporal trajectory of patch structure is central to understanding the ecology of landscapes (Forman 1995, Torgersen et al. 1999, Arscott et al. 2001, Fausch et al. 2002). As patch size increases, the complexity and diversity of stream habitat is also expected to increase (Frissell et al. 1986, Dunham and Rieman 1999). However, patch heterogeneity is scale-dependent with decreasing heterogeneity at coarse-scales (Torgersen 1999, Fausch et al. 2002). Few studies have addressed the hierarchical nature of patch structure, the functional linkages between patches across scales, or the relationship between scale-dependent patches and biotic distribution and pattern. Fahrig (1997) determined that the effects of habitat loss (i.e., patch size decrease), outweighed the effect of habitat fragmentation (i.e., number and distance between patches). Additionally, patch lifespan or temporal heterogeneity outweighed the effect of patch size or spatial scale (Fahrig 1992). In the end, stream networks and landscapes are dynamic mosaics that change over time, generating a series of patch structures. It is this interplay of patches across spatial and temporal scales that defines abiotic and biotic resource availability. The functional linkages between patches across scales establishes resources patterns that in turn affect species distribution, pattern, demographics, competition, dispersal, and colonization rates (Frissell et al. 1986, Wu and Loucks 1995, Dunham and Rieman 1999). Therefore, classification must capture the factors driving abiotic and biotic resource heterogeneity across scales to (a) predict resource pattern and (b) determine resource vulnerability to anthropogenic stressors.

Existing Classification Systems

Using evaluation parameters from Table 1, we now turn our attention to the review and assessment of existing classification systems. Classification systems will be stratified by their primary means of partitioning and hence classifying ecosystem variability - structure and process. Certainly there are classification approaches that combine structure and process. In these instances, the dominant factor (i.e., structure or process) driving classification will be used to stratify the approach. Classification system strengths and weaknesses will be addressed in the next section.

Structure-Based Classification Systems

Physical structure has provided the basis for numerous classification systems. Typically, classification addresses potential ecosystem capacity and disturbance through an identification of structural landscape components allowing one to map distinct biophysical classes across variable landscapes (Albert et al. 1986, Richards et al. 1996, Lunetta et al. 1997, Abell et al. 1998, Cohen et al. 1998, Higgins et al. 1998, Staus and Strittholt 2001). There is an assumption that function follows structure. With few exceptions, this assumption has not been tested across spatio-temporal scales or ecosystem types. As we will observe in the following classification approaches, structure-based classification systems applied to fairly straightforward resource questions and related to coarse-scale biotic or abiotic distributions may have some utility. However, structure-based classification systems lack precision and in general are unable to predict resource pattern, structure, and persistence at scales relevant to biota and management. Classification systems relying on structure as a surrogate for function are unable to reliably partition natural variability and hence distinguish between various process-based land and river patches. Although, structure-based classification systems may be easily applied across broad regions, by omitting the processes driving resource dynamics (i.e., availability, delivery, transport, storage, and processing), structure-based classification systems lack the sophistication to identify system discontinuities (i.e., patch heterogeneity) across scales necessary to predict resource patterns; evaluate potential natural resource management outcomes; diagnose system impairment and recovery options; or make inferences within and across landscape classes. We will explore these concepts below and in the following sections.

Structural classification systems have stemmed from the classic work conducted by Bailey (1976) and Omernik (1987). In their work, ecoregions were defined based on the hypothesis that ecosystems and their internal components display regional patterns that are reflected in spatially variable combinations of causal factors. Areas relatively homogeneous in their soils, land use, land surface form, and potential natural vegetation were mapped as distinct ecoregions. Ecoregional maps were developed to provide a geographic framework for organizing ecosystem resource information that would facilitate resource management. Indeed, the application of classification systems to natural resource management often incorporates the relative simplicity of ecoregion delineation. For instance, the U.S. Environmental Protection Agency's Environmental Monitoring and Assessment Program (EMAP), delineates distinct ecoregions to stratify landscapes for monitoring of physical, chemical, and biological stream health (http://www.epa.gov/emap/). As ecoregions form the basis of EMAP, the partitioning of variability across landscapes is based on structure acting as a surrogate for function. As we will note from the following examples this approach, lacking explicit incorporation of disturbance and recovery processes, resource dynamics, and linkages to process dynamics and hierarchy, may prove relatively useful at a coarse-scale, but begins to unravel at scales of resolution necessary to effectively manage resources of concern. Ultimately, conclusions regarding ecosystem variability may be inaccurate.

Although testing and validation of classification approaches is limited, several studies point to shortcomings associated with a strict application of ecoregional delineation to partition resource variability. Rohm et al. (1987) and Whittier et al. (1988) found that Bailey's (1976) and Omernik's (1987) approach to mapping ecoregions could serve as a geographic framework for classifying streams. However, they found that ecoregions alone are insufficient to classify fish assemblages, predict resource pattern, and diagnose biotic impairment (Hughes et al. 1994, Boulton 1999, Meixler and Bain 1999). Hughes et al. (1994) suggest that ecoregions may better classify fish regions than river basins, but both should be considered when delineating fish faunal regions regardless of the geographic scale, or the size or type of the water body. This conclusion is most likely due to 1) the strong orientation of patterns and processes associated with lotic systems, 2) unique catchment features that are lost at coarser-scales associated with ecoregions, and 3) single scale of enquiry for all research and monitoring questions. Ultimately, ecoregions and catchment delineation do not provide the necessary information to effectively partition natural variability and allow for predictive and diagnostic capabilities.

A discussion of ecoregion delineation and application to classification is not complete without mentioning the concept of reference condition, which is a fundamental component to ecoregion application. Hughes et al. (1994) state that reference sites should aid in characterizing ecoregional potential. Reference sites are selected to illustrate "undisturbed" (i.e., free of cultural alterations) ecological conditions. However, undisturbed reference sites originating within the same ecoregion and subject to identical formative processes, patch pattern, and dynamics are essentially non-existent. Reference condition discussions also often neglect the importance of stream network context in establishing patch function. Most importantly, disturbance is a fundamental structuring force in lotic systems and should be accounted for within the classification approach rather than as a stand alone discussion related to reference condition.

Vegetation structure is often used as an indirect measure of function (Bailey 1976, Omernik 1987). Potential and existing vegetation parameters have been applied to the delineation of landscape classes. The incorporation of vegetation parameters in classification has been used to infer biotic distribution as well as resistance to disturbance (USGS GAP Analysis; http://www.gap.uidaho.edu/), trophic structure (Ormerod et al. 1993), and channel condition (Ormerod et al. 1993, Richards et al. 1996, Lunetta et al. 1997). Ormerod et al. (1993) classified streams according to adjacent bank vegetation resulting from forest management actions. As instream trophic energy structure and chemistry are related to riparian vegetation, the authors offered this simple classification system to aid in the prediction of macroinvertebrate community structure. Schlosser (1995) also evaluated functional interactions between aquatic species and terrestrial plants by classifying riparian vegetation. Vegetation is an important variable representing both structural and process components important to resource dynamics. However, as a stand alone variable, vegetation structure and function rarely captures the array of information necessary to understand complex ecosystems. It is, however, an important variable to be addressed by classification systems.

Frissell et al. (1986) and Rosgen (1994) developed hierarchical classification systems to predict stream structure at multiple scales. Frissell et al. (1986) emphasized the importance of physical structure in organizing biological systems. Habitats were classified by potential capacity, and consider biogeoclimatic region, geology, topography, soils, biota, and cultural infrastructure at the watershed-scale; channel slope, shape, pattern, and order at the stream-segment scale; habitat units, structure and substrate at the reach-scale, and habitat features such as pool depth, cover, water velocity, and instream wood at the micro-habitat scale (Frissell et al. 1986). This hierarchical approach has been adopted by researchers and natural resource managers and has been important in advancing the concept of nested hierarchies in lotic ecology and resource management. The authors noted, however, that not all variables are necessary to distinguish classes in all circumstances; specific metrics or indices may vary regionally or with study objectives (Frissell et al. 1986). This finding reflects the individuality of stream networks and the importance of understanding processes driving resource dynamics as well as identifying appropriate scales of enquiry relevant to particular research or management questions. Frissell et al. (1986) discussed vertical and lateral dimensions of the stream network, however, linkages and interactive pathways within and between scales were poorly defined (Imhof 1996). Although the authors provided a hierarchically relevant framework, system omissions limit the utility of the framework to define (a) resource dynamics, (b) system discontinuities, (c) patch dynamics, or (d) disturbance processes. As such, questions related to system variability as well as cause and effect relationships important to resource management are difficult to answer. Rosgen (1994) developed a classification system using variables of channel pattern, entrenchment, width to depth ratio, sinuosity, slope, and bed material size. A lack of explanation of the rationale underlying this approach as applied to the assessment of response potential among channel types is a shortcoming that reflects a disjunct between structure- and process-based classification systems (Montgomery and Buffington 1998). Explicit linkages between catchment influences, disturbance and recovery processes, and patch dynamics and hierarchy are not developed. As such, this approach is geographically limited in its applicability and, as such may lead to erroneous conclusions if misused.

Jensen et al. (2001) investigated the linkages between stream habitats and broader-scale drainage networks and biophysical environments in which they occur. This study builds upon work conducted through the Interior Columbia Basin Ecosystem Management Project (ICBEMP) (see Quigley et al. 1996), a classification effort to link landscape, aquatic, terrestrial, social, and economic characterizations to describe biophysical and social systems. ICBEMP provided a coarse-scale filter of landscape sensitivity to anthropogenic disturbance. Jensen et al. (2001) using ICBEMP data determined that multiple scale classification of sub-watersheds based on indirect environmental variables (e.g., climate, potential vegetation, land type association) was effective in predicting the distribution of valley bottoms and stream types (based on Rosgen 1996) commonly mapped at finer resolutions. Additionally, the authors determined that indirect biophysical variables may effectively be used as surrogates for the direct biophysical variables that influence aquatic patterns. However, as project data were derived from regional data sets, further validation is required to ascertain the effectiveness of catchment-scale variables alone to predict finer-scale aquatic biotic and abiotic resource patterns across landscapes or relating aquatic pattern to function. As will be noted in the subsequent paragraph, catchment-scale data are important in depicting the availability of resources, but alone they do not capture the array of critical processes related to the distribution and pattern of resources. Also, as stream types were delineated using the classification approach developed by Rosgen (1994), information on bedform processes are absent. Therefore, difficulty inferring relationships between key habitat forming processes and biotic distribution, assemblage, and pattern as well as response/vulnerability to disturbance may prove difficult.

Hawkins et al. (1993), Richards et al. (1996), Richards et al. (1997), Johnson et al. (1997), Davies et al. (2000), Lunetta et al. (1997), and Cohen et al. (1998) developed relationships between selected catchment characteristics and physical structure within the stream network. Classification accuracy was determined through empirical testing of identified classes. Predictive capacity related to resource dynamics and distribution, disturbance response and recovery potential, as well as inference to other classes is typically low in these examples. Reduced applicability and utility is due to (a) the absence of conceptual models depicting mechanisms driving resource patterns and strengths of connectivity vectors; (b) posteriori classification systems leading to geographic specificity; (c) omission of disturbance and recovery processes; (d) exclusion of heterogeneity, patch dynamics, and hierarchy concepts, and (e) arbitrary selection of observation scales.

Hawkins et al. (1993) provided a classification system to aid understanding of biotic-habitat relationships. The authors defined stream reach habitat based on channel geomorphic units representing areas of relatively homogenous depth and flow, bounded by sharp gradients in these variables. Classes were intended as habitat templates on which patterns of biological diversity and production occurred (Hawkins et al. 1993). Ultimately, this classification system is a simple method to organize information on stream reach habitat, but does little to address the issues listed in the proceeding paragraph. Richards et al. (1996) noted that catchment-scale parameters describing area, soils, and geology had the strongest influence on instream physical habitat structure. Building on these findings, Richards et al. (1997) used stream reach- and catchment-scale physical properties to predict the occurrence of specific species life history and behavior traits of macroinvertebrates. Study results indicated that reach-scale properties were highly predictive of species traits. However, catchment properties, in particular surficial geology, influence macroinvertebrate assemblages through control over channel morphology and hydrological patterns. Additionally, catchment-wide geology and land-use variables were more important in predicting system resistance and resilience to disturbance than reach-scale variables (Richards et al. 1996). The authors concluded that catchment-scale variables had direct influence over reach-scale properties. At fine-grained scales (e.g., microhabitats, riffles, pools), the authors noted that species traits may not be observable since disturbance and environmental change occurs rapidly and species presence was regulated more by mobility and re-colonization sources. This study highlights the importance of scale when designing and evaluating studies as well as the complex scalar relationship between process, structure, and biotic assemblage patterns. The emergent properties of systems as well as system constraints imposed by patch context are a result of the interplay of patches across scales and are critical to understanding the response of biota to their environment. Richards et al. (1997) concluded that discontinuity in stream networks was an important factor in predicting species behavior and traits. However, the authors do not suggest methods to elucidate the mechanisms driving discontinuity or to predict discontinuous hierarchies in patch mosaics.

Johnson et al. (1997) determined that relatively coarse-scale variables (e.g., geological factors and landscape structure) provided useful descriptors of water quality in landscapes dominated by agricultural practices. Davies et al. (2000) used large-scale catchment features (e.g., area, stream length, relief ratio, alkalinity, dominant geology, dominant soil type) to place reference sites into appropriate reference site groups. This technique provided sufficient information to classify 69% of the reference sites (Davies et al. 2000). Clearly, there is a relationship between catchment-scale and finer-scale stream features. As noted by Richards et al. (1997), catchment-scale variables have a direct influence over reach-scale properties. However, attempting to predict biotic distribution at reach- and habitat unit-scales based solely on catchment characteristics omits information on important mechanisms driving stream network heterogeneity and resource dynamics, thereby leading to low predictive success (Fausch et al. 2002). As such, the proceeding classification systems do not provide a useful template for addressing the breadth and depth of natural resource management and research questions. Uniformly, these classification systems fail to elucidate parameters important to prediction and inference including linkages and relationships between scales and mechanisms driving resource dynamics and stream network discontinuities (Bult et al. 1998, Poole 2002).

Classification systems developed by Lunetta et al. (1997) and Cohen et al. (1998) begin to address resource dynamics and disturbance and recovery processes important to predicting biotic and abiotic patterns. Lunetta et al. (1997) applied a process-based landscape and channel classification system developed by Montgomery and Buffington (1998) to stratify reaches by slope and to make inferences regarding the likelihood of a reach to provide salmonid habitat. The authors used riparian forest seral stage as an indicator of large woody debris (LWD) delivery to the stream channel. LWD input processes reflected potential anthropogenic disturbances to the delivery of LWD to the stream channel, and hence habitat formation in certain geomorphic settings (Rot et al. 2000, Fox 2001). By identifying reaches potentially providing anadromous salmon habitat and the degree to which LWD delivery had been altered, the authors were able to meet their stated project goal, to provide a rapid technique to assist restoration prioritization. This approach was not applied to more complex questions concerning disturbance and recovery processes or resource dynamics.

At the stream reach-scale, Cohen et al. (1998) found that hydro-ecoregions (i.e., delineated by climate, geology, relief, and hydrogeology), valley slope, and stream order were useful in predicting regional meso-habitat (i.e., bedform) distributions (e.g. rapids, riffles, runs, glides, pools) in alluvial systems. However, valley slope and stream size did not play the same role in each hydro-ecoregion i.e., the mechanisms governing bedform distribution varied (Cohen et al. 1998). The authors concluded that predicting bedform distribution required an understanding of instream sediment and hydrological processes. In alluvial systems, valley slope and stream order served as a means to measure stream energy, and therefore there was some success in predicting bedform distribution. However, for cohesive substratum streams predictive capacity was low. In the section on process-based classification, Montgomery and Buffington (1998, 1997, 1993), Montgomery (1999), Winter (2001), and Church (2002) provide process-based classification approaches that remedy shortcomings identified by Cohen et al. (1998).

Process-Based Classification Systems

Classification systems based on physical processes are another means by which researchers have differentiated land and river classes. The distribution of organisms is the result of multiple processes functioning at multiple scales - both because biota react to their environment at a range of spatial and temporal scales and because of the propagation of effects from one scale to the next (Bult et al. 1998, Poole 2002). Process-based classification systems embrace several ecological concepts important in predicting biotic pattern and distribution such as disturbance and recovery processes (Naiman et al. 1992, Reeves et al. 1995), stream connectivity and connectivity vector strength (Ward 1989, Stanford and Ward 1992, Townsend 1996, Poole 2002), patch dynamics (Pringle et al. 1988, Kotliar and Wiens 1990, Schlosser 1991, Dunning et al. 1992, Wu and Loucks 1995, Schlosser 1995, Poole 2002), and hierarchy theory (Frissell et al. 1986, O'Neill et al. 1986, Pringle at al. 1988, Wu and Loucks 1995, Imhof 1996). Wu and Loucks (1995) suggest a hierarchical patch dynamics paradigm that emphasizes the nested, discontinuous hierarchies of patch mosaics and the centrality of pattern, process, and scale to the patch dynamics perspective. The authors offer various modeling techniques to facilitate incorporation of the hierarchical patch dynamics paradigm into research and management (Wu and Loucks 1995, Poole 2002, Fausch et al. 2002). However, to date this approach has not been applied to classification.

Physical process-based approaches to classification have been applied at multiple spatial scales. Winter (2001) described the hydrologic landscape as multiples or variations of fundamental hydrologic landscape units (FHLU). FHLU were mapped based on land-surface slope, hydraulic properties of soils and geologic framework, and the difference between precipitation and evapotranspiration. This approach resulted in information on surface and ground water flow within different hydrologic classes. Paustian et al. (1992), Whiting and Bradley (1993), Grant and Swanson (1995), and Montgomery (1999) evaluated watershed processes in the context of process domains (i.e., portions of the landscape exhibiting distinctive suites of processes). A process domain approach to classification contends that the spatial and temporal variation in landscape processes exert distinct influences on lotic and riparian ecosystems, and therefore are critical to understanding resource heterogeneity and biotic pattern and distribution. Paustian (1992) provided an example of a valley-scale classification emphasizing region-specific associations with channel morphology and processes. Whiting and Bradley (1993) presented a process-based classification for headwater channels that associates channel morphology with the potential for debris flow impacts, channel substrate size, and processes and rates of fluvial sediment transport. The distribution and morphology of valley floor landforms and channel reach morphology in headwater streams was the subject of work conducted by Grant and Swanson (1995). The correspondence between channel reaches and the type and degree of constraint imposed by hillslope processes formed the basis of this classification system (Grant and Swanson 1995). Montgomery (1999) stated that landscape geomorphic context viewed at multiple scales (i.e., geomorphic province, litho-topo units, process domains) and disturbance processes profoundly influence associated ecological systems. Ultimately, watersheds characterized by different geomorphic processes, disturbance regimes, response potential, and recovery time and classified by process domains (i.e., specific landscape areas within which distinct suites of processes govern physical habitat) should have ecological significance (Montgomery 1999).

Montgomery and Buffington (1997, 1998) provided further refinement to channel classification as initiated by Strahler (1957), Leopold and Wolman (1957), Henderson (1963), Kellerhals et al. (1976), Schumm (1977), and Church (1992). The authors articulated three key relationships: (a) reach morphologies are associated with physical processes and environments that limit the range and magnitude of possible channel responses to changes in hydraulic discharge and sediment supply; (b) reach-specific response potential is also affected by external influences, such as channel confinement, riparian vegetation, and in-channel large woody debris; and (c) the location of the reach within the stream network and the sequence of reach types (i.e., patches) influence the response of reaches to watershed disturbance (Montgomery and Buffington 1997, 1998). Based on these relationships, Montgomery and Buffington (1997, 1998) proposed a simple reach classification system using channel gradient and confinement (see Lunetta et al. 1997). Church (2002) proposed an elementary classification of alluvial river channels and riverine landscapes with similarities to the work of Montgomery and Buffington (1997, 1998). The author determined that the balance of sediment supply and transport capacity influenced the bed structure and the pattern of the channel, creating distinctive physical habitats in different parts of the rivers (Church 2002). Similar to Montgomery and Buffington (1993, 1997, 1998), topography, gradient, and riparian vegetation were included as variables affecting reach-specific response potential. Classification was tied to the sequence of geomorphic thresholds occurring along the stream network. Thresholds were established by significant changes in the processes by which sediment was moved and stored (Church 2002). These thresholds also determined the nature of the adjacent floodplain. Church (2002) concluded that geomorphic thresholds led to distinctive riverine landscapes, containing a variety of patch structures and patterns.

As process-based classification approaches characterize critical processes driving stream network structure and resource dynamics, they typically include reference to disturbance and recovery processes (Grant and Swanson 1995, Montgomery and Buffington 1998, Whiting and Bradley 1993, Montgomery 1999). To effectively evaluate natural resource management actions and land use change, it is essential to understand the interaction of natural and anthropogenic disturbances on stream structure and resource dynamics. Allan et al. (1997) found that land-use throughout a sub-catchment upstream of a site generally was a better predictor of habitat quality and biotic integrity than either riparian corridor or reach surveys. As disturbance and recovery processes are critical to landscape function, structure, and pattern, classification systems explicitly incorporating anthropogenic and natural disturbances are necessary to identifying ecosystem trajectories, restoration priorities, and passive and active restoration options (Ebersole et al. 1997, Berman 1998 (http://ims.reo.gov/website/swop/), Roni et al. 2002).

Process domain-based classification approaches not only incorporate disturbance and recovery processes, they also explicitly link catchment influences to stream structure and resource dynamics and elucidate the mechanisms of stream network discontinuities. Essentially, these classification systems begin to define patch structure across scales and highlight the importance of patch context in shaping system resilience and resistance to disturbance. Their shortcomings are related to omissions of cross-scale relationships and linkages that shape emergent system properties and system constraints related to context. These approaches do, however, offer insight into classification designs that begin to meet the evaluation parameters listed in Table 1. In addition to physical process-based classification, it is also instructive to evaluate classification systems that incorporate biological processes.

Classification has been applied to macroinverebrate and fish communities, although biologically-based classification systems are in the early stages of development with much empirical work being conducted. Dunning et al. (1992) focused on the classification of habitat and biotic structure and function to analyze the effect of habitat composition and spatial arrangement on biotic distribution, pattern, and demographics. Poff (1997) developed a framework, combining biological and physical processes, for understanding and predicting the distribution and abundance of species in stream communities. Specifically, Poff (1997) presented a framework that required species be described in terms of their functional relationships to habitat selective forces, which act as filters occurring at hierarchical landscape scales. The framework identified key elements of process-based classification (e.g., pattern, process, hierarchy, heterogeneity) and highlighted several areas for future study that will contribute to the understanding of biological processes (see section on Strengths and Weaknesses of Classification). Poff's (1997) framework offers significant contributions to classification system development.

Instream process and structure patches created through geomorphic and hydrologic processes at the reach-scale may also be used to predict biotic distribution and pattern. For example, Jowett (1990) found that trout distributions in New Zealand were explained by: 1) minimum annual water temperature, 2) percentage of volcanic ash in the catchment, 3) ratios of mean flow and mean annual minimum flow to median flow, and 4) presence of lake and spring-fed rivers with stable flow regimes. The author concluded that trout distributions were largely related to climatic factors affecting availability and timing of water as constrained by structures and process regimes responsible for sediment input and thermal stability. However, factors determining trout abundance were related primarily to reach features such as instream habitat, morphology, flow and flow variation. An understanding of patch dynamics and the mechanisms underlying stream network discontinuity would provide greater resolution of those forces structuring trout populations. Pess et al. (2002) concluded that adult coho salmon abundance supported by a stream reach was significantly correlated with stream-reach and watershed area characteristics such as wetland and floodplain habitat amount and quality, riparian vegetation, surficial geology, stream gradient, slope stability, and land use. The authors concluded that fish distribution and abundance were controlled by structures and processes functioning at multiple scales as well as across scales. Incorporating a hierarchical approach to classification allows for inclusion of spatial variability and trans-scale interactions that affect species response to disturbance as well as distribution and pattern. Understanding these relationships also facilitates watershed analysis and recovery programs. With the exception of work conducted by Poff (1997), classification efforts focusing on biotic processes require more explicit linkages to process dynamics responsible for system heterogeneity as well as trans-scale interactions affecting resource pattern.

Strengths and Weaknesses of Existing Classification Systems – The Need for a New Classification Model

Classification requires that the intended application and specific classification goals first be identified. Secondly, appropriate spatial and temporal scales as well as levels of biological organization to address application goals be determined, and thirdly, the biophysical template be characterized and the influential physical and biological processes, patterns, and structures identified (Hawkins et al. 1993). As there is no agreed upon approach to addressing these watershed classification requirements, existing classification systems vary in their utility to address specific questions as well as their ability to permit accurate, repeatable descriptions and convey information about biophysical elements useful in natural resource management. Hawkins and Norris (2000) concluded that any attempt to make empirical comparisons between approaches was hampered by the multitude of methods employed. Although it is true that each classification approach is a reflection of the particular constraints imposed by the author and the issues of interest, it is possible to move beyond surficial differences and delve into the scientific underpinnings of the assumptions and limitations of these systems. In this section, we will explore the strengths and weaknesses of existing classification approaches.

Kondolf (1995) warns that although classification is useful to inventory large areas by bringing order to a system, this process of fitting natural streams to an existing classification system may lead to an overly confident view of stream system knowledge. During the 1998 annual meeting of the North American Benthological Society, Symposium on Landscape Classifications and Aquatic Biota, researchers concluded that although classification accounts for more biotic variation than expected by chance, the amount of variation related to landscape features is low. Hawkins et al. (2000) therefore recommended a tiered classification approach based on both reach- and large-scale landscape features to predict composition of freshwater fauna. However, based on the proceeding review of existing classification approaches, the failure of classification systems to capture system variability and to predict resource and biotic patterns appears more related to the simplified approaches commonly employed. In fact, previous examples of classification approaches illustrate the danger of focusing solely on reach- and catchment-scales to predict freshwater biota composition and pattern. To reduce the likelihood that a natural system is arbitrarily "fitted" to the constructs of a particular classification system, key ecological parameters taken from lotic system theory must form the core of any classification system. Specifically, the three evaluation parameters: a) catchment influences on stream network structure and resource dynamics; b) disturbance and recovery process influence on connectivity vector strengths, resource dynamics, and biotic pattern; and c) hierarchy, scale, and patch dynamic influences on energy and materials flow through the system should be central to the identification and mapping of landscape classes. It is also these same evaluation parameters, refined through application in classification and monitoring that should serve as measures of ecosystem condition.

Many programs in the United States concerned with the diagnosis and prediction of biotic impairment use regional classifications to specify expected biotic conditions. However, inferences regarding expected biological conditions are rarely based on a mechanistic understanding of how large-scale environmental features influence biota (Hawkins and Norris 2000). Emergent system properties are rarely, if ever, addressed. Hawkins and Norris (2000) concluded that most inferences are actually based on "if, then" logic e.g., if a stream flows through ecoregion A, its expected condition is therefore X. Lacking a mechanistic understanding, predictive ability and management utility of classification are low. Additionally, classification applications often attempt to tie coarse-scale (i.e., catchment) variables to reach- and micro-habitat-scale properties rather than addressing multiple scales of concern based on specific research or management questions and the scales associated with the response of interest. As biota are associated with their environment over a range of spatial scales and their distribution is the result of processes functioning at multiple scales, consideration of species constraints is necessary to select appropriate scales for study (Bult et al. 1998, Poole 2002). It is not surprising, therefore, that Hawkins et al. (2000) concluded that identified classes were inconsistent at best in partitioning known ecosystem variability.

To increase the accuracy, precision, resolution, and predictability of classification systems, approaches improving our ability to partition ecosystem variability across spatial and temporal scales must be employed. As a first step, conceptual models of landscape and lotic system interaction embracing pattern, process, and hierarchy must be developed. Application of these models to classification provides researchers with a framework to test the validity of hypotheses at the foundation of classification approaches (e.g., cause and effect linkages). With few exceptions, classification systems are not based on explicit models of ecosystem function nor have they undergone rigorous evaluation for accuracy, repeatability, or performance (Hawkins and Norris 2000). Without such evaluation, erroneous assumptions regarding the performance of classification approaches or the validity of underlying ecological theories are perpetuated. Ultimately, a robust classification system should provide a conceptual framework to integrate ecological theory and to test hypotheses concerning watershed dynamics (Naiman et al. 1992, Schlosser 1995).

Given the omissions of existing classification approaches outlined above, it is time to turn our attention to the components of classification necessary to address these important structural and scientific gaps. Classification based solely on structure excludes information on hierarchy, pattern, and process so important in predicting ecologically relevant discontinuities and resulting abiotic and biotic patterns (Hughes et al. 1994, Bult et al. 1998, Boulton 1999, Meixler and Bain 1999, Hawkins et al. 2000). To a much greater extent, the process-based classification approaches addressed the evaluation parameters and were generally successful in meeting project objectives. To accurately partition ecosystem variability, infer system structure and function across landscapes, predict watershed response to disturbance, diagnose lotic system impairment, and design effective recovery strategies, a classification approach embracing the fundamental tenets of hierarchical patch dynamics (HPD) theory is needed – an approach emphasizing the nested, discontinuous hierarchies of patch mosaics and the centrality of pattern, process, and scale. The discontinuum view central to the HPD theory recognizes general trends and trend reversals in habitat characteristics along the longitudinal profile of the stream network, and serves as a framework to understand the ecological importance of the unique habitat patterns created by processes and structures varying along the stream network (Figure 1) (Poole 2002). Without such advances, classification will not be responsive to the needs of researchers or natural resource managers.

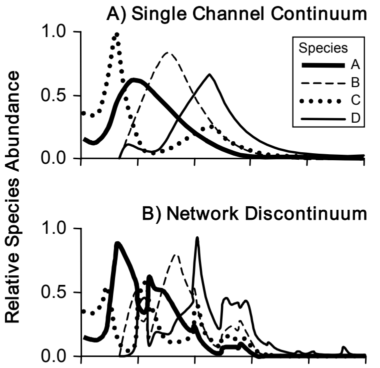

Figure 1. Relative abundance of 4 species of aquatic organisms from headwaters to mouth predicted by a simple heuristic model of a simple linear continuum (A) vs. a patchy, networked discontinuum (B). (From Poole 2002)

The importance of spatial patchiness over a range of scales has been recognized in traditional landscape ecology as well as its newer relation, fluvial landscape ecology (Wu and Loucks 1995, Poole 2002, Fausch et al. 2002). Critical to exploring the dynamics of ecosystems is an understanding of the scale-dependence and hierarchical structure of patches (Wu and Loucks 1995). Patch heterogeneity reflects the strength of vertical, longitudinal, and lateral linkages along the stream profile (Townsend 1996). Linkage (i.e., connectivity vectors) strength, in turn, reflects the unique geomorphological structure of stream segments within the stream network (Wu and Loucks 1995, Montgomery 1999, Poole 2002). This multi-scale relationship between geomorphic system constraints and longitudinal system heterogeneity creates a nested, discontinuous hierarchy of patch mosaics differing in pattern, structure, and function. Processes spanning spatial and temporal scales, influence the function or structure of patches at coarser- and finer-scales, thereby creating a dynamic system of patches influencing the distribution of abiotic and biotic resources (den Boer 1968, Pringle et al. 1988, Schlosser 1991, Wu and Loucks 1995, Yahner and Mahan 1997, Cohen et al. 1998, Crook et al. 2001). Alterations in the structural and functional relationships of landscape elements and stream patches can significantly affect resource distribution, and is therefore critical to predicting the effect of land management options on lotic systems (Schlosser 1991, Rice et al. 2001, Poole 2002). The HPD perspective provides a conceptual framework to understand and explore the multi-scale processes and structures driving patch formation and dynamics, while providing a mechanistic understanding of lotic systems necessary to improve the accuracy and precision of classification.

Combining HPD theory (Wu and Loucks 1995) with concepts derived from Montgomery's (1999) process domains, Townsend's (1996) connectivity vectors, and Poff's (1997) landscape filters provides a framework that integrates ecological theory and is the model for a new classification system capable of categorizing ecosystem processes across multiple scales, predicting stream network discontinuities and resource distributions, and testing hypotheses concerning watershed dynamics. I call this new model the generic process hierarchy (GPH; Figure 2). The GPH allows trans-scale assessment of critical processes associated with the availability and delivery of materials (sediment, water, nutrients, pollutants, etc.) to the stream network and the routing of these materials within the network – processes critical to regulating biological distribution and pattern (Naiman et al. 1992). As such, GPH may also be applied to describe the mechanisms driving system discontinuities as well as the scale-dependent functional pathways by which human actions influence and biotic communities respond to ecosystem structure and function. The GPH is geographically-dependent reflecting the unique hierarchical patch mosaic associated with each stream network – "every stream an individual" (Hynes 1975, Wu and Loucks 1995).

In the following section, a general protocol for GPH application will be developed. The GPH is a general protocol for the hierarchical classification of landscape processes that influence materials flux within watersheds. As biotic populations respond to both ecosystem patterns and processes, the GPH protocol combines classification of landscape processes and structures to improve assessment of ecosystem integrity and vulnerability. Classification of watershed processes using the GPH protocol may be applied at any spatio-temporal scale, but always incorporates the scale where the community response is observed as well as the encompassing (i.e., coarse-scale) and component (i.e., fine-scale) scales. At the encompassing scale, the GPH classifies land use trajectories and other processes influencing materials availability. At the observation scale, the GPH classifies rates and means of materials delivery to streams and at the component scale, the GPH classifies materials transport and storage within the stream.

This protocol may be applied to: (1) predicting flow-regime metrics of ecologically relevant materials (water, sediment, nutrients, large wood, pollutants, etc.) within watersheds and stream networks; (2) predicting ecologically relevant patch hierarchies and associated resource discontinuities responsible for abiotic and biotic resource distribution and pattern; (3) characterizing the expected biological integrity and vulnerability of aquatic communities; and (4) identifying potential watershed responses to anthropogenic stressors.

A Proposed Classification Model: Generic Process Hierarchy

There are several mechanisms that will contribute to the improved predictive ability of the combined process and structure classification espoused in the GPH:

1. *explicit integration of relevant ecological theory* to capture critical metrics in classification;
2. *improved organization and integration of data* that characterize ecosystems thereby providing a better foundation for ecosystem monitoring, adaptive management, and regulation;
3. *greater accuracy and resolution* in assessing ecosystem vulnerability and diagnosing biotic impairment;
4. *improved understanding of landscape variation* in geomorphic processes, disturbance regimes, response potential, and recovery time, and therefore greater accuracy and predictive ability associated with management/monitoring plans;
5. *explicit integration of the spatial geometry (i.e., patch connectivity, patch isolation) of patches* in assessing ecosystem vulnerability and biological impairment.

Approach/Framework. Ecosystem dynamics at any spatial or temporal scale depend upon both coarser- and finer-scale structures and processes. As biota react to their environment over a range of spatial and temporal scales, consideration of species constraints is necessary to select appropriate scales for study (Poff 1997, Bult et al. 1998, Poole 2002). Therefore, classification systems intending to map the linkages between ecosystem structure/function, natural/anthropogenic disturbance, and biotic community response must be organized and implemented using an appropriate hierarchy of processes and structures. To succeed, the hierarchy must incorporate the scale-dependent functional pathways by which biotic communities respond to ecosystem structure and function (Fausch et al. 2002). At the core of this issue is the ability to categorize across scales those ecosystem processes driving the discontinuous distribution of abiotic and biotic resources.

Important to predicting resource distribution and pattern is the ability of classification frameworks to effectively characterize important scale-spanning processes and their temporal and spatial distributions. Specifically, temporal and spatial variation in geomorphic processes exerts distinct influences on lotic and riparian ecosystems (Paustian et al. 1992, Whiting and Bradley 1993, Grant and Swanson 1995, Montgomery 1999). These influences alter the strength and direction of connectivity vectors important in establishing stream profile patterns and are responsible for establishing the discontinuous hierarchies of patch mosaics unique to each landscape (Townsend 1996). Mapping trans-scale geomorphic processes and the resulting variability in the direction and magnitude of connections between rivers and landscapes leads to a mechanistic understanding of hierarchical patch mosaic development and resulting biotic pattern. Variability related to geomorphic processes and connectivity vectors act as landscape filters occurring at hierarchical landscape scales and driving biotic pattern (Poff 1997).

To begin our discussion of the GPH protocol, we must understand the landscape geomorphic context and disturbance processes influencing associated ecological systems. Geomorphic context may be viewed at multiple spatial scales:

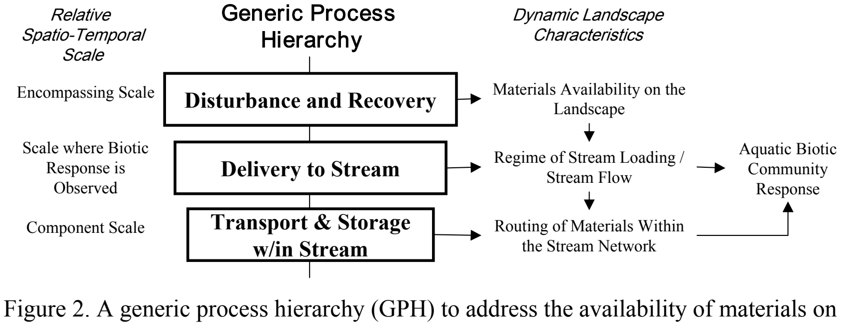

Figure 2. A generic process hierarchy (GPH) to address the availability of materials on the landscape, delivery of materials to the stream network, and transport of materials within the stream network

(1) *geomorphic provinces* differ in regional climate, geology, and topography, and within which suites of landscape-forming processes govern channel characteristics and processes; (2) *litho-topo* units differ in rock type and relief, and within which similar suites of geomorphic processes influence gross habitat characteristics and dynamics; and (3) *process domains* define specific areas of a landscape within which distinct suites of ecosystem processes govern physical habitat type, structure, and dynamics; the disturbance regimes associated with process domains dictate the disturbance template upon which ecosystems develop (Frissell et al. 1986, Montgomery 1999). The process domain concept espoused by Montgomery (1999) maintains that watersheds characterized by different geomorphic processes, disturbance regimes, response potential, and recovery time and classified by process domains will have ecological significance.

As described by Montgomery (1999), the process domain concept focuses on geomorphic processes that occur at a specific spatial scale, the *litho-topo unit*. However, the process domain concept has broader applicability. Specifically, relationships between ecosystem process and aquatic community response will occur at multiple spatial and temporal scales, depending on the processes and communities being assessed. As such, the GPH (Figure 2) can be applied to identify "process domains" for a variety of ecosystem functions occurring at any number of spatio-temporal scales. When developing a process classification, the GPH must target the spatial scale where the community response of interest can be observed/measured (i.e., *observation scale*), and then applied across the *encompassing* and *component scales* (Figure 2). These three scales are termed the *application scales*. At each scale, process filters constraining biotic distribution and driving biotic pattern, are also identified.

The GPH is based on a simple conceptual model of terrestrial influence on abiotic and biotic resources in rivers and streams. According to this conceptual model (Figure 2), human activities influence the processes of disturbance and recovery at the encompassing scale, and thus affect the availability of materials to be delivered to the stream. At the observation scale, human activities influence mechanisms by which materials are delivered to rivers and streams, thereby affecting loading patterns and rates. At the component scale, human activities influence the processing (e.g., storage, transport, and transformation) of materials in the stream, and thus affect materials flux within the river. Parallel to this hierarchy of physical resource dynamics (e.g., availability, delivery, transport, storage, processing) there is also a concomitant hierarchy of biological resource dynamics. The patch hierarchy of these two parallel structures differs in that physical resources are described by the patch context (i.e., encompassing scale/availability and delivery), patch structure (i.e., observation scale/transport and storage), and the metastructure (i.e., component scale/internal processing) while biological resources are described by the individual, community, and population. The GPH describes the resource dynamic implications across patch scales to predict biological resource dynamics as well as the mutual effects of physical and biological resources on one another.

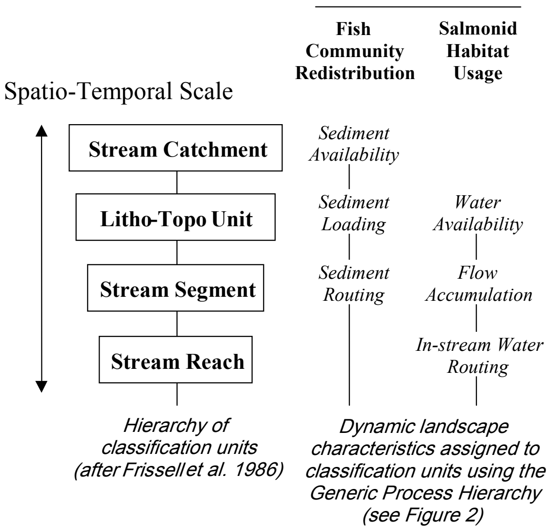

Figure 3. Scale-specific application of the Generic Process Hierarchy to address the influence of sediment flux on fish community response and water flux on salmonid habitat distribution.

Incorporating this conceptual model into a classification scheme involves classifying *resource dynamics* (Figures 2 and 3) that derive from ecosystem processes. Yet classification is best suited to landscape characteristics that are relatively static. To bridge this incompatibility, landscape units or patches at each scale will be classified based on that unit's *potential* to express dynamic landscape characteristics (i.e., the range of potential states for materials availability, delivery, or routing, depending on the scale at which the unit is delineated). Landscape units will be further classified according to their *vulnerability* to anthropogenic disturbances (i.e., how various types and intensities of disturbance will influence the unit's state). Appropriate spatio-temporal scales and associated classification units will be based on the structure proposed by Frissell et al. (1986) (Figure 3).

Ecosystem vulnerability is particularly high for aquatic systems because watershed processes continue to be modified by humans. The biological effects of anthropogenic alterations to habitat are not random, but manifest through effects on organism fitness according to specific autecological characteristics such as thermal tolerance, reproductive behavior, and/or trophic specialization. Where native and endemic organisms have life-history and ecological traits that are adapted to historical environmental regimes, habitat alteration selects against specialized native forms, placing them at greater risk of imperilment than more generalized species. Endemic or specialized taxa are therefore of particular interest as regional ecological indicators and as targets for conservation. Changes in these species' distributions and relative abundance will be used to assess biological impairment and ecosystem vulnerability within the context of the classification framework (Poff 1997).

<u>Data</u>

Readily available data may be organized and integrated using the classification framework and future data needs may be assessed. As adaptive management and monitoring generates new data, the classification system may be refined and hypotheses tested. Data associated with key biological and physical processes and structures can be integrated and data layers developed using a geographic information system (GIS).

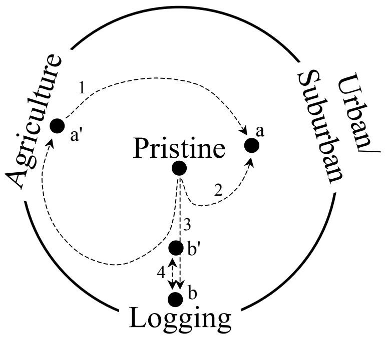

Figure 4. Conceptualization of land-use transitions. There are multiple possible transitions leading from pristine conditions to point "a," which represents a mixture of forested and urban cover types (e.g., (1) abandoned agricultural lands followed by urbanization or (2) direct land clearing for urbanization). Similarly, point "b" may be reached via various transitions (e.g., (3) initial logging of old growth or (4) intensive logging on a time rotation.) Assessment of existing cover type can identify landscape units at location "a" and "b," but assessment of historic transitions is required to differentiate potential legacy effects associated with transitions 1 and 4 but, absent from transitions 2 and 3.

GIS can be used to map and classify process and structure data at the selected application scales. Process descriptions embedded within each class designation can be related to the spatial pattern and statistical distribution of disturbance events and the availability, input/delivery, storage, and transport of materials. Class function and structure can then be described at the three scales of application. Biological data can be spatially rectified and used as an overlay to the class designations. Based on class designations, the distribution and pattern of biological communities can be described. Patch connectivity and isolation analysis can be conducted to further explain biotic distribution and pattern. Class vulnerability to anthropogenic disturbances can be assessed based on disturbance attributes, system vulnerability, and stream responsiveness; implications for biota can then be addressed. Classification products may include summary statistics, graphic and spatially explicit data presentation, and other data base products for comparative watershed evaluations, basin analysis, long-term monitoring and adaptive management needs, and recovery planning.

Methods/Techniques

<u>*Structural Classification*</u>: Structural classification of landscapes can be conducted according to contemporary classification

techniques. Catchment boundaries are derived from digital elevation models and topographic maps. Litho-topo units are defined using the process domain framework of Montgomery (1999); and stream segments according to the hierarchical stream classification framework of Frissell et al. (1986) using the approach of Montgomery and Buffington (1993) combined with the channel pattern classification of Nanson and Knighton (1996).

Process Classification

The GPH requires classification of disturbance/recovery, delivery, and transport of materials within a watershed (Figure 2). Classification of disturbance/recovery at the catchment scale is typically accomplished by simply categorizing the percent of the basin which exists in various land cover categories. This process works well for relatively pristine landscapes as they first experience anthropogenic disturbances, but does not capture the effects of historical land use. Landscapes across much of the country have experienced episodes of changing land-use intensity. Disturbance and recovery will be addressed by classifying transitions in dominant land use to understand and ultimately classify land-use trajectory (Figure 4). Rather than simply classify basins by cover type, basins are classified by the percent of the land area that is transitioning from one cover type to another. Using this approach, GPH captures the synergistic influences of either combined natural and anthropogenic disturbances and/or a series of various anthropogenic disturbances. Also at the catchment scale, materials availability affecting system loading patterns and rates are identified. In addition to disturbance and recovery, classification will be based on a range of potential states related to materials availability. Classification of materials delivery to the stream network is based on the characteristics of the litho-topo unit as modified by the overlying land use trajectories and materials availability classes. Classification is based on the range of potential states related to the nature, rate, and timing of materials delivery to the stream network.

Classification of materials transport and storage within the stream network is based on the characteristics of each stream segment as modified by the upstream delivery to the stream channel as well as the overlying land use trajectories, materials availability, and materials delivery classes. The range of potential states related to the timing and rate of materials transport and storage within the stream segment will form the basis of the transport and storage classification. Finally, further classification based on vulnerability to anthropogenic disturbances will occur at each application scale.

Proposed Case Study: Umpqua Basin, Oregon

The classification framework may be applied to assess the integrity and vulnerability of distinct ecosystems based on analysis of different landscape disturbances, materials, and biotic community response, thereby testing the flexibility and generality of this framework. As the framework is based on a conceptual model of ecosystem processes and their linkages and interactions, classification may yield testable hypothesis regarding stream response to watershed disturbance. Ultimately, the GPH should facilitate inference within and across landscape classes.

In the Umpqua Basin, Oregon case study, the GPH protocol would be applied to basin-wide hydrological processes and patterns affecting stream network thermal dynamics and native salmonid distribution. The hydrological process hierarchy would allow one to map and classify patterns of water availability across litho-topo units, water delivery to streams within stream segments, and water transport and storage within stream reaches (Figure 3). The final composite picture of hydrological and thermal processes and patterns across stream reaches developed by application of the hydrological process hierarchy would be related to salmonid distribution and biological impairment.

Complex channel morphology and hydrology yields thermal diversity in streams (Figure 5). Application of the GPH to hydrological processes would facilitate identification of stream segments that contain cold-water patches, indicating geomorphic and hydrologic complexity. The pattern and structure of stream temperature governs the distribution and pattern of stream fishes. Native Pacific Northwest salmonids are members of the cold-water stream community, and therefore the spatial and temporal pattern of cold-water patches is critical to their persistence. The hydrologic process hierarchy applied to the Umpqua Basin case study would allow one to: (1) describe scale-dependent hydrological metrics (e.g., water availability, delivery, transport, storage) for each classification unit at each scale within the process hierarchy; (2) describe how anthropogenic disturbances would alter watershed characteristics that influence hydrological processes and thus affect reach-scale thermal pattern, salmonid distribution, and assemblage composition; (3) characterize biological integrity by predicting changes in stream fish distribution and community composition based on thermal requirements of native salmonids; (4) describe ecosystem vulnerability (sensitivity) by predicting instances where increased distributions of habitat generalists adapted to either broad temperature ranges or warmer temperatures and decreased or fragmented distributions of stenothermic species occur owing to disruption of hydrological processes; and (5) describe spatial geometry related to thermal patch pattern and isolation and affect on native salmonid distribution and assemblage composition.

Temperature is an ecological resource subjected to competition and partitioning that directly contributes to population and individual fitness (Magnuson et al. 1979). How this resource manifests itself spatially and temporally reflects the unique distribution of biophysical processes and structures across landscape (Schmutz and Jungwirth 1999, Torgersen et al. 1999, Poole and Berman 2001). Fish, in turn, reflect thermal pattern and structure through spatial and temporal variability in distribution, occurrence, and assemblage patterns (Berman and Quinn 1991, Nawa et al. 1991, Matthews et al. 1994, Schlosser 1995, Richards et al. 1996, Kruzic 1998, Torgersen et al. 1999, Baxter and Hauer 2000, Dunham et al. 2001, Scott and Helfman 2001). Stream temperature typically trends away from baseline temperature and toward atmospheric temperatures in a downstream direction (Sullivan et al. 1990). External drivers of temperature (e.g., air temperature, precipitation, vegetation, landform, geology) control the rate of heat and water delivery. Insulating and buffering mechanisms associated with the stream network control the rate of heat exchange (Poole and Berman 2001). Regardless of the magnitude of stream trends, downstream temperature profiles are punctuated by trend reversals (i.e., discontinuities in thermal profiles) reflecting local geomorphology and stream structure (i.e.,

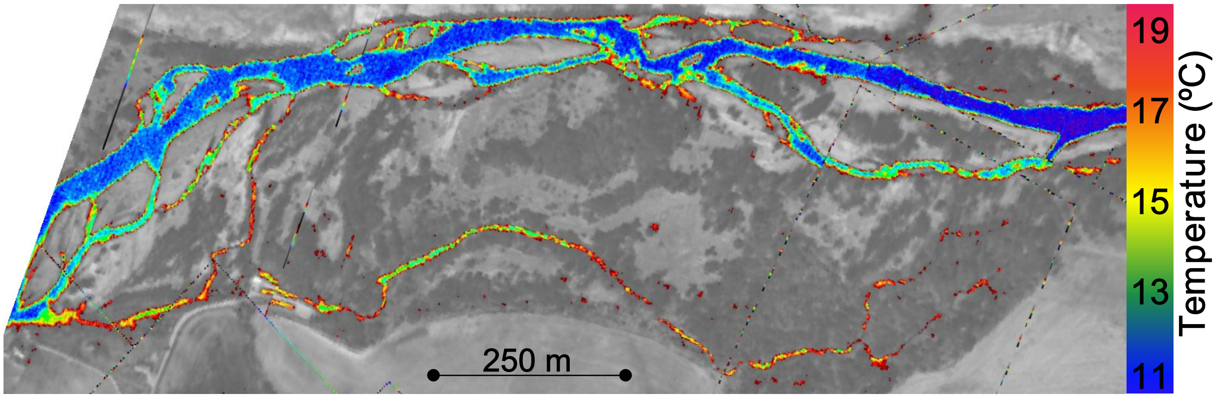

Figure 5. Springtime (April, 2001) surface water temperature in a section of the Umatilla River, OR, with complex channel morphology. Image derived from Forward Looking Infrared (FLIR) videography.

connectivity vector strength) (Schmutz and Jungwirth 1999, Torgersen et al. 1999, Poole and Berman 2001). These reversals are biologically significant as they provide critical habitat for cold-water species (Sedell et al. 1990, Berman and Quinn 1991).

Land use practices have altered hydrological processes associated with the availability, delivery, transport, and storage of water. As hydrological complexity decreases, thermal diversity also decreases (Quigley 1997, Berman 1998, Poole and Berman 2001). Torgersen et al. (1999) contrast two river systems, one dominated by various human activities and one within a designated wilderness area. The managed system was spatially heterogeneous with disjunct patches of relatively cool water. In contrast, the wilderness reaches provided larger, contiguous areas of cool water during summer months. As patch size is related to the occurrence and persistence of fish (Frissell et al. 1986, Wu and Loucks 1995, Dunham and Rieman 1999, Rieman and Dunham 2000, Dunham et al. 2001, Scott and Helfman 2001), and thermal pattern is related to fish distribution and occurrence, biophysical processes that affect thermal patch size, distribution, and frequency should be important drivers of native salmonid distribution and assemblage composition. I predict that landscape classes (i.e., litho-topo units) most vulnerable to hydrological alteration and hence loss of thermal patch diversity will support fewer cold-water salmonids and more cool- and warm-water species. Furthermore, I predict the immigration of cool- and warm-water fishes into upstream stream reaches (Scott and Helfman 2001).

Explaining distribution and assemblage composition of native salmonids in relation to cool- and warm-water fish species requires an assessment of in-stream thermal pattern and structure. In turn, stream thermal regimes are clearly influenced at multiple scales by landscape structure, geomorphic processes, and past and present human activities. To address water availability in stream catchments, a structural classification of lithology and vegetation along with a process classification of climate and anthropogenic disturbance and recovery would be conducted. As these basins have experienced extensive land cover change, it is anticipated that extensive alteration of hydrological processes critical to shaping thermal pattern and structure has occurred. Disturbance and recovery would be addressed by categorizing transitions in dominant land use (Figure 4) to understand and ultimately classify land-use trajectories of litho-topo units. The land-use trajectory classification would incorporate both historical and current land-use, as current thermal dynamics are often affected by historical land use patterns (Hatten and Conrad 1995, Harding et al. 1998).

Previous work conducted by O'Daniel and Poole (in prep) in the Umatilla Basin, Oregon indicates that hydrologic process classification (in this case, the relative potential for ground and surface water exchange or "hyporheic flow") in rivers accurately predicts the location of stream segments exhibiting water temperatures cooler than surrounding segments (Figure 6). I would propose to build upon and expand the work of O'Daniel and Poole as follows. At the litho-topo scale, the coarsest scale of analysis, I would assess the availability of water to the stream based on classification of precipitation regimes, topography, cover type, and disturbance history to determine relative water use (evapo-transpiration) and storage capacity characteristics from the litho-topo classification. At the stream segment scale, I would

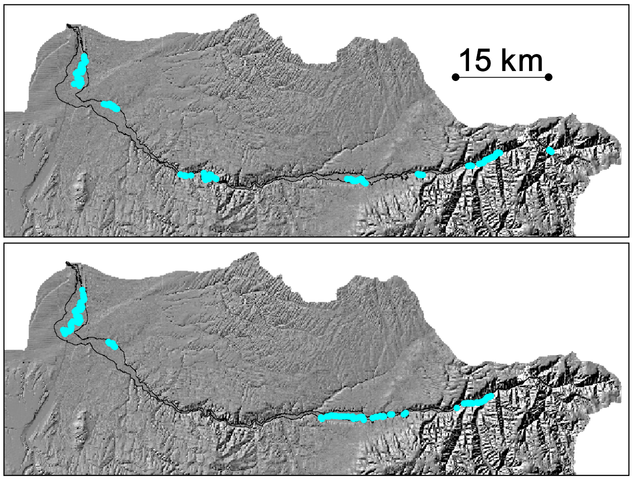

Figure 6. Observed cool water zones (top) vs. predicted zones with high potential for hyporheic flow derived from geomorphic assessment (bottom). (Umatilla River, OR; O'Daniel and Poole In Prep.)

assess delivery of water to the stream via surface and groundwater flow pathways. To accomplish this, I would integrate a classification of each stream segment's valley and floodplain morphology with the water use and storage classification of surrounding litho-topo units. Finally, at the stream reach scale, I would assess reach morphology and channel complexity to identify zones of high/medium/low surface- and ground-water storage within the stream corridor. Portions of the stream network with more even annual water delivery regimes, high channel complexity, and a high capacity to store surface- and ground-water would be classified as having the highest potential for thermal complexity and cold water refugia. Thus, the pattern of thermal complexity within the stream network derived from a composite of reach-scale thermal classification would be compared to remote sensing data (FLIR – see below) to assess the accuracy of the classification. Thermal patch structure, isolation, and connectivity would then be assessed to predict expected habitat use by salmonids, and resulting predictions compared to existing and proposed supplemental field data on salmonid distribution and habitat use (see below).

The classification system can be applied assuming lack of human disturbances to estimate historical habitat distributions and relative abundance of cold-water salmonid species across the region. Additionally, the classification system could be used to assess future land-use scenarios on system hydrology, thermal pattern, and salmonid distribution. This effort would result in landscape sensitivity maps and an assessment of associated risks to stenothermic biota.

To capture the spatial geometry of temperature at the watershed-scale, forward looking infrared (FLIR) videography would be employed (Figure 5; Faux et al. 2001, Torgersen et al. 2001). In-stream temperature measurements using digital temperature recorders as well as hand-held, digital thermometers would be used to ground truth thermal imagery (Torgersen et al. 1999). Conventional methods of stream temperature measurement using in-stream data recorders provide temporally continuous information, but is spatially limited (Torgersen et al. 2001). Spatial data are needed to map thermal patch structure at biologically relevant scales (Torgersen et al. 1999). Additionally, FLIR data would be used to specify placement of digital temperature recorders to provide information on temporal variability of thermal patches. Summer and winter FLIR data would be collected.

New data related to fish distribution and species assemblage are available from the Oregon Department of Fish and Wildlife. This information would be collected and analyzed for completeness. Data gaps would be identified and data necessary for the completion of our study would be collected through snorkel surveys and seining. Methods for determining fish occurrence would be based on Dunham and Chandler (2001) and Rieman and McIntyre (1995).

Using FLIR and in-stream temperature data, sites would be identified where additional information related to fish movement within (i.e., component patch elements) and between (encompassing patch elements) thermal patches would augment our findings concerning biological impairment. Fish residing within these sites would be the subject of additional data collection. Temperature-sensitive radio transmitters (Advanced Telemetry Systems) would be used to obtain information related to fish movement in relation to patch heterogeneity and isolation. This work would contribute to our understanding of the relation between patch structure and biological impairment.

Temperature directly governs the metabolic rate of fish and directly influences the life history traits of Pacific salmon (Elliott 1981). By residing within thermal patches that facilitate efficient metabolic functioning, fish conserve energy for critical physiological and behavioral processes including gamete production and reproductive functions. Berman and Quinn (1991) determined that a 2.5°C decrease in internal temperature of adult spring chinook salmon (1.8 to 6.1 kg), would produce a 3.2 to 20% reduction in total daily energy expenditure, depending on activity level. Since telemetry data suggest that salmon develop habitat usage patterns that control internal temperatures to optimize energy conservation (Berman and Quinn 1991), land use activities that alter the context, internal component structure, or isolation of thermal patches in the stream network may reduce salmonid fitness. Data obtained from the proposed radio telemetry study would therefore be critical to improving our understanding of the relationships between salmonid habitat use and reach-scale thermal patch configuration and requisite for relating the hydrologic process classification to salmonid distributions within the stream network.

During a previous study conducted by Berman (http://ims.reo.gov/website/swop/) for the Northwest Forest Plan, a characterization and preliminary classification of the Umpqua Basin was conducted. These data would be available for continued study of the system. Data layers were developed at three scales. Litho-topo scale data include: vegetation, geology, soils, landform, DEM, regional climate, rain-on snow zone, land cover, and salmonid distribution. Stream segment-scale data include: stream gradient, stream flow, riparian vegetation, and valley confinement. Stream reach-scale data include physical habitat, biotic assemblage diversity, and salmonid occurrence and pattern.

Basic Research Needs

In reviewing the classification literature, it was evident that much research is still required to elucidate the complex relationships between terrestrial and fluvial systems. Areas for research include: (1) studies relating formative processes at multiple scales and habitat patch development, as well as relating patch mosaics to biotic distribution and pattern (Imhof et al. 1996, Palmer and Poff 1997); (2) studies relating the spatial arrangement and connectivity of habitat patches on population demographics (Palmer and Poff 1997, Fausch et al. 2002); (3) the degree to which habitat features at different scales are linked functionally or statistically i.e., the trans-scale linkage of processes and emergent properties related to heterogeneity (Palmer and Poff 1997, Poole 2002); (4) species traits possessed by strongly interactive species (e.g., keystone species) and the habitat filters that most strongly constrain the distribution of these species (Poff 1997); (5) the functional significance of a range of species traits and the extent to which these traits are correlated, and therefore respond in concert to the presence or modification of a particular filter (Poff 1997); (6) the spatial scale at which different landscape attributes influence aquatic patterns of interest (Hawkins et al. 2000, Jensen et al. 2001); and (7) the application of new tools and technologies to address ecological complexities and to improve analysis across scales e.g., coarse-grain continuous sampling (Fausch et al. 2002), remote sensing (Johnson and Gage 1997, Torgersen et al. 1999, Fausch et al. 2002), modeling and programming techniques (Wu and Loucks 1995, Poole 2002, Wright and Li 2002). Additionally, Powers et al. (1988) and Palmer and Poff (1997) provide an integrated perspective on future research needs based on their views of biota/habitat relationships and of regional processes (i.e., biotic dispersal and materials flux) that act to unite or alter heterogeneous systems locally.

Expected Benefits

The GPH framework produces more accurate mapping of the integrity and vulnerability of biological communities to natural and anthropogenic disturbances. The protocols should assist those interested in determining ecosystem vulnerability, diagnosing biological impairment, designing monitoring systems, and identifying restoration opportunities. Where these concepts have been tested in the Rogue and Umpqua Basins, Oregon, they were found to significantly contribute to identifying recovery options and priorities, designing monitoring strategies, and designing Total Maximum Daily Loads.

Ultimately, as the classification system may be used to extrapolate stressor-effect relationships to ecosystems with similar process/structure relationships, application of the classification system should provide watershed managers with information and options to reduce risks to vulnerable ecosystems and to identify appropriate goals and methods for watershed restoration. Classification products would include summary statistics, graphic and spatially explicit data presentation, and other data base products for comparative watershed evaluations, basin analysis, long-term monitoring and adaptive management needs, and recovery planning.

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References

Abell, R., D. Olson, E. Dinerstein, P. Hurley, W. Eichbaum, S. Walters, W. Wettengel, T. Allnutt, and C. Loucks. 1998. A Conservation Assessment of the Freshwater Ecoregions of North America. Final Report Submitted to the U.S. EPA, April 1998. World Wildlife Fund. Washington, D.C., USA.

Albert, D.A., S.R. Denton, B.V. Barnes. 1986. Regional Landscape Ecosystems of Michigan. Ann Arbor, MI: University of Michigan, School of Natural Resources. 32 pp.

Allan, J.D. and Johnson. L.B. 1997. Catchment-scale analysis of aquatic ecosystems. Freshwater Biology 37: 107-111.

Arscott, D.B., K. Tockner, and J.V. Ward. 2001. Thermal heterogeneity along a braided floodplain river (Tagliamento River, northeastern Italy). Canadian Journal of Fisheries and Aquatic Sciences 58(12): 2359-2373.

Bailey, R.G. 1976. Ecoregions of the United States (map). Ogden, Utah: USDA Forest Service, Intermountain Region. 1:7,500,000.

Baxter, C.V. and R. Hauer. 2000. Geomorphology, hyporheic exchange, and selection of spawning habitat by bull trout (*Salvelinus confluentus*). Canadian Journal of Fisheries and Aquatic Sciences 57: 1470-1481.

Berman, C.H. 1998. Oregon Temperature Standard Review: Biological Assessment. Prepared by the U.S. Environmental Protection Agency for the National Marine Fisheries Service and the U.S. Fish and Wildlife Service.

Berman, C.H. 1998. http://ims.reo.gov/website/swop/.

Berman, C.H. and T.P. Quinn. 1991. Behavioural thermoregulation and homing by spring chinook salmon, *Oncorhynchus tshawytscha* (Walbaum), in the Yakima River. Journal of Fish Biology 39: 301-312.

Bisson, P. A., and D. R. Montgomery. 1996. Valley segments, stream reaches, and channel units. Pages 23-52 in F. R. Hauer and G. A. Lanberti (eds.). Methods in Stream Ecology. Academic Press, San Diego, California.

Boulton, A.J. 1999. An overview of river health assessment: philosophies, practice, problems and prognosis. Freshwater Biology 41: 469-479.

Bult, T.P., R.L. Haedrich, and D.C. Schneider. 1998. New technique describing spatial scaling and habitat selection in riverine habitats. Regulated Rivers: Research and Management 14: 107-118.

Church, M.E. 2002. Geomorphic thresholds in riverine landscapes. Freshwater Biology 47: 541-557.

Church, M. 1992. Channel morphology and typology. Pages 126-143 in P. Calow and G.E. Petts (eds.). The Rivers Handbook. Blackwell, Oxford, UK.

Cohen, P, H. Andriamahefa, and J.G. Wasson. 1998. Towards a regionalization of aquatic habitat: distribution of mesohabitats at the scale of a large basin. Regulated rivers: Research and Management 14: 391-404.

Crook, D.A., Robertson, A.I., King, A.J., and Humphries, P. 2001. The influence of spatial scale and habitat arrangement on diel patterns of habitat use by two lowland river fishes. Oecologia 129(4): 525-533.

Davies, N.M., Norris, R.H., and Thoms, M.C. 2000. Prediction and assessment of local stream habitat features using large-scale catchment characteristics. Freshwater Biology 45: 343-369.

Den Boer, P.J. 1968. Spreading of risk and stabilization of animal numbers. Acta Biotheoretica 18: 163-194.

Detenbeck, N.E., P.W. DeVore, G.J. Niemi, and A. Lima. 1992. Recovery of temperate-stream fish communities from disturbance: a review of case studies and synthesis of theory. Environmental Management 16(1): 33-53.

Dias, P.C. 1996. Sources and sinks in population biology. TREE 11(8): 326-330.

Dunham, J.B. and G.L. Chandler. 2001. Models to Predict Suitable Habitat for Juvenile Bull Trout in Washington State. Final Report prepared for the U.S. Department of the Interior, U.S. Fish and Wildlife Service, Olympia, Washington. pp. 75.

Dunham, J.B., B.E. Rieman, and J.T. Peterson. 2001. Patch-based models to predict species occurrence: lessons from salmonid fishes in streams. In J.M. Scott, P.J. Heglund, M. Morrison, M. Raphael, J. Haufler, and B. Wall (eds.). Predicting Species Occurrence: Issues of Accuracy and Scale. Island Press, Covelo, California, USA.

Dunham, J.B. and B.E. Rieman. 1999. Metapopulation structure of bull trout: influences of physical, biotic, and geometrical landscape characteristics. Ecological Applications 9(2): 642-655.

Dunning, J.B., B.J. Danielson, and H.R. Pulliam. 1992. Ecological processes that affect populations in complex landscapes. Oikos 65(1): 169-175.

Ebersole, J.L., W.J. Liss, C.A. Frissell. 1997. Restoration of stream habitats in the western United States: restoration as reexpression of habitat capacity. Environmental Management 21(1): 1-14.

Elliott, J.M. 1981. Some aspects of thermal stress on freshwater teleosts. Pages 209-245 in A.D. Pickering (ed.). Stress and Fish. Academic Press, New York, New York, USA.

EPA. 2000. Mid-Atlantic Highlands Streams Assessment. USEPA, Environmental Monitoring and Assessment Program, National Health and Environmental Effects Research Laboratory, Western Ecology Division, Office of Research and Development, Corvallis, OR; and Region 3, Philadelphia, PA. EPA-903-R-00-015.

Fahrig, L. 1997. Relative effects of habitat loss and fragmentation on population extinction. Journal of Wildlife Management. 61(3): 603-610.

Fahrig, L. 1992. Relative importance of spatial and temporal scales in a patchy environment. Theoretical Population Biology. 41: 300-314.

Fausch, K.D., C.E. Torgersen, C.V. Baxter, and H.W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. BioScience 52(6): 1-16.

Faux, R.N., H. Lachowsky, P. Maus, C.E. Torgersen, and M.S. Boyd. 2001. New Approaches for Monitoring Stream Temperature: Airborne Thermal Infrared Remote Sensing. Inventory and Monitoring Project Report -- Integration of Remote Sensing. Remote Sensing Applications Laboratory, USDA Forest Service, Salt Lake City, Utah.

Forman, R. T. T. 1995. Some general principles of landscape and regional ecology. Landscape Ecology 10(3): 133-142.

Forman, R. T. T. and M. Godron. 1986. Landscape Ecology. John Wiley and Sons, New York.

Fox, M. 2001. A New Look at the Quantities and Volumes of Instream Wood in Forested Basins within Washington State. M.S. Thesis. College of Forest Resources, University of Washington, Seattle

Frissell, C. A., W. J. Liss, and D. Bayles. 1993. An integrated, biophysical strategy for ecological restoration of large watersheds. Pages 449-456 in D. F. Potts (ed.). Proceedings of the Changing roles in water resources management and policy. American Water Resources Association, Bellevue, Washington.

Frissell, C.A., W.J. Liss, C.E. Warren, and M.D. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10(2): 199-214.

Grant, G.E. and F.J. Swanson. 1995. Morphology and processes of valley floors in mountain streams, western Cascades, Oregon. Natural and Anthropogenic Influences in Fluvial Geomorphology, Geophysical Monograph 89: 83-101.

Harding, J.S., E.F. Benfield, P.V. Bolstad, G.S. Helfman, and E.D.B. Jones III. 1998. Stream biodiversity: the ghost of land use past. Proceedings of the National Academy of Sciences 95: 14843-14847.

Hatten, J.R. and R.H. Conrad. 1995. A Comparison of Summer Stream Temperatures in Unmanaged and Managed Sub-basins of Washington's Western Olympic Peninsula. Northwest Indian Fisheries Commission Report. 52 pps.

Hawkins, C.P., R.H. Norris, J. Gerritsen, R.M. Hughes, S.K. Jackson, R.K. Johnson, and R.J. Stevenson. 2000. Evaluation of the use of landscape classifications for the prediction of freshwater biota: synthesis and recommendations. Journal of the North American Benthological Society 19(3): 541-556.

Hawkins, C.P. and R.H. Norris. 2000. Performance of different landscape classifications for aquatic bioassessments: introduction to the series. Journal of the North American Benthological Society 19(3): 367-369.

Hawkins, C.P., J.L. Kershner, P.A. Bisson, M.D. Bryant, L.M. Decker, S.V. Gregory, D.A. McCullough, C.K. Overton, G.H. Reeves, R.J. Steedman, and M.K. Young. 1993. A hierarchical approach to classifying stream habitat features. Fisheries 18(6): 3-12.

Henderson, F.M. 1963. Stability of alluvial channels. Transactions of the American Society of Civil Engineers 128: 657-686.

Higgins, J., M. Lammert, M. Bryer, M. DePhilip, D. Grossman. 1998. Freshwater Conservation in the Great Lakes Basin: Development and Application of an Aquatic Community Classification Framework. A Report by The Nature Conservancy, Great Lakes Program to The George Gund Foundation, Cleveland, Ohio (# 95-65) and the U.S. Environmental Protection Agency, Great Lakes National Program (#GL995819-02-0).

Hughes, R.M., S.A. Heiskary, W.J. Matthews, and C.O. Yoder. 1994. Use of ecoregions in biological monitoring. Pages 125-151 in S.L. Loeb and A. Spacie (eds.). Biological Monitoring of Aquatic Systems. Lewis Publishers, Boca Raton, Florida.

Hunsaker, C. T., and D. A. Levine. 1995. Hierarchical approaches to the study of water quality in rivers. *Bioscience* 45: 193-203.

Hynes, H.B.N. 1975. The stream and its valley. Internationale Vereinigung Für Theoretische Und Angewandte Limnologie, Verhandlungen 19:1-15.

Imhof, J.G., J. Fitzgibbon, and W.K. Annable. 1996. A hierarchical evaluation system for characterizing watershed ecosystems for fish habitat. Canadian Journal of Fisheries and Aquatic Science 53 (Suppl. 1): 312-326.

Jensen, M.E., I.A. Goodman, P.S. Bourgeron, N.L. Poff, and C.K. Brewer. 2001. Effectiveness of biophysical criteria in the hierarchical classification of drainage basins. Journal of the American Water Resources Association 37(5): 1155-1167.

Johnson, L.B. and S.H. Gage. 1997. Landscape approaches to the analysis of aquatic ecosystems. Freshwater Biology 37: 113-132.

Johnson, L.B., C. Richards, G.E. Host, and J.W. Arthur. 1997. Landscape influences on water chemistry in Midwestern stream ecosystems. Freshwater Biology 37: 193-208.

Jowett, I.G. 1990. Factors related to the distribution and abundance of brown and rainbow trout in New Zealand clear-water rivers. New Zealand Journal of Marine and Freshwater Research 24: 429-440.

Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain system. Pages 110-127 in D.P. Dodge (ed.). International Large River Symposium Proceedings. Honey Harbor, Ontario.

Kellerhals, R., M. Church, and D.I. Bray. 1976. Classification and analysis of river processes. Journal of the Hydraulics Division, American Society of Civil Engineers 102: 813-829.

Kondolf, G.M. 1995. Geomorphological stream channel classification in aquatic habitat restoration: uses and limitations. Aquatic Conservation 5:127-141.

Kotliar, N.B. and J.A. Wiens. 1990. Multiple scales of patchiness and patch structure: a hierarchical framework for the study of heterogeneity. Oikos 59: 253-260.

Kruzic, L.M. 1998. Ecology of juvenile coho salmon within the upper south Umpqua Basin, Oregon. MS Thesis. University of Idaho, Moscow, Idaho.

Leopold, L.B. and M.G. Wolman. 1957. River channel patterns: braided, meandering and straight. United States Geological Survey Professional Paper 282-B. US Government Printing Office, Washington, D.C., USA.

Lunetta, R.S., B.L. Cosentino, D.R. Montgomery, E.M. Beamer, and T.J. Beechie. 1997. GIS-based evaluation of salmon habitat in the Pacific Northwest. Photogrammetric Engineering and Remote Sensing 63(10): 1219-1229.

Magnuson, J.J., Crowder, L.B., and Medvick, P.A. 1979. Temperature as an ecological resource. American Zoologist 19: 331-343.

Matthews, K.R., Berg, N.H., Azuma, D.L., and Lambert, T.R. 1994. Cool water formation and trout habitat use in a deep pool in the Sierra Nevada, California. Transactions of the American Fisheries Society 123(4): 549-564.

Meixler, M.S. and M.B. Bain. 1999. Application of GAP Analysis to New York Waters. Final Report prepared by the New York Cooperative Fish and Wildlife Research Unit, Department of Natural Resources, Cornell University for the GAP Analysis Program, Biological Resources Division, U.S. Geological Survey.

Minshall, G.W. 1988. Stream ecosystem theory: a global perspective. Journal of the North American Benthological Society: 7(4): 263-288.

Montgomery, D.R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35(2): 397-410.

Montgomery, D.R. and J.M. Buffington. 1998. Channel processes, classification, and response. Pages 13-42 in R.J. Naiman and R.E. Bilby (eds.). River Ecology and Management: Lessons from the Pacific Coastal Ecoregion. Springer-Verlag, New York, New York, USA.

Montgomery, D.R. and J.M. Buffington. 1997. Channel reach morphology in mountain drainage basins. Geological Society of America Bulletin 109: 596-611.

Montgomery, D. R., G. E. Grant, and K. Sullivan. 1995. Watershed analysis as a framework for implementing ecosystem management. Water Resources Bulletin 31: 369-386.

Montgomery, D.R. and J.M. Buffington. 1993. Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition. Report prepared for the Washington State Timber, Fish, and Wildlife Agreement. TFW-SH10-93-002. pp. 84.

Naiman, R.J., Beechie, T.J., Benda, L.E., Berg, D.R., Bisson, P.A., MacDonald, L.H., O'Connor, M.D., Olson, P.L., and Steel, E.A. 1992. Fundamental elements of ecologically healthy watersheds in the Pacific Northwest Coastal Ecoregion. Pages 127-188 in R.J. Naiman, (ed.). Watershed Management: Balancing Sustainability and Environmental Change. Springer, New York, New York, USA.

Nanson, G.C. and A.D. Knighton. 1996. Anabranching rivers, their cause, character, and classification. Earth Surface Processes and Landforms. 21: 217-239.

Nawa, R.K., C.A. Frissell, J.L. Ebersole, and W.J. Liss. 1991. Life History and Persistence of Anadromous Fish Stocks in Relation to Stream Habitats and Watershed Characterization. Annual Progress Report. Prepared by the Department of Fisheries and Wildlife, Oregon State University for the Oregon Department of Fish and Wildlife.

O'Daniel, S. and G.C. Poole. In preparation. Hyporheic flow as a mechanism for variation in stream temperature along the Umatilla River, Oregon.

Omernik, J.M. 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77(1): 118-125.

Ormerod, S.J., S.D. Rundle, E. Clare Lloyd, and A.A. Douglas. 1993. The influence of riparian management on the habitat structure and macroinvertebrate communities of upland streams draining plantation forests. Journal of Applied Ecology 30: 13-24.

O'Neill, R.V, D.L. DeAngelis, J.B. Waide, and T.F.H. Allen. 1986. A Hierarchical Concept of Ecosystems. Princeton University Press, Princeton.

Palmer, M.A. and N.L. Poff. 1997. Heterogeneity in streams: the influence of environmental heterogeneity on patterns and processes in streams. Journal of the North American Benthological Society 16(1): 169-173.

Paustian, S.J., K. Anderson, D. Blanchet, S. Brady, M. Cropley, J. Edgington, et al. 1992. A channel type users guide for the Tongass National Forest, southeast Alaska. USDA Forest Service Technical Paper R10-TP-26. Alaska Region R10.

Pess, G.R., D.R. Montgomery, E.A. Steel, R.E. Bilby, B.E. Feist, and H.M. Greenberg. 2002. Landscape characteristics, land use, and coho salmon (*Oncorhynchus kisutch*) abundance, Snohomish River, Wash., U.S.A. Canadian Journal of Fisheries and Aquatic Science 59: 613-623.

Poff, N. L. 1997. Landscape filters and species traits: Towards mechanistic understanding and prediction in stream ecology. Journal of the North American Benthological Society 16: 391-409.

Poole, G. C. 2002. Fluvial landscape ecology: addressing uniqueness within the river discontinuum. Freshwater Biology 47(4): 641-660.

Poole, G.C. and C.H. Berman. 2001. An ecological perspective on in-stream temperature: natural heat dynamics and mechanisms of human-caused thermal degradation. Environmental Management 27(6): 787-802.

Power, M.E., R.J. Stout, C.E. Cushing, P.P. Harper, F.R. Hauer, W.J. Matthews, P.B. Moyle, B. Statzner, and I.R. Wais De Badgen. 1988. Biotic and abiotic controls in river and stream communities. Journal of the North American Benthological Society 7(4): 456-479.

Pringle, C.M., R.J. Naiman, G. Bretschko, J.R. Karr, M.W. Oswood, J.R. Webster, R.L. Welcomme, and M.J. Winterbourn. 1988. Patch dynamics in lotic systems: the stream as a mosaic. Journal of the North American Benthological Society 7: 503-524.

Pulliam, H.R. and B.J. Danielson. 1991. Sources, sinks, and habitat selection: A landscape perspective on population dynamics. American Naturalist 137(Suppl): S50-S66.

Quigley, T.M. and Arbelbide, S.J., tech. eds. 1997. An assessment of ecosystem components in the interior Columbia Basin and portions of the Klamath and Great Basins: volume 3. Gen. Tech. Rep. PNW-GTR-405. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest research Station. 4 vol. (Quigley, T.M., tech. ed.; The Interior Columbia Basin Ecosystem Management Project: Scientific Assessment).

Quigley, T.M., R.W. Haynes, R.T. Graham, tech. eds. 1996. Integrated scientific assessment for ecosystem management in the interior Columbia basin and portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-GTR-382. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 303p.

Ralph, S. C., and G. C. Poole. 2003. Putting monitoring first: designing accountable ecosystem restoration and management plans in D. R. Montgomery, S. Bolton, D. B. Booth, and L. Wall (eds.). Restoration of Puget Sound Rivers. University of Washington Press, Seattle, WA.

Reeves, G.H., L.E. Benda, K.M. Burnett, P.A. Bisson, and J.R. Sedell. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. Pages 334-349 in J.L. Nielsen (ed.). Evolution and the Aquatic Ecosystem: Defining Unique Units in Population Conservation. American Fisheries Society Symposium, Special Publication 17.

Rice, S.P., M.T. Greenwood, and C.B. Joyce, 2001. Tributaries, sediment sources, and the longitudinal organisation of macroinvertebrate fauna along river systems. Canadian Journal of Fisheries and Aquatic Sciences 58: 824-840.

Richards, C., Haro, R.J., Johnson, L.B., and Host, G.E. 1997. Catchment and reach-scale properties as indicators of microinvertebrate species traits. Freshwater Biology 37: 219-230.

Richards, C., Johnson, L.B., and Host, G.E. 1996. Landscape-scale influences on stream habitats and biota. Canadian Journal of Fisheries and Aquatic Science 53(Suppl. 1): 295-311.

Rieman, B.E. and J.B. Dunham. 2000. Metapopulations and salmonids: a synthesis of life history patterns and empirical observations. Ecology of Freshwater Fish 9: 51-64.

Rieman, B.E. and J.D. McIntyre. 1995. Occurrence of bull trout in naturally fragmented habitat patches of varied size. Transactions of the American Fisheries Society 124(3): 285-296.

Rohm, C.M., J.W. Geise, and C.C. Bennett. 1987. Evaluation of an aquatic ecoregions classification of streams in Arkansas. Journal of Freshwater Biology 4: 127-140.

Roni, P., T.J. Beechie, R.E. Bilby, F.E. Leonetti, M.M. Pollock, and G.R. Pess. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. North American Journal of Fisheries Management 22: 1-20.

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

Rot, B.W., R.J. Naiman, and R.E. Bilby. 2000. Stream channel configuration, landform, and riparian forest structure in the Cascade Mountains, Washington. Canadian Journal of Fisheries and Aquatic Science 57: 699-707.

Schlosser, I.J. 1995. Critical landscape attributes that influence fish population dynamics in headwater streams. Hydrobiologia 303: 71-81.

Schlosser, I.J. 1991. Stream fish ecology: a landscape perspective. BioScience 41(10): 704-712.

Schmutz, S. and Jungwirth, M. 1999. Fish as indicators of large river connectivity: the Danube and its tributaries. Large Rivers 11(3): 329-348.

Schumm, S.A. 1977. The Fluvial System. John Wiley & Sons, New York, New York, USA.

Scott, M.C. and Helfman, G.S. 2001. Native invasions, homogenization, and the mismeasure of integrity of fish assemblages. Fisheries 26(11): 6-15.

Sedell, J.R., G.H. Reeves, F.R. Hauer, J.A. Stanford, and C.P. Hawkins. 1990. Role of refugia in recovery from disturbances: modern fragmented and disconnected river systems. Environmental Management 14(5): 711-724.

Snyder, E.B. and J.A. Stanford. 2001. Review and Synthesis of River Ecological Studies in the Yakima River, Washington, with Emphasis on Flow and Salmon Habitat Interactions: Final Report. Prepared for the U.S. Department of Interior, Bureau of Reclamation (http://www.umt.edu/biology/flbs/).

Stanford, J.A. and J.V. Ward. 1993. An ecosystem perspective of alluvial rivers: connectivity and the hyporheic corridor. Journal of the North American Benthological Society 12: 48-60.

Stanford, J.A. and J.V. Ward. 1992. Management of aquatic resources in large catchments: recognizing interactions between ecosystem connectivity and environmental disturbance. Pages 91-124 in R.J. Naiman (ed.). Watershed Management. Springer-Verlag, New York, New York.

Staus, N.L. and J.R. Strittholt. 2001. Conservation planning for aquatic biological integrity in the Klamath-Siskiyou Ecoregion using multiple spatial scales. Prepared by the Conservation Biology Institute for the World Wildlife Fund. 71pp.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. Transactions, American Geophysical Union 38: 913-920.

Sullivan, K., J. Tooley, K. Doughty, J.E. Caldwell, and P. Knudsen. 1990. Evaluation of Prediction Models and Characterization of Stream Temperature Regimes in Washington. Washington Department of Natural Resources. Timber/Fish/Wildlife Report TFW-WQ3-90-006.

Tockner, K., F. Malard, and J.V. Ward. 2000. An extension of the flood pulse concept. Hydrological Processes 14: 2861-2883.

Torgersen, C.E., R.N. Faux, B.A. McIntosh, N.J. Poage, and D.J. Norton. 2001. Airborne thermal remote sensing for water temperature assessment in rivers and streams. Remote Sensing of Environment 76(3): 386-398.

Torgersen, C.E., Price, D.M., Li, H.W., and McIntosh, B.A. 1999. Multiscale thermal refugia and stream habitat associations of chinook salmon in northeastern Oregon. Ecological Applications 9(1): 301-319.

Townsend, C. R. 1996. Concepts in river ecology: pattern and process in the catchment hierarchy. Archiv Für Hydrobiologie Supplement 113: 3-21.

Urban, D. L., R. V. O'Neill, and H. H. Shugart. 1987. Landscape ecology: a hierarchical perspective can help scientists understand spatial patterns. BioScience 37: 119-27.

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 Science 37: 130-137.

Ward, J.V, K. Tockner, and F. Schiemer. 1999. Biodiversity of floodplain river ecosystems: ecotones and connectivity. Regulated Rivers: Research and Management 15: 125-139.

Ward, J.V. and J.A. Stanford. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research and Management 11: 105-119.

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

Ward, J.V. and J.A. Stanford. 1983. Serial discontinuity concept of lotic ecosystems. Pages 29-42 in T.D. Fontaine and S.M. Bartell (eds.). Dynamics of Lotic Systems. Ann Arbor Science, Ann Arbor, Michigan.

Whiting, P.J. and J.B. Bradley. 1993. A process-based classification system for headwater streams. Earth Surface Processes and Landforms 18: 603-612.

Whittier, T.R. and R.M. Hughes. 1988. Correspondence between ecoregions and spatial patterns in stream ecosystems in Oregon. Canadian Journal of Fisheries and Aquatic Sciences 45: 1264-1278.

Wiens, J. A. 1989. Spatial Scaling in Ecology. Functional Ecology 3: 385-397.

Winter, T.C. 2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association 37(2): 335-349.

Wright, K.K. and J.L. Li. 2002. From continua to patches: examining stream community structure over large environmental gradients. Canadian Journal of Fisheries and Aquatic Science 59: 1404-1417.

Wu, J. and O.L. Loucks. 1995. From balance of nature to hierarchical patch dynamics: a paradigm shift in ecology. The Quarterly Review of Biology 70(4): 439-466.

Yahner, R.H. and C.G. Mahan. 1997. Behavioral considerations in fragmented landscapes. Conservation Biology 11(2): 569-570.