Process Domains as a Unifying Concept to Characterize Geohydrological Linkages in Glaciated Mountain Headwaters

Anne A. Weekes

A dissertation
submitted in partial fulfillment of the
requirements for the degree of

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Abstract

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Chair of the Supervisory Committee:
Professor Susan Bolton

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This dissertation presents the results from multi-year study on spatial and temporal geohydrologic habitat controls in glaciated mountain landscapes and explores the implications of these controls on ecological monitoring. Geomorphic field work in Mount Rainier National Park in Washington State in conjunction with hydrologic indices (e.g., streamflow gauging, stable isotope analysis and water temperature measurements) and continuous spatial data were used to investigate the relationship between glacial macroforms, disturbance processes, and hydrologic response. The linkage between valley-scale geomorphic structures and hydrologic response was found to be best expressed in process domains defined as colluvial, alluvial, and bedrock systems (Montgomery, 1999). Study results show a correlation between process domains within a headwater catchment and the characteristic hydrologic regime and streamflow of the basin. Consequently, they provide a framework useful to ecological monitoring programs that aim to compare physical habitat as a control of biotic response.

Decades of studies and conceptual models in hydrology, geomorphology and ecology have provided context for all aspects of this dissertation, from the field study sampling design to the conclusions. However, comparatively little work has been done in glaciated mountain headwaters. Earlier research in plot-scale hillslope and catchment hydrology (e.g. Dunne, 1978), fluvial geomorphology (Montgomery and Buffington, 1997) and ecological work on riverine scales and scaling (Frissell, et al., 1986; Baxter and Hauer, 2000; Torgersen, 2002) are central to understanding physical habitat in

complex systems. The Process Domain Concept (Montgomery, 1999) and the results of recently published studies of the meso-scale spatial structures found in glaciated mountain basins in British Columbia (Brardinoni and Hassan, 2006) provide the conceptual basis for this dissertation.

The results of this investigation strongly support the insight that meso-scale geomorphic processes and structures are first order drivers of hydrologic regimes. To develop a prototype for monitoring physical habitat in glaciated mountain headwaters, I investigate and compare the implications of results of this research in conjunction with the assumptions inherent in popular aquatic monitoring protocols. This prototype is explored using the National Park Service (NPS) North Coast and Cascade Network (NCCN) monitoring program as a case study.

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ACKNOWLEDGEMENTS

Any field-based study that attempts to confront the intricacies of what is “out there”, particularly in remote mountain environments, will have to grapple with the sheer scale of how much is unknown in such complex systems. I am very grateful for the assistance of my committee. This study would not have been possible without the dedication, intellectual curiosity and support from my committee chair, Susan Bolton. David R. Montgomery has been an invaluable source of guidance and inspiration throughout this process. Christian Torgersen and Andrea Woodward have also contributed important perspectives and comments, and have improved the study in numerous ways.

I thank the National Park Service, particularly Jon Riedel, Regina Rochefort, Reed Glesne, and Mike Larrabee at North Cascades National Park and Barbara Samora, Paul Kennard, and Rebecca Lofgren at Mount Rainier National Park. Many people offered invaluable assistance in the field, especially Andrea Woodward, Paul Kennard, Stephanie Kampf, Van Kane, Dan Ribero, Henry Burden and Mike Larrabee. Special thanks also to Leslie Wall.

Funding for this research was provided by the National Park Service North Coast and Cascade Network (NCCN) “Vital Signs” Monitoring Program, the North Coast and Cascades Learning Network and teaching assistantships provided by Susan Bolton and the University of Washington, College of Forest Resources. Support from the USGS Forest and Rangeland Ecosystem Science Center (FRESC) was also invaluable. I sincerely appreciate all their contributions to my degree program.

Throughout my formal and informal education, I have been fortunate to learn from many insightful teachers and am particularly grateful to Steve Burges, Dan Mecklenburg, Andy Ward, Peggy Carr, Luna Leopold and Andy Miller. Finally, these many years of education would not have been possible without the unfailing support and patience of David Weekes.

DEDICATION

This dissertation is dedicated to David and Andrew

Chapter 1

INTRODUCTION

New perspectives in riverine science emphasize the innate discontinuities and heterogeneities found along the longitudinal profile of many stream environments (Ward 1998a, Fausch et al., 2002). Stream ecologists have observed that differences between upstream and downstream channel reaches and the boundaries between geomorphic valleys, valley segments, reaches, and channel units may appear gradual or heterogeneous depending on the scale of observation (Frissell et al., 1986, Torgersen, 2002). However, the importance of spatial and temporal variability in longitudinal processes is also dependent upon the geomorphic complexity of the particular region in question (Montgomery, 1999). Physical habitats in glaciated mountain headwaters are often more structurally complex within small areas than those found in lowland river systems. For example, spatially intricate hanging glacial valleys separated by bedrock controls and valley steps produce a stair-step longitudinal profile uncommon in large lowland fluvial valleys (Brardinoni and Hassan, 2006). While stream ecologists have been aware of the importance of landscape context for many years (Hynes, 1975), the unique spatial heterogeneity and scale in these habitats has not been incorporated in ecological stream concepts.

Glaciated mountain systems require a conceptual framework that encompasses the non-linearity and process diversity that produce multiple types of geohydrologic response. While in theory, these streams are continuous because they are connected through an aqueous medium, structural discontinuities and abrupt shifts between colluvial and fluvial channel processes in mountain stream profiles appear to contradict models such as the River Continuum Concept (RCC), a model that conceives of longitudinal patterns in river systems as continuous gradients in physical habitat and associated biotic response from headwaters to downstream reaches (Vannote et al., 1980). Implicit in the conceptual model is the idea that alterations in landscape structure and related changes in biotic community response are gradual. While at larger (e.g. large river catchment, regional and geomorphic province) scales, discontinuities often disappear in the smoothed appearance of the concave longitudinal profile, valley scale channel sections with abrupt break points in slope and bed material can have significant implications for biological response. Channel longitudinal patterns may be described as gradual because their sampling approaches are too coarse to quantify heterogeneity at finer scales (e.g.; Ward et al., 1994, Torgersen, 2002). Physical structures (e.g. natural and manmade dams, geologic formations such as bedrock outcroppings, and the products of short and long-term geomorphic disturbance processes including glacial episodes) often disrupt the continuity of downstream change in mountain stream systems (Ward and Stanford, 1993; Baxter and Hauer, 2000; Benda et al., 2005; Brardinoni and Hassan, 2006). These discontinuities are especially prevalent in glaciated headwaters.

It is axiomatic that our understanding of rivers and streams is largely a function of the manner in which we perceive them. Our perceptions are both the result of how streams are sampled and the conceptual framework through which we filter our observations. Stream ecologists have recognized the importance of heterogeneity and scale in freshwater ecosystems. However, while stream ecologists are in the process of developing new sampling techniques that can assess spatial variability in stream habitat as related to the distribution of aquatic organisms (Torgersen, 2002) there is not a synonymous focus on multi-scaled sampling designs that would identify the effect of colluvial and fluvial processes on the streamflow regimes of complex aquatic habitats.

Each component of mountain habitats (i.e. geomorphic, hydrologic and ecological) presents challenges in sampling design that are complicated further by the lack of a conceptual model or framework that encompasses controlling interdependent geohydrologic mechanisms. For example, one of the most problematical factors in comparing physical habitats is the spatial intricacy and temporal variability of streamflow regimes. Hydrologic systems involve the interaction between atmospheric, ground surface and subsurface processes at a variety of scales. All of these processes are complex regardless of the type of environment being described. However, the hydrology of mountainous terrain at an intermediate or valley scale poses some uniquely daunting problems. Because all hydrologic processes are linked, studies of a single process in isolation may miss important variables and feedback mechanisms. Attempts to measure even a single process such as precipitation, surface flow or groundwater present significant challenges. For example, streamflow gages are often perceived as a surface water measurement. However, streamflow is an integrated measurement that combines surface and subsurface flow paths and runoff generation processes, subsurface aquifers, and the expression on the ground of topography, geology, geomorphic disturbance, and atmospheric fluxes such as evaporation, transpiration, as well as net radiation and rainfall patterns.

A variety hydrological modeling methods incorporate point-based streamflow time series measurements into distributed networks of universal physical or analytic equations derived from fine-scale physical laws (Kampf, 2007). In contrast, aquatic ecological patterns depend on “a science of contingent generalizations, where future trends depend on past history and on the environmental and biological setting” (May, 1986). This observation rings true in headwater stream basins in which biota depend on distinct spatially and temporally variable physical habitats. At fine scales, streamflow response reflects the multi-scaled intricacy of evaporation, transpiration, as well as net radiation and local rainfall patterns. At larger scales, streamflow is broadly controlled by identifiable basin structures at scales determined by the dominant geomorphologic and geologic processes. Methods that reduce streamflow into its component parts (e.g.; hydraulic conductivity) and use basic principles to express the components mathematically as universal laws may have difficulty scaling up to the contingent nature of a particular terrain that at larger scales may present unique emergent properties.

The following three chapters explore the geomorphic and hydrologic characteristics of glaciated headwaters in an effort to find a unified conceptual framework that identifies intermediate-scale drivers, especially disturbance processes that control system response. Chapter 2 examines the scientific basis for a scale-appropriate geomorphic spatial context that incorporates hydrological controls in glaciated mountain headwaters. Particularly at intermediate scales, glaciated mountain headwaters differ from lowland stream systems, chiefly in their often discontinuous longitudinal dimensions, disturbance processes, and associated sediment supply and transport capacity relationships (Brardinoni and Hassan, 2006). These differences have consequences that directly affect the life history strategies and persistence of biota living in these systems. To investigate the unique suite of spatial and temporal processes and patterns characteristic of these systems, I will explore these dynamics in the context of existing ecological and geomorphic conceptual models. In particular, the Process Domain Concept (PDC) defined as spatially identifiable areas characterized by distinct suites of geomorphic processes (Montgomery, 1999) is a promising model for complex mountain basins as it incorporates long and short term disturbance history at intermediate scales.

Chapter 3 investigates the use of process-based categories (colluvial, alluvial and bedrock channels and valleys representing the continuum of sediment supply and transport capacity relationships that drive physical habitat characteristics) and their relationship to hydrologic indices in glaciated mountain headwater basins in the Cascade Mountains of Washington State. Process understanding of the mechanisms of mountain recharge is weak at intermediate scales pertinent to ecological research. However, many existing tools are available to better characterize the geohydrologic mechanisms that drive habitat structure. Streamflow hydrographs, stable isotopes and temperature measurements revealed that hydrologic response correlates with geomorphic parameters as integrated into a valley-scale process domain framework. The PDC appears to be a useful framework to integrate hydrologic response with disturbance processes within the primary organization of the glacial macroform structure.

Independent integrative measurements including recession constants (K_r), stable isotope analysis (^{18}O) and water temperature measurements showed consistent patterns that differed between the study basins regardless of season. Channels that flowed through debris flow and landslide colluvium, observed in conjunction with numerous springs and seeps, corresponded to the hydrologic regimes characteristic of subsurface flow as verified by $K_{r,}$ ^{18}O and temperature values. Because the presence or absence of major colluvial features at the valley-scale limit velocity and control water routing and response both in the stream and within connected hillslopes, colluvial percentages appeared to be a good indicator for identifying hydrologic relationships important to aquatic biota.

Chapter 4 explores the assumptions of monitoring programs developed for fluvial process-dominated lowland basins and compares these concepts to the characteristics of colluvial and fluvial channels in glaciated headwater basins. The functional differences in headwater stream dynamics, topography and intermediate-scale structural patterns between lowland fluvial systems and less well studied alpine domains have a significant effect on the choice of physical habitat parameters and sampling designs appropriate for use in monitoring protocols. I compare these assumptions with abiotic habitat controls, especially those at less commonly studied intermediate spatial scales, found in relict glaciated mountain headwaters and introduce a more inclusive conceptual framework that incorporates these unique habitat characteristics. Based upon this analysis, I use process domains, developed from the Process Domain Concept (PDC), to select appropriate variables for sampling designs suitable for aquatic monitoring in these systems (Montgomery, 1999). I then present a prototype for monitoring mountain aquatic habitat based on a unifying concept of spatial structure and process controls. Finally, these recommendations are applied to the North Coast and Cascade Network (NCCN) “Vital Signs” Monitoring Program.

Notes to Chapter 1

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Chapter 2

The Ecological Importance of Geohydrologic Controls on Physical Habitat

INTRODUCTION

A mental image of glaciated mountains immediately conjures a landscape dominated by rock, ice and snow. It is no wonder that scientists have generally assumed that the upper reaches of glaciated mountain headwaters are dominated by surface runoff; these areas should provide little habitat for diverse communities of aquatic biota. This assumption has been supported by the combination of rapid snowmelt inputs, the lack of obvious storage capacity, and the hydraulic gradients of steep channels, as well as the high percentage of over-steepened glacial valley walls found in many alpine catchments (Liu et al., 2004). Recent research on mountain recharge mechanisms and the physical environments that they create has shown that these systems are often more complex than previously thought. Intuitively, alpine basins should be driven by surface run-off, but studies have shown that subsurface water flow pathways and channels are common. Research using plot-scale tracer and stable isotope studies in the Colorado Rockies demonstrated the presence of high-altitude aquifers that honeycomb parts of some high valleys, trapping snow melt and feeding multiple recharge mechanisms in addition to overland stormflow (Liu et al., 2004).

Ecological research in cirque and glacial valleys in the Swiss Alps have also demonstrated that physical habitats in these terrains can be complex. Robinson (2007) demonstrated the hydrologic importance of different types of groundwater and surface water flows to resident biota. Complex hydrology is the product of distinct differences in water source and recharge areas. Variable hydrologic controls produce diverse populations of aquatic biota. These heterogeneous physical habitats within relatively small spatial areas have important implications for understanding the mechanisms of ecological response. While scientists have identified stream habitat based on the dominant type of flow regime (Poff and Ward, 1989), there are presently few spatially explicit methods that characterize the interdependence between valley-scale geomorphic processes and structures and hydrological response. There is a need for better insight into spatial controls on the movement of water and materials at multiple scales in these glaciated mountain terrains.

Mountain recharge processes in their geomorphic context have great importance because of the potential consequences of climate change to the environments of aquatic biota living in these harsh environments. Many aquatic communities provide a valuable reference condition to decipher the effects of climate forcings on ecological processes in an otherwise anthropogenically undisturbed state. Undisturbed reference conditions are especially useful for biological monitoring and have been employed in the past to detect changes in aquatic environments due to land use alterations that impact stream systems. Alpine habitats are home to a variety of macroinvertebrate species with a range of colonization and life cycle strategies on short time scales. The ability of such fauna to cope with the environmental heterogeneity of mountainous post-glacial environments suggests that their distribution patterns are a sensitive indicator of species resilience in the face of natural and anthropogenic changes, particularly climate change (Brittain and Milner, 2001). However, while small aquatic species are perceived as excellent ecological indicators, their usefulness for this purpose is only as good as our understanding of the physical habitats in which they live and our ability to successfully monitor species and habitat.

Ward (1989) describes how physical processes influence species life history strategies and abundance in larger stream systems through the variability of habitat characteristics in four dimensions: longitudinal (downvalley), lateral (channel-floodplain), vertical (channel or valley incision) and temporal (hydrologic regime). In glaciated mountain headwaters, the vertical dimension appears to incorporate subsurface and buried flow paths. It is known that geomorphic structures and processes have a significant impact on aquatic habitats, including the routing of water (Frissell et al., 1986; Swanson et al., 1988; Montgomery, 1999; Wiens, 2002) and water flowpaths and stream discharge (Davis and DeWiest, 1966; Tague and Grant, 2004; McGuire et al., 2005; Voss, 2005). However, in alpine headwaters, the nature of the combination of geomorphic and complex hydrologic controls is seldom incorporated in an explicit spatial framework at scales that encompass the larger organizational structures found in mountain terrains.

This chapter examines the scientific basis for a scale-appropriate spatial context that incorporates hydrological controls. Glaciated mountain headwaters differ from lowland stream systems, particularly in their often discontinuous longitudinal dimensions and associated sediment supply and transport capacity relationships (Brardinoni and Hassan, 2006). These differences have consequences that directly affect the life history strategies and persistence of biota living in these systems. To investigate the unique suite of spatial and temporal processes and patterns characteristic of glaciated mountain headwater dynamics, I will explore these dynamics in the context of ecological and geomorphic conceptual frameworks that address the system components that, in combination, characterize mountain headwaters. To do this requires an understanding of the connections between long and short term disturbance history (and potential) and interdependent hydrologic regimes.

This study begins with an examination of differences in focus between plot and catchment scale hydrologic studies and geomorphic and ecologic research. Hydrological studies generally do not differentiate between hydrologic regimes caused by distinct geomorphic structural patterns and processes at multiple scales. In contrast, geomorphic research has explored the nature of disturbance processes and their critical importance to aquatic habitat dynamics in unglaciated mountain streams. However, geomorphic concepts do not address temporal characteristics of hydrologic regimes at multiple scales. While ecologists emphasize the importance of disturbance processes in natural systems (Forman and Godron, 1978), interdependent relationships between geomorphic and hydrologic response in a spatial context is missing from conceptual models of aquatic ecological systems.

HYDROLOGIC SYSTEMS

Plot-Scale Hydrology

Hydrological relationships in any terrain can be complex. As a result, small plot scale field-based experiments and laboratory studies, not studies at the intermediate scales more directly useful to management, have dominated empirical research in hillslope hydrology. Landmark plot scale field experiments in natural hillslopes began with the work of Horton (1933) and Hursh (1936). Papers and reviews by Hewlet and Hibbert (1967) (variable source area concept), Dunne and Black (1970a-b), and Dunne (1978) still provide much of the conceptual basis for our hydrologic conceptualizations today (McDonnell, 2003). Experiments in small constructed plots (Hewlett and Hibbert (1967) and Nieber and Walter (1981), Kampf and Burges (2007) are also important. Notable field studies that document runoff by subsurface storm flow (SSSF) during storm events or propose mechanisms to explain stream discharge response in steep soil-mantled landscapes include Harr (1977); Mosley (1979); Pierson (1980); Beven and Germann (1982); Tsukamoto and Ohta (1988); McDonnell (1990); Onda (1994), and Montgomery et al. (1997). Monitoring studies executed on steep hillslopes address runoff generation processes include Harr (1977); Moseley (1979); McDonnell (1990); Anderson et al. (1997), and Montgomery and Dietrich (2002).

Most plot-scale hydrological studies and experiments have been concerned with quantifying the characteristics of porous matrix flow. There is little precedent for identifying recharge processes through coarse substrates, such as talus and colluvium, at spatial scales that encompass the larger organizational structures found in glaciated mountain terrain. Flows through the porous matrix, usually defined as Darcian flow, are likely to be an important component of hillslope recharge processes in mountain areas with well-developed soil horizons. However, enduring geomorphic features, such as (soil-deficient) talus slopes and glacial troughs above treeline, contribute to complex networks of subsurface pathways and small aquifers.

Modeling of hillslope recharge using the many offshoots of Darcy's Law is often applied at a scale different to that at which equations were derived. The result in practice can be a conceptual representation of hillslope processes with scale dependent parameters (Klemeš, 1983; Anderson and Rogers, 1987; Beven, 1989, 1996; Grayson and Blöschl, 2001). Empirically-derived plot-scale hillslope recharge mechanisms do not necessarily scale up to larger scales in heterogeneous landscapes (Klemes, 1988). These representations may be especially ill-suited to generalizations to the linked surface/subsurface flows found within complex mountain terrain. For example, small scale runoff plots installed on a hillslope may exhibit high rates of overland flow during storms that are up to an order of magnitude higher than overland flow measured at the hillslope scale (Sidle, 2006). Among other factors, spatially isolated attributes that promote high rates of infiltration at the hillslope scale, such as areas of high hydraulic conductivity, microtopography and surface roughness, are much less likely to occur in small plots (van de Giesen et al., 2000).

There appear to be a diversity of water sources and flowpaths that might be found in glacially-derived landforms, especially in cases where the stream channel is coupled with the adjoining hillslope. A schematic of the continuum of possible water pathways that might be found in glaciated mountain headwaters illustrates the potential types of flows that range between Darcian laminar flow in the porous matrix to surface channel flows (Figure 2.1). Intermediate conditions might include preferential water pathways that self-organize into colluvial channels in which sediment supply (q_s) far exceeds transport capacity (q_c). When transport capacity equals or exceeds sediment supply, fluvial processes dominate.

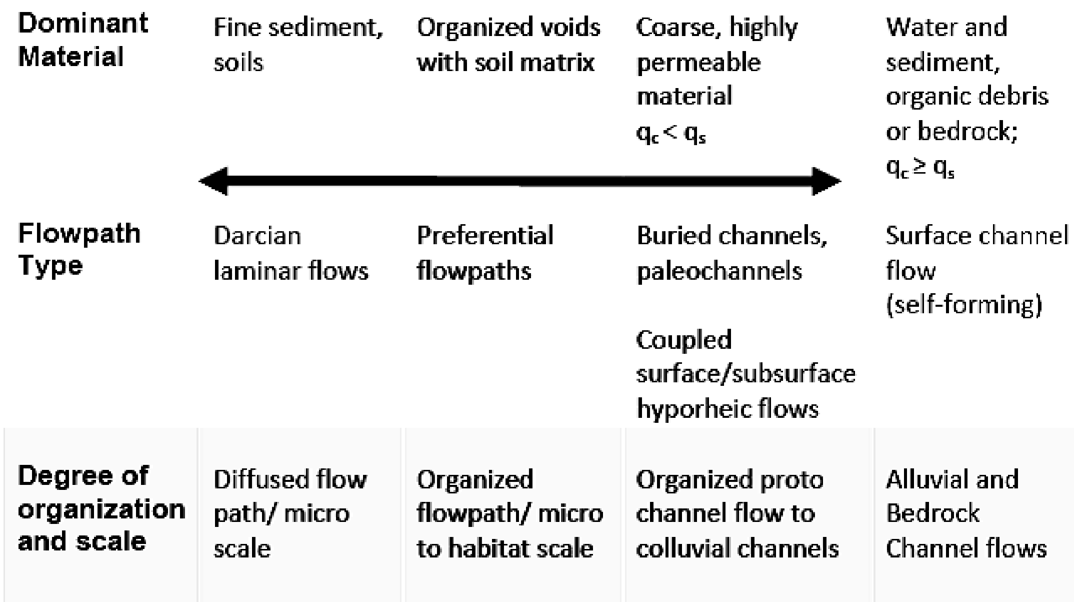


Figure 2.1. Schematic of the continuum of possible water pathways found in glaciated mountain headwaters including hillslope source areas and relict glacial valleys.

Numerous studies have suggested that subsurface/surface water interactions in mountain systems could be viewed as a continuum of possible flow characteristics rather than disjunct groundwater and surface flows (Castro and Hornberger, 1991; Stanford and Ward, 1993; Brunke and Gonser, 1997). This heterogeneity is not confined to spatial elements and their interconnection with hydrologic response. Even within small but complex relict and active glacial features, temporal changes in surface/subsurface water sources and recharge mechanisms are evident throughout a single season (Brown et al., 2003).

Intermediate and Catchment-Scale Hydrology

A recent empirical modeling study to test the dominant physical controls on water residence time in a mesoscale-sized catchment in the western Cascade Mountains of Oregon found that the internal form and structure of the catchment, as opposed to absolute catchment area, defines the first-order control on water residence time (McGuire et al., 2005). The authors suggest further that a more robust familiarity with landscape organization (defined as topography) will allow better understanding of the scaling relationships observed in nature. Hydrologic field studies in mountainous terrains have been hampered by a lack of attention to the basic geomorphic structural patterns and processes characteristic of particular mountain landscapes at multiple scales (Montgomery, 1999). The ability to explain recharge and runoff patterns, particularly those that include spatially and temporally intermittent subsurface flowpaths, has been limited by the lack of a vehicle to classify or categorize the spatial complexity of linked geohydrologic forms and processes found in these mountain landscapes. Field studies are often not designed to observe and interpret spatial patterns in the context of the specific landscape structure characteristic of the system in question (Grayson and Blöschl, 2001). Research has relied on temporal patterns or time series measurements to try to understand dominant controls at different scales (Grayson and Blöschl, 2001). Well instrumented hillslopes in small catchments have not demonstrated clear break points which indicate distinct scale differences in hydrologic controls. Little guidance is found in the literature regarding field methods that might be used to stratify hydrological processes into hierarchies of scale (Bonell, 1993; Silvaplan, 2003; McGuire et al., 2005).

The lack of focus on landscape organization is in part the result of the search for physical and analytical equations that can be used universally across catchment scales and regions with appropriate parameters, a set of equations that will describe all phenomena (Laughlin and Pines, 2000). From this perspective, heterogeneity in flowpath mechanisms is an undesirable trait; for example, groundwater physical equations are well understood and proven to work for simple geological systems. However, applying these equations to complex systems whose structures are not well known can be problematical (Beven, 1996).

Most catchment-scale research, with the exception of geochemical and tracer studies (McDonnell et al., 1991; Soulsby et al., 2000; Kirchner et al., 2001; McGlynn et al., 2003; McDonnell, 2003; Soulsby et al., 2003; McGuire et al., 2005), has been performed using hydrological models. Instead of teasing out the scale(s) associated with the component parts of the actual stream or river valley in question, scaling is based upon a theoretical framework derived from the physically based equations used in hillslope hydrology. Many properties for which scaling relationships have been developed do not lend themselves to field verification. For example, variables measured at small scales, such as hydraulic conductivity, are calibrated to fit larger scales in models (McGuire et al., 2005). The identification of spatial controls on temporally complex hydrological regimes has often been quantified using DEM-generated grids. These models can be highly effective at regional scales, but may not provide the differentiation of finer-grained geomorphic structures that control hydrological response in alpine headwaters. In mountain landscapes, hydrological processes require a view of scale that is not purely quantitative, a simple reduction or magnification of size that can be changed at will over a wide and continuous range. As described by Klemes (1983, p. 1), this type of extrapolation "does not fit well with things which are not or our making, i.e. nature. In nature, scales of things are not arbitrary, but arise as a function of their material substance and of the balance between interacting forces."

INTERMEDIATE-SCALE GEOMORPHIC CONTROLS ON MOUNTAIN STREAMS

Geomorphic and ecological hierarchical frameworks often structure aquatic stream environments according to habitat, channel reach, valley and valley-segment and catchment scales (Frissell et al., 1986; Montgomery, 1999). While in hydrological modeling, the term mesoscale (100 km^2 to 1000 km^2) is associated with scales more commonly used in catchment management and planning efforts (McGuire et al., 2005), research in mountain aquatic ecosystems has demonstrated a need for intermediate or mesoscale (1 km^2 to 100 km^2) measurements that account for stream processes that are not evident at smaller scales. In headwater mountain basins, the term mesoscale refers to the reach, section or valley segment scale (Torgersen, 1999; Baxter and Hauer, 2000; Fausch et al., 2002). Functionally, these intermediate scales are known to present difficulties because they are most difficult for scientists to visualize and sample (Klemes, 1988). While the term has been used to describe scales which vary by at least 4 orders of magnitude (between 1 km^2 and 1000 km^2) depending upon the research and its intended purpose, it is recognized that hierarchies of scale in aquatic habitat should be based on the structural features of the river, its valley and the watershed (Frissell, et al., 1986); the precise meaning of the term depends on the size of system.

Several ecological studies in freshwater environments have shown the importance of intermediate spatial scales, particularly the valley segment scale, when investigating life history strategies of fish species in a spatial context (Torgersen, 1999; Baxter and Hauer, 2000). For example, recent research on spring Chinook has shown that hyporheic conditions necessary for favorable thermal characteristics occur at 5 to 10 km intervals in low-gradient bounded alluvial valley segments (Torgersen et al., 1999). The water temperatures important to spring Chinook survival are found in spatial patterns at a valley segment scale that might not have been evident in a traditional sampling scheme that focused on shorter channel reaches chosen randomly. Research on bull trout in alluvial mountain streams also showed the changing relationship of spawning habitat selection based on geomorphology and hyporheic groundwater exchange across multiple spatial scales. Bull trout selected upwelling zones controlled by intermediate geomorphic features for spawning and downwelling zones at more localized spatial scales for redd selection (Baxter and Hauer, 2000). These important spatial patterns would have appeared as unexplained variation in a randomly-chosen reach-scale sampling design with limited spatial coverage (Baxter and Hauer, 2000). This work demonstrates the need to integrate research on stream ecosystems within the context of a hierarchy of scales (Frissell et al., 1986, Swanson et al., 1988; Montgomery, 1999).

CONCEPTUAL MODELS OF STREAM PROCESSES

Dynamic equilibrium versus directional change

Early on, stream ecologists recognized the interactive relationship between a stream and its valley (Hynes, 1975). In a significant advance in riverine ecology, Vannote et al. (1980) presented a credible case for the linkage of the physical stream, as a self-forming and maintaining geomorphic entity, with its aquatic inhabitants in a scale-dependent fashion. Termed the River Continuum Concept (RCC), stream order (stream size) was thought to deterministically affect a stream's natural characteristics, including the biological communities that live in the stream, such as fish and macroinvertebrates. From headwaters to downstream extent, the progression of physical variables theoretically presents a continuous gradient of steadily increasing stream variables (e.g. width, depth, velocity, flow volume and temperature) (Vannote et al., 1980). The ideal of a linear homogenous river basin progression assumes that streams are dominated by surface flows. As a biological analog to the physical system, Vannote hypothesized that the biological organization within rivers conformed structurally and functionally to the kinetic energy dissipation patterns of the physical system as an open system in dynamic ("quasi") equilibrium. However, the RCC ignored the discrete spatial differences caused by geomorphologic processes. Longitudinal variations in channel continuity were thus perceived as "noise".

The term dynamic equilibrium was originally used to describe consistent adjustments and patterns in the relationships between stream width, depth, velocity, and sediment load in *alluvial* rivers (Leopold and Maddock, 1953). These "steady state" systems only rarely characterize an actual spatial location; generally the river channel tends toward a mean form, definable only in terms of statistical means and extremes (Chorley, 1962); hence, the idea of a "dynamic" equilibrium. Research has shown that channel discharge in meandering alluvial river roughly scales with drainage area (Leopold and Maddock, 1953). According to the RCC, the dynamic balance characteristic of many alluvial channels theoretically makes it possible to view the aquatic inhabitants in a time independent fashion, as regardless of variations in climate variables, structural and functional characteristics of stream communities distributed along river gradients evolve to conform to the most probable position or mean state of the physical system (Vannote et al., 1980).

The concept of dynamic equilibrium does not account for directional change over time in stream systems. Change in the longitudinal profiles of streams that are downcutting through depositional material to a new base level, or accumulating sediment over long time periods (e.g. decades to centuries) may not return to a mean steady state (where sediment supply = sediment transport). The dynamics evident in the longitudinal profile may be directional at intermediate temporal scales (e.g. years to decades). The Serial Discontinuity Concept described departures from the RCC predictions produced by dams (Ward and Stanford, 1983) and the Patch Dynamics Concept (Pickett and White, 1985; Pringle et al., 1988, Townsend, 1989) defined stream heterogeneity as natural component of lotic systems. Recognition of groundwater–surface water interactions led to the "hyporheic corridor" concept (Stanford and Ward, 1993), which incorporated heterogeneity in both lateral and vertical dimensions. With each conceptual and empirical step, ecologists have embraced more of the complexity of stream ecosystems across more dimensions (Ward 1989). However, a model incorporating the implications of directional change in channel morphology has not been fully developed in aquatic ecology.

Riverine ecosystems within the same ecoregion often present a non-equilibrium variability of physical response. A recent study comparing rivers in the Puget Lowland Rivers in Washington State demonstrated that different types of channels respond very differently to glacial episodes. Meandering alluvial river channels flowing on Holocene fluvial deposition within wide Pleistocene glacial troughs may show little change in pattern in the historical period of record (Collins et al., 2003). In contrast, rivers in Holocene valleys may have steeper profiles created by post-glacial fluvial incision in glacial deposits and an anastomosing (e.g. branching, multi-channel) morphology that is prone to avulsion (Collins et al., 2003). If one were to monitor a habitat-scale sampling unit on the meandering alluvial river, it may be possible to interpolate hydrologic metrics such as channel discharge and width-depth relationships. In contrast, the spatial patterns found in a habitat-scale sampling unit in the Holocene valley river are likely to change over short time frames. As the river switches back and forth between multiple channels, the implications for the hydrologic regime of a habitat at a particular location in space are highly variable.

Ecological disturbance theory differentiates between stable baseflow hydrological regimes, which theoretically run much of the time (Gordon et al., 1992; Poff et al., 1997), and disturbance flows that periodically disrupt stable conditions. However, in the anastomosing channel, the location of the main channel, and hence that of reliable perennial baseflow could easily change. While the net surface discharge at a particular channel cross section may remain constant for a particular flow regime over short time scales, other patterns may shift. For biota in these types of physical habitat, the distinctions between baseflow and disturbance flow at any point in space and time are variable within their specific geomorphic context.

Disturbance Processes and the Process Domain Concept

Disturbances are often defined as deviations from normal (sustained) conditions. It is often assumed that significant natural physical disturbance processes that impact stream systems are cyclical (e.g., flood pulses) and do not vary significantly from a readily measureable mean condition. In contrast, directional disturbances are often perceived as the product of anthropogenic disturbance (e.g., clean water to polluted water). However, in complex physical systems, disturbance processes can be either cyclical or directional depending on the temporal and spatial scale. One definition of disturbance holds that it is a potentially damaging force that can be applied to the habitat of a population, community or ecosystem and might cause species mortality, resource depletion or a degraded or destroyed habitat structure (Lake, 2000). Disturbance regimes or processes are defined by the spatial extent, pattern, intensity, temporal duration, frequency and predictability of an episodic or discontinuous abiotic event (Figure 2.2).

A pulse disturbance, the typical form of the stream hydrograph during a precipitation or snowmelt event typical of alluvial rivers commonly produces a cyclical disturbance response. In contrast, channel response to natural episodic disturbance in glacial valleys can be directional. For example, a small headwater stream in a comparatively large glacial valley may be buried by excess sedimentation caused by debris flows and landslides. If there is limited transport capacity available to rearrange or remove colluvial debris, the course and type of the channel may change. In some cases, the channel will not return to an earlier state but will develop a new pattern and surface flow regime. This sort of directional disturbance is described by Lake (2000) as a press disturbance and can be the product of natural forces.

A ramp disturbance is defined by Lake (2000) as an event where the strength of the disturbance steadily increases over time (which could also include progressive enlargement of the disturbance in space). Droughts are a good example of a ramp disturbance. Abnormal conditions such as lack of snowpack, or unusually hot and dry summer and fall seasons may cause springs, and other water source areas to dry up. Conditions might progressively affect ever-expanding portions of the longitudinal profile of the downstream channel or other receiving water body. In alpine terrains, the combination of complex topography, highly variable climate forcings and hydrologic response means that pulse, press and ramp disturbances can occur due to both natural and anthropogenic elements. These properties describe abiotic changes in the aquatic habitat, not biotic response (Rykeil, 1985; Lake, 1990; Poff, 1992; Montgomery, 1999; Lake, 2000).These processes (e.g., flooding, debris flows, and landslides) may damage habitats occupied by a population, community or ecosystem producing either cyclical (or temporary) or directional (e.g., resulting in a physical change in state) disturbance. The disturbance may be generated by deviations from normal conditions such as high-flow events (floods) and low-flow events (droughts).

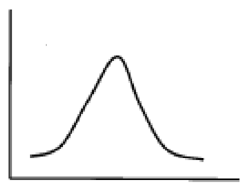
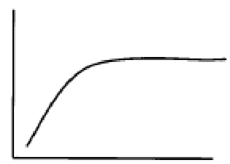
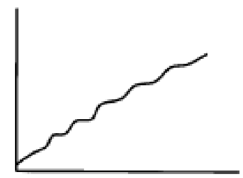
Disturbance Type	Pulse Disturbance	Press Disturbance	Ramp Disturbance
	Magnitude	Magnitude/ Frequency	Duration
Typical event	*Floods*	*Mass movements*	*drought*
Disturbance characteristics over time			
Geomorphic Response	Greater fluvial transport capacity producing increased incision and scour	Landslides, Debris flows Avalanche – Increased mass movements; Scour to bedrock Reshape valleys	Wind transport of sediment fines in high valleys, disrupted sediment transport patterns
Hydrologic Response	Increased, sustained water volume delivered quickly over several days – Extreme hydrograph peaks – magnitude of pattern most acute	Decrease water flowpath and source complexity of some channel and valley segments, increase in others. Temporary catastrophic disruption of streams, flowpaths	Decreased snowpack, increased short term runoff -- disruption of water delivery from water flowpaths and sources – sustained drought conditions, particularly in high elevation valleys above treeline
Biotic Habitat Response	Potential loss or disruption of groundwater, hyporheic and colluvial habitats, especially refugia -most acute effects in lower elevation valleys and valley steps		Potential loss of groundwater, hyporheic and perennial channel flows- most acute effects in higher elevation valleys Increased water temperatures

Figure 2.2. Schematic of three types of reach and valley segment-scale channel disturbance distinguished by temporal patterns in the strength of the disturbing force as related to potential geohydrologic and biotic response. Time is represented in the x-axis and the strength of the disturbing force on the y-axis (after Lake, 2000).

Many ecological theories have focused on disturbance processes as a non-linear control on the physical heterogeneity of the landscape. The Serial Discontinuity Concept (Stanford et al., 1988; Stanford and Ward, 1993) stressed the importance of disturbance regimes and processes as an important control on habitat heterogeneity at multiple scales in alluvial rivers. The Flood Pulse Concept also argued that a variety of geomorphic and hydrologic conditions produce flood pulses, a principle driving force between the existence, productivity and interactions of biota in river-floodplain systems (Junk et al., 1989). Ward and Tockner (2001) proposed biodiversity theory as a broad theoretical construct in which interactions between disturbance regimes and habitat heterogeneity produce a hierarchy of ecosystems at multiple scales that integrate functional biotic processes with spatio-temporal heterogeneity. While all of these theories are explicitly biocentric, they show both the importance of an integrated approach to ecosystem research and the need for recognition of disturbance processes in space and time.

The patch dynamics concept describes the mechanism with which spatial and temporal variations in landscape-forming processes create or maintain habitat structure and function (Forman and Godron, 1978; Pickett and White, 1985; Pringle et al., 1988) and is a useful concept for integrating temporal variability into mountain streams. Patch-forming episodes can occur over many scales, but the concept is usually applied to inherently local biotic influences. Habitat patches can be created by a wide range of temporally variable processes that define the environmental template for the stream. However, like the RCC, the patch dynamics model does not address the underlying spatial structure of geomorphic processes and as such provides a mechanism without a means to provide a spatial context.

The Process Domain Concept (PDC) can provide a geomorphic spatial context that can be used to apply patch dynamics ideas across watersheds. It can also be used to integrate the temporal variability of geomorphic and hydrologic disturbance processes including the effects of hillslope mass movements on stream dynamics. The PDC does this by providing a framework that allows for the identification of landscape units that correlate with differences in ecosystem organization (Montgomery, 1999). Process domains are defined as spatial areas, within which one or a suite of earth surface processes, particularly disturbance regimes, control and therefore can be used to characterize abiotic habitat structure. As predictable areas of the landscape within which distinct suites of geomorphic processes govern physical habitat type, structure, and dynamics, the disturbance regimes and prior geomorphic histories associated with these domains dictate the template on which ecosystems develop. Insights into these ecosystems require knowledge of the form, behavior and historical context of landscapes (Swanson et al., 1988; Montgomery, 1999). The PDC is especially useful to categorize intermediate valley, valley segment and channel reach spatial structures that are formed by geomorphic and hydrologic processes in mountain headwaters.

CHARACTERISTICS OF GLACIATED MOUNTAIN HEADWATERS

Due to the controlling effect of the glacial macroform structures and subsequent disturbances on recharge processes, at each hierarchical scale: basin, valley, valley segment/channel reach/mountain lake and habitat patch, system characteristics are diverse. These basins can be thought of as a mosaic of habitat patches, but at scales associated with ordinary mountain disturbance processes such as avalanches and debris flows. Within the template of glacial macroforms (e.g.; cirque wall, hanging valley, etc.) the gradient and morphology of glaciated mountain channels are tremendously variable and prone to forcing by external influences.

Ecological classification systems for the physical organization of alpine streams have separated channel segments according to hydrological drivers, including glacial, snowmelt and groundwater streams (Milner and Petts, 1994). This type of classification is only possible at the habitat scale because wide spatiotemporal variability in water recharge and storage inputs from differing structural components of the glacial landscape contribute to the heterogeneity of alpine stream systems (Smith et al., 2001). At intermediate scales, headwater channel dynamics can be classified according to colluvial, alluvial and bedrock categories as a means to make important distinctions between the processes controlling channel morphology (Montgomery and Buffington, 1997). Because geomorphic spatial features are interconnected with streamflow response, these processes represent the integration of intermediate scale channel and valley morphology and the way in which water characteristically moves through and on sediment (e.g.; sand, gravel, colluvium or talus) and bedrock.

At the valley and basin scale, many channels are better understood as complex mosaics of water source pathways (Burgherr and Ward, 2001) in which basin shape and network position play important roles. In relict and active glacial terrain, the percentage of discharge in the channel flowing at any one time from a particular source within the main channel varies significantly, both seasonally and according to diurnal cycles driven by climate conditions. Streamflow characteristics in glacial valleys are also a function of the time elapsed since glaciation (Milner and Petts, 1994) and subsequent valley and channel evolution.

The source areas of glaciated headwater basins are fed by a complex suite of hydroclimatic events including temporally variable rainfall, rain on snow, and snowmelt. While streams originating from these sources often share common features, each produces a characteristic discharge regime and a distinctive set of physical and chemical characteristics (Milner and Petts, 1994; Ward, 1994). The spatial and temporal regimes of water sources and pathways often vary in characteristic ways, especially diurnally and seasonally. Furthermore, the distribution of recharge mechanisms differ spatially from the stream reach to catchment scale, resulting in stream segments with characteristics reflecting the proportions of runoff sources (Brittain and Milner, 2001; Smith et al., 2001; Brown et al., 2003). For example, networks of springs, lakes and channels in colluvium or alluvium-filled valleys found in glacial hanging valleys have a significant effect on the ensuing surface and subsurface water pathways, and ultimately the biological configuration of the basin. The controlling role of spatial and temporal patterns and processes drive disparities in the annual flow regime, in water temperature and in water chemistry resulted in significant differences in populations. Other hydroecological studies have documented that spatial differences in the locations of mountain headwater water sources and flowpaths combine with their temporal characteristics to control important dynamics of species distributions and life history strategies (Robinson and Matthaei, 2007).

Notes to Chapter 2

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Chapter 3

Characterizing Geohydrologic Linkages:
The Structural Basis for Streamflow Response Differences in Unimpaired Cascade Mountain Streams

INTRODUCTION

Hynes (1975) was among the first to articulate the idea that effective knowledge of ecological response requires an understanding of the hydrophysical drivers of the stream and its valley. The ensuing thirty years have produced much additional research and many conceptual models related to Hynes' basic theme. However, mountain stream systems have not received the attention paid to lowland rivers (Benda et al., 2005).

Streamflow is considered an important driver of stream ecological characteristics, particularly in high elevation systems, because streamflow determines discharge, water temperature and substrate movement. These elements in turn drive channel ecological characteristics, which ultimately influence zoobenthic assemblages (Ward, 1994; Füreder et al., 2001). Recent ecological studies have focused on the dependence of stream biota on hydrologic drivers in glacial valleys and have demonstrated the close relationship between water sources and channels to aquatic response (Ward et al., 1998; Robinson and Matthaei, 2007).

However, the streamflow regimes manifest in montane aquatic physical habitats integrate geomorphic and hydrologic drivers at multiple scales. The dual nature of these processes is not well explored in these systems, presenting difficulties in ecological research and monitoring. Alpine headwaters represent an end member condition of intrinsic spatial complexity and temporal variability. To be used effectively as monitoring reference sites, there is a need for a systematic way to characterize the spatial distribution of geohydrologic response. Without a solid foundation in alpine landscape structure, information gleaned from individual hydrologic studies lacks the context needed to tie streamflow measurements to the actual spatial organization of the terrain. Effective characterization of the physical habitats found in these landscapes requires a method to incorporate the innate structural controls of the system at the scale(s) relevant to the terrain, in conjunction with measurements of hydrologic response.

A way forward: glacial macroform structure and process domains

Fortunately, the structural organization of alpine headwaters can provide a framework on which to build a unifying concept to characterize these complex geohydrological linkages. Recent studies in the geomorphology of relict glacial basins, building on previous work from unglaciated mountain environments, have shown the persistence of the stepped longitudinal profile characteristic of glacial macroform structures. While there is considerable variability in the way valley and valley segment-scale components are organized, there appear to be identifiable building blocks that define the nature of these terrains (Brardinoni and Hassan, 2006; Brardinoni and Hassan, 2007). Because of the reciprocity between geomorphic structures and hydrologic response, alpine landscape structure would appear to provide a useful vehicle in which to frame the information gleaned from point-based hydrologic time series measurements.

The glacial macroform structure alone does not solve the larger issue of identifying typical geomorphic and hydrologic processes and forms found in glaciated mountain headwaters. Woods (2002) suggested that stream basins might better be understood as a spatial mosaic of independent temporal filters, or subareas, each developing processes which respond differently to local water and energy imputs, and linked to one another by a valley structure (or structures) with their own corresponding stream network. Processes at different scales might be included in the concept of a spatial mosaic of independent temporal filters, including patch dynamics at the habitat-scale (Wiens, 1976; Pickett and White, 1985; Pringle et al., 1988; Townsend, 1989), this mosaic is associated with larger scales in these mountain environments and is linked with the underlying spatial structure of the terrain. Thus, patch dynamics concepts can be usefully applied to intermediate-scale disturbance processes within glacial macroform structures. The Process Domain Concept (Montgomery, 1999) explicitly does this at the intermediate-scale of mountain geomorphic disturbance processes. As originally defined, process domains are spatially identifiable areas characterized by distinct suites of geomorphic and disturbance processes.

Process domains are used in this study to categorize the multi-scaled components of complex glaciated headwater basins, especially disturbance regimes, within the context of their glacial structures. In alpine settings, disturbance processes do not produce a linear or homogenous landscape. Instead, they interact with fluvial processes and relict glacial forms over the long time-scales of landscape evolution. Surficial runoff and recharge patterns are restricted by and inextricably interconnected with the underlying glacial footprint and the spatial variability of geomorphic processes. Process domains thus can integrate complex patterns of hydrologic response with the dynamics of Holocene geomorphic disturbance processes and sustained physical conditions as they evolve within relict glacial macroforms.

General study design and hypothesis

To investigate the potential relationships between geomorphic structure and hydrologic response I characterized valley-scale glacial macroforms in small (1 – 20 km^2) glaciated headwater basins. I then examined differences between geomorphic processes within these structures that might control basin runoff and recharge. I found distinct streamflow regimes that vary in a continuum between fast-response to slow-response hydrographs that vary with the amount of basin area dominated by subsurface flows. I hypothesize that basin-wide, upper basin (source) and lower basin (sink) percentages of colluvial process domains would correlate with hydrological recession constants, $\partial\ ^{18}O$ ‰, and stream temperature. I accomplish this by measuring the streamflow regimes of comparable small headwater basins within a common mountain region over multiple years. Using recession constants, stable isotopes and temperature measurements, I characterize potential differences in hydrological pattern among basins and identify the valley or valley-segment scale landforms and disturbance regimes that constitute basin process domains, and assess the use of process domains as context to explain differences in streamflow regime, stable isotope patterns and temperature within and between basins.

Because of the known temporal variability of the stable isotopic signal in snow meltwaters (Taylor et al., 2002; Liu et al. 2004) and the potential for complex mixing effects, I looked at patterns of $\partial\ ^{18}O$ for possible differences in the signal between basins rather than attempting hydrograph separation in such complex systems. Temperature differences in temporal pattern and values between basins were also used as a comparative measurement.

A Note on the Use of the Term Headwaters

"Headwaters" is used in this paper for lack of a better term, in spite of the confusion associated with the expression. While the term "headwater" commonly refers to the small channels at the source of the drainage network, the range of criteria used to define the term has resulted in a great deal of uncertainty regarding its meaning. For example, headwaters are often classified as first and second order channels in the Horton-Strahler channel ordering system even though topographic maps, created from air photo interpretations, do not show a majority of first and second order channels, particularly in wooded areas (Strahler, 1957; Morisawa, 1957; Hack and Goodlet, 1960; Shreve, 1969; Meyer and Wallace, 2001). The so-called blueline topographic mapping designation does not include ephemeral, intermittent or channels that flow subsurface for a portion of their length within upper basin source areas. In colluvial glaciated montane landscapes such as many small drainage basins in the Cascade mountains, this can also mean that use of the Strahler-Horton channel ordering system would preclude most of the "headwater" system. For the purposes of this paper, the term headwaters is used to refer to the range of channels, both steep and low gradient, fluvial and colluvial, found in small (< 20 km^2)

basins; this catchment size limit is based upon the extent of colluvial and debris flow zones in these relict glaciated catchments.

STUDY AREAS, REGIONAL SETTING AND GEOLOGICAL BACKGROUND

Study areas

Runoff characteristics of perennial streams from five headwater basins on the east side of Mt. Rainier National Park (MORA) were compared (Figure 3.1). The five basins were evaluated in terms of their drainage area, bedrock hardness, mean slope, elevational range, and topographical structure along the longitudinal profile of the stream (Table 3.1). Deer, Lost and Laughingwater Creeks have similar drainage areas (~14 km^2), while Crystal and Shaw (4 km^2 and 8 km^2 respectively) are smaller. The five catchments range in elevation between ~2200 – 950 m with the exception of Laughingwater Creek which is lower (Figure 3.2). Comparison of the basic metrics common to the study watersheds showed that the five basins have similar elevational variation (mean: 1090 m; range of variation: 84 m) and comparable mean slope and headwater drainage areas (Table 3.1). Aspect is important as a surrogate for solar radiation. However, it is especially useful when combined with an understanding of the spatial distribution of large-scale features such as narrow/ deep bedrock canyons and valleys that retain cold air. In the case of the creeks described above, all include cold sinks within canyons and narrow valleys, especially lower Deer, Crystal and Lost Creeks.

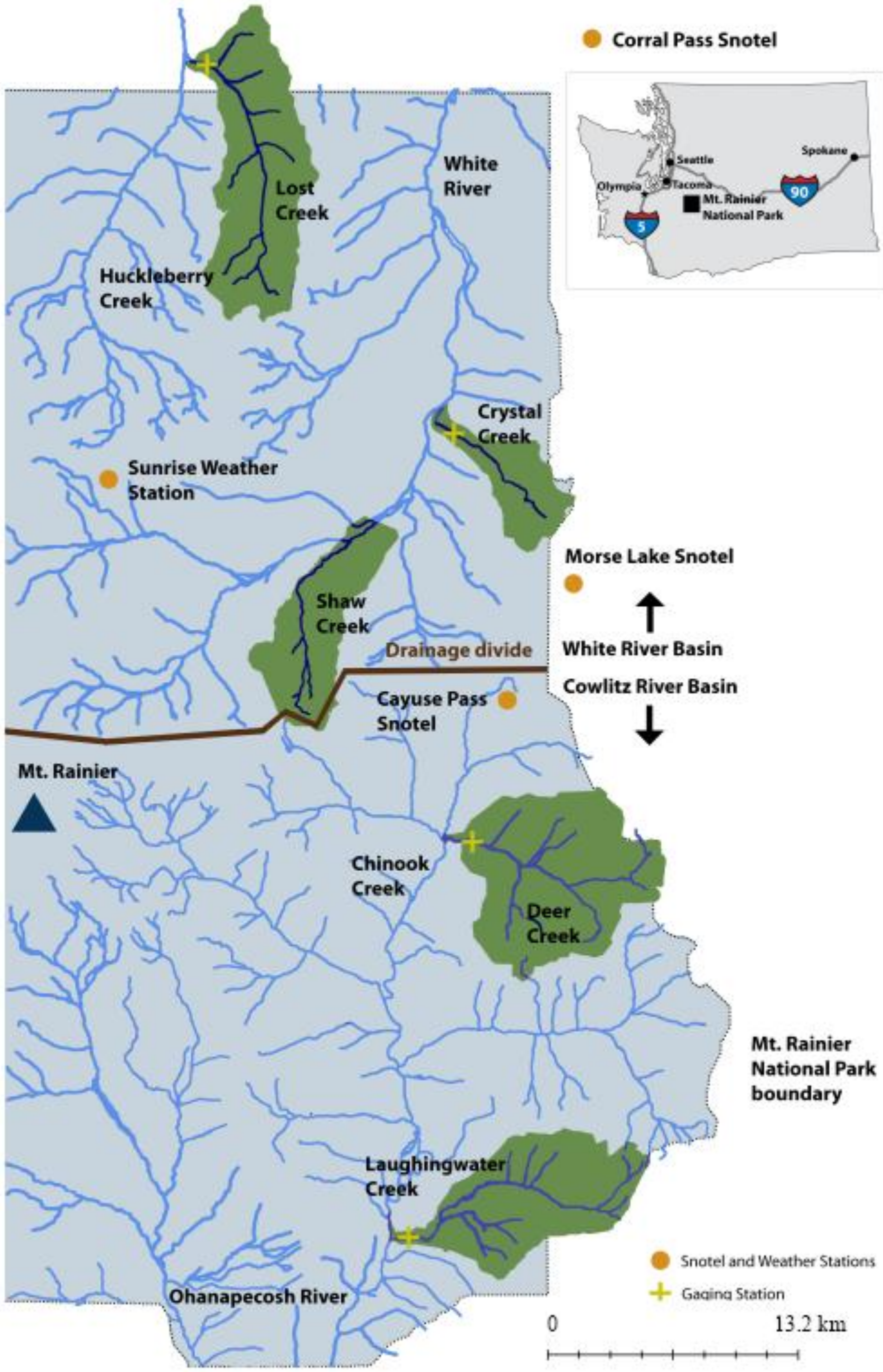

Figure 3.1. Location of study watersheds, snotel stations and streamflow gage sites in Mount Rainier National Park in Washington State.

Table 3.1. Comparison of the basic metrics common to the study watersheds. While Crystal Creek has a slightly steeper mean slope and smaller drainage area, the other basin metrics, especially mean basin elevation, are similar.

Stream/ subwatershed	*Major Watershed*	*Drainage Area (km^2)*	*Mean Slope (Mainstem)*	*Max/Min Basin Elev. Difference (meters)*	*Dominant Aspect (Mainstem)*
Crystal	White River	4.1	17%	1180	WNW
Lost	White River	14	11.3%	1141	N
Shaw Creek	White River	8.2	11.4%	1037	N
Deer	Cowlitz River	14.5	11%	1015	WNW
Laughingwater	Cowlitz River	14.2	11.8%	1106	W

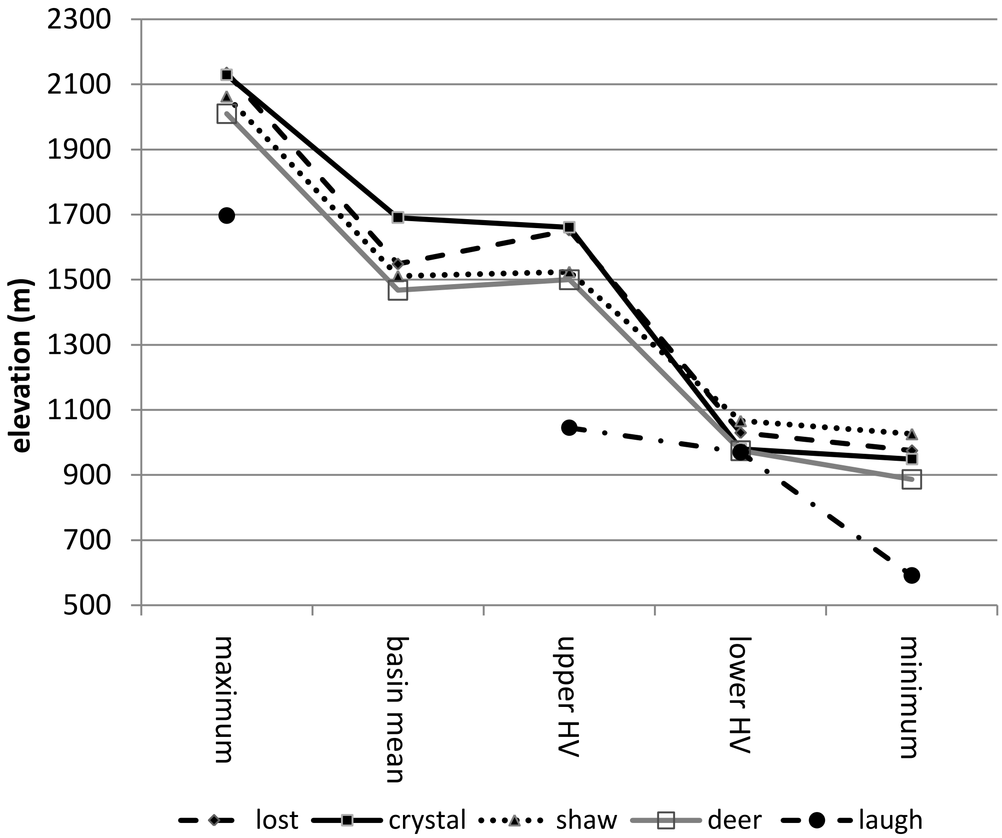

Figure 3.2. Metrics for the five MORA basins including maximum, mean, upper hanging valley (HV), lower hanging valley and minimum basin elevations. Laughingwater Creek elevation metrics are lower than the other basins with the exception of the lower hanging valley.

Basin shape differed between the five catchments; the Deer Creek basin is the most circular in shape, followed by upper Crystal and Shaw Creeks. Laughingwater and Lost Creek basins display the more linear glacial trellis pattern (Figure 3.3). All basins showed evidence of typical mass movement-type disturbance processes characteristic of steep-walled glacial landscapes including landsliding and rock fall, debris flows and avalanche. Common depositional features included debris cones, debris aprons, talus slopes, and blockfields.

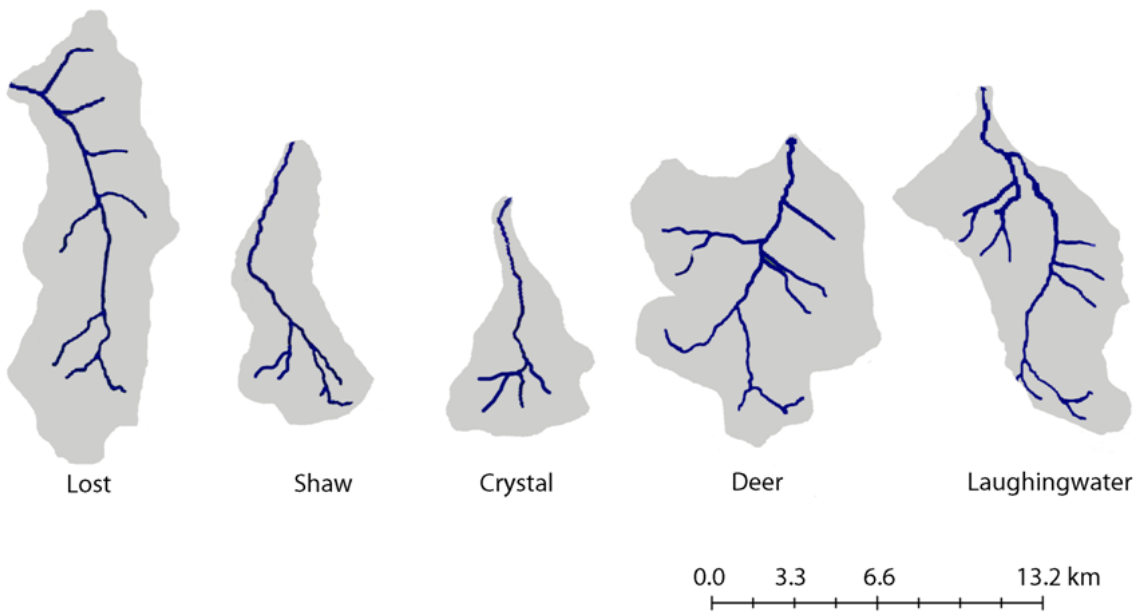

Figure 3.3. Basin shape comparison showing the difference between the larger and smaller catchments. Shaw and Crystal Creeks, the two smaller basins, have complex upper valleys and simple mainstem channels, while Laughingwater and Lost Creek basins exhibit modified glacial trellis drainage patterns.

Numerous springs and seeps were found in the upper valleys of Crystal, Lost and Shaw Creek basins. These water pathways were frequently associated with talus slopes and rock glacier deposits (Crandell, 1969). The lower valleys of Shaw and Crystal Creek basins consist of large accumulation zones that merge with the debris apron of the White River glacial trough valley.

Regional setting

Crystal, Shaw and Lost Creeks are tributaries of the White River catchment, Deer and Laughingwater Creeks are part of the Cowlitz River system. The broad NW oriented White River glacial valley is the product of active glaciers on Mt. Rainier itself, and experiences episodic floods, large debris flow events and lahars. Crystal and Shaw Creeks reach their confluence with the White River through areas composed of material deposited along the steep face of the White River glacial trough wall. The interface between these individual tributary basins and the confluence include large colluvial aprons and debris cones.

Climate

Annual precipitation in the study area ranges between 1800 – 2400 mm, with variation among sites due to the rain shadow effects of Mt. Rainier. Most of the precipitation falls from October to March. Precipitation type varies between storm events; snowfall dominates at higher elevations, especially above 1500 m. At intermediate and lower elevations highly variable precipitation regimes include snow, rain and rain-on-snow. Large low pressure systems from the southwest (i.e. pineapple-express storms) can deposit large volumes of rain on antecedent snow cover. Rapid snowmelt, recorded at up to 19 mm per hour can produce up to 10-15 mm of snow water equivalent in 3 hours (Tsukada et al., 1981). Five USDA snotel sites at differing elevations surround the Mt. Rainier study sites, with two, Morse Lake and Cayuse Pass, centrally located between the basins (Figure 3.1). Regionally, the variability in precipitation patterns over time has not been great; throughout the Holocene, the study basins experienced a very stable and relatively humid climate (Tsukada et al., 1981).

Geology and glacial geomorphology

All five Mt. Rainier study sites are mapped with both Ohanapecosh and Tatoosh formation rock; the bedrock geology of Mount Rainier's east side is dominated by the two formations. The Ohanapecosh formation appears to have been a catch-all term to describe the lithology of large areas in the little-studied east side of the park that predates the original eruption of Mt. Rainier (Fiske et al., 1963, Vance et al., 1987). The Tatoosh pluton, chiefly granodiorite intruded into the Ohanapecosh formations (Fiske et al., 1963). Because the Ohanapecosh formations on the east side are known to be incompletely mapped (personal communication Jim Valence and Derek Booth), I tested rock strength in bedrock exposures in study stream channels, floodplains and canyon walls using standard methods (Selby, 1993; Goudie, et al., 2006). The tested rock proved to be strong or very strong.

Glaciation in Mt. Rainier National Park (MORA) was not affected by the Cordilleran Ice Sheet. All study valleys were covered by alpine glaciers during the late Pleistocene while upper basin summits were ice-free (Figure 3.4). At the time the Evans Creek Drift was deposited, ice fields and glaciers mantled the slopes of the volcano and adjoining mountains above an altitude of about 1600 meters. Each major valley was occupied by a glacier 300 – 460 m thick extending 8-56 km beyond the park boundaries (Crandell, 1969).

The Mt. Rainier study sites all include relict cirque basins at various stages of evolution. Located at the heads of deep valleys, the product of paraglacial action and glacial erosion, cirques consist of a bowl-shaped rock basin extending from a steep headwall of shattered rock to an outlet rim. Fully developed cirques with a fairly consistent ratio of height to length were found in Crystal, Lost and Shaw Creeks. However, clusters of smaller less developed glacial trough forms, running perpendicular to the direction of glacial flow were found clustered above the main cirque features in Lost and Crystal Creeks. Deer Creek has an individual cirque at the head of several tributary channels. Characteristic glacial features found in all basins also included alpine lakes and U-shaped hanging valleys with steep valley walls.

Rock glacier deposits were mapped in higher elevation terrains in Lost, Crystal, and Shaw Creeks (Crandell, 1969). Large talus slopes are another common feature. Humlum (1982) differentiates between talus-derived and glacier-derived rock glaciers. He suggests that they may be members of a continuum with normal talus slopes and normal glaciers as endmembers (Humlum, 1998). Situated at the foot of steep cirque north-facing headwalls, the Rainer rock glacier deposits may be talus-derived rock glaciers. If the MORA rock glaciers were originally deposits of debris cemented by interstitial ice and/or discrete ice lenses, as opposed to a core of glacial ice, the hydrology of these landforms would have had a different genesis.

Differences in age between glacial deposits and features are significant for water movement because the permeability of glacial depositional landforms may decrease with time (Hornberger et al., 1998). There appears to be a north - south gradient in glacial landform age; Lost, Shaw and Crystal are the youngest and highest drainages with remnant rock glaciers in their cirques. The Laughingwater Creek catchment has the same elevational variation as Shaw Creek (975 m), but is more than 300 m lower than the other study basins: the period since alpine glaciation, compared to the other catchments, is greater. Glacial valleys characteristically have an overdeepened long profile; near the trough head the floor is steeply inclined, while down-valley there is a lower or slightly reversed gradient (Summerfield, 1991).

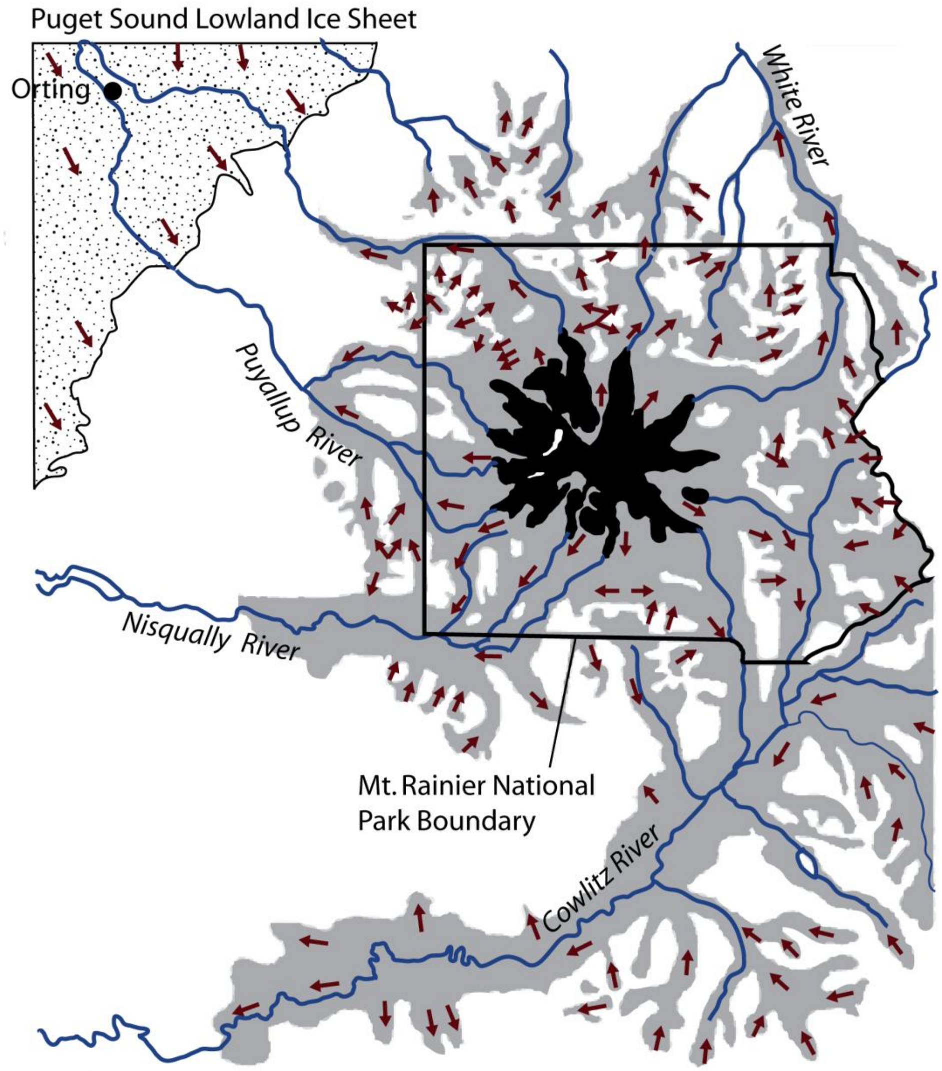

Figure 3.4. Extent of glaciation during the Cordilleran Ice Sheet at Mt. Rainier National Park and environs. Stippled area represents ice sheet and solid area alpine glaciation. Arrows represent ice flow direction. (After Crandell and Miller, 1974).

Surficial deposition, mass movements and disturbance regimes

The oversteepened slopes of glacial valleys, in conjunction with Mt. Rainier's heavy rainfall, large snowpacks, and rain on snow events are especially conducive to debris flows in failure prone areas. Debris flows are slurries of water and sediment (60 percent or more by volume) that look and behave much like flowing concrete. Non-cohesive debris flows, typical of those in the MORA study sites, contain relatively little clay. These debris flows are triggered when water, in the form of unusually heavy rain, or an abrupt release of stored water, mixes with weathered loose rock debris or saturated regolith (Hoblitt et al., 1995). Such flows can transport large boulders and trees in a fast moving slurry of wet mud and rock. As larger material is deposited along the debris flow track, thinner muddy flood waters eventually merge with the stream channel and its floodplain. In narrow valleys with episodic flows, debris flow channel deposition can form a debris cone or apron at the lower portion of the valley (Selby, 1993).

METHODS

Field Sites and study design

This study compares five headwater basins. All are located on the east side of Mt. Rainier National Park (Figure 3.1). They were chosen for their common regional and catchment-scale metrics, including drainage area, bedrock hardness, basin shape, topography, elevational range and similarities in slope along the longitudinal profile of the stream. Climate and aspect were also compared. This research combines several independent integrated time series measurements including recession curve analysis from stream gage data, stream temperature and the use of the stable isotope ^{18}O. Stream gage data and recession constants were used to measure the study basin streamflow regimes over multiple years. Intercatchment comparison of streamflow regime in the study basins was accomplished using discharge time series measurements within the lower portion of each basin, but above the catchment outlet. Hydrograph analysis produces a basin-wide signal.

Shaw Creek was used for this study in spite of the lack of a perennial surficial channel to compare discharge measurements. While originally chosen as a study site, Shaw Creek experienced a large debris flow in 2004; evidence of previous debris flows can be seen in aerial photographs. However, the 2004 event eliminated the possibility of gage installation, as much of the lower channel was buried by colluvium. Most buried channel segments have quickly recovered and returned to surficial perennial flow over the last four years. Stable isotope and temperature measurements in the newly daylighted channel were compared with the other basins. The channel recovery process has been highly instructive as a model of the mechanisms and characteristics of the aftermath of such events. Another major disturbance event in November of 2006 destroyed the gage installation at Laughingwater Creek; debris flows from this episode limited access for the remainder of the study. A flood and rotational slide in late fall, 2006 removed any trace of the Laughingwater Creek gage site. The creek remained inaccessible through the following year. Therefore there are no 2007 water temperature measurements for the site. Like the Shaw Creek event, the Laughingwater Creek mass movement is an example of the importance of disturbance in these basins. Thus, complete data sets for recession constants and water temperature are missing for Shaw and Laughingwater Creeks (Figure 3.5). However, the disturbance-prone nature of these systems is important and the effects of these events are integrated into the delineation of basin process domains.

Mapping - The GIS software applications ArcGIS 9.2 and Arc Info from ESRI are used for mapping and analysis. A first approximation of process domains were developed by identifying significant breaks in slope along the longitudinal profiles of the mainstem channels for each study basin using ArcGIS 9.2. Preliminary delineation of major channel slope breaks matched the locations of characteristic glacial landforms, including cirque walls, hanging valleys, valley steps, and glacial troughs. Process domains delineations were groundtruthed in the field with USGS 7.5 minute quadrangles and GPS coordinates.

Layers generated by park service personnel included a composite of USGS 7.5 minute quadrangles, roads, trails, glaciers, ice and snowfields, landforms, vegetation, Ikonos satellite information, and bedrock geology. Additional layers included composite USGS 7.5 minute 10-meter-grid elevation models (DEMS) and flow direction and flow accumulation grids, hillslope gradient distributions and watershed delineations for individual study basins.

Aerial photos from Mount Rainier National Park (MORA) were scanned into ArcGIS and manipulated to develop stereoscopic 3D images of the basins using the ESRI 3-D analyst extension with ArcScene. MORA aerial photographs were flown by the United States Department of Agriculture (USDA) in 1984 and again in 2002. These images are especially valuable as a means to delineate evidence of glacial geomorphology and mass movements within the basins. Landform maps for the study basins have also been completed by NPS.

Process domains – The best method to categorize differences between the naturally-occurring spatial units found in these complex basins proved to be through the use of process domains. These domains were identified using a simplified form of methods developed by Montgomery et al. (2002) and Brardinoni and Hassan (2006) and based on the spatial hierarchy developed by Frissell et al. (1986). Using Brardinoni and Hassan’s (2006, 2007) work on glaciated basins in British Columbia as a model, we define valley-scale geomorphic forms as process domains. This addition offered a framework within which to better integrate the spatial and temporal variability of both geomorphic and hydrologic response at controlling scales.

The spatial location and extent of the valley and valley-segment-scale landforms that comprised the process domains along the basin longitudinal profile were checked using both map and field techniques. Landscape reconnaissance proved to be the most reliable method to identify the critical streamflow components of present basin structure such as springs, topographic features that significantly altered streamflow downstream, and significant talus deposits on cirque and glacial valley walls.

Streamflow gaging - Global Water W15 pressure transducers were located at the lower portion of the five MORA study watersheds at channel cross-sections with bedrock control if available. If not, stable locations with comparatively regular channel geometries were selected according to standard methods for ensuring geomorphic control (Rantz, 1982). Stage-discharge rating curves were developed for each gage site using standard techniques (Rantz, 1982). No discharge measurements were taken at extremely high flows – thus the upper end of the rating curve is less well defined. The Winxpro Software package was used for evaluating the high end of the rating curve.

Creek	Process Domain	Recession Constants	Stable Isotope Analysis	Water Temperature
Crystal	X	X	X	X
Lost	X	X	X	X
Shaw	X		X	X
Deer	X	X	X	X
Laughingwater	X	X	X	

Figure 3.5. Process domains and hydrological indices used for the study according to creek. Due to a debris flow in 2004, Shaw Creek was not gaged, but was used for stable isotope measurements and water temperature.

Recession constants - A typical hydrograph resulting from an isolated period of rainfall consists of a rising limb, peak, and falling limb, or recession. The rising limb is influenced primarily by the character of the storm that caused the rise. Recession flow is the discharge contributing to the recession limb of the storm hydrograph (Dunne, 1978) described by the recession constant K_r. The lower portion of the recession curve is thought to provide a measure of the time period of runoff response representing stored subsurface water (Linsley et al., 1982).

There is an extensive literature (and some debate) on baseflow and stormflow recession analysis reviewed by Tallaksen (1995). Tallaksen defines baseflow broadly as including groundwater, unsaturated soil, and lake drainage. Hydrogeologists also include subsurface flows in weathered bedrock, talus and colluvium in the unsaturated or vadose zone.

Two commonly used recession equations are useful for the purposes of this study. Tallaksen cites the commonly used linearized Depuit-Boussinesq equation for the storm hydrograph;

$$Q_t = Q_p\, K_r^{\,t} = Q_p e^{-a\,t} \qquad (1\text{-}1)$$

where Q_t is the flow at time t (hours or days), Q_p is the peak discharge at the start of continuing periods of declining discharge and K_r is a recession constant that is less than unity. Equation (1-1) can be written in the more general form

$$\mathrm{In}Q_t = \mathrm{In}Q_p^{\,-a\,t} \qquad (1\text{-}2)$$

where a = - In K_r (Tallaksen, 1995) and can be calculated from the slope of semi-logarithmic plots of discharge recession (Montgomery and Dietrich, 2002). The time unit used is frequently 24 hours. This commonly used function for the recession curve is also described by Linsley (1982) using graphical techniques, first introduced by Barnes (1939). These techniques can be applied to separation of the entire hydrograph (Linsley et al., 1982) as well as the partitioning of different flow components (Hewlet and Hibbert, 1963).

$$K_r = (Q_t / Q_0)\,(1/ t) \qquad (1\text{-}3)$$

where Q^0 is the flow at any chosen time, Q^t is the flow one time unit later and K_r is a recession constant that is less than unity. The choice of a discharge value for Q^0 is sometimes based on a judgment about the point on the recession limb where surface runoff-fed flows have theoretically ceased, described by a break in slope on the falling limb. To avoid observer bias, other workers combined this method with an empirical equation to separate the overland flow component from the baseflow.

$$D = A^{0.2} \qquad (1\text{-}4)$$

where D = the number of days between the storm peak and the end of the overland flow and A = the drainage basin area in square miles (Fetter, 1994).
Equation (1-4) is not dimensionally correct and lacks a method to differentiate between storm intensity.

While the prerequisite conditions for Boussinesq formal recession analysis are not met in the Cascade mountain headwaters, (the Boussinesq equation theoretically describes the outflow volume from an unconfined, horizontal, homogeneous aquifer), exploratory analysis of the relationship between InQ_p and InQ_t appears to provide insight into system behavior. Many studies in mountainous landscapes have shown that changes in the relationship over the distribution of flows indicate changes in dominant streamflow generation processes (Tague and Grant, 2004) in spite of the very different conditions found in these regions.

Comparative K_r values published from plot scale studies provide insight into recession flowpaths. Dunne (1978) showed that K_r values cluster in different ranges for the following runoff mechanisms from a variety of field sites:

Horton overland flow	0.02-0.34
Subsurface storm flow	0.27-0.99

Montgomery and Dietrich (1995) using equation (1-4), field tested K_r values for periods dominated by different runoff pathways in a low-gradient source area in Marin County, California. They established the following ranges for recession constants for runoff produced by different mechanisms at their site:

Throughflow, interflow, groundwater	0.88-0.97
Throughflow and macropore flow	0.69-0.89
Saturation overland flow	0.51-0.57

Montgomery and Dietrich (2002) ascertained mean K_r values of 0.98 in two small, steep channel-head source areas (average slope 43° and 40°, DA= 0.00086,0 .0032 km^2) in Coos Bay, Oregon with a highly conductive, thin but variable soil profile over weathered and fractured sandstone bedrock. Using equation (1-2), least-squares linear regression of the natural log-transformed discharge versus time was used to calculate stormflow discharge recessions. The results were surprising, as, in spite of steep slopes and high conductivities, discharge responded over timescales similar to subsurface stormflow recessions in low-gradient sites of comparable size. The authors conclude that because unsaturated vadose zone flow is essentially vertical, it is not slope dependent. If these results hold true for other mountainous systems, the recession ranges published above could serve as a point of comparison for other steep mountain catchments.

Stable Isotope analysis

Stable isotopes in this study were used for comparative analysis between basins. Isotopes are the nuclides of a single element that have different atomic weights. ^{18}O is useful as a marker for hydrologic studies because of the process of isotopic fractionation, the partitioning of a sample into two or more parts that have different ratios of heavy (more massive) and light (less massive) isotopes than the original ratio. Oxygen isotopes are conservative tracers, meaning that their ratios are uniquely intrinsic to the water molecule and reveal the origin, phase transitions and transport of H_2O.

Routine stable isotopic measurements are made by electronically counting and comparing the intensities of beams using a mass spectrometer. The isotopic constitution of the sample is determined by the *difference* in intensity from that of an accepted standard. For ^{18}O (and deuterium), standard mean ocean water (SMOW) is the most useful as a standard and is calibrated using the meteoric water line (MWL). The measured difference between the unknown and the standard is reported in terms of dimensionless δ-values. A factor of 1000 converts the δ-values to per mil (‰) (Criss, 1999).

The isotopic values of meteoric precipitation are principally correlated with temperature; the variation in the ratio between $\partial^{18}O$ and $\partial^{16}O$ in water is dependent on temperature-related equilibrium and kinetic effects. However, ^{18}O values also become more negative with increases in altitude, latitude and proximity to the ocean (Burk and Stuiver, 1981, Dansgaard, 1964).

The standard of error is 1% for all study isotope measurements except as noted. Measurements were taken at each gage site at the same elevation on the same day. Initially three or more samples were taken at half hour intervals at each gage site to check for error, or fluctuating heterogeneous conditions. When it became apparent that values for each creek were consistent within the standard of error, later samples consisted of one or two samples per gage.

Tallaksen (1995) suggests that isotopic and chemical hydrograph separation techniques provide a less subjective method of identifying sources and pathways of stream runoff (Sklash, 1990) than graphical methods. Recession constants obtained from semi-logarithmic plotting can be used in conjunction with the time of detention of chemical concentrations in ground and surface water (O'Connor, 1976). Stable isotope concentrations should also provide information on the sources of flow during recession periods (Maloszewski et al., 1992; Vivitar et al., 2002).

The documented altitude effect for the composition of precipitation at Mt. Rainier National Park has been developed into an empirical equation derived from Mt. Rainier data (May through September, 1976-1978) relating altitude and ^{18}O in precipitation (per mil) (SMOW).

$$M = -313 * {}^{18}O - 2729 \qquad (1\text{-}5)$$

where M is the elevation in meters based on the measured ^{18}O values for precipitation. In conjunction with the temperature lapse rate on Mt. Rainier of 5.2° C per 1000 m (which compares favorably to the value of 5° C per 1000 m found in the meteorological literature), it has been suggested that it is possible to bound probable values for recharge input (precipitation) within the Mt. Rainier catchments (Buck and Stuiver, 1981). However, the ^{18}O values of flowing streams do not always match the corresponding precipitation values during a particular event because stream waters volumetrically integrate not only the parent meteoric waters that fall within their watersheds, but also the mixing of meltwaters released at different times within the basin. ^{18}O values from a particular channel location in time may also reflect the range of isotopic values caused by fractionation of meltwaters during snowmelt. Studies have shown that the isotopic change in snow meltwaters over the season typically show ratios of 3.5 – 5 ‰ (SMOW) (Taylor et al., 2002). While the isotopic ratios of individual storms are unique, and in general, deviate from the ratios of the average precipitation, groundwater and streamflow, the unknown amount of pre-event water released as streamflow during a storm or melt event, as well as the relative contributions from multiple sources during baseflow suggest that use of stable isotopes for hydrograph separation can be very complex, particularly at the small basin scale. The complexity of the study basins, with a wide range of elevations, geomorphic landforms and water sources and flowpaths, makes these problems particularly acute. The measurement of the isotope ratios of precipitation in mountain storms is complicated by the abrupt shifts in surface elevation in these areas.

One would expect that snowmelt would consist of colder, depleted ^{18}O, baseflow would be somewhere in between, and early fall warm weather stormflow would be composed of more enriched ^{18}O percentages. However, in spite of the progressive enrichment of snowmelt during spring melt (Taylor et al., 2002), pre-event water does not always differ from enriched waters later in snowmelt. Because of the correspondence between depletion of ^{18}O in parent precipitation according to altitude, latitude and proximity to the ocean (Burk and Stuiver, 1981, Dansgaard, 1964), the bulk range of ^{18}O values in recharge waters reflects the dominance of a particular composition of precipitation in spite of snowmelt phase change effects. For example, snowmelt ranges of values in maritime and continental climates at different latitudes showed that, while the 3.5 – 5 ‰ variation in ^{18}O was found in all regions studied, the range of values for each mountain landscape varied a great deal (Taylor et al., 2002). This suggests that there is still an integrated signal that shows dominate patterns in the parentage of basin recharge waters in spite of diverse processes such as snowmelt fractionation and in some cases, the mixing of subsurface waters and their subsequent release. The general range of isotope values characteristic of each study basin would seem to best relate to the integration of source water processes that produce a distinct mixing signal produced by a particular suite of basin characteristics.

Since the advent of stable isotopes in hydrologic studies, an unexpected result has been the extent to which surface waters are linked with shallow groundwater and subsurface flow systems. One of the principle effects of rainfall is to displace groundwater into stream channels. Studies tracking differences between isotope values from precipitation during individual storms and channel discharge suggest that more than 50% of the streamflow represents pre-event water. This result holds true even during the sharp rises in streamflow that accompany major storm events (McDonnell, 2003; McGlynn et al., 2005).

Temperature

Onset Stowaway Tidbit Temperature Loggers (Onset Corp., N. Falmouth, MA, USA) were installed at 9 locations in Mt. Rainier National Park in April, 2007. A logger was placed at each stream gage location within Crystal, Lost, Deer and Laughingwater Creeks under rocks at the thalweg of the channel. Two temperature loggers were placed within Shaw Creek, one in the channel in the colluvial valley and one within the main channel. Three additional gages were installed within Crystal Creek catchment; at a low elevation seep adjoining the channel, at the mouth of the hanging valley and within a ground water source spring in the lower cirque valley. The Laughingwater gage site and all equipment were destroyed in the November 2006 flood. Due to extensive damage to the access road, Laughingwater was inaccessible during the 2007 season, so the logger was not replaced. The hanging valley temperature logger at Crystal also disappeared during the 2007 summer season.

RESULTS

Process Domains

Process domains varied significantly between basins (Figure 3.7-3.11). The overriding structure of the glacial macroforms produces similarities in the elevations of the upper, middle and lower valleys. However, differences caused by variation in geohydrological (colluvial and fluvial) response to geomorphic disturbance over long timeframes are profound. The following observations from the individual basins highlight the many ways in which these basins diverge from a common structure.

Deer Creek (Figure 3.7). - The fundamental structure of the Deer Creek basin is composed of glacial landforms. However, beginning with its source at Anderson Lake, Deer Creek flows on bedrock throughout much of its longitudinal profile. A series of bedrock canyons and waterfalls are incised within the lower hanging valley; at the reach-scale, step-pool and cascade channel types are common. The valley step connecting Deer Creek with the confluence with Chinook Creek is also marked by a series of waterfalls in a bedrock canyon. As a result, while the underlying structure of the basin reflects its glacial history, the channel mainstem is dominated by fluvial processes decoupled from the surrounding hillslopes. Process domains thus reflect both the antecedent glacial footprint and the sustained fluvial processes that appear to control modern basin evolution. Talus slopes, a rock glacier deposit, and mountain lakes within cirque and hanging valleys are found in tributary basins of Deer Creek.

Crystal Creek –Crystal's mainstem upper valleys are similar in elevation to Lost Creek, while the lower colluvial valley is closer to Shaw, Deer and Laughingwater Creeks (Figure 3.7). The basin differs from the other study watersheds in its smaller drainage area, overall basin shape and higher mean slope (Table 3.1; Figure 3.3).

The relict glacial structures and process domains along the Crystal Creek longitudinal profiles include both source and sink colluvial valleys (Figure 23). In the upper basin, talus slopes and rock glacier deposits comprise a large percentage of the total cirque wall and valley area. The source colluvial valleys display ephemeral and perennial subsurface channels and seeps; these pathways appear to be the primary water sources during baseflow conditions in some areas.

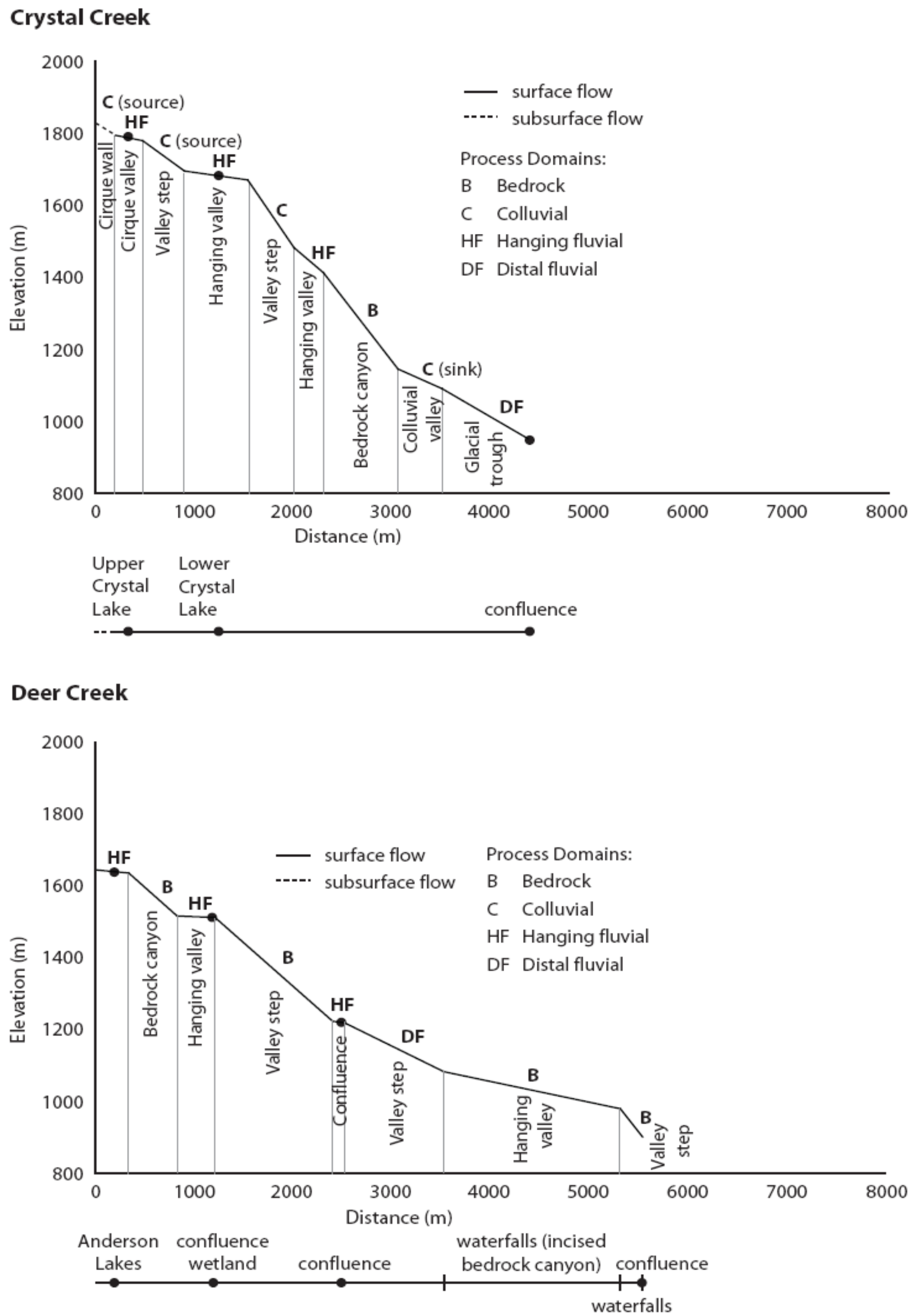

Figure 3.7. Crystal and Deer Creek longitudinal profiles.

Laughingwater Creek - Due to a massive landslide which occurred in 1969, Laughingwater Creek changed course, flowing around one side of the slide debris. Field reconnaissance along the Laughingwater Creek long profile shows several bedrock canyons. After exceptionally high rainfall from the November 6-7, 2006 storm, a localized rotational slide at the lower reaches of the creek (above the confluence with the Ohanapecosh) dumped > 3 m of boulder sized sediment and old growth woody debris into the channel floor along a 274 m reach. This event increased the width of the lower valley from ~8 m to ~60 m.

Like Deer Creek, the glacial footprint is evident in the basic structure of the Laughingwater Creek basin (Figure 3.8). However, the lower elevation of the basin elements suggests that glacial retreat would have occurred earlier than the other study sites. The recent large-scale disturbance episodes are important controls on stream and valley structure and evolution in the watershed. The presence of incised bedrock canyons and fluvial process domains within the template of glacial landforms and the steep confluence with the Ohanapecosh River demonstrate structural similarities with Deer Creek.

Lost Creek – The basin has a long, linear trellis-shape and exhibits massive disturbance and depositional features including talus slopes, and landslide and rock glacier deposits. The main channel travels underground for 1.53 km within a large hanging valley. There appears to be a subsurface connection between upper Palisades Lake and the receiving valley below. Numerous small, ephemeral and perennial source channels, many originating as springs, are found throughout the upper colluvial valleys. The lower colluvial valley is also permeated with subsurface pathways horizontal to the main channel. Thus, the process domains found within the components of the glacial structure predominately reflect colluvial rather than fluvial processes (Figure 3.8).

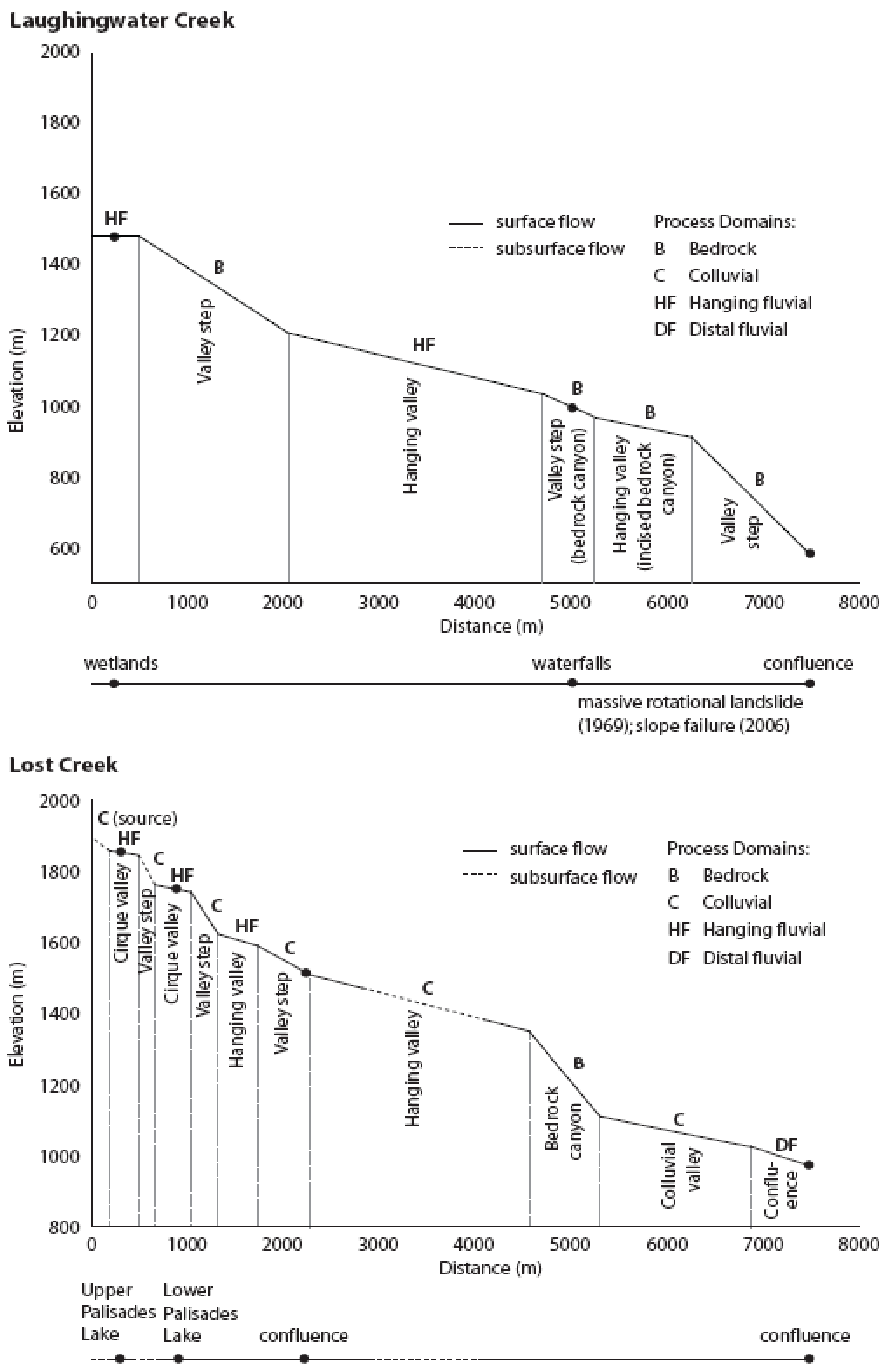

Figure 3.8. Laughingwater and Lost Creek longitudinal profiles.

Shaw Creek –In the lower colluvial valley, greater portions of the channel have resurfaced for increasing periods over the last five years. Other areas of subsurface flow in the basin include Tamanos Creek, which daylights from a large spring fed by a perched cirque valley on the west rim of the basin, and subsurface/surface flowpaths that emerge from the large talus slope on the east side of the upper basin.

While the glacial structure, main channel length along the longitudinal profile and elevation of Shaw Creek is most similar to Deer Creek, basin shape and aspect more closely resembles Lost Creek (Figure 3.3; Table 3.1). Process domains along the main channel alternate between coupled colluvial systems with daylighting springs and seeps and surface-flow dominated channels and lakes (Figure 3.9).

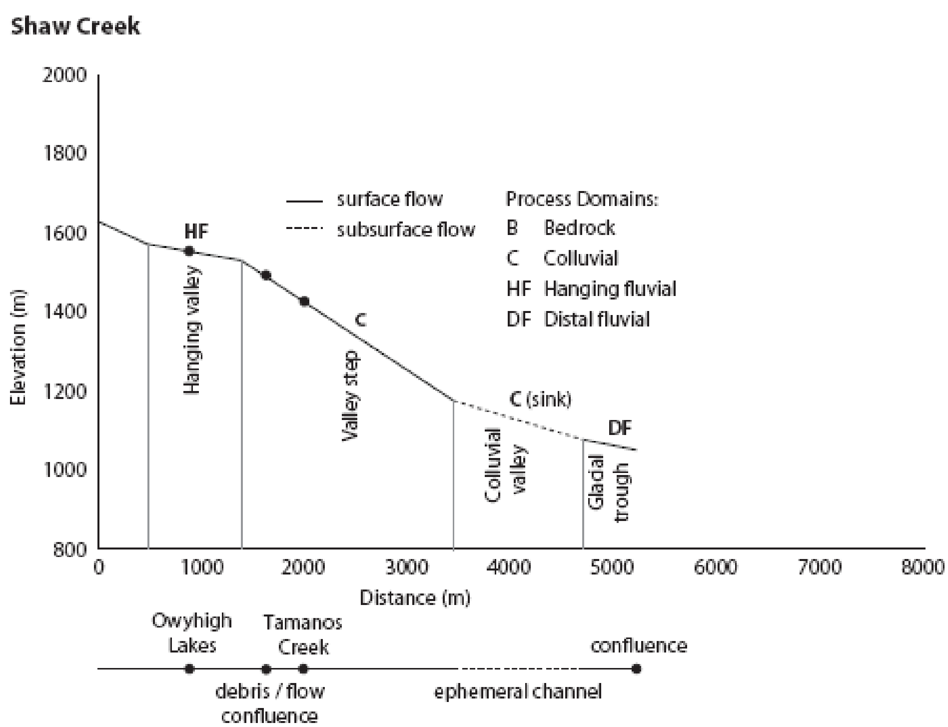

Figure 3.9. Shaw Creek longitudinal profile.

Comparison between percentages derived from the lengths of colluvial process domains along channel longitudinal profiles and characteristic hydrologic patterns produced by K_r, ^{18}O and temperature values corresponded with each other. Because the presence or absence of major colluvial features at the valley-scale limit velocity and control water routing and response both in the stream and within connected hillslopes, colluvial percentages appear to be a good indicator for identifying hydrologic relationships. The amount of colluvial valleys and channels in a basin proved to explain slow response hydrological characteristics.

Recession Constants

Each basin demonstrated a trend in the range of recessions (K_r) characteristic of each catchment, regardless of the type of precipitation or snowmelt event. In most conditions, Crystal and Lost Creek displayed higher (slower) recession constants comparable to the groundwater, interflow, throughflow values (.99 - .88) published for plot scale porous matrix hillslope studies, while Deer and Laughingwater Creeks remained in the throughflow, macropore flow, saturation overland flow range (.88 - .51) attributed to flashier basins (Montgomery and Dietrich, 1995).

Snowmelt -The snowmelt season in the Central Cascades ranges between April to early July and is highly variable between years. The water years 2004 and 2005 had earlier snowmelts and produced drier summer months, while 2006 and 2007 had later melts with wetter summers. However, the lack of consistency in the details of the weather pattern did not affect the interbasin differences reflected in the range of typical recession values computed for each basin during snowmelt.

Recession constant (Kr) values for snowmelt reflected the differences in streamflow response between catchments with multiple subsurface flowpaths (Crystal and Lost Creeks) and those with a higher percentage of surface flow (Deer and Laughingwater Creeks). While individual recession events show natural variation, interbasin differences are consistent (Figure 3.10).

The snowmelt period represents the largest volume of continuous water delivery over a prolonged period within the water year. By the snowmelt peak, perennial springs that outlet into hydraulically scoured channels were readily observed within cirque and hanging valley landforms. Other springs and seeps are ephemeral and emerge only during the snowmelt and major stormflow events. Volumes of water derived from colluvium and talus-filled subsurface troughs and reservoirs that discharge from springs appear to be a significant source of flow within the small catchments.

Seepage faces along channel banks and some canyon walls were especially active during snowmelt and were found in all the catchments studied. The ephemeral nature of these seeps, which appeared to correlate with wet antecedent moisture conditions, cannot be defined as examples of subsurface stormflow, as many remained active after the end the snowmelt period. However, they were especially prevalent in the higher Kr value systems.

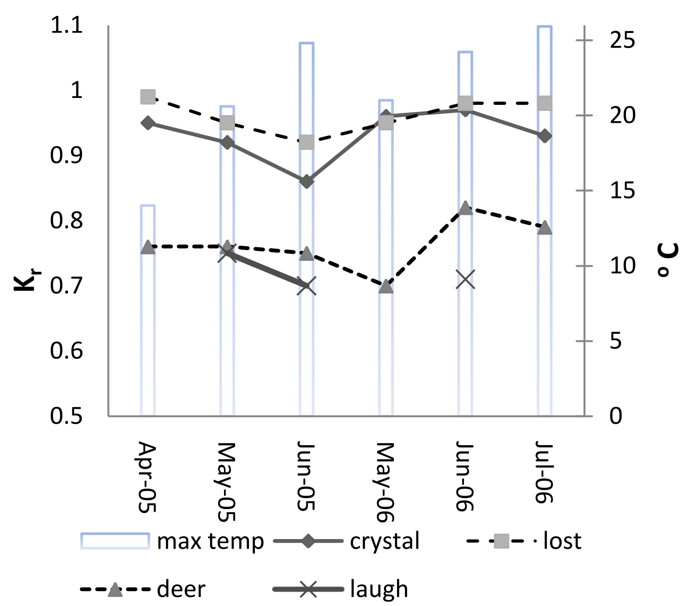

Figure 3.10. Snowmelt recession constants observed between May, 2004 and June, 2007 with associated maximum and mean temperatures from Cayuse and Morse Lake snotel stations.

Baseflow - The distinction between snowmelt and baseflow in small mountain headwater streams is not straightforward because of lingering areas of snow in high elevation areas with a north facing aspect. For the purposes of this study, there was a 30 day transition period allowed between no snow recorded at Morse Lake and Cayuse Snotel sites (elevation ~1500 m) and the baseflow recession onset. The ensuing baseflow recession characteristics suggest that there is an important distinction between the flat hydrographs produced by periods without precipitation over 60 days in length, and precipitation events driving shorter storm recessions of 30 days or less (Figure 3.11).

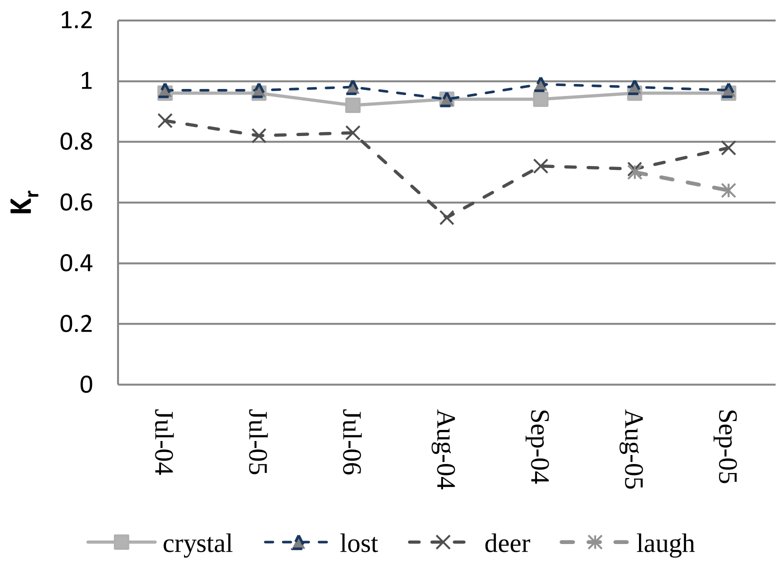

Figure 3.11. Baseflow recession constants observed between July, 2004 and late September, 2007.

All streams remained perennial, even after > 60 days of dry summer weather in 2004 and 2005 (especially dry water years). However, the difference between the baseflow recessions is significant. For example, during the recession extending from July 2 through August 6, 2006, Crystal and Lost Creeks produced slower recessions and greater discharge volumes (after being adjusted for drainage basin area) compared to Deer Creek. Evaluation of temperature time series and discharge measurements during the transition from snowmelt to summer baseflow illustrates the distinction between Deer and Lost Creeks recession and temperature time series (Figure 3.12).

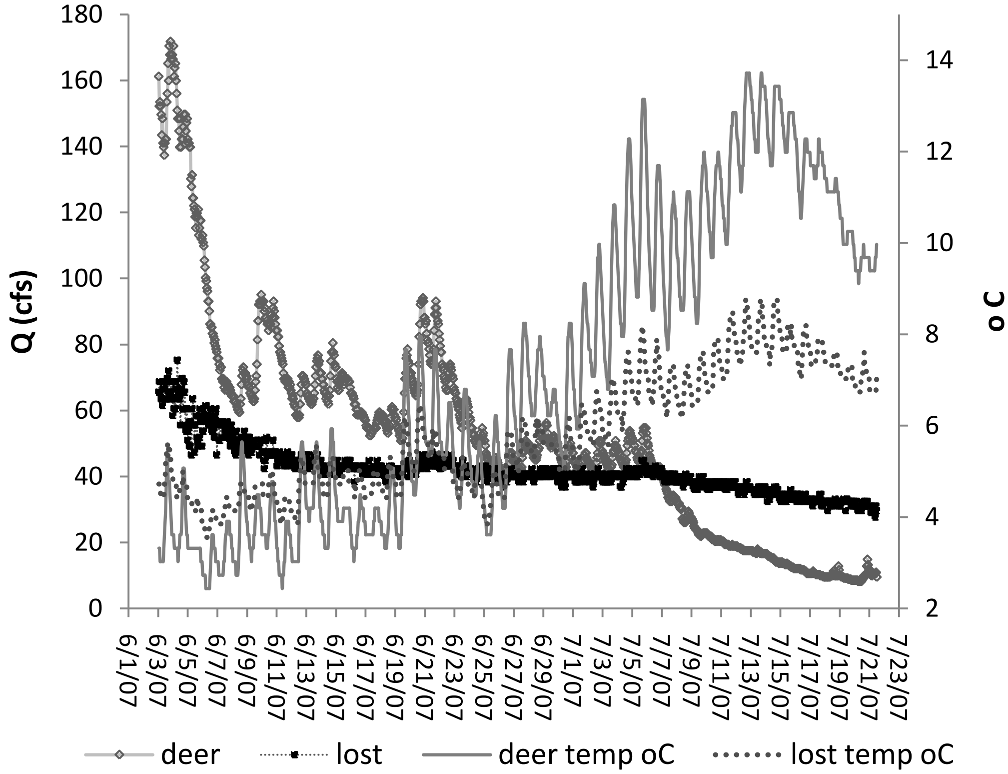

Figure 3.12. Comparison of discharge and water temperature, snowmelt and transition to baseflow for Deer and Lost Creeks.

The Lost Creek streamflow volumes and the extent of diurnal cycle amplitudes and water temperatures remained comparatively constant. In contrast, Deer Creek exhibited greater extremes in peak and low flows, larger diurnal cycle amplitudes and greater variation in water temperature. The slope of the post-snowmelt recession for Deer Creek at the inflection point (7/7/07) where Deer Creek begins to have less discharge than Lost is later than the inflection where Deer Creek water temperatures begin to surpass those of Lost Creek (6/20/07). While the many complexities of the catchments heat budgets, especially local microclimate effects, are beyond the scope of this study, the consistent differences in pattern between discharge and water temperature between the two basins match the differences in recession constants computed for the two basins. The relative lack of slope in both the temperature and discharge time series for Lost Creek as compared to Deer Creek appears to match the effects of the relative bulk volume of subsurface source waters and channel pathways in the two basins.

Stormflow - Stormflow recessions exhibit the widest variation, both in K_r values and in the weather patterns that created the hydrograph peaks (Figure 3.13). Stormflow recessions vary between small early fall rain events after dry antecedent conditions , major pineapple express, rain on snow flood events with antecedent moisture, and winter storms with variable antecedent conditions.

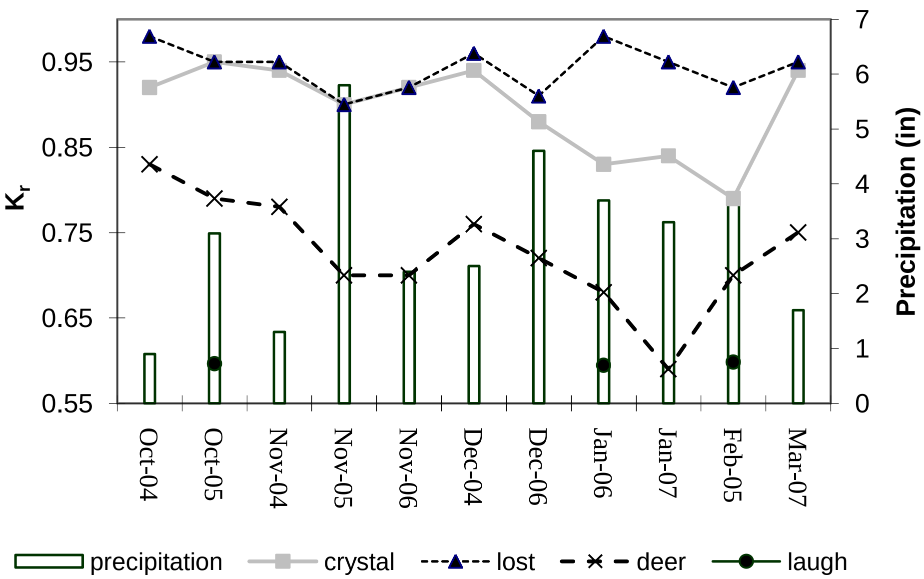

Figure 3.13. Stormflow recession constants observed November, 2003 through February, 2007 contrasted with daily precipitation data from Morse Lake snotel station.

Crystal Creek appears to be affected by cold conditions to a much greater extent than Lost Creek; during the snowmelt and baseflow recessions, recession constants for Lost and Crystal Creeks are more alike. Deer Creek recessions are more variable both within and between seasons, and are generally lower than Crystal and Lost Creeks, as are Laughingwater.

Descriptive statistical analysis of the combined snowmelt, baseflow and stormflow Kr values for the MORA study sites show noteworthy differences between basin recessions (Figure 3.14). Crystal and Lost Creeks, with more basin storage and less overland flow, have median recession constants > 0.9 for all distinct recession curve declines in the 2004-2007 period of record. With medians of <0.75, Deer and Laughingwater Creeks have more flashy runoff events dominated by surface flowpaths.

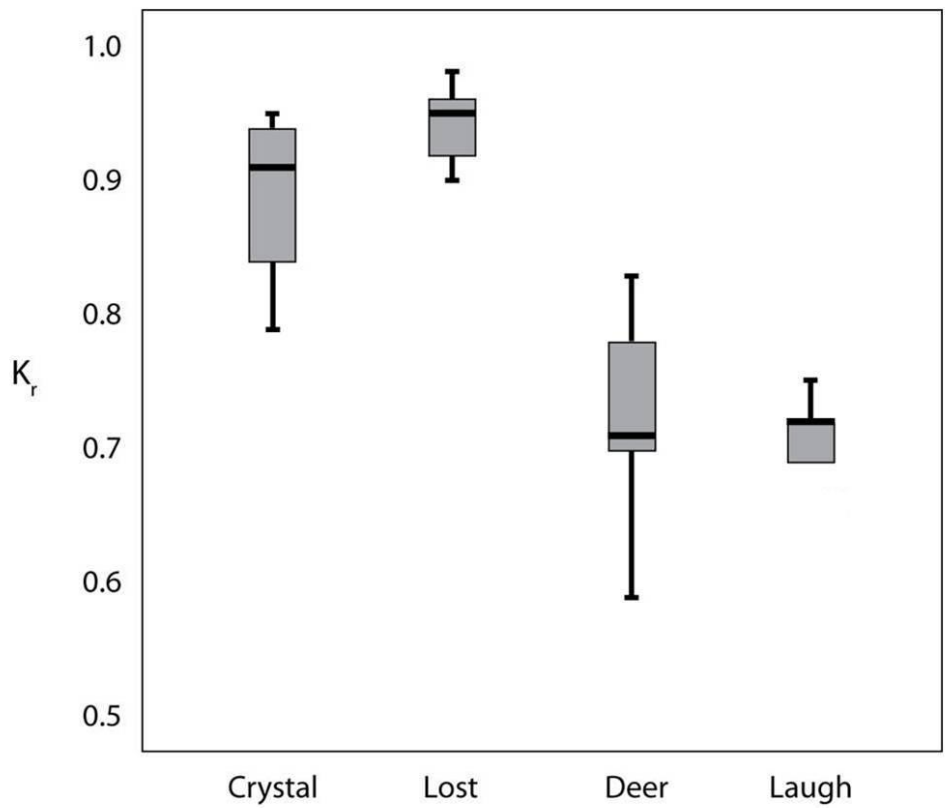

Figure 3.14. Box plot showing median K_r values from streamflow recessions (snowmelt, baseflow and stormflow) for all gaged sites. The analysis does not include K_r anomalies caused during periods of extreme cold.

Anomalous cold weather peaks - The important exception to the typical recession constant signatures found throughout snowmelt, stormflow and baseflow dominated periods occurs during periods of extremely dry, cold winter weather. Crystal Creek (normally a slow response basin), displayed extreme hydrograph peaks that were not caused by either precipitation or snowmelt.

The anomalous effect of unusually cold conditions on the response characteristics of Crystal Creek is demonstrated by four unusual streamflow events during the three winters of record (Figure 3.15). Each of the four recessions shown was preceded by at least six days of dry weather and the lowest minimum temperatures of the year (<10 ^{o} C).

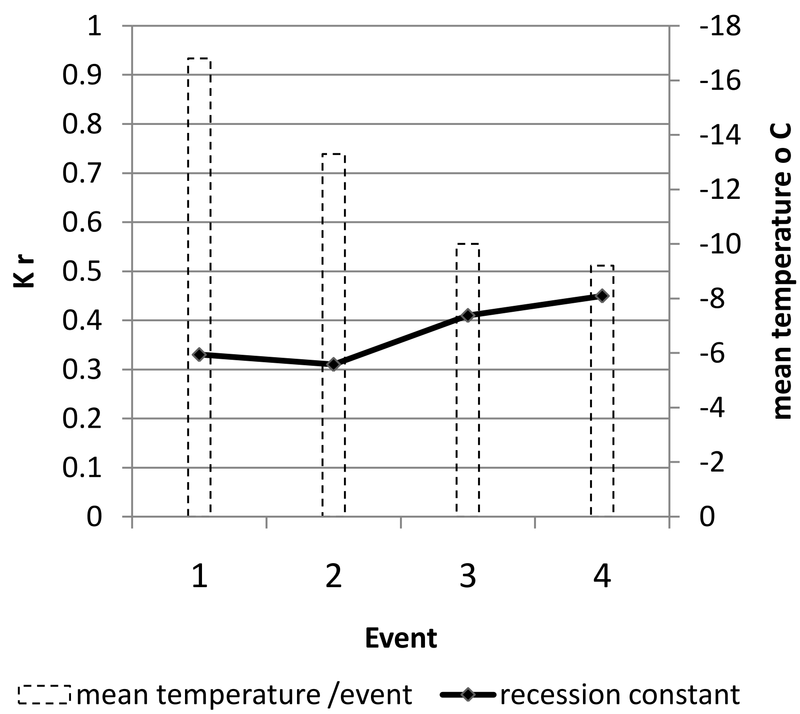

Figure 3.15. Anomalous recession constants for Crystal Creek during unusually cold weather events during January and February winter 2005-2007.

During very cold, dry conditions Crystal Creek had the highest flood peak of the 2005 water year. K_r values from these events were lower than those of any creek at MORA at any time during the study. At the same time, Deer and Laughingwater Creeks had no change in flow during the period. Mean K_r values computed for each site for snowmelt, baseflow, stormflow and anomalous cold conditions (Figure 3.16) reflect this anomalous characteristic. With the highest mean elevation and its small size, Crystal Creek is susceptible to freezing, potentially inhibiting infiltration and blocking groundwater flow. Crystal Creek's distinct basin shape, with 60% of its drainage area composed of a series of cirque valleys, suggests the possibility of the development of an ice dam in the narrow channel outlet below lower Crystal Lake. This outlet drains the entire upper valley in a narrow defile; warmer groundwater stored behind an ice dam could easily produce a dam burst flood event.

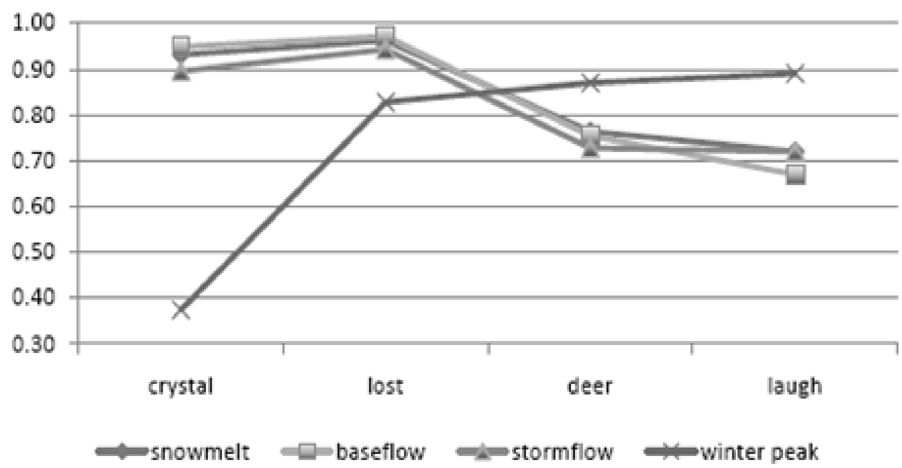

Figure 3.16. Comparison of average recession constants by season with winter peak flow anomaly caused by exceptionally cold, dry weather in Crystal Creek.

Stable Isotope Analysis

Stable Isotope analysis for each basin showed differences in pattern that remained constant during snowmelt, baseflow and stormflow (Figure 3.17). Phase change-caused ^{18}O enrichment during snowmelt, differences in dominant basin elevation controlling parent precipitation and complex intra-basin mixing complicates identification of the isotope signal as measured at the downstream gage sites However, stable isotope values for individual basins maintained a consistent pattern with respect to each other in all seasons. During the snowmelt season, median ^{18}O values correlated with trends in mean basin elevation. However, during baseflow and stormflow, this trend did not remain constant; Crystal, Lost and Shaw Creeks clustered together with less enrichment in^{18}O, while Deer and Laughingwater Creeks were consistently more enriched in ^{18}O than is accounted for by differences in mean elevation. Particularly during baseflow, the depletion in Shaw Creek's ^{18}O percentages is pronounced compared to its comparatively lower elevation.

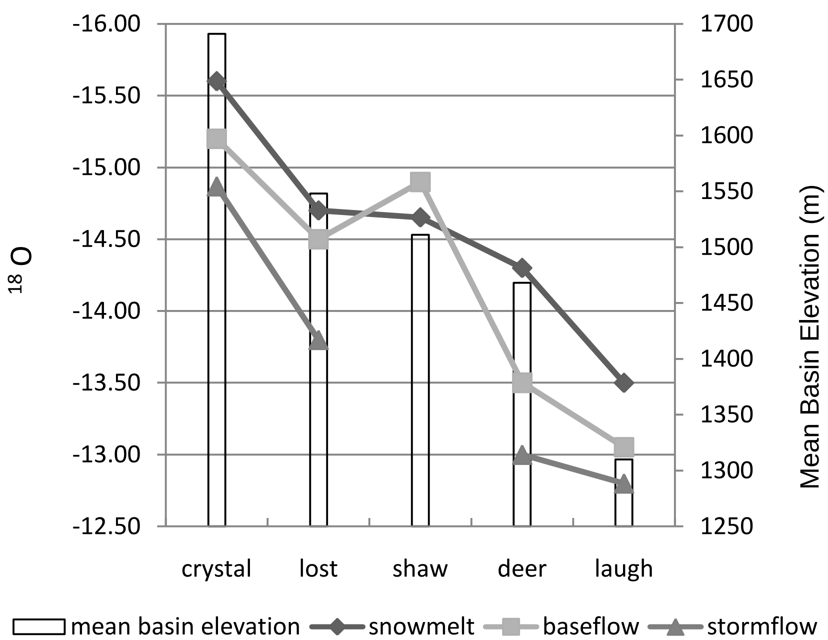

Figure 3.17. Average stable isotope values for Crystal, Lost, Shaw, Deer, and Laughingwater Creeks grouped according to season. The relationship between ^{18}0 and mean basin elevation is generally consistent with the exception of the baseflow average for Shaw Creek. Due to the 2004 debris flow, the sink colluvial channel was freshly buried by colluvium.

A boxplot of median ^{18}O percentages for all basins during snowmelt, baseflow and stormflow shows a rough overall trend reflecting differences in mean elevation (Figure 3.17). However, the inversion of the Shaw and Lost Creek values also suggests that other drivers are at work.

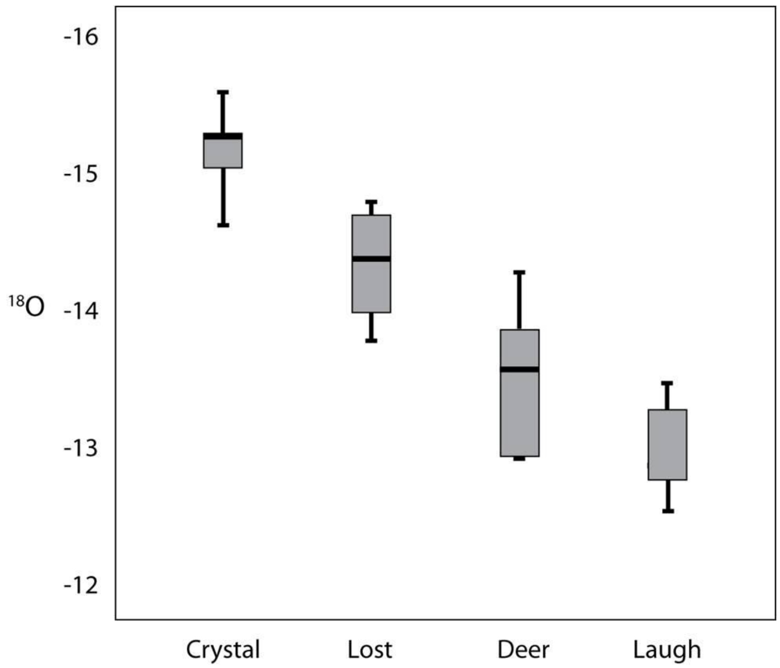

Figure 3.18. ^{18}O percentages from grab samples taken at the gage locations showing median and standard deviation.

Relationships between recession constants and ^{18}O percentages

The recession constants and ^{18}O percentages combined provide an integrated signature for gaged Mt. Rainier study sites that highlights their differences. Hierarchical Cluster Analysis, a statistical test (SPSS) used to organize individuals with two independent characteristics was performed using the paired independent variables K_r and ^{18}O. The dendogram generated by this method yields a blind test suggesting that the paired variables characterizing Deer and Laughingwater Creeks belong to distinct groups compared to those belonging to Crystal and Lost Creeks (Figure 3.19). However, Deer Creek appears as an outlier at the bottom of the second cluster, an artifact resulting from relative similarity between Lost and Deer Creek ^{18}O numbers.

Temperature

There was little difference in temperature forcings between the adjacent snotel stations. Results from 2007 warm season time series measurements also showed variation in values between basins. The results differed from the K_r and ^{18} O signals, both in the nature of the seasonal patterns and the clustering of similarities between basins. During peak snowmelt, all sites measured exhibited very similar range and mean water temperatures (Figure 3.20 a-b). Deer and Crystal Creeks had 3 ^{o} higher temperatures and significantly more pronounced diurnal amplitudes well into the transitional late snowmelt period. The range, mean temperature and diurnal amplitudes for Lost and Shaw Creeks remained steady from snowmelt to baseflow.

Deer and Crystal Creeks baseflow mean water temperatures remained ~ >3 ^{o} higher than Shaw and Lost Creeks. However, the maximum diurnal amplitude fell for Crystal Creek and Deer Creeks. Shaw and Lost Creeks remained low. Pattern changes between seasons were most pronounced for Crystal Creek, especially diurnal amplitude, while Deer Creek showed the greatest range in mean temperature through snowmelt and baseflow.

Comparison of basin temperatures in the summer of 2007 showed differences in both temperature patterns and diurnal cycles that were consistent with variations in process domains as expressed in water source and pathway. Streamflow discharge from snowmelt peaked June 6th and declined until ~ July 6th when gage site hydrographs reached summer baseflow conditions. By June 21st remaining patches of snow were isolated in high elevation areas with northerly aspects. Water temperature measurements during this period displayed dampened temperature and diurnal amplitudes in all basins compared to later in the season, while Deer and Crystal Creeks amplitudes were comparable (Figure 3.20 c). Crystal maintained higher mean temperature values until the onset of baseflow conditions; as low flow progressed, Crystal became cooler than Deer Creek. In contrast, the Deer Creek gage water temperatures in the early season were the lowest recorded.

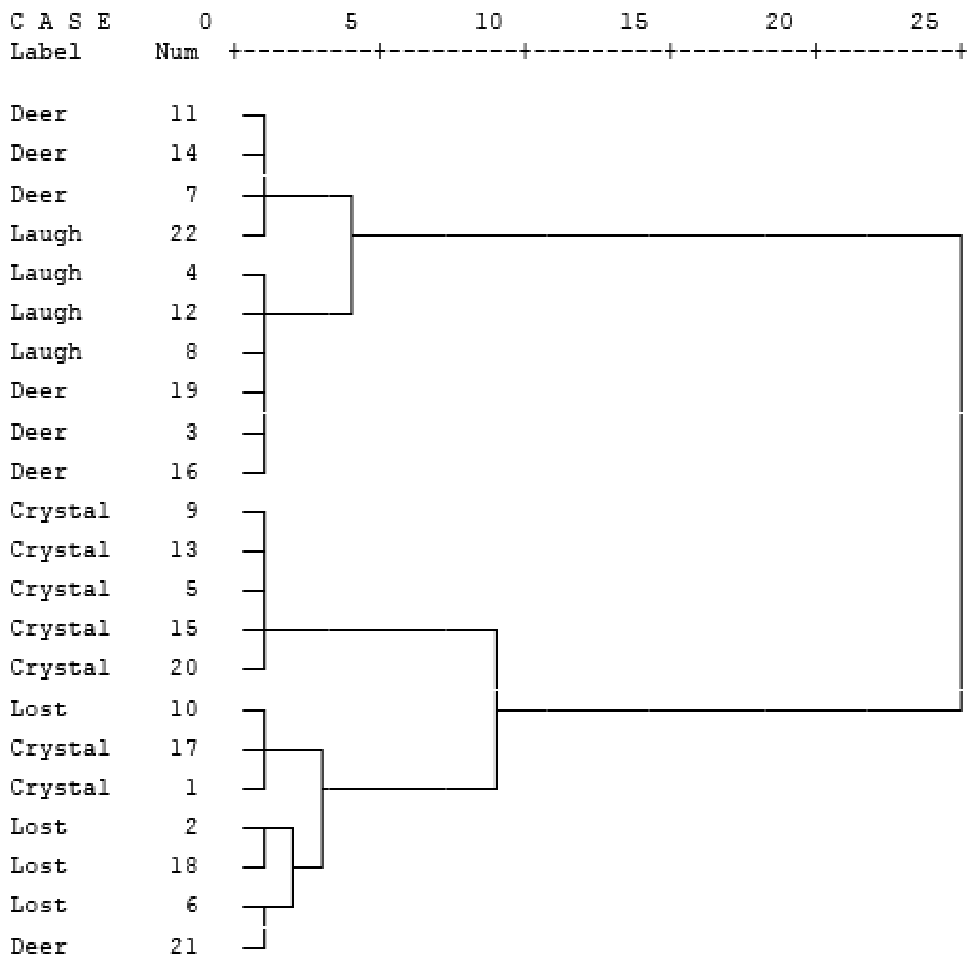

Figure 3.19. Dendogram of rescaled distance cluster analysis using average linkage (between groups) for Deer, Laughingwater, Crystal and Shaw Creeks using paired K_r values and^{18}O percentages.

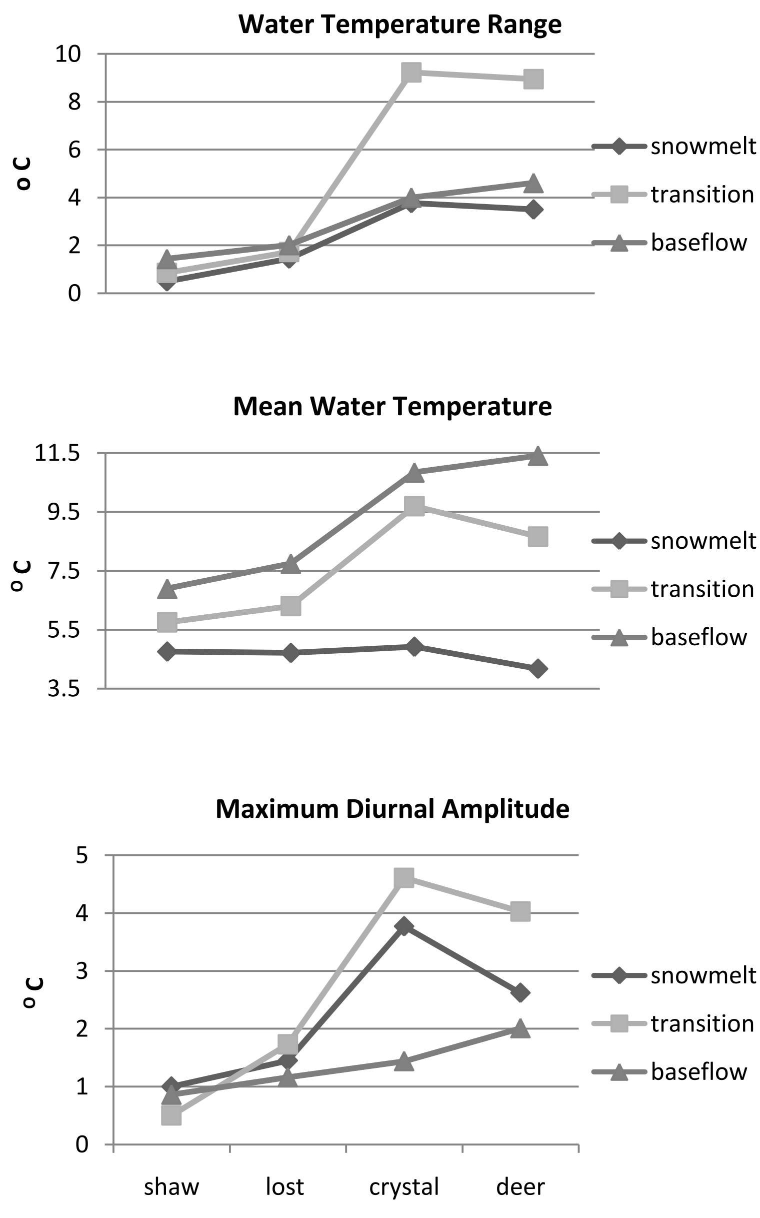

Figure 3.20. Water temperature metrics for Shaw, Lost, Crystal and Deer Creek basins from 2007 comparing snowmelt, transition and baseflow response.

Process Domains and Hydrologic Indices

Recession constants - Streamflow trends integrated into the Crystal, Lost, Deer and Laughingwater recession constants were closely correlated with the percentages of colluvial water pathway length computed from the total basin (Figure 3.21). In contrast, mean basin elevations were not as effective as a means to predict K_r values (Figure 3.22).

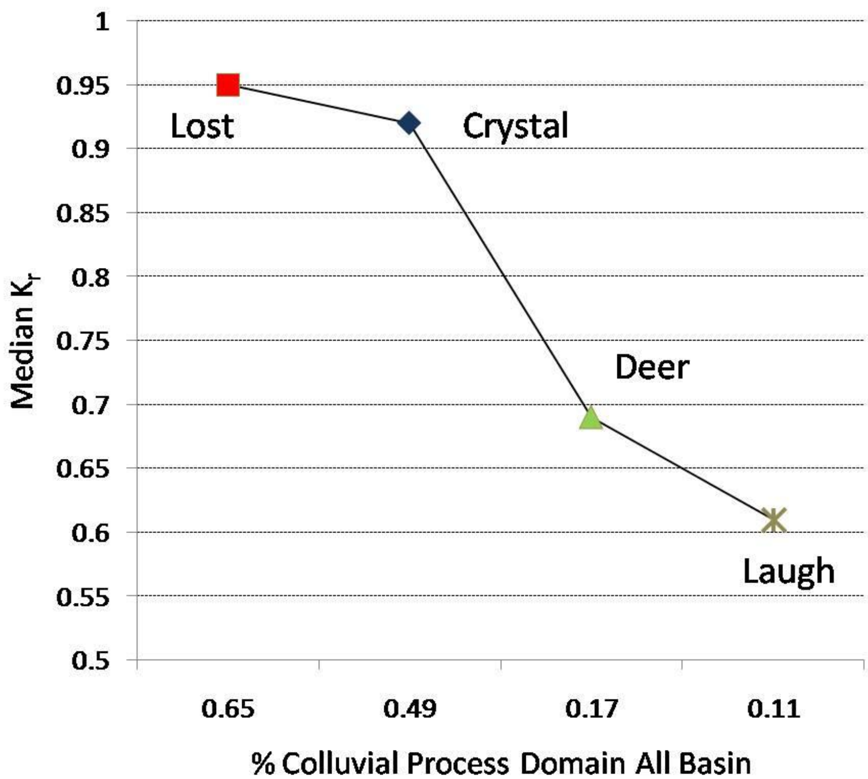

Figure 3.21. Median recession constant values (K_r) compared to a summary of all-basin colluvial process domain percentages.

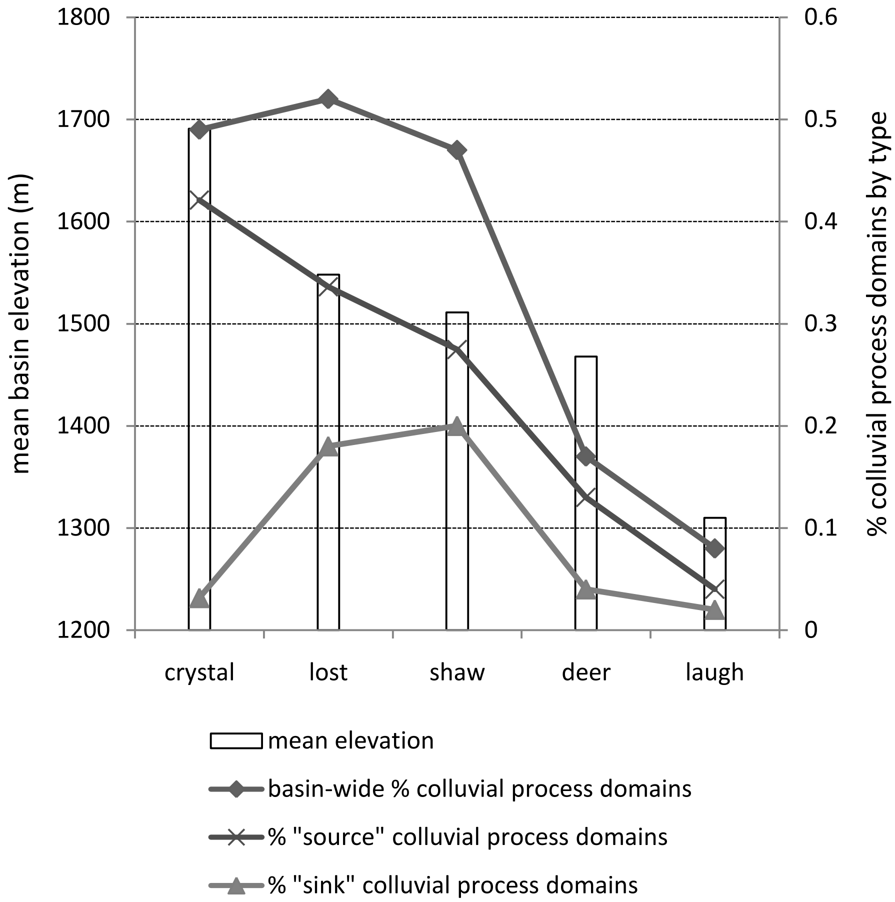

Figure 3.22. Spatial relationships between mean elevation, basin-wide percent of colluvial process domains and “source“ and “sink” colluvial process domains as a percentage of total basin channel length.

A comparison of mean basin elevation, % basin-wide colluvial process domain, upper basin “source” colluvial % and lower basin “sink” colluvial % as a function of basin-wide domains was computed using total water pathway length. Regression analysis showed significant differences in the shape of the resulting patterns for each basin (Figure 3.22). Crystal Creek had the highest percentage of total basin area found in the “source” colluvial zone, and a relatively limited area of “sink” colluvial process domain within the narrow main channel. In contrast, Lost, Shaw and Deer Creeks mean elevations where within 80 m of each other. The relative area of upper valley colluvial source geohydrologic processes were considerably less in Deer Creek integrated volumetrically in the basin (Figure 3.22). Both Lost and Shaw Creeks had high source and sink colluvial values relative to their basins as a whole. As a result, Shaw and Lost Creeks had more subsurface flow throughout the basins, while Crystal Creek is dominated by surface flow in its central bedrock channel.

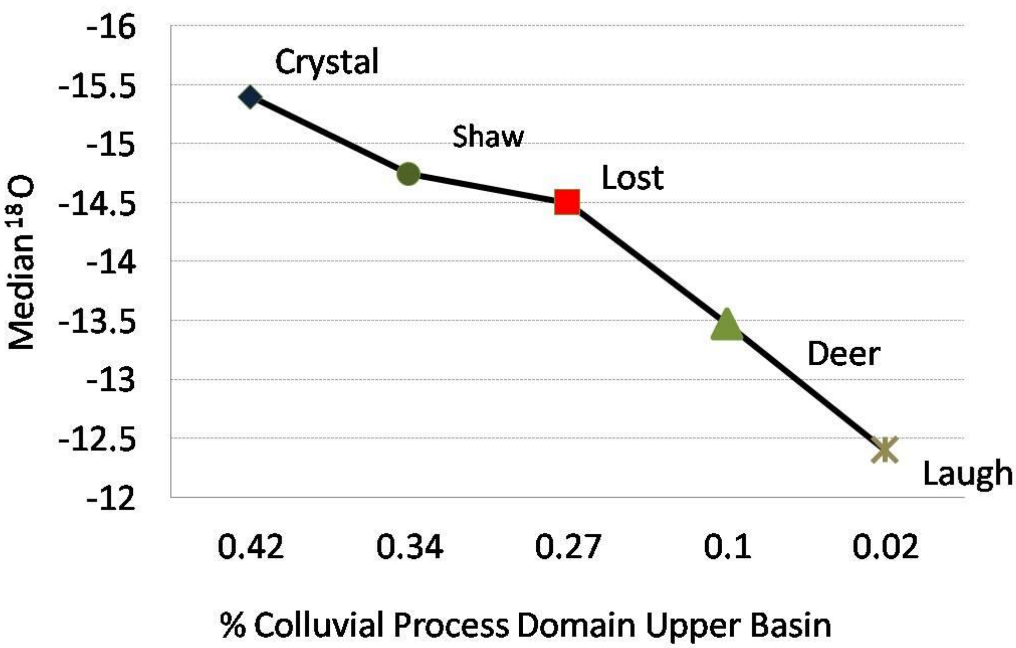

Figure 3.23. Comparison between median ^{18}O values and upper basin percentage of colluvial process domains.

^{18}O – Comparison between median ^{18}O ‰ samples from the lower basin gage sites and the upper basin colluvial (source) process domain percentages showed a strong correlation between ^{18}O patterns and upper valley "source" colluvial process domains in Crystal, Shaw and Lost Creeks (Figure 3.23).

In Shaw Creek, baseflow persists, but runs mostly through subsurface pathways in the lower colluvial valley before re-emerging at the confluence with the White River.

Values are reversed from the typical upward trend in relative ^{18}O enrichment as the summer season progresses. Unlike the other study basins, Shaw Creek ^{18}O values became more depleted as air temperatures increased. In contrast, the Deer Creek and Laughingwater Creek percentages are more in keeping with expected patterns in a fluvial routing system.

This relationship is especially compelling when thought of in combination with basin shape. While ^{18}O values integrate a complex variety of mixed, stored, slowed and routed waters within the basin over time, ultimately ^{18}O values reflect differences in the bulk amount of water from the dominant basin elevation integrated in streamflow. In cases where a larger percentage of stream length is within the higher elevation source water process domains compared to the overall basin, the result is a predictably greater incidence of depleted parent waters routed to lower elevations. The greater amount of higher elevation stream length correlates with basin shape: a larger volume of the gross amount of precipitation is water stored and processed within the upper colluvial process domains, and is relatively undiluted by lower elevation waters. Given Crystal Creek basin's higher relative mean elevation greater upper basin area, and efficient downstream routing system, it follows that the creek would consistently present the highest ^{18}O percentages among the 5 basins. Like Crystal Creek, a significant percentage of Shaw Creek's flowpaths and water source areas are found in the large upper valley area. "Source" colluvial waters continue to flow steadily during the dry season, while the alluvial and bedrock channel flow volumes decrease significantly. However, unlike Crystal Creek, the lag associated with Shaw Creek's large percentage of "sink" colluvial valley process domains is evident in the delivery of flow depleted in ^{18}O later in the season. Crystal Creek's values are also consistent with expected changes in the temporal patterns of seasonal ^{18}O percentages; median values became lower as the seasons progressed, as did those of Lost, Deer and Laughingwater Creeks.

Temperature – Water temperature measurements integrate more localized differences in surface and subsurface water flowpaths in the lower valleys. Lost and Shaw Creeks registered mean temperatures 2.5 ^{0}C below those of Deer and Crystal

Creek during all recorded seasons (Figure 3.24). During baseflow, this difference was >3 ^{0} C. Comparison between the percentages of more localized lower sink colluvial process domain area with mean temperature yields a inverse relationship in contrast to the positive relationships found between the median K_r (Figure 3.21) and median ^{18}O percentages (Figure 3.23).

While Shaw and Lost Creek water temperatures are the products of the dominance of subsurface flow in the sink colluvial valleys, comparison with Tamanos Creek showed values 3.3 ^{0}C lower than Shaw and Lost Creek, and no diurnal cycles during the snowmelt season. When examined in conjunction with the ^{18}O ‰ coming from the Tamanos spring, compared to the more depleted ^{18}O ‰ recorded ≤ 1000 m below, the important distinction between subsurface runoff and subsurface colluvial “sink” flows with potential storage become apparent. Some cirque wall talus slopes, like those feeding Tamanos Creek, appear to be subsurface runoff delivery systems that reflect snowmelt temperatures. Flows are delayed compared to surface runoff, but not to the degree found in others. For example, the northernmost Crystal cirque basin is bisected by small glacial trough-type forms (often buried by talus) that potentially store water as well as provide subsurface flow.

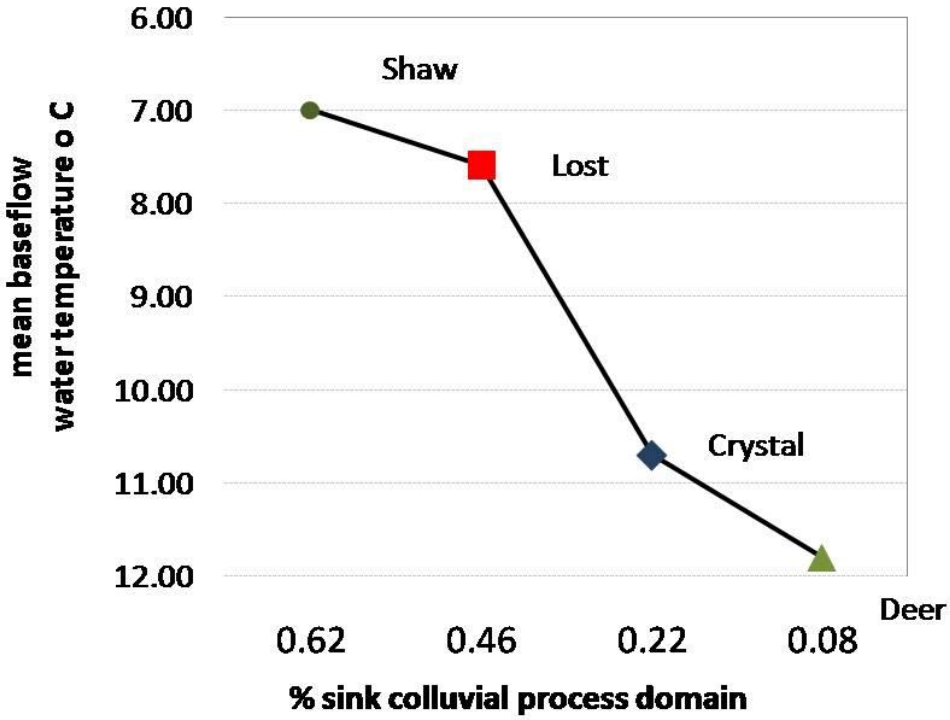

Figure 3.24. Relationship between mean baseflow temperature and % sink process domains within the total basin.

Streams flowing through “sink” colluvial valleys characteristically demonstrate a moderated stream temperature range, damped diurnal amplitudes and significantly lower baseflow temperatures. Temperature values are an important aid in identifying colluvial and alluvial versus bedrock flowpaths. They are more localized in their effectiveness as an integrated measurement.

DISCUSSION

Independent integrative measurements including recession constants, ^{18}O analysis and temperature values showed consistent patterns that differed between the study basins, regardless of season. The three measurements provided information on singular aspects of the study catchments that in combination support the identification of basin-wide hydrologic regimes controlled by valley-scale geomorphic structure. Seasonal differences and sustained patterns in recession constant values, stable isotope and temperature measurements between basins were congruent with the differences in the bulk percentage of specific process domains. Analysis of the character of these process domains and their catchment location matched disparities in hydrologic response. The intermediate-scale process domain framework appears to correlate well with the hydrologic patterns from all precipitation-driven flow events including snowmelt, baseflow and stormflow. Basin information derived from the recession constants was enhanced and validated by the ^{18}O and temperature measurements.

Thus, the results of this study show that process domains at the valley scale provide a systematic way to characterize both the spatial distribution of geomorphic controls within the stream hierarchy and to integrate hydrologic response. By incorporating the dual nature of geohydrological response, process domains are a parsimonious way to categorize the intermediate scale drivers of streamflow and hence, aquatic stream habitats. The larger-scale regional context, including topography, bedrock hardness, and climate, may drive bulk streamflow response in more homogenous basins, and are important drivers of basin response in glaciated basins. However, complex terrains produced by relict glacial macroforms, episodic disturbance and sustained fluvial geomorphic processes require a valley-scale context to explain streamflow response within the continuum of colluvial to bedrock processes.

Streamflow regimes evolve and change over time. Basin evolution during the Holocene appears to have varied significantly between catchments in spite of the relict glacial signature and current regional-scale commonalities. However, within the short period of record of this study, the constancy in the recession data suggest that the aggregate impact of surficial channels and subsurface pathways found in each basin result in a distinctive signature of basin response. Depending on a host of other factors including network position and basin shape these elements produce positive feedback mechanisms that enhance basin characteristics over time.

For example, basins such as Deer and Laughingwater Creek lack a significant percentage of colluvial area. The hydrologic regime produced by the basin reflects bedrock and alluvial channel flow. In contrast, Crystal, Lost and Shaw Creek basins have an excess of colluvial sediment in large accumulation zones especially in the upper basin talus slopes and rock glacier deposits. Even during high rainfall events, the storage capacity of these domains, their subsurface channels and diffusive water flowpaths limit the ability of flood events to move sediment along the longitudinal profile. Downstream, colluvial valleys, even those below high gradient valley steps with bedrock and cascade type channels, receive smaller surface flow volumes most noticeably during peak precipitation and snowmelt events.

The differences in process drivers in glaciated and unglaciated headwater mountain basins produce very different aquatic habitats in spite of the similarities in fluvial channel flow dynamics and sediment characteristics. In glaciated basins, the longitudinal profiles of channels, including those periodically scoured by debris flows, are largely controlled by the inherited glacial topography. In contrast, the upper portions of unglaciated headwater channels generally have the steepest slopes in mountain stream networks (Hack and Goodlet, 1960; Montgomery and Buffington, 1996; Benda et al., 2005). The stepped profiles of glaciated systems often mean that log-log drainage slope area relationships can be repeatedly “reset” at valley steps, especially in upper relict glacial valleys, resulting in multiple inflection points (Figure 8, Lost Creek). Combined with the frequent mixing of flows from a range of hydrologic source areas, the “kinks” in the log-log drainage slope area metrics confound simple drainage to discharge relationships.

In steep unglaciated basins the interplay between episodic scouring by debris flows and sediment retention due to increased accumulation of roughness elements can create episodic variability of sediment transport and storage in space over time (Benda et al., 2005). In contrast, at MORA, while debris flow oscillations that periodically scour to bedrock, valley and valley steps also store accumulations of mass movement-produced materials in debris aprons, cones and other depositional landforms that are drained by subsurface flowpaths. As such, source and sink colluvial areas in this study appear to be a comparatively enduring morphology, different from common colluvial dynamics in unglaciated headwaters. Rock fall and landslides from steep cirque headwalls and glacial valley walls can fill glacial troughs and valley areas with porous colluvium. Sink colluvial valleys are also accumulation zones, where an excess of sediment storage can increase over time. Buried subsurface or underfit surface channels lack the stream power necessary to transport coarse material resulting in an increasingly transport limited landscape. Materials deposited in the debris cone or apron of sink colluvial valleys produce comparatively stable accumulation zones in time frames from decades to centuries.

Colluvial channel flow regimes may resemble some aspects of those found in hyporheic alluvial channels including cooler stream temperatures, increased sediment contact time and subsurface flowpaths with decreased velocities. However, they appear to differ in important ways. Colluvial headwater streams have normally lower discharge volumes and lack sediment transport capacity. Large alluvial valleys are often decoupled from the surrounding hillslopes while colluvial channels are usually not buffered from hillslope processes produced from the glacial valley wall. The horizontal floodplain dynamics found in alluvial valleys are in marked contrast to the vertically layered colluvium-filled valleys typical of sink colluvial channels.

In ecological terms, channel, lake or spring position within a network of process domains is especially important for the life history strategies and persistence of aquatic biota. Habitats that are positioned within the basin network so that upstream or downstream disturbance processes are buffered by physical features such as bedrock controls, gentle slopes and subsurface flows are more likely to persist and foster stable aquatic communities. Colluvial valleys in particular may have hydrologic regimes that have developed over long time frames; interstitial and subsurface faunas may be well adapted to these persistent colluvial habitats.

The same dynamic morphological and process longevity may be characteristic of the bedrock canyons incised in glacial valleys (Deer Creek). While headward erosion and knickpoint retreat are controlling processes on over long timeframes, the drop pool waterfall and cascade channel types in crystalline bedrock are durable channel types. With the exception of extremely limited areas in Deer and Laughingwater Creeks, bedload transport capacity within these basins is high, and large boulders appear able to move by fluvial action, without the agency of debris flows and other mass movements (for example, field inspection of the Deer Creek gage sites after the November 6-7, 2006 flood showed fluvial transport of large boulders). Peak discharge was an order of magnitude higher than Lost Creek for the same storm. For this reason, the persistence of the bedrock channel form may not translate into persistent aquatic habitats capable of supporting a diverse a community of aquatic species.

Composite USGS 7.5 minute 10-meter-grid elevation models (DEMS), flow direction and flow accumulation grids, and hillslope gradient distributions were used to identify the breaks in slope of process domains along the longitudinal profile and potentially locate additional flowpaths in the upper basin. However, channel dimensions in the field sites, even in the lower valleys, were well below the 10m resolution threshold of the DEMs. Important features were also below this threshold; the coarse resolution meant that narrow and deep bedrock canyons and other structural elements were averaged out. Water source channels were also not apparent using automated methods; channel blue lines often began at an upper lake. The DEM's in conjunction with stereoscopically enhanced aerial photographs, were effective tools in indicating potential glacial valley-scale process domain boundaries. However, the detail required for confident delineation of process domain boundaries and the identification of geohydrologic controls necessitated field observations and measurements. Use of stereoscopically enhanced aerial photographs with a topographical overlay proved to be a better method for aiding in the analysis of macroforms. Lidar may be useful to increase ArcGIS capabilities, but field insight may be a necessity. Ultimately, hydrological measurements, field observation and automated technologies were all necessary to distinguish the geomorphic structures and basin streamflow regimes.

CONCLUSIONS

The interconnections between geomorphic controls and hydrologic response in complex glaciated headwater basins are difficult to test without an intermediate-scale spatial framework. This study found that independent integrative measurements including recession constants, ^{18}O analysis and temperature values correlated with geomorphic parameters synthesized into valley scale process domains. Process domains varied significantly between basins; while the overriding structure of glacial macroforms produced a common valley-scale signature between catchments, differences caused by variation in geohydrological (colluvial, alluvial and bedrock) response to geomorphic disturbance over long timeframes are profound. Because the presence or absence of major colluvial features at the valley-scale appear to limit velocity and control water routing and response both in the stream and within connected hillslopes, colluvial percentages proved to be a good indicator for identifying hydrologic relationships. The spatial extent of colluvial valley area and channel length in the basins correlated with slow response hydrological characteristics. While alluvial channel types with large well-developed riverine floodplains also produce subsurface (hyporheic and groundwater) flows, this channel type was not present in the study. Both Deer and Laughingwater Creeks are dominated by fluvial response producing narrow vertical canyons within the glacial valleys.

Recession constants plotted against colluvial process domains show a straightforward relationship between colluvial structures and hydrological regime. Each basin demonstrated a consistent pattern in the range of recessions in response to precipitation and snowmelt events, regardless of season. Descriptive statistical analysis of the combined snowmelt, baseflow and stormflow Kr values show noteworthy differences; Crystal and Lost Creek had means of > 0.9 for all distinct recession curve declines in the 2004-2007 period of record, while Deer and Laughingwater Creek's mean was 0.75.

Stable isotope values for individual basins also maintained a consistent pattern with respect to each other in all seasons. Patterns in isotope values demonstrated both the dominant source elevations of basin waters, and ancillary information on the nature of the pathways within the basin also demonstrated by basin shape. Results from the 2007 warm season time series were also variable between basins in spite of little difference in temperature forcings between the adjacent snotel stations. During peak snowmelt, all sites measured exhibited very similar range and mean water temperatures. Differences in the spatial extent of "sink" colluvial process domains in the lower portion of the basins provided a useful mechanism to explain this difference; warm season temperatures showed a significant inverse correlation with percentages of "sink" colluvial process domains.

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Chapter 4

Monitoring Relict Glaciated Mountain Headwaters

INTRODUCTION

Understanding geohydrologic characteristics and associated scaling relationships in glaciated mountain headwaters is fundamental to designing aquatic monitoring protocols that hope to measure change in ecological condition. Because biological patterns in streams are largely adjusted to and controlled by habitat patterns (Frissell, 1986; Lake, 2000), the need to understand physical controls is especially important in complex alpine systems which often exhibit a naturally wide range of geohydrological variability. There are currently no monitoring protocols that incorporate important intermediate-scale physical habitat controls found in glaciated mountain headwater basins. Fortunately, research providing better understanding of these controls in conjunction with recent ecological conceptual models suggests ways to improve headwater monitoring designs.

In this chapter I will present a method to address these issues, based on the following elements: 1) identify habitat assumptions found in extant monitoring protocols, particularly the EPA Environmental Monitoring and Assessment Program (EMAP) influenced by ideas from the River Continuum Concept (RCC), 2) compare these assumptions with abiotic habitat controls, especially those at less commonly studied intermediate spatial scales, found in relict glaciated mountain headwaters and 3) introduce a more inclusive conceptual framework that incorporates these unique habitat characteristics. Based upon this analysis, I will explore the use of process domains, developed from the Process Domain Concept (PDC), to select appropriate variables for sampling designs suitable for aquatic monitoring in these systems (Montgomery, 1999). I then hope to present a prototype for monitoring mountain aquatic habitat based on a unifying concept of spatial structure and process controls.

Finally, these recommendations are applied to the North Coast and Cascade Network (NCCN) “Vital Signs” Monitoring Program.

Monitoring programs like the NCCN initiative have the fundamental purpose of detecting change in resource condition to anticipate future management needs. Because the remote alpine landscapes found in the NCCN are protected within National Parks and other jurisdictions, they are often in a comparatively pristine state and lack the many common anthropogenic disturbances found in lowland aquatic ecosystems. Thus, these mountain terrains offer large land areas that can provide excellent reference sites useful for detecting the effects of climate change. Given the widespread interest in the potential effects of climate change on ecosystems, these glaciated mountain landscapes present a good opportunity to measure changes produced by climate forcings independent of other anthropogenic stressors.

The hierarchical stream framework

A hierarchical stream framework provides a useful tool to guide classification of the innate physical organization particular to glaciated mountain basins (Frissell et al., 1986). The considerable natural variability found in these systems necessitates an integrative, systematic approach that will simply and meaningfully order stream heterogeneity. The hierarchical stream framework also provides a method to interpret such systems in a broader context. Smaller-scale habitats develop within the constraints of the larger systems of which they are a part (Frissell, 1986). For example, at smaller scales colluvial channels in a mountain basin may be the immediate result of local slope and the addition of contributing sediments and water from the surrounding valley walls or upstream mass movements. However, these segments are in turn controlled by larger-scale variables such as climate and basin lithology, structure and topography, and paleohydrologic history (Frissell, 1986; Montgomery and Buffington, 1996; Montgomery, 1999). In particular, long-term climate variables, expressed on the land surface by relict cordilleran ice sheet and alpine glacial footprints from the Pleistocene and Holocene are important for understanding mountain geohydrological processes.

A hierarchical classification system is based on identifiable variables that are produced by the geomorphic processes and forms found in the stream system. Each system level (e.g. valley, valley-segment, reach, pool/riffle and microhabitat system) is associated with geologic and geomorphic disturbance processes and events at decreasing spatio- temporal scales (Frissell, 1986, Montgomery, 1999). It is no accident that hierarchical classification systems, in contrast to conceptual models that stress longitudinal continuity (i.e. RCC), were developed in and are particularly suited to mountain basins in the Pacific Northwest.

It is axiomatic that different ecological patterns emerge at different scales (Torgersen, 2002). While reach and regional-scale parameters are commonly used in lowland monitoring efforts, the identification of valley and valley segment-scale physical controls are important for monitoring initiatives in mountain basins for a variety of reasons. In glaciated mountain basins, the reach-scale, while physically meaningful in lowland alluvial channels, may not be a physically discrete spatial unit in the headwater stream hierarchy. Focus on the reach-scale structures and processes ignore important valley-scale context, creating great difficulty in the identification of controlling parameters (Frissell, 1986). Controlling valley-scale variables may limit the necessity for multiple variables at lower levels (Frissell, 1986, Baxter and Hauer. 2000) and constrain the population of reach-scale or habitat-scale sampling units suitable for direct comparison.

Interdependence of geohydrologic spatial controls and ecological patterns

Indicator species, such as benthic macroinvertebrates, are commonly used to assess status and trends within mountain headwaters. However, the many types of geomorphic structures, disturbance processes and hydrologic regimes at multiple spatial and temporal scales found in alpine environments require skillful categorization of physical habitat types. The spatial location within the larger system, depending on scale, also has ecological ramifications. Spatial position within the complex interconnected network of subsurface and surface channels, lakes, springs and other waters may drive ecosystem response (Robinson and Matthaei, 2007).

The local hydrologic expression of synoptic climate forcings (changes in precipitation or snowmelt) in glaciated mountain landscapes is mediated by the complex topographic and geologic/geomorphic characteristics of the landscape (Figure 4.1). Aquatic communities in these environments are dependent on the local manifestations of both sustained conditions and episodic disturbances in streamflow and water temperature regimes, and substrate materials characteristic of headwater hydrologic response mechanisms. Consequently, the linked geomorphic and hydrologic conditions have a high degree of natural variability that often shifts from sustained conditions to episodic disturbances. Geomorphic and hydrologic response is also bi-directional; for example, hydrologic dynamics such as flooding produce changes in floodplain patterns. Geomorphic disturbances (e.g., debris flows and other mass movements) can alter streamflow regimes.

Mountain physical habitats integrate a broad spectrum of potential conditions; differentiating the normal range of variability in these systems is not a trivial endeavor. This problem is exacerbated by the general lack of long-term physical or biotic data in glaciated mountain environments to describe natural variation.

Beyond mountain geohydrologic response, climate-related scale issues contribute added monitoring complexity. Climate change generated disturbances are of unknown duration, frequency and magnitude and may continue to develop over long time scales (decades to centuries).

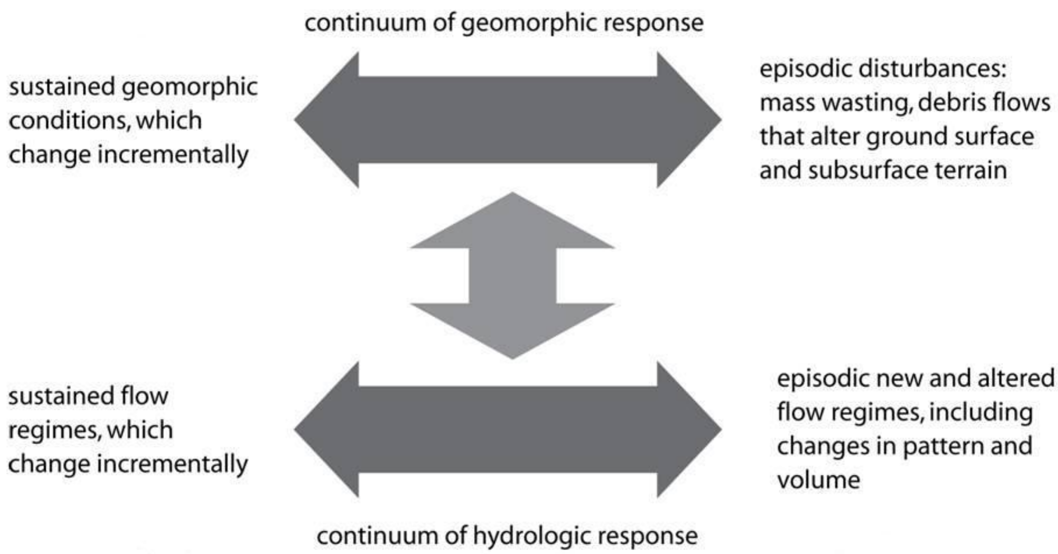

Figure 4.1. Schematic diagram of the potential temporal and spatial variability found in complex glaciated headwater basins. Dark grey horizontal bi-directional arrows indicate the range of geomorphic and hydrologic response possible in mountain systems. The vertical arrow indicates the multi-directionality of feedbacks between geomorphic processes and hydrologic processes.

Moreover, the potential for threshold-like “tipping points” that might create an abrupt change in physical habitat state is also unknown. Thus, parameters must be sensitive and specific enough to enable scientists to differentiate between physical habitat effects that are a product of normal system variability and large-scale patterns of climate change.

The National Park Service (NPS) Vital Signs Monitoring Program

The National Park Service (NPS) Vital Signs Monitoring Program in the North Coast and Cascades Network (NCCN) provides an excellent case study to illustrate a proposed physical habitat monitoring prototype. Several NCCN parks encompass significant landscapes within the Cascade and Olympic mountains in Washington State, comprising nearly 7600 km^2. A primary objective of the NCCN aquatic monitoring program is the identification of interannual trends in physical, chemical and biological parameters caused by anthropogenic climate change that characterize specific "vital signs" in park ecosystems. To achieve this objective it is first necessary to establish a benchmark condition and a scale-appropriate method to stratify and differentiate discrete populations of comparable physical habitat types.

MONITORING OF AQUATIC SYSTEMS

Monitoring is often defined as a systematic method to identify "the "normal" range of variation in resources of interest, establishing a temporal baseline from which trends in processes or functions may be detected. Many ecologically-based monitoring initiatives are also based on the concept of biological integrity, which is sometimes expanded to encompass "*ecosystem integrity*" (Jenkins et al., 2002). Both terms describe the capability of a system to support and maintain a functional ecological community composed of species whose diversity and organization are similar to natural habitats found in the region. Ecosystem structures and functions, particularly the suite of physical, chemical and biological components of the ecosystem collectively are thought to describe the "integrity" of the ecosystem. Indicators of ecosystem integrity are meant to provide early warning detection of stressors that might be detrimental to the sustainability and resilience of ecosystems (Jenkins et al., 2002).

Monitoring for "ecosystem integrity" is the conceptual basis of aquatic monitoring protocols developed for the Environmental Protection Agency (EPA). These protocols were originally a response to the Clean Water Act meant to restore and maintain the chemical, physical, and biological integrity of the nation's waters. The amended Clean Water Act (CWA) established a basic structure for regulating discharges of pollutants into the waters of the United States. The CWA evolved to include watershed-based strategies; however, the Act only covers surface waters.

One of the outcomes of the CWA was the development of aquatic ecological indicators and monitoring protocols designed to reveal the effects of human-caused cumulative impacts on aquatic habitat which would then affect the organisms living in these conditions (Karr, 1981; Karr and Chu, 1999). Karr's (1981) original Index of Biological Integrity (IBI) established a template for aquatic ecological indicators; it was specifically developed to assess fish communities and benthic macroinvertebrates in third-order Midwestern streams (Ranking and Yoder, 1995). To assess communities in other areas, the IBI must be calibrated and/or modified to "fit" the region (Karr and Chu, 1999).

IBIs are meant to measure the ability of a stream to support and maintain a balanced, integrated adaptive community of organisms which have a species composition, diversity and functional organization comparable to that found in natural habitat(s) of the region. To develop IBIs, selected reference sites at minimally impacted sites in ecoregions (Bailey, 1996) are chosen to represent natural habitats.

Table 4.1. A conceptual model shows the effects of hydrologic conditions on physical habitat. Disturbance regimes or processes are defined by the spatial extent, pattern, intensity, temporal duration and frequency of episodic events and the potential extremes of the "normal range" of variation caused by natural disturbance processes. Areas of dark shading constitute geohydrologic response that permanently alters habitat structure and linked water sources and flowpaths.

	Peak flows that alter process domains	**"Normal range" of variation**			**Drought conditions that alter process domains**
Change in magnitude/ intensity of disturbance process	Magnitude of discharge peak exceeds system resilience ⇩	Discharge of flow events ←	Mean baseflow discharge	Lowest volume event below baseflow →	Severity of drought conditions exceeds system resilience ⇩
Change in frequency of disturbance process	Number of flood events exceed system resilience	Number of flow events > baseflow ←	Number of days of mean baseflow discharge	Number of flow events < baseflow →	Number of low flow events exceed system resilience
Change in duration of disturbance process	Sustained flood flows - system characteristics are altered	Length of occurrence of flow events > baseflow ←		Length of occurrence of flow events < baseflow →	Sustained drought conditions - system characteristics are altered

Sites are evaluated based on how they compare to the reference conditions using an extensive sampling design developed to measure ecosystem integrity versus impairment over the landscapes of the United States. These extensive sampling designs used broadly defined physical features such as reach-scale channels. These constitute a population across a regional landscape that could be easily mapped and thereby sampled.

Specific programs

There are many pre-existing monitoring protocols used in the Pacific Northwest (PNW), which are based on the IBI concept. These protocols were not developed to compare pristine mountain headwaters. Commonly used protocols often track the impacts of land use change on aquatic species or a particular fauna of interest; some were meant to produce statistically robust comparisons between a reference condition, ideally a pristine landscape, and an impacted resource (Karr and Chu, 1999; EPA, 2006) and were not developed to answer questions about stressors at the scale of climate change.

Virtually all of these stream monitoring protocols assume that channels are predominately surface flow systems. Assessments are based on the assumption that "within a given physiographic-climatic region, stream drainage area and overall stream gradient are likely to be strong natural determinants of many aspects of stream habitat, because of their influence on discharge, flood stage, and stream power (the product of discharge times gradient)" (Kaufmann et al., 1999). Implicit in this description is an assumed correspondence between streamflow discharge and drainage area that changes in a continuous and predictable pattern in the downstream direction.

Dependence on Assumptions from the River Continuum Concept as a sampling design basis

Ideas from the River Continuum Concept (RCC) underlie the IBI and the EMAP monitoring assessment programs. The River Continuum Concept promoted the idea that rivers, from their headwaters to their mouth, present a continuous (and linear) gradient of physical conditions. The focus on a longitudinal continuum was important, as it provided a framework for thinking about the entire channel as an ecologically functional and interconnected system based upon the physical geomorphic template of the stream system. Biologic communities and their associated processes were linked with particular portions of the channel. Thus one could expect to observe recognizable patterns in the community structure based upon where species were found in the river (Vannote, et al., 1980).

The RCC follows from the idea that physical stream networks are open systems in dynamic "quasi" equilibrium (Vannote, et al., 1980; Leopold and Maddock, 1953). Accordingly, the stream and its channel tend towards a mean form that can be defined in terms of statistical means and extremes (Chorley, 1962). Vannote postulated that the structural and functional characteristics of stream communities are selected to conform to a most probable physical condition or *mean state* operating in the context of evolutionary and population time scales (Vannote et al., 1980).

The concept was a powerful basis for extensive monitoring designs (e.g. replacing space for time) because it assumed that the biological subsystems in natural systems were in equilibrium with the physical channel at each point in the continuum. Therefore, biological change in physical setting in a state of "quasi' equilibrium might be viewed in a time independent fashion because the system will return (cyclically) to a mean condition. Community structure in natural river systems would only *g*ain and lose species in response to the perceived low probability of cataclysmic disturbance or in response to anthropogenic disturbance (Vannote et al, 1980). However, these assumptions, including the ubiquity of physical dynamic equilibrium, the rarity of non-anthropogenic cataclysmic disturbance and the inferred narrow range of variability in channel characteristics, should be carefully considered when applied to monitoring protocols for headwater mountain streams.

Dynamic equilibrium - Defined as a physical state where the rates of force and resistance are equal, dynamic equilibrium is used to describe systems where there is no net change over the time period of interest. In geomorphology, the concept is often applied to the evolution of landscapes in a state of steady-state equilibrium over geologic time frames (Hack, 1975). This model is especially applicable to slowly eroding landscapes that have not experienced major climatic shifts (e.g., Pleistocene glaciation) and are therefore isolated from significant base level changes. For example, in the Puget Sound Lowlands, Pleistocene and Holocene glaciation may produce conditions such as an altered base level that may drive directional channel evolution and disequilibrium in some watersheds over decades to centuries (Collins et al, 2003).

Lowland alluvial stream channels in undisturbed humid temperate watersheds, especially in the Northeast and Midwest United States, may display the characteristics of systems in dynamic equilibrium. In contrast, large naturally-occurring habitat disturbances of variable frequencies and magnitudes are common in mountain terrains; these disturbance processes may produce geomorphic and hydrologic responses that do not reflect a mean average condition. The footprint of relict glacial landforms found in high mountain systems may in some cases supersede the influence of current processes, producing a condition of on-going adjustment until the next glacial epoch (Brardinoni and Hassan, 2006).

Natural vs. anthropogenic disturbance recovery - Ecologists have hypothesized that channels recover more quickly from natural disturbances than from human impacts. However, this hypothesis has not been tested in situations where it is difficult to determine the difference between human disturbance (e.g. climate change) and natural disturbance (e.g., episodic debris flows) on the landscape. It may be possible in a highly variable pristine system to distinguish between sampling units in a sustained habitat condition and those that are recovering from disturbance.

However, the difficulty with the IBI continuum model is that in practice it contrasts two endmember conditions (Figure 4.2). Often used as a basis for environmental management and monitoring, the continuum is illustrated as a multitude of states between undisturbed healthy stream systems and those that are severely degraded by human disturbance (as shown on the top panel). The model implies that the integrity of aquatic ecosystems is not damaged by natural disturbance processes and that severely disturbed habitats are not sustainable (Karr and Chu, 1999). However, when used for water quality management purposes, the IBI uses a threshold value to stratify channels into two contrasting categories, stable-pristine versus unstable-disturbed (see bottom panel). Water quality is deemed either in good or impaired condition based on a statistical score.

Identification of abnormal condition requires a sense of the difference in the normal patterns of abiotic disturbance, and baseline information on particular physical processes and drivers. Physical habitat benchmarks in monitoring are meant to separate “normal” types of disturbance (e.g., cyclical flood events and droughts) from unprecedented conditions (e.g., extreme severity and frequency of precipitation events or drought conditions) that produce a shift in geomorphic and hydrologic state. Examples include alterations in streamflow volume, timing and water temperature regimes that modify aquatic habitat types or categories (e.g., colluvial to bedrock channel).

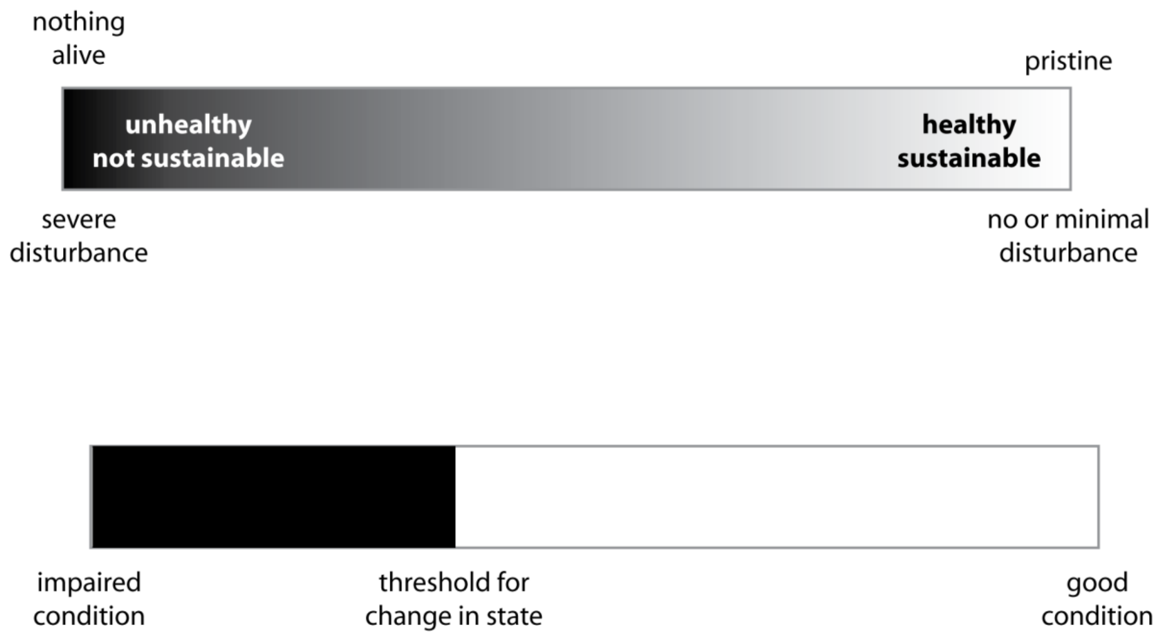

Figure 4.2. Karr and Chu's (1999) conceptual model of the continuum between conditions of severe disturbance and pristine undisturbed habitats. The top panel shows the concept as a continuum (Karr and Chu, 1999). However, the bottom panel illustrates how the IBI is applied in practice.

Natural disturbance in ecological systems is often thought of as cyclical while anthropogenic disturbance is directional. However, physical disturbance processes in mountain headwaters can be either cyclical or directional depending on the scale of the observational frame and the nature of channel adjustment to relict landforms. For instance, the effects of sedimentation in a small stream may persist indefinitely after a landslide or debris flow caused by oversteepened glacial valley walls if fluvial transport processes are not sufficient to rework depositional material.

Normal range of variation can be described – Many monitoring designs assume that comparison of variability between randomly selected channel reaches is known, understood and easily quantifiable, and that the detected difference can be unambiguously related to a known causal agent. It is also assumed that the state of ecological understanding of causal mechanisms driving physical habitat metrics is such that the choice of a statistically robust population and representative sample is based on extensive knowledge of the physical controls of the system. This knowledge is meant to ensure valid comparison of similar morphologies and processes in space and time. However, the general lack of process-based context in environmental monitoring and management has produced many sampling protocols that define environmental variability as a statistical problem. As a result, such approaches may ignore critical spatial and temporal mechanisms that produce change in physical habitat that is directional, not cyclical.

The Channel Reach as a Basic Sampling Unit

The reach-scale stream sampling unit has endured as a useful scale to monitor and compare aquatic wadeable stream habitats and biota in diverse landscapes (Platts et al., 1983; Roper, et al., 2002). Current practice in stream monitoring has seen a proliferation of field survey protocols that are meant to describe and evaluate stream habitat characteristics at the reach scale (Rosgen, 1988; Bain et al., 1999, Bauer and Ralph, 1999; Larsen et al., 2001). The original goal of these protocols was to produce a sensitive, quick and universal procedure to evaluate the condition of the stream channel applicable over a wide geographic area that would demonstrate the results of changing land use (Montgomery and MacDonald, 2002).

Reach-scale sampling is popular for a variety of reasons. The reach scale is a convenient measurement unit, well suited to field assessment crews. The time it takes assessment teams to complete a more detailed channel-unit scale survey is a real concern when calculating the cost of monitoring programs. The widespread acceptance of reach-scale metrics within protocols such as USEPA’s Environmental Monitoring and Assessment Program (EMAP) and the National Aquatic Resource Survey (NARS) is the assumption that drainage area, slope and discharge relationships are linear, predictable and sequential within a particular region; thus it is possible to compare channel reaches as a 1:1 correspondence within the context of a common ecoregion or hydrologic region. It is also thought that the reach scale is large enough to integrate channel-forming flow characteristics and processes into a snapshot of the stream morphology and habitat metrics, while small enough to sample biota in a meaningful way.

The use of stream reach attributes as a basis for monitoring has been criticized for observer measurement error, sampling variance and a lack of appreciation of environmental heterogeneity (Ramsey et al., 1992; Clark et al., 1996; Roper and Scarnecchia, 1995; Poole et al., 1997; Bauer and Ralph, 2001). Montgomery and MacDonald (2002), writing about unglaciated mountain headwaters, suggest that the spatial location of the reach within the channel network, channel type, temporal variability in water and sediment inputs (i.e., historic condition) and the persistence of sediment delivery over space and time) are necessary to compare temporal and spatial changes in morphology and response. There are often many ways to explain why a particular physical channel condition has occurred (Montgomery and MacDonald, 2002).

DYNAMICS OF RELICT GLACIATED HEADWATER SYSTEMS

Characteristics of Headwater Systems

Regional-scale metrics (e.g., climate, topography and geology) are necessary to fix smaller scale controls within a broad context. However, while the reach scale may be appropriate for use as the next hierarchical level in lowland stream basins, in mountain glacial systems, naturally occurring glacial macroforms (e.g., hanging glacial valleys and valley steps) provide key elements needed to identify process controls (e.g. colluvial, alluvial or bedrock systems). These controls in turn drive hydrologic response.

Basic Structures Created by Alpine And Cordilleran Ice Sheet Glaciation - Colluvial, alluvial and bedrock structures and processes are found along the channel longitudinal profile in relict glacial headwater basins, Situated within glacial macroforms, these natural organizing glacial structures are found along the path of former ice flows, the signature of Quaternary alpine and cordilleran ice sheet glaciations. The juxtaposition of glacial macroforms with current mass movements is often reflected as a disequilibrium condition along the longitudinal profile (Brardinoni and Hassan, 2006). While the glacial/paraglacial geomorphic signature persists as the controlling structural form, colluvial and fluvial processes operating within these valleys and valley steps produce markedly diverse hydrologic regimes and habitat types. Colluvial channel types in particular are unique to these landscapes and differ from those found in unglaciated mountain headwaters in spatial extent, location and importance to the streamflow regimes of their basins.

An important control on the physical habitat of these landscapes is the type of glaciation that has occurred or is occurring in the area of concern. Alpine basins with mixed glacial footprints, such as those found in the North Cascade Mountains of Washington State, often combine the dynamics of active glaciation in higher elevations with the on-going disturbance processes and the relict signature of the cordilleran ice sheet in lower portions of the catchment. Other systems, for example Mount Rainier, are situated beyond the furthest extent of the Cordilleran ice sheet. Headwater catchments that do not directly drain Mount Rainier are the product of relict alpine glaciation. Basins on the mountain combine active glaciers and relict alpine glaciation. While all these glacial landscapes reflect the signature of glacial macroforms, the type and extent of the glacial footprint is a fundamental control.

Geohydrological relationships vary according to the active or relict glacial status of the headwater basin. High discharge volumes from glacial meltwaters in active glacial basins dominate the streamflow regimes during the summer season. As a result, flow volumes increase during the normal baseflow season in rivers draining active glacial basins; such high flows are in marked contrast to the warm season low flows found in channels draining relict glacial basins.

Colluvial vs. fluvial processes and channel types - Headwater channel processes and morphologies in unglaciated basins are understood as primarily surface water systems, with the exception of low-order colluvial channels found at the tips of the channel network (Montgomery and Buffington, 1997). Alluvial floodplains with hyporheic flowpaths are an exception, but they are commonly found in larger river valleys (Baxter and Hauer, 2000). In contrast, in relict glaciated mountains, colluvial morphologies are found in both upstream “source” cirque wall and hanging valleys, and downstream in “sink” colluvial valleys (Brardinoni and Hassan, 2007).

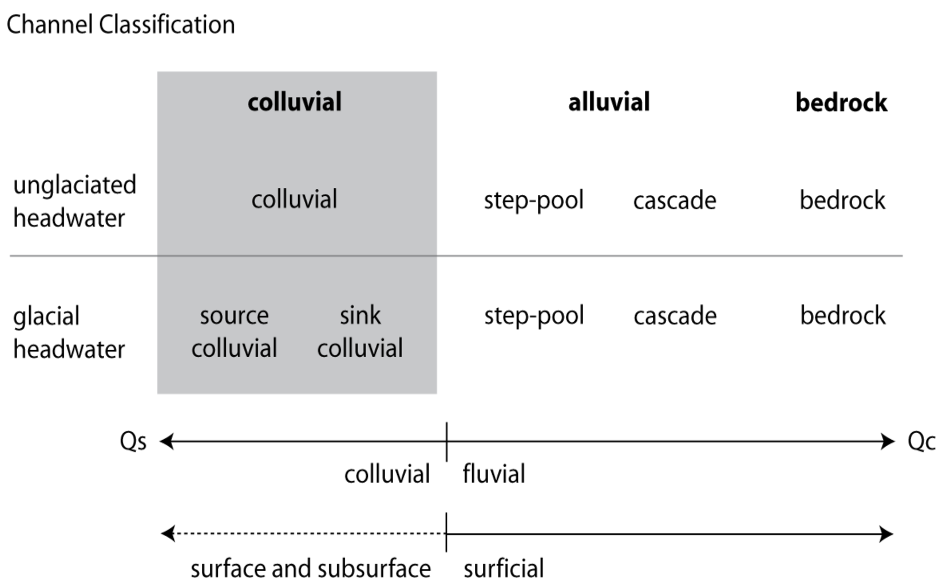

Figure 4.3. Schematic illustration showing glaciated and unglaciated headwater channel types. Colluvial channels and valleys (in grey) are transport limited and sediment rich. Alluvial channels in glaciated mountain headwaters are distinguished by fluvial transport capacity (Q_c) that either equals or exceeds sediment supply (Q_s).

Colluvial channels and valleys are transport limited and sediment rich. Water sources and pathways in depositional portions of the cirque wall feed interconnected lakes and stream channels. “Sink” colluvial channels (depending on the time elapsed since the last debris flow or mass movement) may flow only partially on the surface (Figure 4.3). Examples of alluvial channels within glacial valleys and valley steps include cascade and step-pool channel types (Montgomery and Buffington, 1997).

Fluvial processes also produce bedrock channels, canyons and waterfalls where transport capacity systematically exceeds sediment supply.

The interconnectedness of water as it flows and seeps through depositional sediment in colluvial domains is especially important for aquatic monitoring because of generally lower flow velocities, moderated temperatures and increased contact time with channel substrates. These conditions provide stable habitats and in some cases, refugia from extreme disturbance for many stream species.

Unique Headwater Processes

Valley types controlling structure –Glacial macroforms persist as a fundamental organizational structure that reflects regional-scale patterns from past climate forcings. Delineation of the basic relict glacial structure on the landscape synthesizes standard variables, especially local slope, and elevation. Cirque walls, hanging glacial valleys and valley steps are often found at similar elevations throughout a regional glaciated mountain landscape in conjunction with common aspect-specific precipitation gradients and snowmelt patterns that can be markedly consistent. These structural building blocks encompass a range of disturbance, geomorphic and hydrologic processes which are readily identifiable as functional units. And yet, valley and valley segment-scale structural controls are not addressed in existing monitoring protocols.

Episodic disturbance dynamics – To some ecologists, particularly those who study floods and droughts in streams, hydrologic disturbance is considered the dominant organizing driver in stream ecology (Resh et al., 1988, Lake, 2000). The original theory of patch dynamics, as developed by Pickett and White, (1985) held that in ecological systems, equilibrium landscapes are the exception rather than the rule. Attention to heterogeneity in the aquatic landscape has not been lacking; numerous papers have confirmed the importance of variability, particularly the connections between habitat heterogeneity and species composition (Ward et al., 1998; Wiens, 2002; Poole et al., 2003).

However, while the short term effects of disturbance can be damaging, mountain aquatic species are likely to be adapted to episodic disturbance events with a long (years to decades) period of recovery. Thus, there are many possible types of disturbances and response that might be understood as "normal" for mountain systems, even if their variance structure might be exceedingly wide. Data analysis must therefore detect trends with a large range of variation. The baseline context necessary to establish benchmarks for this endeavor requires that controlling processes and patterns are used to provide context.

Subsurface flow- As shown in Chapter 3, colluvial channels and valleys are characterized by mixed surface and subsurface flowpaths and consequent channels. Buried channels, springs and seeps flowing through accumulated sediment produce moderated streamflow velocities, stormflow discharge peaks, and water temperatures as well as increased contact time with channel substrates. For this reason, colluvial channels are important for ecological monitoring in relict glaciated headwaters.

Colluvial channels do not exhibit the same transport capacity - sediment supply relationships characteristic of fluvial channels. Therefore, assumptions valid for fluvial channels, such as the interpolation of drainage area-discharge relationships (based on an assumption of surface flow) may be inaccurate. For example, buried channels and flowpaths may account for half or more of the flow volumes in disjunct sink colluvial valleys. Surface discharge downstream could be less than upstream in some portions of the longitudinal profile. As a result, the geohydrological characteristics of adjoining physical habitats may be highly diverse.

Problems with reach-scale units - As we have seen, monitoring protocols use the channel reach-scale as the preferred sampling unit for physical habitat comparisons in headwater streams. Based upon the well understood process dynamics of alluvial streams, particularly riffle-pool channels, the length of the reach is often calibrated according to the width of the stream at bankful discharge. However, the discontinuities characteristic of the glacial stepped longitudinal profile are markedly different than the concave longitudinal profile often found in basins controlled by fluvial processes. The internal heterogeneity within valleys and valley step structures suggests that relationships commonly used in alluvial channels may not necessarily be meaningful. For example, a colluvial channel with subsurface pathways may present unknown channel geometries. Reach and habitat-scale sampling units are too small in scale to capture the controlling mechanisms found in glacial headwaters unless they are defined within a valley scale context.

PROCESS DOMAINS: AN ALTERNATIVE PARADIGM

The choice of biological sampling units with comparable geohydrologic characteristics is facilitated using the valley-scale organizational structure particular to these basins. This structure provides a context that integrates differences in controlling mechanisms characterized by process domains. Naturally occurring glacial macroforms (e.g., hanging glacial valleys, valley steps, and cirque walls) provide the framework. Within these structures it is then possible to identify the geomorphic process controls that drive hydrologic response. Because geomorphic and hydrologic responses are inextricably linked, process domains provide a succinct method to classify crucial differences in geohydrological regimes along the basin longitudinal profile.

The Process Domain Concept (PDC) was intended as an alternative the RCC. Mountain geomorphic settings are characterized by steep topography, variable climate and more complex geology compared to more homogeneous lowland landscapes (Montgomery, 1999). These geomorphic conditions are more disturbance-prone than many lowland systems and in turn produce distinct ecological characteristics and patterns. According to the PDC, spatial and temporal variability in geomorphic processes influences biological systems as controlled by the size, frequency and duration of the associated habitat disturbance. As a result, valley segment and channel reach-scale units of aquatic systems can be *categorized* based on the incidence of geomorphic disturbance processes (Montgomery, 1999).

Addressing the Complexity of Headwater Dynamics - Process domains characterize spatial patterns found in the basin longitudinal profile. In contrast to the idealized fluvial longitudinal profile found in many riverine systems, the diverse geomorphic disturbance processes within valley-scale structures are discontinuous along the stepped glacial longitudinal profile (Figure 4.4). Process domains accommodate complex ecological systems in response to the reality of patch dynamics (Pickett and White, 1985), in which an equilibrium condition may be the exception rather than the rule.

If glaciated mountain landscapes did not have a naturally occurring organizing structure, sampling design would be difficult indeed. However, because glacial macroforms determine the core basin structure, subsequent fluvial and episodic disturbance processes can be defined. Monitoring designs quantify the extent to which episodic physical disturbance dynamics produce complex spatial mosaics. The suite of physical characteristics that comprise each macroform structure (e.g., channel slope, valley-scale structure, elevation, transport capacity and sediment supply relationships, disturbance processes and hydrologic regimes) are too interrelated to be usefully reduced to smaller scale individual parameters. By classifying the holistic nature of these interrelated processes, process domains provide a systematic vehicle to link physical habitats with ecological processes. For example, subsurface and surface flows are too closely linked in colluvial process domains to be easily separated into different habitats. These areas may also be too biologically important to ignore in favor of better-studied valley and channel types.

Like hyporheic flows in alluvial channels and floodplains, persistent colluvial habitats in stable (< 5-8% slope) macroform accumulation zones can be a critical moderating influence on the habitat conditions in which aquatic biota live. In some cases, they may provide more stable habitats than other mountain headwater process domains.

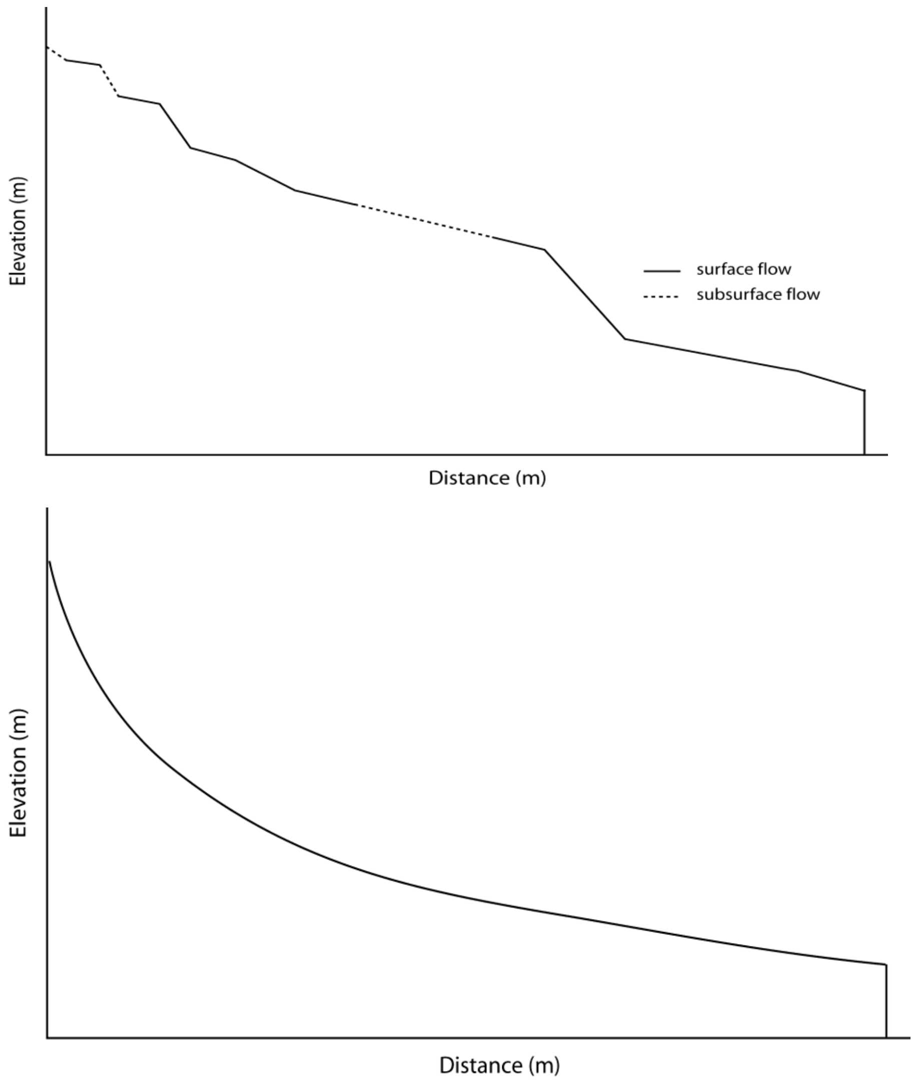

Figure 4.4. Schematic diagram of a. stepped longitudinal profile produced by alpine glacial processes and b. an idealized fluvial concave longitudinal profile.

HIERARCHICAL CONTEXT OF THE SAMPLING UNIT

Difficulties in accounting for physical context affect the ability to define sampling units in complex landscapes. A significant challenge in any extensive monitoring design with a large sample size is the requirement that comparisons be made between like units. To ensure that physical habitat replicates are equivalent requires the stratification of sampling units within a more complex hierarchical physical framework than that essential for monitoring more homogenous landscapes. This would entail including regional, valley-scale and reach-scale metrics unique to these terrains (Figure 4.5). Critical parameters that can be used to isolate differences in habitat types must identify fundamental drivers that control response at the largest possible scale. Climate, topography and geology are typically regional-scale controls on stream processes.

However, the scale at which such drivers function depends upon the spatial and temporal characteristics of the ecosystem. In mountain basins, large elevational gradients produce what might appear as chaotic spatial diversity when viewed at small scales that do not relate to controlling mechanisms. In contrast, spatial parameters at the regional-scale may also miss important drivers that occur at valley scales. Choosing appropriate parameters requires careful attention to sources of order and pattern that control habitat.

Regional-scale metrics

Important regional-scale metrics that drive mesoscale process domain characteristics include the type and extent of relict and/or current glaciation, exposed bedrock hardness, and the general climate, particularly the precipitation gradient. The precipitation regime (e.g., leeward or windward) is probably sufficient to explain a great deal about basic climate variables. Pleistocene glaciation, a product of past climate, is also a determining factor in the creation of aquatic habitat. Because glacial scour and deposition can have a larger effect on the landscape than more recent (Holocene) fluvial processes, the signature of past and present glaciation is a key geomorphic agent. In turn, past and sometimes present glacial history is a fundamental driver of hydrologic response. As an example, Cordilleran Ice Sheet-formed glacial troughs often produce wider and deeper valleys than smaller Holocene alpine glaciers and are found at lower elevations. Because of their great width, mass movement debris from over-steepened valley walls is often decoupled from the present channel and its floodplain. In contrast, colluvial deposition in narrow alpine hanging valleys may repeatedly bury the existing channel. The results from these differences in glacial type have significant implications for the hydrologic regimes of these basins. Geomorphic processes in the decoupled glacial trough are more likely to produce fluvial channels (e.g., alluvial valleys where transport capacity is equal to or greater than sediment supply and bedrock canyons created by fluvial incision) while the dominant channel process in the smaller hanging valley may be colluvial.

The presence of active alpine glaciation above relict sheet or alpine glaciers in a watershed will also affect the nature of both channel and glacial valley. For example, summer meltwaters from active glaciers may accelerate fluvial processes by increasing channel transport capacity. Channel network configurations in which channel flows within a lower glacial valley are concentrated by the confluence of multiple headwater sub-basins, are also more likely to produce channels dominated by fluvial processes. In situations where the main channel and its floodplain are decoupled from a wide glacial trough valley, alternating bedrock canyons (from channel incision) and alluvial floodplains are found along the longitudinal profile of the basin. Small tributary colluvial channels flowing through colluvial debris cones and aprons into large alluvial rivers are often decoupled from the main channel.

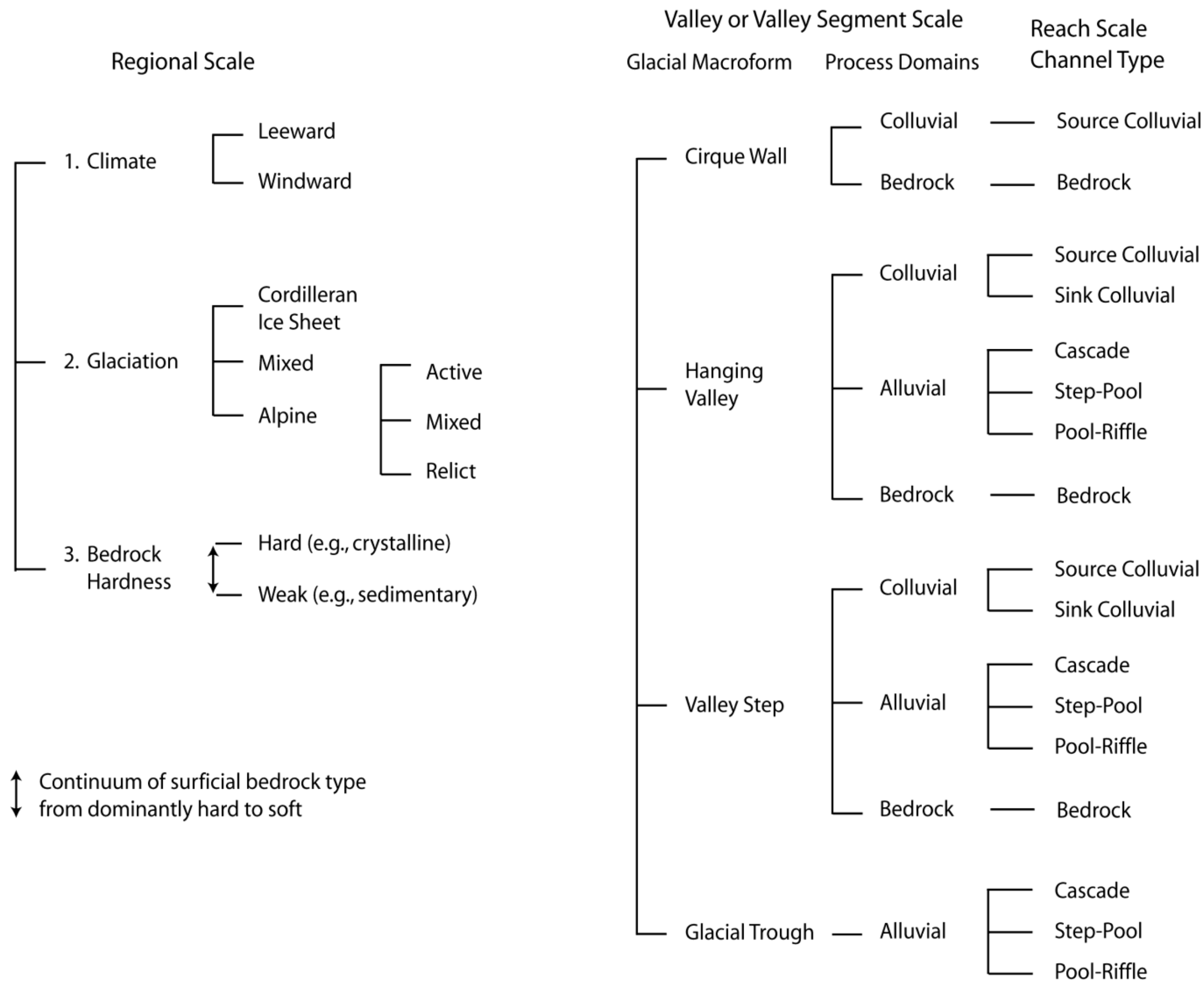

Figure 4.5. Regional, valley and valley segment and reach-scale parameters unique to glaciated mountain basins can be used to differentiate geohydrologic process-form relationships.

Generalized surficial bedrock hardness at the regional scale is another controlling parameter. Soft lithologies where rock debris rapidly disintegrates into fine material (e.g., sedimentary basins with weak rock types) and highly permeable rock types do not produce the enduring glacial macroforms discussed in this review.

Valley scale metrics: glacial macroform structure

The glacial macroform structure provides a framework to characterize common conditions, manifested as patterns in elevation and slope that were produced in the Pleistocene. It is no accident that valley types occur at consistent elevations within a mountain subregion. While these metrics can be used as surrogates for the identification of glacial macroform structures in monitoring design stratification, they are highly variable internally and do not provide the direct insight into system characteristics that can be derived from process domains.

Valley and valley segment scale metrics: process domains

Process domains integrate characteristic geomorphic processes and forms with associated flow characteristics found within glacial macroform structures. The possible types of process domains found within glacial valleys and valley steps are limited by the continuum of transport capacity versus sediment supply relationships. Endmember conditions include extremes of excess sediment supply found in colluvial process domains and the high transport capacity associated with bedrock channel incision. Thus the identification of a process domain within a particular macroform structure provides information on disturbance processes and streamflow and water flowpath characteristics. This information is critical to sampling physical habitats, as the nature of the process domain will determine the likelihood that a particular habitat space will be a useful choice for long-term biological monitoring. The physical range of variance might diverge significantly between adjacent process domains.

The potential disequilibrium between relict glacial macroforms and ensuing disturbance processes may mean that in some cases, the concept of a “quasi” equilibrium form, in which the habitat space returns to a mean state, is not appropriate. For example, a large-scale press disturbance such as a massive rotational landslide can result in episodic reconfigurations of the valley structure. Excess colluvium could displace an alluvial channel in a glacial valley that could be permanently rerouted, or buried, resulting in a change in state from a fluvial to a colluvial system. Such events can take place at any time regardless of their reoccurrence intervals and would be defined as normal physical variance. Furthermore, once such an event has occurred, the now-colluvial channel will not return to a self-forming equilibrium state characteristic of some alluvial channels. Depending on the valley structure, the type of depositional material and the nature of any newly-created depositional landforms, there could be a long term change in the transport capacity/sediment supply relationship.

Because of the directional nature of many geomorphic disturbance processes and their disproportionate effects on the hydrologic regime of aquatic habitats, the choice of potentially stable process domains for biological monitoring is a priority. In relict headwater mountain dynamics, stability may have a different meaning than that produced by the cyclical nature of meandering pool-riffle alluvial channel morphologies and processes.

Channel reach and habitat unit metrics

The metrics often used to define the length of a reference reach channel were originally based on pool-riffle alluvial channel geometry where meander length ranges from 7 to 10 times the channel width (Leopold, 1994). In contrast, EMAP's Western Pilot Study Field Operations Manual for Wadeable Streams based the proscribed channel sampling unit dimensions (channel length is 40 times channel width) because this distance is thought necessary to collect at least 90% of the fish species occurring in the stream reach; (Peck et al., 2001). These examples suggest that the choice of the sampling unit length is dependent on the need to encompass representative physical habitat and the composition of the target biological community. Sampling unit reach length would then depend upon the habitat needs of the biotic community of interest.

A common goal for extensive monitoring is to sample a common physical habitat unit over a large area. Consequently, the identification of process domains and channel reach types that are widespread in these environments will improve opportunities for a large sample pool.

RECOMMENDATIONS FOR LONG TERM BIOLOGICAL MONITORING

Nested, multi-scale sampling designs based on the basic landscape structure found in these environments are most desirable. However, complex glaciated headwater landscapes are lacking in rich physical data sets and are expensive to monitor due to access issues. These challenges require that potential monitoring applications do not fall back on over-simplified protocols developed for more homogeneous terrains. A first priority must be to ensure that habitat samples are indeed comparable. Local habitat metrics including water temperature, substrate and flow regime may be limited to a small area and provide little insight into controlling processes and conditions. While fundamental to the current living conditions of the biological community at the time of the sample, they could be an artifact of multiple larger spatial and temporal processes. The challenge of monitoring these systems is to detect ecologically relevant change beyond merely tracking status and trends in disjunct sites. For these reasons, habitat metrics must be placed in the context of the larger controlling processes at work within the structural constraints (e.g., glacial macroforms) found in the watershed.

Habitat samples would best be chosen from the most representative types within the hierarchy of physical controls found in the target landscape (Figure 4.5). In particular, sampling units are best chosen within the array of regional and process domain elements that are likely to be temporally and spatially persistent. For example, headwater sub-watersheds dominated by active glaciers may have more significant floods and glacier-originating debris flows due to climate change impacts than in a relict glacial basin. If glacial mass wasting is rapid, the temporal and spacial persistence of downstream habitats are likely to be affected. Choosing spatially and temporally persistent process domains are important when choosing comparable physical habitat samples for long-term monitoring (Figure 4.6). For example, sink colluvial process domains in extended narrow relict glacial valleys with moderating subsurface flow regimes may also have the capacity to accumulate a great deal of sediment without producing or experiencing periodic longitudinal debris flows (e.g., Lost Creek at Mount Rainier National Park).

Disturbance processes, including floods, may generate a change in physical state in adjoining process domains, but if the macroform and process domain structure aid in buffering the dynamics caused by surrounding disturbance, the domain and its hydrologic regime may endure throughout the interglacial period. Valleys that are buffered from state-changing events produced by geomorphic disturbance processes provide a better environment to assess species trends due to climate change. More revealing changes in physical habitat might be found in those process domains that are better able to accommodate physical disturbance (Figure 4.6). Because such locations within headwater basins may require the extraordinary power of active glacial dynamics to rework the landscape, the range of habitat variability is muted.

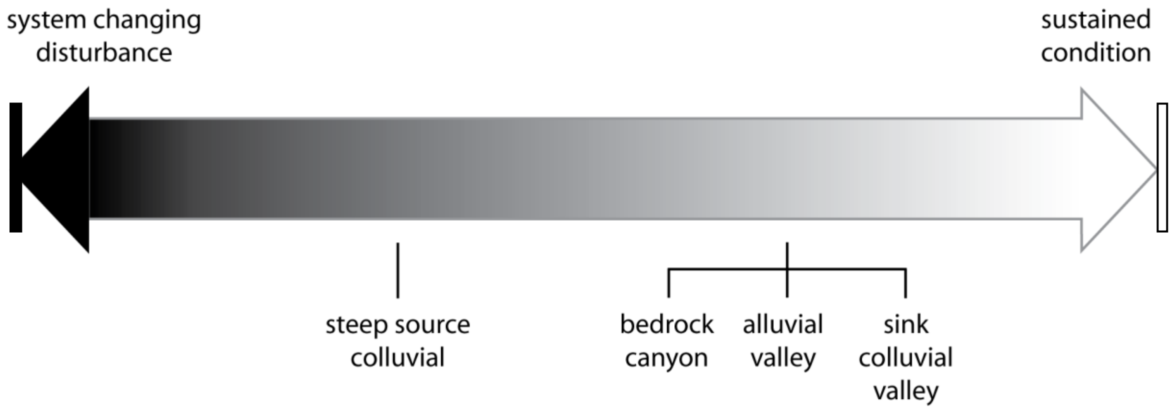

Figure 4.6. Schematic illustration of the relative persistence of process domains. Those domains towards the right hand side of the continuum are likely to maintain a more stable morphology in spite of episodic disturbance. Habitats in process domain types towards the left side of the continuum are likely changed by disturbance processes.

In contrast, some process domains in relict glacial valley steps are directly affected by mass movement disturbance processes and are likely to have a wide variance structure. Source area colluvial channels in unglaciated systems found at the steep fingertips of fluvial headwater drainage networks can be periodically scoured to bedrock by debris flows, resulting in an extremely unstable habitat. These domains differ from colluvial source areas in relict alpine headwaters (e.g., Upper Crystal Creek at Mount Rainier National Park). Colluvium accumulation zones that cover flat glacial troughs are better able to accommodate diffuse subsurface flowpaths within the substrate without producing debris flow initiation zones.

Relict glaciated colluvial process domains characterized by linked subsurface and surface flows may produce sampling units with greater hydrological complexity and habitat diversity. They also could be linked to increased biological diversity and endemism. Lag effects, resilience and the presence or absence of refugia, characteristic of these domains, are important controls on species and community assemblage survival. Subsurface flowpaths buffer the intensity of hydrological forcings such as flood flows, differences in the seasonal and diurnal patterns and mean values of water temperature and discharge. If there is a significant lag in hydrological response due to the resilience of the system or an even greater lag in biological response in spite of the short life spans of many interstitial-dwelling species, this is useful information to assess climate change. The unknown nature of potential threshold effects in these systems should become apparent if there is a disconnection between climate forcing and ultimate biological response.

The sampling unit habitat must be suitable to the life history needs of the target aquatic communities. If the goal of the biological monitoring program is to measure term "*ecosystem integrity*" (the capability of a system to support and maintain a balanced, adaptive community of organisms comparable to other like natural habitats within a region) then process domains that are likely to persist for long time periods and provide preferred living conditions for target populations are desirable. For this reason, bedrock canyons and waterfalls incised into valley and valley step glacial structures may be a poor choice for long-term biological monitoring despite their relative longevity as landforms. Channel confinement produces few refugia during flood events; instead extreme discharge volumes and high water often limit species dispersal choices.

Temporal variability –The "normal range" of variation is a difficult metric to quantify in complex mountain headwaters in comparatively short time periods (i.e., 3-10 years). It is probable that the incidence of mass movements such as debris flows as well as flood events may increase during the transition to a warmer climate if the timing, frequency and duration of precipitation patterns should be amplified by climate change.

Measuring significant trends due to climate change both within and between systems might require longer monitoring timeframes (> 10 years) than are usually assumed when attributing system adjustments to land use alterations and other, more localized drivers. Biological monitoring programs designed to detect climate change-driven trends in mountain systems are complicated by many issues. These include the lack of region-specific, long-term geohydrologic data, the complexity of mountain weather patterns, the temporal variability of the data within the existing record, and the subsequent difficulty in differentiating between normal reoccurring patterns and directional climate change. Moreover, outliers or extreme climatic events may have greater importance than mean conditions.

CASE STUDY: A MONITORING PROTOTYPE

The North Coast and Cascades Network portion of the NPS Vital Signs Monitoring Program provides an excellent case study to illustrate the proposed physical habitat monitoring prototype. The three big NCCN parks, including Olympic (OLYM), Mt. Rainier (MORA) and North Cascades (NOCA) National Parks in Washington State encompass a wide range of physical habitat conditions (Figure 4.5).

A goal of the NCCN program is to monitor the ecological condition of high mountain lakes in the context of climate change and atmospheric deposition. At the habitat scale, the sampling design calls for stratification according to lake size (0.4 – 6.0 ha), depth (>2.5 m) and elevation range (1500-1800 m). Lake sampling sites will also be restricted to those with limited spawning habitat (e.g., limited outflow, limited gravel substrates and lack of nearshore springs) as a surrogate for low fish density. At the regional scale, lakes are stratified by relative precipitation gradient (i.e., “wet” to “dry”) in each park.

Mountain lakes are classified as segment-scale elements in mountain valleys (Frissell, 1986). The choice of high mountain lakes as the sampling unit simplifies the amount of hierarchical stratification necessary to contextualize habitat heterogeneity. To reflect these differences, the stream hierarchical framework has been modified below to reflect the higher-order position of lake habitats (Figure 4.7).

The comparative simplicity of the valley-segment scale, however, does not preclude the need to take into account the biological importance of the heterogeneous water sources and pathways feeding into and out of the sample unit. It is reasonable to assume that lakes occur in all categories of regional parameters used to define physical habitat condition. It is also important to account for the location of the lake within the valley network. Spatial patterns in species composition have been found to reflect the hierarchical interaction of landscape features on longitudinal gradients (lake/stream position) in the stream network (Robinson and Kawecka, 2005).

Budget constraints limit the number of sample sites possible in the NCCN program. Due to these constraints, relict glacial habitats may offer a better choice for long term physical monitoring than environments downstream from active glaciers. The hydrologic regimes of relict valleys are heterogeneous, but lack the added complexity of those driven by active glacial processes. Large scale glacial dynamics can produce extremely unstable physical conditions in a warming climate. These conditions may occur on short temporal scales that would confound the identification of climate-produced effects with yet another layer of system complexity.

The choice of the 1500-1800 m elevation range for high mountain lake stratification is helpful for determining climate impacts. Climate change-caused hydrologic response may be particularly apparent in subalpine hanging valley habitats because climate volatility is reflected in abrupt phase changes between rain, rain on snow and snow events. If significant upward trends in atmospheric temperature or precipitation gradients occur in the near future (i.e., decades), the incidence of rain or rain on snow events in the winter season may have recognizable effects on hydrologic regimes.

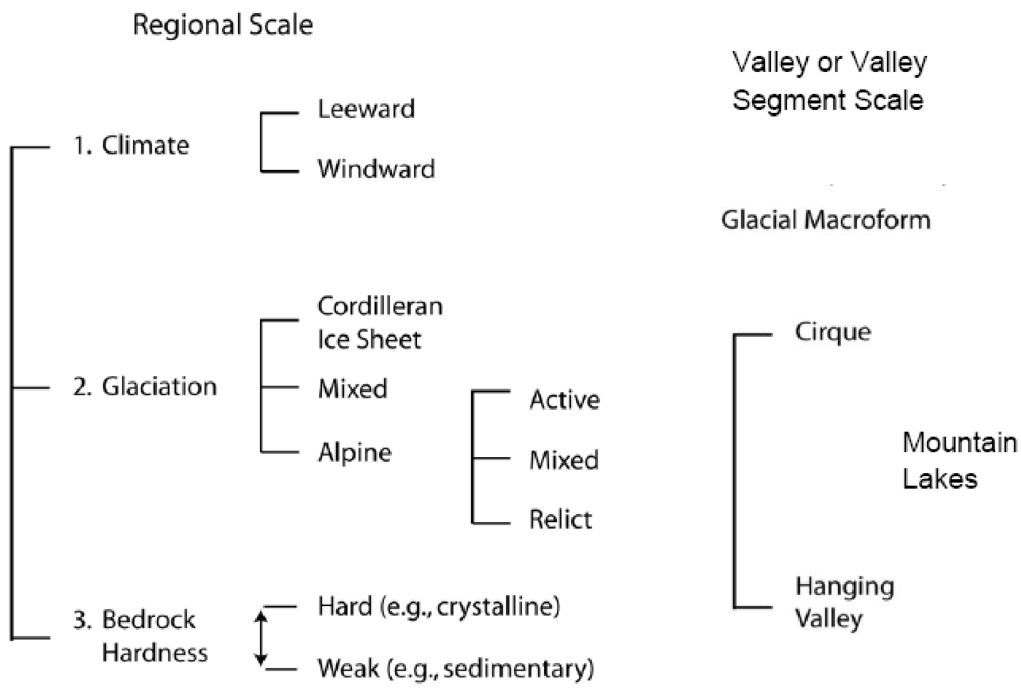

Figure 4.7. The headwater stream hierarchical framework (Figure 4.5) modified to reflect the position of NCCN high mountain lakes within cirque and hanging glacial valley features.

High mountain lakes frequently occur in relict alluvial and colluvial hanging valley process domains and have great value as sampling unit locations. Alluvial and colluvial hanging valleys typically consist of mountain lake(s), outlet channel(s) at the head of a valley step and inlet channel(s) or springs. These process domains can be adjacent to upvalley colluvial source areas and talus slopes produced from relict cirque wall depositional processes and former rock glaciers. As such, they may offer a suite of fine-scale surface and subsurface habitats and habitat complexity similar to (on a much smaller scale) biologically rich hyporheic environments in intact pool-riffle floodplain rivers. The interconnections between water sources, pathways, channels and lakes within a common glacial macroform context may produce a multiplicity of interconnected habitats. Species diversity and relative abundance (e.g., zooplankton and macroinvertebrates) in a particular mountain lake is likely to be strongly influenced by relative position within the valley mosaic and effects from upstream process domains.

The potential for comparative stability in these valleys is important for monitoring climate change. These types of process domain may have the ability to buffer disturbance processes in adjacent domains. Durable structural features such as bedrock controls at the lake outlet may also buffer the influence of channel incision and base level changes downstream.

Recommendations for application to the NCCN Aquatic Monitoring Protocol

Multiscale physical patterns and response are a first order control of biological response in NCCN mountain systems. Incorporate sufficient abiotic context in sampling design within a hierarchical spatial context. Like many important natural resource initiatives, the NCCN monitoring effort has a big mandate and a small budget. This is a serious difficulty when looking to produce meaningful results from long-term monitoring of complex, interconnected and not well-studied abiotic habitats. To make up for budgetary limitations that bound the comprehensiveness of the sampling design, the NCCN program has limited the aquatic sampling sites to lakes at elevations between 1500 and 1800 m. The stratified random sampling design depends on extrapolation and interpolation of biological patterns based on comparisons of small-scale physical habitat variables (e.g. temperature, substrate, dissolved oxygen, water level) with site visits limited to one per summer season. However, in practice, the limited number of samples influences the inferences that may be drawn from the study.

To detect ecologically relevant change and add to the breadth of information gleaned from the monitoring program it would be helpful to place the status and trends produced from site based monitoring within the hierarchical spatial context appropriate to these ecosystems. Many lakes at 1500-1800 m elevations in the NCCN parks are valley segment-scale features found in the upper headwaters of relict glacial basins. There is extreme hydrological variability surrounding these upper basin lakes. For example there is a wide range in their degree of connectedness; many are interconnected by streams and other colluvial flowpaths forming a chain-like mosaic of diverse habitats. Intravalley connections between lakes and water bodies, especially outlet streams can be ephemeral (Donath and Robinson, 2001). Outlet channels can also be dominantly subsurface pathways (e.g. Upper Palisades Lake in MORA). Seasonality in water sources are a major feature of high elevation valleys (Robinson and Matthaei, 2007). Lake and stream ecosystems are often strongly linked and spatial patterns in species composition have been found to reflect the hierarchical interaction of landscape features on longitudinal gradients (lake/stream position) in the stream network (Robinson and Kawecka, 2005). The position of the lake in the stream network has important implications controlling the structure and functioning of downstream receiving waters (Cattaneo, 1996; Soranno et al, 1999; Kling et al., 2000). For these reasons, the site based sampling design must account for enough of the physical context in space and time to legitimately compare different lake habitats and understand the significance of research results.

This is a challenge as biological sampling alone requires significant outlays of resources and manpower in complex terrain. Spatially continuous measurements of stream biota from diverse habitats along the chosen valley longitudinal profile are most desirable, but can be prohibitively expensive. Traditional site-based benthic invertebrate sampling protocols are time consuming and labor intensive, not to mention the processing of samples in the laboratory. For these reasons, if sampling is limited to lakes, it is important that the physical context of the segment-scale habitat be well understood. To this end, specific factors characteristic of the landscape, such as the geomorphic and hydrologic effects of glaciation, should be included in the choice of monitoring variables. Figure 4.5 provides a list of strata that at the regional, valley and valley segment scales that drive these habitats.

Regional metrics should be stratified by the type of glacial episode(s) found in a particular terrain beyond broad categories of climate (i.e. leeward and windward), and bedrock (i.e. weak vs. hard). The presence or absence of active and relict glaciation within a headwater basin is a major control of physical habitat, both in terms of ongoing disturbance processes and streamflow regime. The hydrologic regimes of active glaciers, particularly those undergoing mass wasting, produce distinct hydrographs with markedly higher streamflow discharge during the summer season. In contrast, baseflows in relict glacial terrains can vary significantly between subsurface flows found in colluvial systems and extreme low flow regimes in surface flow dominated systems. These differences should be included when stratifying a potential population of habitat types.

Relict glacial headwater streams are best conceptualized as spatially disjunct process domains at the valley scale and spatially continuous lateral and longitudinal mosaics at smaller scales. Stratify the physical habitat population of interest within the glacial hierarchical spatial structure. Glacial macroforms are one of the few comparatively enduring structures in a landscape known for spatial and temporal dynamism and disturbance processes. They also are associated with discrete slope and elevational metrics that serve to simplify the number of variables associated with a particular population.

The colluvial, alluvial and bedrock process domains found within glacial macroform structures also control suites of process characteristics and variables. Because glacial macroform structures are often disjunct features on the basin longitudinal profile, they provide a separate valley-scale unit that may provide a great deal of contextual information about smaller-scale habitats.

Proposed modifications to the design stratification and sampling frequency components of the NOCA "Vital Signs" Mountain Lakes Monitoring Protocol. Table 4.7 shows an example of suggested modifications to the design stratification and sampling frequency components of the NOCA monitoring protocols for high elevation mountain lakes. These additions are meant to take into account the physical habitat differences between headwater mountain systems and lowland river valley systems as reflected in the monitoring design.

Regional scale metrics – Two mapping components, the active or relict status of Pleistocene glaciation and rock hardness, are added to the regional-scale design stratification requirements. The nature of past and active glaciation is a determining factor in the creation of aquatic habitat. Because glacial scour and deposition may have a disproportionate effect on landscape processes compared to more recent fluvial processes, the signature of past and present glaciation is a key geomorphic agent. In turn, past and present glacial history is a fundamental driver of hydrologic response. The choice of comparable lake sampling units is dependent on similarities between their basic hydrologic regimes.

Valley-scale metrics- The physical dimensions and process characteristics of the glacial valley surrounding the lake sampling unit is another important driver of the aquatic system. The relative location of the lake in the larger glacial valley system, its position relative to upstream channels, talus slopes, springs and other lakes has physiochemical habitat implications that directly affect biotic communities. Such contextual information will greatly increase the interpretability of habitat scale biotic and abiotic data.

Process domains- The lake sampling unit constitutes in many cases a valley segment-scale process domain. The habitat characteristics of the lentic sampling unit are defined by its geohydrologic response as an alluvial or colluvial process domain. The nature of inlet and outlet channels, whether inlet flows are surface or subsurface systems, whether the lake is coupled or decoupled from its valley walls and the nature of its seasonal flow regimes are of critical importance to the biotic community. Establishing the characteristics of the lake as a process domain will ensure sufficient geohydrological information to account for the physical context in space and time to legitimately compare the similarity of lake habitats.

Sampling frequency – In mountain systems, the hydrological regime of the lake environment can be exceptionally complex. Sudden fluctuations and threshold events, including winter ice dams and melting, and sudden lake level variations during the summer could be related to important patterns that may reflect important causal mechanisms. For this reason, continuous information about the lake hydrological habitat provided by discharge and temperature loggers would significantly enhance the interpretability of aquatic species data. Continuous measurement would also provide better information on the one, or ideally two site visits per year. For example, while the goal of the single scheduled site visit is to measure the lake biota at peak productivity, it would be possible to calibrate differences in the period of peak productivity for sample lakes as well as ensure that the site visit was indeed during the peak period.

Table 4.2. Proposed modifications to the design stratification and sampling frequency components of the NCCN "Vital Signs" Mountain Lakes Monitoring Protocol.

	Scale	Existing	Proposed	Sampling Method
Design Stratification	Regional/ Basin	Wet/dry	Wet/dry (climate)	Interpretation of precipitation gradient
		--------	Active/relict glaciation (topography)	Mapping
		--------	Hard/weak rock (geology)	
	Valley	1219-1890 m elevation	Hanging glacial valleys (1219-1890 m elevation)	Mapping
		---------	Drainage area at valley head and outlet	
		---------	Glacial valley dimensions	
	Process Domain	---------	Fluvial [1] vs Colluvial [2] (>40%) [3]	Field scoping
Sampling Frequency	**Habitat**	**1 x per year August/September**	**2 x per year June/July August/September**	**Simultaneous field sampling site visits for each park/wet or dry**
		---------	**Continuous temperature and stage (discharge) for lake inlet(s) and outlet**	**Data loggers**

[1] Alluvial – surface flow – decoupled
[2] Colluvial – surface/subsurface flow – coupled
[3] Ideally would have sufficient replicates of fluvial and colluvial categories

Notes to Chapter 4

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Chapter 5

SUMMARY AND CONCLUSION

The results of this research support the concept that innate discontinuities and heterogeneities along the longitudinal profile of drainage basins are important to explain the mechanisms that control physical habitat (Ward 1998a, Fausch et al., 2004). However, it is evident that the spatial and temporal dynamics of glaciated mountain headwaters present a unique and complex set of discontinuous geohydrological conditions. They do not resemble the meandering alluvial channels that provided the empirical basis for concepts developed for lowland river systems in ecology and fluvial geomorphology. In alpine headwaters, such discontinuities are manifest within a hierarchical spatial structure dominated by glacial macroforms (e.g. cirque walls, hanging glacial valleys, and valley steps). These landforms provide an innate organizing framework that underlies colluvial and fluvial process domains, the source of distinct streamflow regimes. The result of such geohydrologic processes are the diverse aquatic habitats found in these alpine headwaters.

The theoretical and empirical basis for a hierarchical stream framework suited to glaciated mountain headwaters is explored in Chapter 2. Process understanding of controlling mountain recharge mechanisms specific to these systems is limited. Glaciated mountain headwaters present multiple inflection points and abrupt breaks in slope along their channel long profiles associated with distinct sediment supply and transport capacity relationships. The plot-scale study designs common to field-based hydrologic research lack a spatial focus large enough to investigate the unique suite of valley and valley segment-scale spatial processes and patterns driving hydrologic response. Catchment-scale hydrological models often lack the ability to identify categories of spatial complexity common to these basins, frequently the very elements that control ecological response. Many ecological conceptual models, such as patch dynamics, were not developed for systems with a valley-scale controlling structure and pertain specifically to biological rather than geohydrological response. However, the Process Domain Concept (PDC) appeared to present a reasonable scientific basis with which to integrate complex geohydrologic processes and long and short term disturbance histories in a conceptual framework.

Chapter 3 investigated the potential correlation between colluvial process domain percentages and hydrologic response. Source and sink colluvial process domains were used as a limiting endmember condition in this study because they produce habitats characterized by interconnected surface and subsurface channels and flowpaths, lower flow velocities, moderated temperatures and increased contact time with channel substrates. The spatial extent of the colluvial channel was compared to independent hydrologic measurements, (e.g., recession constants, stable isotopes and temperature measurements) individually and together. All three hydrologic measurements showed consistent patterns that differed between the study basins, regardless of season. Basin information derived from the recession constants was enhanced and validated by the ^{18}O and temperature measurements.

Analysis of the position of colluvial process domains along the basin long profile corresponded to disparities between the different metrics of hydrologic response. For example, temperature values are more localized in their effectiveness as an integrated measurement compared to recession constants. Temperature measurements revealed that the position discontinuous features, such as a mid-basin bedrock canyon segment between colluvial process domains affected water temperatures downstream.

Process domains proved to be a parsimonious way to categorize the intermediate-scale drivers of streamflow. Regional context metrics, including topography, bedrock hardness, and climate, are important drivers of basin response in glaciated basins. However, the variable terrains produced by the combination of relict glacial macroforms, episodic disturbance and sustained fluvial geomorphic processes were best identified using the valley and valley segment-scale spatial framework detailed in Figure 4.5.

Chapter 4 presents the application of the research outcome from Chapter 3 to the question of how best to do physical habitat monitoring in these systems. After identifying habitat assumptions common to standard monitoring protocols used in the Pacific Northwest, I compared these with characteristics of the study basins. I found that assumptions, including the idea that headwater stream systems are in a condition of dynamic equilibrium, non-anthropogenic cataclysmic disturbances are rare and that channel characteristics exhibit a narrow range of variability, do not apply to all post-glacial landscapes. The condition of on-going adjustment characteristic of some of the MORA relict glacial headwaters mediates the influence of current geomorphic processes. Large naturally-occurring habitat disturbances of variable frequencies and magnitudes are common in these terrains; such disturbance processes may produce geomorphic and hydrologic responses that do not reflect a mean average condition.

To ensure that physical habitat replicates are equivalent requires the stratification of sampling units within a hierarchical physical framework that includes regional, valley-scale and reach-scale metrics, some unique to these terrains. Important regional-scale metrics that drive mesoscale process domain characteristics include the type and extent of relict and/or current glaciation, surficial bedrock hardness, and the precipitation gradient. The glacial macroform structure provides a valley-scale framework common to these basins in which process domains integrate characteristic geomorphic processes and forms with associated flow regimes.

Reach-scale metrics also are defined by their colluvial or fluvial characteristics and are often used as the sampling unit. The choice of the sampling unit length is dependent on the need to encompass representative physical habitat and the composition of the target biological community. Sampling unit reach length also depends upon the habitat needs of the biotic community of interest. Habitat samples would best be chosen from the most representative types within the hierarchy of physical controls found in the target landscape and must be suitable to the life history needs of the target aquatic communities. If the goal of the monitoring project is to measure "*ecosystem integrity*" (the capability of a system to support and maintain a balanced, adaptive community of organisms comparable to other like natural habitats within a region) then sampling units within a process domain context that are likely to persist for long time periods are desirable.

Finally, attempts to monitor and manage montane aquatic communities in the face of intermediate and long term climate change will require a better understanding of physical habitat mechanisms than we currently possess. Over longer time scales, climate warming, predicted to alter the timing and magnitude of both flow and water temperature regimes, will affect the survival strategies of biota living in these ecosystems (Mantua et al., 1997; Magnuson et al., 2000). Changes in the flow regimes within the hierarchies found in lotic headwater ecosystems may in some cases limit the ability of species to transport themselves to more suitable habitats in adjoining basins. In other cases, colluvial and alluvial systems and their attendant biotic communities may endure and prove remarkably resilient in the face of disturbance within the current interglacial epoch. For these reasons, it is imperative that managers concerned with successful ecosystem function design management and monitoring strategies at scales that match the physical habitat controls and life history strategies of the species involved.

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