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A Process-Based Hierarchical Framework for Monitoring Glaciated Alpine Headwaters

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Abstract Recent studies have demonstrated the geomorphic complexity and wide range of hydrologic regimes found in alpine headwater channels that provide complex habitats for aquatic taxa. These geohydrologic elements are fundamental to better understand patterns in species assemblages and indicator taxa and are necessary to aquatic monitoring protocols that aim to track changes in physical conditions. Complex physical variables shape many biological and ecological traits, including life history strategies, but these mechanisms can only be understood if critical physical variables are adequately represented within the sampling framework. To better align sampling design protocols with current geohydrologic knowledge, we present a conceptual framework that incorporates regional-scale conditions, basin-scale longitudinal profiles, valley-scale glacial macroform structure, valley segment-scale (i.e., colluvial, alluvial, and bedrock), and reach-scale channel types. At the valley segment- and reach-scales, these hierarchical levels are associated with differences in streamflow and sediment regime, water source contribution and water temperature. Examples of linked physical-ecological hypotheses placed in a landscape context and a case study using the proposed framework are presented to demonstrate the usefulness of this approach for monitoring complex temporal and spatial patterns and processes in glaciated basins. This approach is meant to aid in comparisons between mountain regions on a global scale and to improve management of potentially endangered alpine species affected by climate change and other stressors.

Keywords Hydrologic regimes · Sediment · Alpine headwaters · Indicator taxa · Glacial macroforms · Channel longitudinal profile · Climate change · Talus

Introduction

Climate change may change hydrologic regimes due to increased atmospheric temperatures and reduced annual snowpack in many alpine environments, including the western United States (Hamlet and others 2005). As a result, biological monitoring to better understand and manage climate-induced effects on aquatic ecosystems has taken on new importance. Natural biological response to climate patterns is pronounced in high-elevation mountain headwaters having near-pristine condition, providing unique opportunities for monitoring (Füreder and others 2002; Viviroli and Weingartner 2004; Maiolini and others 2006). Because protected mountain ecosystems experience fewer land use impacts, the effects of climate stressors on the headwater aquatic environment may be more directly apparent than the effects of similar stressors on lowland river systems in more populated regions (Füreder and others 2002).

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Monitoring alpine aquatic ecosystems is complicated by the topographical and geological complexity of mountainous terrain (Montgomery 1999; Montgomery and MacDonald 2002). Biological response is not spatially uniform across the land surface. Dynamic physical effects, including spatial and temporal differences in hydrologic response can vary significantly, collectively driving the variability of aquatic habitats (Webb and others 2008; Brown and others 2009). For example, in areas with active-ice glaciers and diminished snowpack, response is amplified through changes in glacial mass balance and hydrologic regime (Hieber and others 2005; Beniston 2006). In contrast, debris-mantled features, such as talus slopes, rock glaciers, and rock-ice features, may buffer response to climate effects (Millar and Westfall 2008). As a consequence, the degree to which community assemblages directly reflect climate forcings is filtered according to the geohydrologic characteristics of a particular location within the landscape (Brown and others 2009).

While trends such as the loss of biodiversity in alpine streams due to glacial retreat have been documented across the globe (Jacobsen and others 2012), the spatial and temporal complexity of alpine terrains presents difficulties in the design of regional-scale long-term monitoring initiatives. For example, statistically based monitoring protocols in the Pacific Northwest often use replicated surveys intended to provide a regional estimate of ecological condition (Conquest and Ralph 1998). However, such surveys are most effective when there is sufficient knowledge about regional geomorphic and hydrologic characteristics at multiple scales to ensure that response variables are not likely to be overwhelmed by confounding natural variability. When the inherent variability of a parameter is not known, the risk of making the wrong conclusion from a statistical analysis of the results is more probable (Conquest and others 1994). In conditions where more information on underlying processes is considered important, supplementary case studies are recommended (Conquest and Ralph 1998). Other monitoring protocols such as the Index of Biotic Integrity (IBI) and River Invertebrate Prediction and Classification System (RIVPACS) are also based on models that rely on pre-existing knowledge about taxa characteristic of a particular habitat (Karr 1991; Clarke and others 2003).

Long-term study of these unique systems is needed to increase ecological knowledge by fostering a more accurate analysis of natural variability within the context of longer-term trends (Brown and others 2006b). The ability to interpret change in biological attributes depends upon the capability of the sampling framework to provide the context needed to evaluate attribute performance or response (Larsen and others 2001). Clearly there is a need for better information on both regionally specific indicator organisms and the causal mechanisms driving these ecosystems in order to monitor response to a stressor as complex as climate change (Muhlfeld and others 2011).

To address this issue, we present an integrative, systematic framework for sampling high elevation aquatic ecosystems. The framework differs significantly from previous nested hierarchies in that it is designed to test unique physical processes and morphologies specific to glaciated mountain headwaters that appear to constrain expressions of local selective forces. Existing monitoring and sampling schemes do not explicitly stratify the recently identified differences in physiographic variability in spatial and temporal patterns of hydrologic response characteristic of these systems. Our approach follows the example of monitoring initiatives that stress the importance of current disturbance regimes, hydrologic characteristics, and geomorphic structures as components of the sampling framework (Hawkins and others 2000).

The channel longitudinal profile, nested within the stream network, is used as the basis for this approach. It offers a system to account for diverse process-form relationships at multiple scales and has a long history as a means to model geomorphic fluvial processes. Beginning with theories of landscape evolution and dynamic equilibrium (Davis 1902; Gilbert 1914), the channel longitudinal profile has been used to model the development of landforms in relation to both geologic history and intermediate time scales (e.g., years) (Mackin 1948; Hack 1957; Leopold and others 1964). Recent studies of glaciated mountain headwaters (Brardinoni and Hassan 2006), reach-scale mountain stream classification (Montgomery and Buffington 1997; McCleary and others 2011), and the hierarchy of scales inherent to mountain ecosystems (Frissell and others 1986; Poff 1997; Montgomery 1999), all focus on the characteristics of the channel longitudinal profile as a basis to test hypotheses about species abundance, distribution, and functional traits.

The longitudinal profile, long used in geomorphology, was adopted by stream ecologists as an organizing framework for modeling relationships between generalized habitat conditions and functional feeding groups along the river continuum (Vannote and others 1980). Later studies have used a linear framework to compare longitudinal patterns of aquatic macroinvertebrate taxonomic richness based on stream order (Lake and others 1994). Poff (1997) proposed a generalized conceptual framework using environmental filters based on the hierarchy of scales presented by Frissell and others (1986)to better understand and predict the distribution and categorical abundance of stream communities using functional species traits. According to this model, occurrence of species in a particular microhabitat means they possess traits suited to the prevailing watershed/basin, valley bottom/stream reach, and channel unit habitat conditions that make up the set of multiple hierarchical filters that affect a particular microhabitat.

Like many stream classification systems, our framework is presented as a generalized tool for differentiating between processes unique to particular spatial structures within the channel network (Montgomery and Buffington 1997; Hawkins and others 2000). Our goal is to contribute to the conceptual basis of monitoring protocols by (1) identifying relationships between physical mechanisms that drive ecosystem trends at multiple scales, (2) presenting an approach that will increase ecological information by expanding the geohydrological context necessary to inform sampling site selection and interpret monitoring results, and (3) facilitating identification of unique geomorphic-ecologic hypotheses to improve process-based knowledge.

Unique Physical Characteristics: Spatial and Temporal Context

Glaciated mountain drainage basins are the product of Pleistocene and Holocene climate changes that caused a profound spatial reorganization of the landscape. Glaciation continues to affect currently active geomorphic processes (Ballantyne 2002; Brardinoni and Hassan 2006). In mountain streams, linked geomorphic and hydrologic response mechanisms often produce a wider range of physical characteristics than are generally found in lowland systems (Montgomery 1999). Local hydrologic response reflects patterns in precipitation or snowmelt and glacial mass balance that are mediated and filtered by complex topographic, geologic and geomorphic processes at multiple scales (Brardinoni and Hassan 2006, 2007).

To incorporate recent developments in our understanding of the associations between diverse physical processes into biological monitoring protocols requires a clear accounting of the processes currently known at the scales in which they occur. Failure to consider intermediate-scale processes and morphologies may limit the interpretation of results produced using smaller-scale metrics. Localized physical variables (i.e., channel width, water temperature and conductivity) taken at small-scale (1–2 m^2) sampling points may not suffice to explain larger patterns that control long term species survival and stability (Hannah and others 2007; Brown and others 2009). Local spatial and temporal variability in water source contributions produced by diverse topographical filtering and conveyance mechanisms have also been found to be a primary control of species assemblages (Brown and others 2009). Extrapolation of attribute response from sampling unit to regional or watershed scales without an adequate understanding of both physical context and ecosystem function may be misleading (Downes 2010). Moreover, scaling hydrologic data from small to large areas can be misleading (Klemes 1988).

Dynamic Equilibrium and Paraglacial Landscapes

Ecological theories fundamentally differ with regard to their stance on whether community structure tends towards an equilibrium condition or is maintained by episodic disturbances that occur frequently enough to affect species life history strategies (Lake 2000). Stream monitoring protocols use conceptual models based on the concept of dynamic equilibrium to account for known or hypothesized relationships between channel morphology and time (Kaufmann and others 1999; Peck and others 2002). Protocols such as the Environmental Assessment Mapping Program (EMAP) utilize equilibrium concepts to increase the size of the sample population or limit the number of years needed to establish a trend. Workers may hypothesize that ecosystem variability over time is a cyclical process and that the basic spatial structure of the channel longitudinal profile will exist in a similar form over intermediate time periods (years to decades). However, recent literature has defined formerly glaciated areas to be paraglacial landscapes (i.e., transitional terrains that are in the process of recovering from glaciation) (Slaymaker 2011). This knowledge can be used to support the use of alternative conceptual models for organizing monitoring studies.

An important model that has influenced monitoring protocols is the river continuum concept (RCC) (Vannote and others 1980). The RCC used the longitudinal profile of a prototypical river basin to link a continuum of physical characteristics with corresponding biological elements. The biological subsystems in natural river systems were thought to be in equilibrium with the physical components of the channel. In turn, the channel presented a *mean state*, or average condition, at each location on the continuum (Vannote and others 1980).

Geomorphic theories from the 20th century are underlain by models of an equilibrium channel profile in which channel slope adjusts regularly downstream in response to increases in drainage area and discharge (Leopold and others 1964) which, in turn, give rise to systematic downstream changes in fluvial processes and landforms. Mackin (1948) observed that “graded” or equilibrium stream channels return cyclically to a mean state at intermediate time scales (e.g., years); any change in controlling variables will cause a displacement of the equilibrium in a direction that tends to absorb the effect of change. Other studies found that lowland alluvial channels display no net change over time periods of years to decades (Leopold and Maddock 1953). In this view, the stream and its channel will progress towards a mean form that can be defined in terms of statistical means and extremes (Chorley 1962).

The equilibrium concept was also extended to physiographic regions; similar landforms are thought to develop an equilibrium response to shared topographic and geologic conditions.

Based upon the understanding of glaciated areas as transitional landscapes, there is a need for an alternative conceptual model that is based on an understanding of headwaters recovering from past glacial disturbance (Slaymaker 2011). These landscapes display episodic processes, especially mass movements, that may alter the landscape until the next glacial episode (Ballantyne 2002; Brardinoni and Hassan 2006; Collins and Montgomery 2011; Slaymaker 2011). Moreover, disequilibrium landscapes and features present a diversity of forms and a dependence on regional conditions that make generalized definitions of the characteristics of these landforms important only as starting points (Millar and Westfall 2008; Wilson 2009). Research on taluses and "rock-ice" features has demonstrated that equifinality (i.e., a similar state produced from differing origins) may result from proglacial (increased activity at the glacial terminus during deglaciation), periglacial (e.g., freeze-thaw or permafrost), and post-glacial erosion processes, or a combination of the three (Wilson 2009; Slaymaker 2011).

Regardless of origin, the paraglacial features and channels discussed in this monitoring framework vary in part according to the nature of mass wasting processes and associated landforms occurring within a particular landscape context. Three types of post-glacial mass movements have consideration for this monitoring framework. The first two types, debris flows and landsliding, are active disturbance events often originating from unstable glacial drift. Both produce distinct taluses and other hillslope features and continue until the sediment supply is exhausted. Debris flows may periodically scour portions of a headwater channel to bedrock producing paraglacial fans below (Ryder, 1971; White 1981). Downstream, headwater channels with sufficient transport capacity characteristically move accumulations of debris from glacial retreat and post-glacial processes produced upslope as sediment waves or pulses that move along the channel longitudinal profile (Ballantyne 2002; Czuba and others 2010).

The third characteristic type, rockfall or rock-sliding, differs from debris flows and other currently active, episodic mass movement regimes. Landforms created by rockfall are often relicts of earlier, more catastrophic periods occurring during deglaciation or colder climate regimes (Wilson 2009). In some temperate regions, under current climate conditions, rockfall may occur intermittently if at all. Hence, present day features are often relict accumulations of massive angular boulders that, over time, have coalesced into a variety of forms ranging from talus footslopes to protalus ramparts or rock glacier deposits (Gerber and Scheidegger 1974; White 1981; Millar and Westfall 2008). The rock mantle characteristic of these features may buffer subsurface sediments, groundwater, ice lenses, or glacial ice from surficial temperatures, thereby establishing protected habitats that are not in equilibrium with current climate forcing (Fickert and others 2007; Millar and Westfall 2008).

Glacial Macroform Structure

The dynamics of glaciated mountain headwaters are dependent on the macroform structures that are remnants of erosional and depositional processes from Pleistocene and Holocene glacial episodes. These landforms constrain basin shape, defining the dominant morphology of many high elevation mountain headwaters and dictate postglacial landscape architecture (Brardinoni and Hassan 2006, 2007). Comparable landforms are often found at analogous elevations, reflecting Pleistocene and Holocene climate patterns. These structures integrate variables such as slope, elevation, and landscape features (Brardinoni and Hassan 2006).

The glacial macroform structure is a fundamental control on the basic architecture of the drainage network at the basin and sub-basin scale in alpine headwaters. The typical trellis-like pattern of the channel network within u-shaped glacial valleys is a function of glacial/fluvial processes associated with mainstem alpine glaciers (Fig. 1). The upper basin channel network pattern is often more complex than that found downstream and is controlled by cirque valley structures created from remnant Holocene alpine glaciation. In contrast, unglaciated stream networks often display self-organized dendritic drainage network patterns created by fluvial processes.

The glacial macroform structure, in conjunction with subsequent disturbance processes, determines the three-dimensional longitudinal profile. In relict terrains, the stepped longitudinal profile is a defining characteristic of erosion and depositional processes from past glacial activity (Brardinoni and Hassan 2007) that displays abrupt transitions between valleys (i.e., cirque, hanging valley and glacial troughs) and valley steps (e.g., cirque walls and bedrock canyons) (Fig. 2). As a result, morphological types are spatially discontinuous, each signifying a range of geomorphic and hydrologic processes. When identified as functional units along the channel profile, these structures are important as drivers of streamflow and sediment transport regimes (Montgomery 1999).

The stepped longitudinal profile produces a sequence of channel types whose features and arrangement differ from the erosional and depositional signature of fluvial processes in unglaciated stream basins (Brardinoni and Hassan 2006, 2007). The downstream sequence of fluvial channel processes along the concave longitudinal profile gives rise to empirical associations based on drainage area or distance

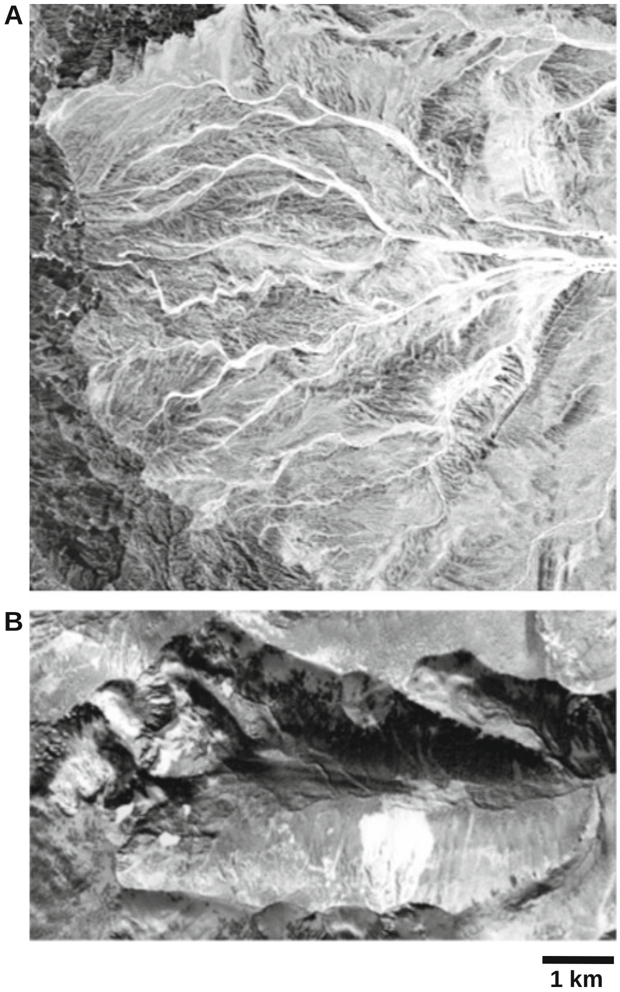

Fig. 1 Examples of stream network patterns generated by different geological processes in mountain drainage basins **a** a dendritic pattern created by fluvial processes in the unglaciated Borrego Badlands, USA, and **b** a trellis pattern shaped by glacial/fluvial processes in Lost Creek basin, Mt. Rainier National Park, USA. The spatial extent of the Lost Creek channel network is constrained by the most recent glacial footprint

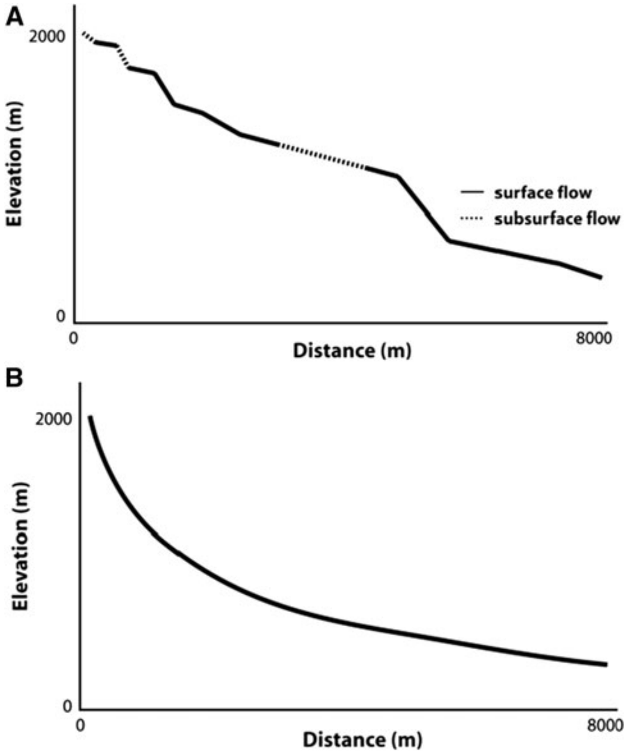

Fig. 2 Examples of channel longitudinal profiles used to model geomorphic channel relationships, including a **a** stepped channel longitudinal profile derived from a survey of Lost Creek, Mt. Rainier National Park, Washington State, USA, common to relict glaciated headwaters, and **b** an idealized concave channel longitudinal profile typical of river basin morphology controlled by fluvial channel processes. Lengthy segments of subsurface channel flow beneath accumulated mass movement debris are more common in the stepped longitudinal profile

downstream and channel variables (e.g., slope, and discharge) (Leopold and others 1964; Montgomery and Buffington 1997). Such variables permit interpolation between elements along an uninterrupted continuum (Hack 1957). In contrast, the stepped longitudinal profile common to relict glaciated mountain headwaters does not provide an uninterrupted continuum, but instead, the overriding effects of diverse glacial and paraglacial features reset local controls on fluvial processes (Montgomery and Buffington 1998; Brardinoni and Hassan 2006).

Colluvial Channels

The term "colluvial channel" was originally used to describe unglaciated reach-scale headwater streams that have a weak or ephemeral fluvial transport capacity within soil-mantled hillslopes along concave longitudinal profiles (Montgomery and Buffington 1997, 1998). These first-order streams occur where drainage areas are large enough relative to local slope to sustain a channel and are associated with hillslope processes such as soil creep, tree throw, animal burrows and small scale slope instabilities. Low-order channels in alpine basins often differ from those of unglaciated mountain headwaters. Lacking soil cover, there are numerous ways in which streamflow is moderated and filtered through depositional material more commonly composed of debris from mass movements.

A recent study of moderate elevation (400–1,200 m) relict glacial basins in British Columbia, Canada with a single intrusive lithology identified two types of colluvial channel, source and sink, that were associated with debris flows and landsliding (Brardinoni and Hassan 2006, 2007). The authors hypothesized that channel types are differentiated according to the spatial distribution of transport processes; very steep source channels are longitudinally scoured by debris flows, whereas moderately steep sink

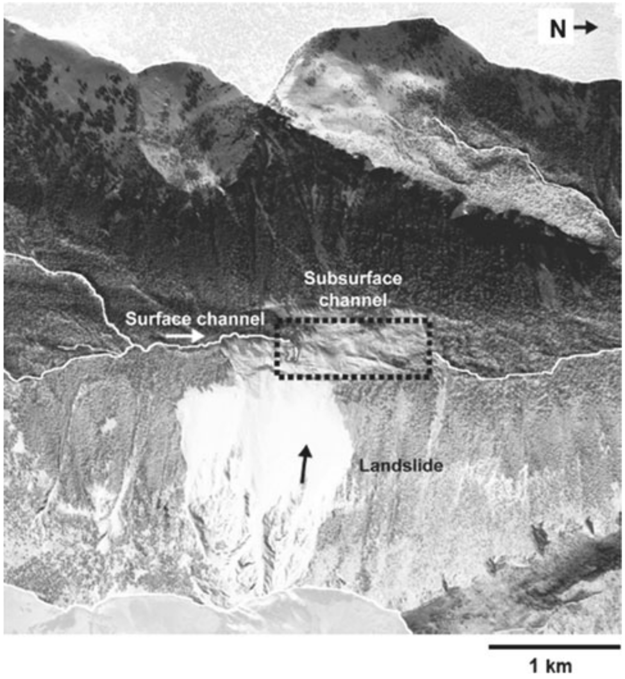

Fig. 3 Detail of a hanging glacial valley section of Lost Creek basin in Mt. Rainier National Park (MORA), Washington State, USA illustrates a sink colluvial channel type. The surface channel (*white line*) transitions to subsurface flow (*black box*) for 1.2 km beneath the debris of a large landslide

channels are associated with incomplete routing of landslide debris. These understeepened reaches occur on valley steps and glacial troughs where the valley floor is constrained. Coupling between valley walls and the understeepened valley floor can produce accumulations of material that may remain in long-term storage from years to decades (Brardinoni and Hassan 2006). These valley-channel associations are widespread in relict glacial valleys and troughs across mountain regions (Swanson and others 1988; McCleary and others 2011).

Sink colluvial channels may also be buried by colluvium for significant distances. For example, a recent study at Lost Creek, Mt. Rainier National Park (MORA), Washington State, USA (Fig. 3), found buried channel flows beneath landslide debris for 1.2 km in a large hanging valley. Sink colluvial channels of this type may not erode for long time periods because debris from episodic landsliding exceeds any form of fluvial transport process. However, the temporal evolution of landslide accumulation zones and other depositional features in glacial valleys may vary significantly based upon differences in geology, climate, and topography between and among regions (Ballantyne 2002). As a result, although the effects of fluvial processes along the channel longitudinal profile generally increase with drainage area, layering of accumulated colluvium may produce buried subsurface flowpaths beneath alluvial surface channels; in this scenario, the visible channel may be too small to represent the full discharge associated with the drainage area at that point.

The upper basin areas in alpine zones, however, are potentially affected by a range of proglacial, periglacial, and post-glacial dynamics that can occur across many different timeframes (Slaymaker 2011); these processes may produce depositional features and linked channels that are functionally similar, but morphologically distinct. For example, talus features originate from a number of initial conditions and disturbance processes, but may result in similar slope features (van Steijn and others 2002; Whalley and Azizi 2003). Footslope talus structures in particular may differ in the time since their formation and the sequence of processes from which they originate, but they are associated with a range of water storage and channel initiation functions that generate source channels, in addition to springs and wetlands (Millar and Westfall 2008).

To account for these important variations in alpine basins, we have subdivided source colluvial channels into two first order channel types. “Active” channels, such as colluvial rills or gullies, flow upon features associated with ongoing mass movements (Fig. 4a). These channel types often exhibit ephemeral or seasonal channel flow and may resemble avalanche gullies and snowmelt swales on actively eroding steep talus slopes. However, all colluvial channel types, although limited in their fluvial transport capacity, act as conduits for channel flow (Montgomery and Buffington 1997). Colluvial channels exhibit flow regimes that are a function of sediment source or debris flow initiation zones and are independent of hillslope sheetflow.

Relict source channels are formed within paraglacial features that are not likely to be significantly altered by mass movements such as rockfall, landsliding, or avalanching from the slopes above. Intermittent or periodic events may carry larger clasts to the talus foot or surface of depositional features, but functionally they are in a quasi-stable or relict state. Falling rocks and boulders rarely affect the subsurface structure beneath the rock mantle (Wilson 2009) (Fig. 4b). Instead, granular weathering and other slow-acting mass wasting mechanisms including slope wash, slump, and creep remove finer debris from the talus pile (Moore and others 2009). The fine-grained sediments produced from these processes (Hinchcliffe and others 1998) form lenses of fine sediments (gravels and sands) underneath the coarse-grained rock mantle that may act to store water or ice (Clow and others 2003; Millar and Westfall 2008). Source channels embedded within these landforms act as exfiltration zones; both landform and channel may exhibit wide variations in their relative capacity to channel, filter, and store precipitation, ice, and snowmelt (Clow and others 2003; Roy and Hayashi 2009).

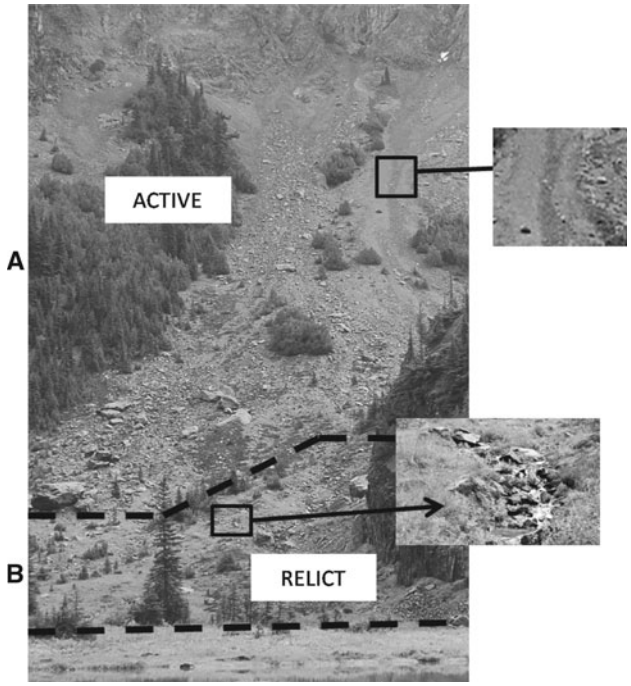

Fig. 4 A Holocene talus slope above Shaw Creek, Mt. Rainier National Park (MORA), Washington State, USA, can be divided into two zones typical of this region; a semi-stable vegetated talus footslope beneath an actively eroding scree slope. An active source channel **a** is shown to the *right* of the larger illustration *above*. In the vegetated zone below, a perennial relict source channel **b** is shown to the *right* of the larger illustration. *Large-sized* clasts from intermittent landsliding and rock fall in the active zone have little effect on the subsurface structure of the footslope, habitat for cold-water benthic macroinvertebrates such as *Zapada columbiana* (Kubo and others in press)

All colluvial channels are similar in their capacity to reset local slope along the channel longitudinal profile, disrupting the characteristic negative relation between drainage area and gradient (Hack 1957; Montgomery and Buffington 1998; Brardinoni and Hassan 2006). However, although active source channels are linked to over-steepened slopes, relict and sink colluvial channels, like soil-mantled colluvial channels, exhibit a range of gradients (5–30 %) due to the range of conditions associated with an excess sediment supply.

Stratifying the Landscape and Organizing Hypotheses

The hierarchical conceptual framework presented here is intended to be used to stratify critical differences in channel origins, morphologies, and controlling processes at spatial scales associated with the glacially derived landscape structure. The channel longitudinal profile, nested within its drainage network, is used as the basis for this approach, offering a system to account for diverse process-form relationships at multiple scales. The taxonomy of geohydrologic features and processes (Fig. 5) identifies each system level of the hierarchical framework (e.g., regional context, basin, valley, valley-segment, and reach) and is associated with different suites of nested processes at decreasing spatial and temporal scales (Frissell and others 1986; Poff 1997; Montgomery 1999). Accounting for physical controls at sequentially smaller scales addresses the mismatch between the small spatial scales of biological sampling (i.e., benthic invertebrates are sampled at scales of 1–2 m^2), and the larger units characteristic of basin processes and morphological context (1–25 km^2). Furthermore, 'scaling down' from regional scales will provide a useful method to understand the effects of nested environmental drivers (Frissell and others 1986; Poff 1997; Montgomery 1999). Below the regional scale, each level is intended to clarify controls imposed by larger-scale geohydrologic features on smaller scale units.

Successful monitoring in any landscape requires an approach that provides the capability to choose aquatic sampling sites in comparable landscapes. Although by no means exhaustive, the framework we propose recognizes a large number of strata. If the framework is used according to concepts of stratification and replication as described by Conquest and Ralph (1998), the study design to the valley segment-scale may require as many as 216 basic strata. In the unlikely event that the full range of alluvial (e.g., cascade, step-pool, plane-bed, pool-riffle, and dune-ripple), and colluvial channel types are present in an alpine headwater basin, such a condition would require 1728 strata. Hence, application of a statistically valid alpine monitoring project at the landscape scale in highly complex environments may be unattainable. Of equal importance, however, is the use of this framework to identify linked geomorphic-ecologic hypotheses nested within specific levels to improve process-based knowledge that could potentially be extrapolated across a region.

The components of the framework are outlined below.

Regional-Scale Context

Climate, topography, and geology are fundamental drivers of physical processes in mountain drainages (Montgomery 1999). In glaciated mountains, identifiable landforms produced by the temporal state of glaciation (e.g., active, mixed, relict) control channel processes at the regional level regardless of influences at finer scales (Brardinoni and Hassan 2006). Such morphological controls may contribute to a process-based context necessary for successful application of the correlative approaches generally used for monitoring purposes. Poff (1997) writes that the use of correlative approaches may be justified when species distribution and abundance are examined in response to

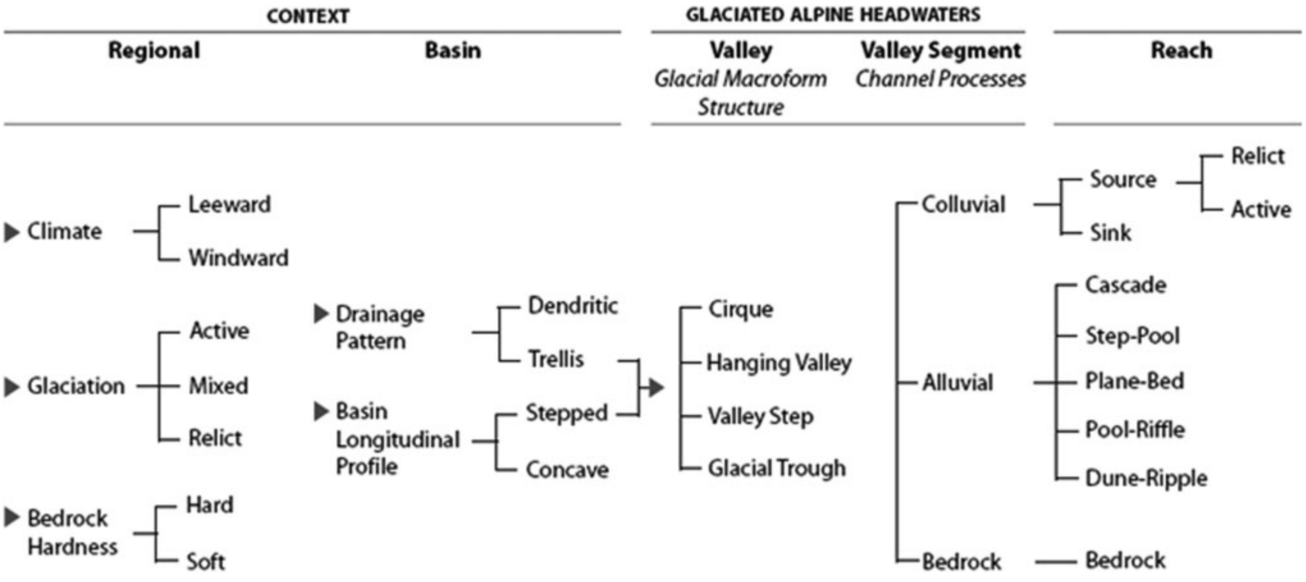

Fig. 5 The hierarchical framework showing regional, basin, valley, valley segment and reach-scale levels is based on processes and morphologies common to glaciated alpine headwaters. Regional processes drive drainage network pattern and valley-scale morphology. The structural characteristics of glacial macroforms supply the basic template (i.e., oversteepened valley walls, depositional landforms, and stepped longitudinal channel profiles) that constrain channel processes. At the valley segment-scale, channels include colluvial, alluvial, and bedrock types. At the reach-scale, colluvial channels include source and sink types. Source colluvial channel vary according to mass movement activity; relict source channels are found in landforms experiencing inactive or intermittent rockfall or rocksliding of less magnitude than former mass wasting processes. Active source channels are associated with active mass movements. Alluvial channels also differ at the reach scale, including cascade, step-pool, plane-bed, pool-riffle, and dune-ripple channel types (Montgomery and Buffington 1997)

strongly selective physiological gradients, for which an unambiguous, mechanistic interpretation at larger scales is available. Otherwise, inferences about species/habitat relationships may be questionable because significant habitat factors may change across sites due to landscape constraints at multiple scales (Poff 1997).

The distinction between active or relict glacial status within a headwater basin has significant implications for the temporal and spatial characteristics of streamflow patterns, water source mechanisms, and sediment production. In basins covered by a significant percentage of active glaciers, discharge volumes from meltwaters may dominate streamflow regimes during the summer season in some regions (Füreder 2007), and may obscure flows from other water sources such as drainage from coupled hillslope aquifers. Increased stream power can accelerate fluvial erosion and transport processes and incise glacial valleys and valley steps. In contrast, channels in relict glacial basins present diverse hydrological conditions that may be of critical importance to aquatic biota if atmospheric temperatures continue their warming trend (Millar and Westfall 2008; Brown and others 2009).

Bedrock hardness is a complex measure that also may have significant implications for the sampling frame developed for large-scale monitoring initiatives. This metric refers to the intact strength of the dominant rock type(s) in conjunction with the presence and orientation of discontinuities and the characteristics of the parent rockwall environment (Moore and others 2009), and is associated with a suite of geological variables that may ultimately control the longevity of relict glacial landforms (Rapp 1960; Ballantyne 2002). These include the rate of retreat of the rock face, the size and type of rockfall debris, and *in situ* weathering processes (Moore and others 2009; Wilson 2009). Although there are few studies that directly address the erosion rates of glacial macroform structures composed of different lithologies, bedrock hardness is associated with mechanistic properties that affect habitat characteristics over long timeframes, ranging from valley-scale structure to the array of possible channel substrates at the reach-scale.

Valley Scale

Valley-scale units, the fundamental building blocks of glaciated basins, are particularly useful for differentiating between geohydrologic process-form relationships along the stepped longitudinal profile (Brardinoni and Hassan 2006). Distinct channel slope, elevation, transport capacity, and sediment supply relationships, and associated filtering, storage and runoff mechanisms are found within each valley-scale unit. However, such mechanisms are also affected at the valley segment-scale due to abrupt differences in channel type forced by smaller features. However, the sequence of valleys and valley steps with their various hydrological properties imparts dynamics unique to each headwater basin.

The hydrologic variability of relict glaciated alpine headwaters is pronounced, even in cases where basic physical parameters are similar. A recent study in the Cascade Mountains of Washington State, USA, showed that streamflow response in adjoining headwater basins with comparable elements can differ by an order of magnitude at each headwater basin outlet (Weekes 2009). Common valley-scale features, such as incised bedrock canyons, cirque walls, and hanging glacial valleys, were found in all the study basins at similar elevations. Basin size, mean slope, elevation range, climate, and lithology were also comparable. The difference in streamflow response was largely due to the sequence, presence, or absence of colluvial depositional features within the valley or valley step.

An advantage of identifying the valley-scale spatial unit according to process -form characteristics is apparent when the objective is to monitor response to climate variability. The disequilibrium between relict glacial macroforms and disturbance processes may produce long-lasting shifts in transport capacity and sediment supply relationships within channels (Brardinoni and Hassan 2007). In conjunction with localized fluvial and disturbance processes, these elements provide a context in which to compare critical temporal and spatial changes in habitat morphology and response.

Valley Segment

The stepped longitudinal profile in alpine environments is often bisected by diverse paraglacial features that can occur in close proximity, producing significant differences in channel form and process that may change abruptly over short distances (i.e., 10–40 m). Hence, valley segment morphology provides a useful scale for determining dominant sediment transport processes (fluvial vs. mass wasting), sediment flux characteristics (transport- versus supply-limited), and associated streamflow characteristics. Characterized by colluvial, alluvial, and bedrock channel types, these morphologies are defined by differences between valley fill, sediment transport processes, channel transport capacity, and sediment supply (Montgomery and Buffington 1998).

Streamflow and sediment regimes found in colluvial, alluvial, and bedrock channel types range from the excess sediment supply and limited transport capacity associated with colluvial domains to the high transport capacity linked to channel incision in steep bedrock canyons. Alluvial channel types fall between these two extremes (Montgomery and Buffington 1997). Differences in streamflow and sediment regimes are a function of the balance between channel slope and sediment size that accommodates changes in hydraulic discharge and sediment supply (Lane 1955). Differences are also caused by the ability of fluvial (alluvial and bedrock) channels to be self-forming. In contrast, colluvial channels in glaciated headwaters lack the transport capacity to change their basic geometry; channel flowpaths are imposed by external structures and processes in concert with climate forcing.

The diverse characteristics of colluvial, alluvial, and bedrock channel morphologies drive hydrologic response within the channel and are useful tools to identify habitat space and integrate functional characteristics along the channel profile. For monitoring purposes, these geohydrologic differences are of critical importance to biota (Füreder 2007), because the spectrum of channel types and associated streamflow regimes bridge the gap between basin context and the fine-scale metrics that characterize aquatic habitat (i.e., water temperature patterns, dissolved oxygen, local sediments) (Frissell and others 1986). Hence, these hierarchical levels can be used to interpolate the spatial extent of slow or flashy streamflow regimes or discern water temperature patterns aided by point-based measurements.

Reach-Scale, Source Waters, and the Sampling Unit

Reach-scale alluvial channel types incorporate a variety of morphologies that are functionally similar at the valley segment-scale, but respond differently to similar sediment load and discharge (Montgomery and Buffington 1998). In contrast, colluvial channels (i.e., relict source, active source, and sink) are unique to alpine terrains. Variation in colluvial channel types is caused by spatial (e.g., location along the longitudinal profile within the channel network) and temporal characteristics (intensity, magnitude, frequency, and sequence of post-glacial mass wasting processes) that cause channel structures and processes to diverge over time.

Relict source channels (Fig. 6a) are embedded in landforms that may have been created during deglaciation by catastrophic proglacial mass movements or formed by periglacial processes during colder climates. Although such mechanisms may be inactive or intermittent in the present climate, large accumulations of boulder-sized lag could become source areas for sediment transport by catastrophic erosional processes, or future glacial epochs. Intermittent rockfall or rocksliding may add to the colluvium; source channels formed beneath these coarse-grained sediments

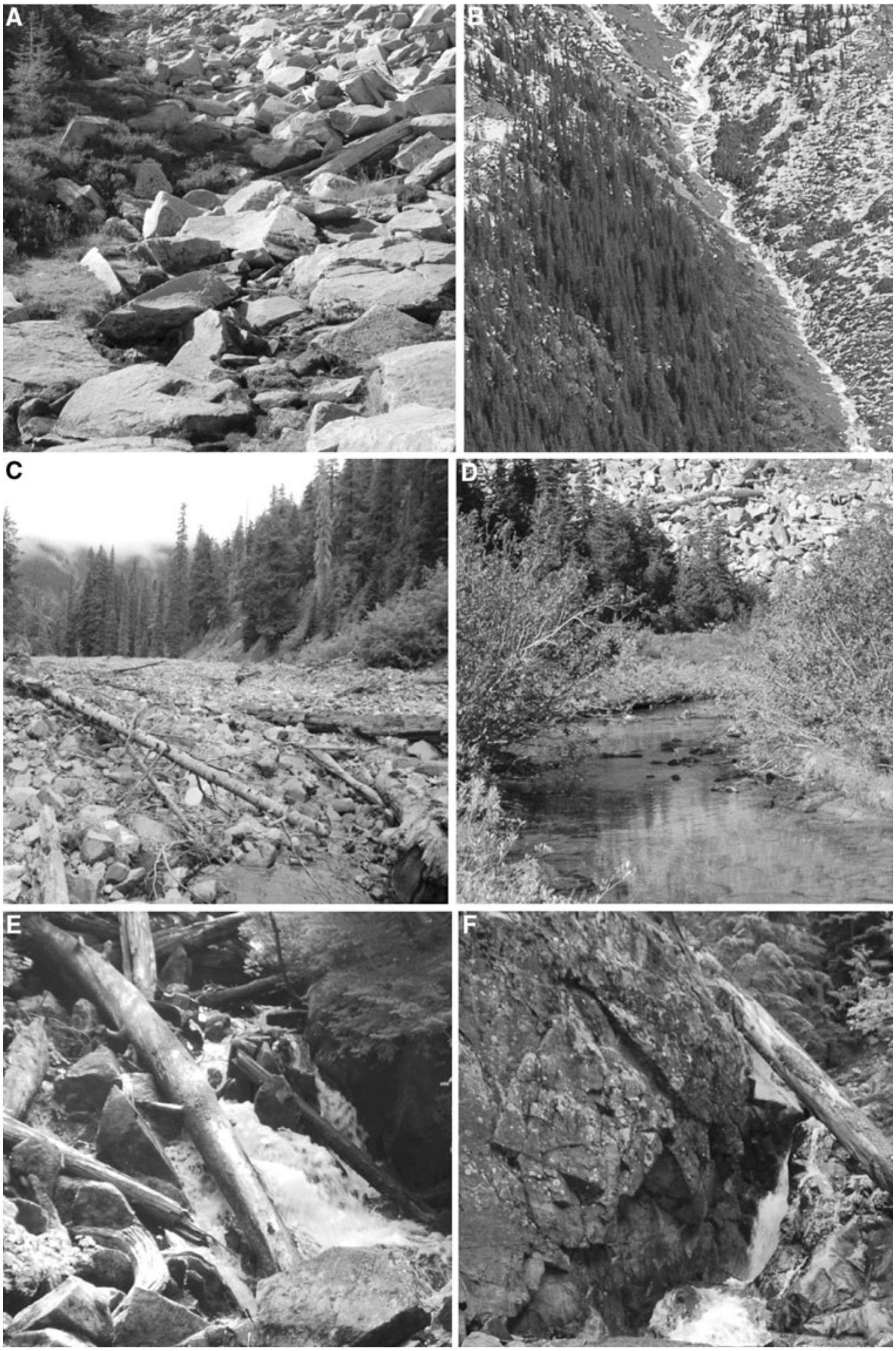

Fig. 6 Examples of stream types found in relict alpine mountain headwaters. Colluvial channel types include a **a** relict source colluvial channel (Snow Lake) showing characteristic lag of large boulders, **b** active source colluvial channel (Wilson Creek) showing loose colluvium within the steep channel bed, and a **c** sink colluvial channel (Shaw Creek). In this case, the undersized channel is flowing beneath the coarse-grained deposition. Fluvial channel types found in cirque and hanging glacial valleys include **d** an alluvial sand-bedded (dune-ripple) channel (Snow Lake), **e** and alluvial cascade channel with boulders and large woody debris (Snow Lake), and **f** bedrock channel (Shaw Creek). All representative channels are found in Mt. Rainier National Park, Washington State, USA

are typically buffered from external processes and atmospheric climate forcings. As a consequence of the relative immobility of these features over time, relict channels are likely to be more hydrologically and structurally complex compared to active source channels.

Active source channels (Fig. 6b) are associated with ongoing mass movements. They exhibit surface channel flow on steep slopes within a matrix of currently dynamic hillslope processes and are altered episodically; channel process-form relationships created in the current channel may not withstand the next disturbance event. Transport by debris flow accounts for most of the sediment movement in these steep headwater channels (Swanson and others 1988). Between disturbance events, active colluvial channels are associated with poorly sorted bed material in finer grain sizes compared to alluvial (and sink colluvial) reaches downstream (Benda 1990).

Sink channels (Fig. 6c) are accumulation zones associated with larger (usually main channel) drainage areas, recipients of debris from lateral active source channels, and mass wasting events. In cases where channel flowpaths are buried beneath debris, sink colluvial channels can exhibit moderated streamflows and water temperatures similar to groundwater and hyporheic flow characteristics on large river alluvial floodplains. In such cases where coarse-grained surficial lag buffers subsurface flowpaths from atmospheric temperatures, sink channels, like relict source channels, may be in disequilibrium with climate like relict source colluvial channels.

Alluvial channels exhibit a wide variety of bed morphologies and roughness characteristics that do not differ significantly between higher-elevation alpine headwaters and unglaciated mountain basins. Alluvial channel types vary from coarse-grained cascade channels (Fig. 6e) found on valley steps, to dune-ripple channels (Fig. 6d) like sand-bed channels flowing on former cirque lakebeds or valley flats. Bedrock reaches (Fig. 6f) are generally confined by valley or canyon walls and the channel bed, exhibit little valley fill, and lack floodplains. Bedrock headwater channels with steep gradients may be created by episodic debris flows that scour active source colluvial channels to bedrock (Benda 1990; Montgomery and Buffington 1998). Sink colluvial channels are less likely to be scoured by debris flows (Brardinoni and Hassan 2006).

Reach-scale morphologies offer more detailed information on aquatic habitats and species functional traits necessary when stratifying differences between sampling unit types for aquatic monitoring. Moreover, this scale is more amenable to finer-scale (m^2) sampling protocols, especially those that would quantify the composition of the source waters integrated into streamflow in the upper headwaters (Brown and others 2003; Brown and others 2009). Streamflow is usefully classified according to the percentage of glacial distributed flow, groundwater, and quickflow, or surface runoff found in the channel habitat during the period of interest (Brown and others 2009). The composition of streamflow derived from these sources is highly variable on interannual and seasonal time scales and controls fine-scale ecological community dynamics in alpine headwaters (Brown and others 2009). This temporal and spatial heterogeneity affects the long-term adjustment of macroinvertebrate communities (Brown and others 2006b; Milner and others 2006) and zooplankton (Robinson and Matthaei 2007). The spatial position of habitat types along the channel longitudinal profile may also affect the persistence and dispersal of alpine aquatic taxa (Robinson and Matthaei 2007).

Classification of upper headwater streams by water source characteristics provides information on a critical driver of biotic response necessary to understanding ecosystem dynamics. However, the temporal variability of water source characteristics within headwater basins is such that this method, if used alone, may be too limited in time and space to interpret monitoring data across landscapes. To better understand the dynamics of species assemblages and their habitats, especially in the context of climate change, water source classification methods, such as alpine river and stream ecosystem classification (ARISE) (Brown and others 2009), would ideally be combined with the nested hierarchical approach presented here.

Implications for Monitoring

A recent case study applied this hierarchical framework to three cirque basins in MORA, USA, to test the usefulness of colluvial and alluvial strata as a means to identify potential differences in aquatic insect assemblages useful for monitoring (Kubo and others in press). These strata reflected the sudden shifts in channel attributes typical of some subalpine cirques and included several types of relict source groundwater channels formed within partially vegetated talus. Alluvial dune-ripple inlet channels were located on the valley flat above their respective cirque lakes, and alluvial cascade lake outlets flowed from the cirque lakes. Each channel segment was associated with marked differences in stream temperature, substrate composition, and hydrologic regime.

Results from the MORA case study showed high variation in assemblage composition (β diversity) among channel strata across basins (Kubo and others 2012). These results may support the hypothesis that similarities in channel processes and context are associated with similar species types (Shelford 1911; Shelford and Allee 1912; Poff 1997). Many taxa in the study were identified to the species level, allowing finer-scale determinations of species habitat preferences related to channel characteristics. For example, researchers have observed that water temperature conditions greatly influence species distribution (e.g., Vannote and Sweeney 1980); specimens of *Zapada* (Plecoptera) exhibit this characteristic. In the MORA, case study, 83 % (by insect density) of the observations of *Zapada columbiana* occurred in relict source colluvial channels, whereas *Zapada cinctipes* and *Zapada oregonensis gr.* were found in outlet channels.

Previous work specific to ice glacier-fed alpine streams has shown that water temperature controls macroinvertebrate distribution along the channel profile (Milner and Petts 1994; Milner and others 2001). In ice glacier-fed streams, taxon richness increased with downstream temperature according to the distance from the glacier. However, in complex paraglacial landscapes, water temperatures in relict glaciated stream systems appear to be highly variable in the downstream direction depending on geomorphic context. Kubo and others (2012) suggest that water temperature requirements are a critical driver of species distribution, but differences in channel type and geomorphic context affect water temperature values.

The results of this study raised questions about the degree to which higher level parameters potentially drive species assemblage composition; channel type characteristics, such as water temperature, substrate composition, and water source contribution are constrained by regional and valley scale parameters (Frissell and others 1986; Poff 1997). For example, relict source channels embedded within talus features exhibit attributes linked to the glacial macroform structure. This contextual information is needed to interpret “hot spots” in the abundance of rare taxa not found in adjacent alluvial channels downstream.

Streamflow Heterogeneity

Complex interactions between heterogeneous sediments, rock, ice, and available water affect when and how different combinations of source waters are delivered to the channel and produce varied streamflow regimes. In the upper headwaters, the amount and timing of spatially disjunct water sources, as incorporated into streamflow, are known to be highly variable seasonally and among years (Brown and others 2006a; Brown and others 2009). The ability to constrain the extent of hydrologic variability may be one of the more difficult tasks of a long-term monitoring initiative, particularly in remote locations. Necessary elements of the sampling framework (i.e., the choice of sampling unit, number of site visits, and length of the time a particular site is monitored) require knowledge of the hydrologic context. Hydrological indices (i.e., streamflow and water temperature measurements) may need to be used in conjunction with assessments of relict and active glacial features and structures.

The time frames associated with the processes operating within a basin are often very different from those associated with glacial macroform structures. Relict glacial structures such as hanging glacial valleys may persist into the next glacial epoch (Brardinoni and Hassan 2007), but significant changes in patterns of response within disjunct valley and valley segment-scale channels may occur much more frequently (e.g., over multiple years). Colluvial, alluvial, and bedrock channels that change from one condition to another due to disturbance processes such as debris flow may remain in a new state for an unknown period of time.

Climate Dynamics and Hydrologic Response

Past climate patterns are unlikely to resemble those of the future (Baron and others 2009). Paraglacial environments are characterized by a lack of alignment between contemporary erosion processes and the underlying erosion signature (Slaymaker 2011). Monitoring approaches intended for use in glaciated mountain headwaters cannot assume a return to a prior condition or mean habitat structure within intermediate timeframes (i.e., years to decades). Therefore, long-term stream monitoring protocols may need to explicitly address the temporal variability of hydrological response in the context of climate patterns (i.e., interdecadal oscillations, mean temperature trends). Approaches that use concepts of dynamic equilibrium as a proxy for temporal variability in the sampling framework may not apply to climate change.

Historical relationships between climate and hydrologic response are also unlikely to be applicable for interpolating status and trends in mountain ecosystems in coming decades. For example, aquatic habitats altered by the lack of summer flows from the loss of active ice glaciers are not likely to return to former hydrological conditions. Response to unanticipated climate patterns is best evaluated by a comprehensive understanding of current ecological and physical mechanisms (Baron and others 2009). Generating and testing coupled physical-ecological hypotheses can help to advance knowledge of these processes (Table 1). The number of explanations possible for a particular physical state (Montgomery and MacDonald 2002) highlights the need to establish clearly defined ecological benchmarks when monitoring these ecosystems. Maps showing landscape organization for a study area are important for formulating linked physical-ecological processes, and for locating sample sites for associated case studies. Such maps show that all types of colluvial channels can occur in the same headwater basin. An example of this situation occurs in Shaw Creek in MORA, where active source, relict source, and sink colluvial channel types have been mapped along the channel longitudinal profile (Fig. 7).

Channel response to natural disturbance processes is one aspect of temporal variability in mountain ecosystems. The fact that the relationships between hydrologic response and climate dynamics along the longitudinal profile are not always linear has important implications for biological monitoring applications. It may be necessary to track the relationship between climate forcings and channel response

Table 1 Examples of linked physical–ecological hypotheses placed in context using the proposed framework

Macroform structure	Channel reach	Forecast disturbance type	Forecast disturbance trend	Linked physical-ecological hypotheses	Signal to noise ratio
Cirque wall with abundant unstable glacial drift	Active source colluvial	Periodic scouring from landslides in glacial drift	Decreasing frequency and intensity until paraglacial deposits are exhausted	Periodic destruction of ecological community with trend towards stability	low
Over-steepened cirque wall	Active source colluvial	Periodic scouring from landslides in eroded bedrock	Steady	Periodic destruction of ecological community	low
Cirque wall and footslope with relict talus features	Relict source colluvial	Intermittent rockfall; slow weathering, slump, creep, groundwater	Intermittent or inactive	Little or no disturbance of ecological community; potential refugia	low
Hanging valley	Sink colluvial	Periodic deposition from upstream mass movements	Linked to upstream reaches	Geomorphic and ecologic stability increases with distance from active deposition zone	Increases with distance from debris flow runout zone

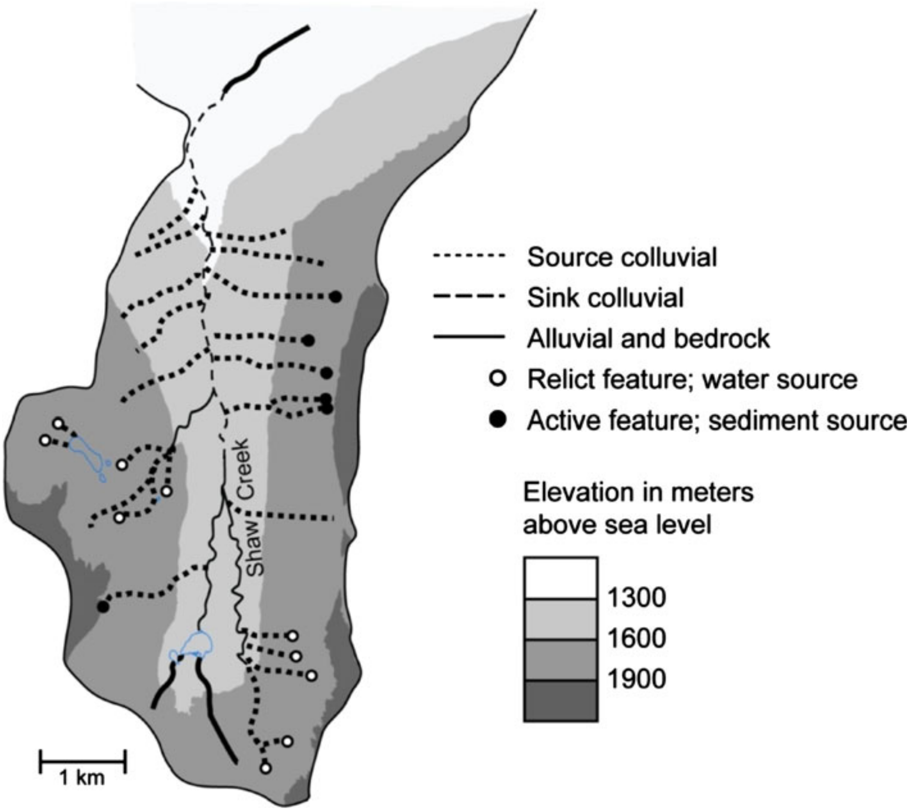

Fig. 7 Map of Shaw Creek (MORA) showing relict, active, and sink colluvial and fluvial (alluvial and bedrock) channels within a relict glaciated basin

at particular spatial locations over time in order to understand these dynamics.

The physical complexity of alpine environments in conjunction with climate-induced change presents real challenges to the identification and quantification of habitat characteristics in terms of selective forces that induce mortality. In paraglacial landscapes, the non-linearity of natural hydrologic processes, especially lag effects and other forms of temporal variation (McDonnell 2003), present a mosaic of aquatic habitats. These varied conditions provide an opportunity to choose sample populations that are likely to be associated with species attributes and functional traits of ecological interest. Although the persistence of alpine aquatic taxa is generally associated with relatively constant conditions, particularly groundwater-fed channels that produce lower flow velocities and moderated temperature regimes (Brown and others 2006b; Milner and others 2006), such conditions are in many cases dependent on the temporal variability of higher level process drivers. If a goal of a monitoring program is to identify species survival strategies in response to changing climate trends, some channel habitats may provide more stable conditions specific to this purpose. Relict source channels, in particular, may prove valuable to better understand alpine species survival strategies, although they may be less helpful for assessing direct species response to climate.

Critical Uncertainties Associated with the Sampling Framework

The use of hierarchical frameworks to account for scaling relationships has been utilized in ecological research and monitoring for some time (Frissell and others 1986). The conceptual model presented here is based on our emerging understanding of alpine habitats as complex paraglacial systems in long-term disequilibrium, but exhibiting unique structural signatures. It is possible that some morphologies will remain stable over short timeframes and could be effectively modeled using equilibrium concepts if the goals of the monitoring initiative focus on localized stressors. However, environmental factors that can be explained by unambiguous, mechanistic explanations associated with larger spatial scales are likely to provide the greatest insight on species distribution and the selective mechanisms that affect populations (Poff 1997).

Monitoring protocols may use correlative approaches to infer potential changes in species-habitat relationships. However, such approaches assume consistent conditions among sites (Poff 1997); this assumption is not valid in paraglacial landscapes. The initial selection of sampling sites, in conjunction with the *de facto* choice of a baseline condition, depends on our current knowledge of past and present physical controls. These decisions are based on empirical data and on a conceptual model of alpine ecosystems. Information on species assemblages and functional traits can aid in identifying indicator taxa.

Understanding and using higher-level mechanistic and process-based information to differentiate among strata may also help to avoid statistical errors of pseudo-replication in complex alpine terrain (Hurlbert 1984). For example, it can be difficult to distinguish between the effect of a "treatment" (e.g., climate change) and the multiple effects of post-Pleistocene geomorphic processes on species assemblages. Species may be responding to one habitat factor, or a suite of elements that are tightly linked to higher level drivers that are not linked to climate change (Poff 1997; Montgomery 1999).

Conclusions

This hierarchical framework provides a tool for differentiating among environmental variables in glaciated mountain headwaters at multiple spatial scales and is designed to aid ecological and geomorphic monitoring of alpine function and process across biogeographic regions. Emerging climate trends, in particular, require monitoring protocols that are adaptable to new conditions and are flexible across scales. Understanding the processes associated with environmental variables that drive and are tightly linked to lower-level processes will help clarify distinctions between "natural" physical variability and climate impacts.

There are numerous challenges associated with designing a sampling framework suitable for alpine conditions where the linkages between a particular environmental filter may need to be grounded in an adequate understanding of pertinent large- or intermediate-scale mechanistic or functional drivers (Frissell and others 1986; Poff 1997). We propose this hierarchical framework as an adaptive model for understanding alpine basins that are hierarchically organized. For example, local water temperature regimes at a site might be regulated by multiple factors: regional conditions (e.g., meltwater from an active glacier that is stagnating or in retreat), basin features (e.g., elevation as a function of position along the channel longitudinal profile produced by glaciation), valley features (e.g., type of glacial macroform structure), valley segment scale variables (e.g., channel morphology), or a combination of elements associated with different hierarchical levels. The linkages between these levels may be critical to understanding species survival and potential for adaptation, providing critical information on the geohydrologic history and probably longevity of the species-habitat relationship. This information is vital for interpolating monitoring data and for modeling the effects of different change scenarios.

The need to successfully monitor species response to stressors such as climate change across biogeographic domains is especially important given the atmospheric and earth surface feedback mechanisms that affect ecosystems at the global scale. This framework is meant to address this challenge by providing a means to begin to compare, identify, and differentiate between controlling mechanisms in the context of post-glacial conditions. The value of aquatic monitoring at landscape scales, especially comparisons between widely separated mountain regions, will increase if global anthropogenic impacts continue, as appears likely.

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