Physical Processes and Climate Change: A Guide for Biologists

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Introduction

Global climate change, and the related warming of global climate, have been well documented (IPCC 2007, ISAB 2007, Hanson et al., 2003, Cubasch et al., 2001). Evidence of global climate change/warming includes widespread increases in average air and ocean temperatures, accelerated melting of glaciers, and rising sea level. Given the increasing certainty that climate change is occurring and is accelerating (IPCC 2007, Battin et al. 2007), we can no longer assume that climate conditions in the future will resemble those in the past.

Biologists, planners and other non physical-scientists working in natural resources conservation are increasingly expected to become familiar with the growing literature on climate change, and to incorporate climate change predictions into their work. Both of these actions would greatly benefit from better understanding of general principles from physics and geomorphology, and how these principles provide a useful and essential context for interpretation of climate change effects. The purpose of this paper is to provide that physical effects discussion from an introductory level.

1. General Principles

This section presents a discussion of general principles from physics and geomorphology based on material contained in Knighton (1998), and in Chorley et al. (1984).

A. General concepts of geomorphic equilibrium

Rivers, hillslopes, coastlines, and other features of the Earth's surface are physical systems, which respond to driving variables of force and material delivery (inputs). Over long periods of time, features of the landscape come into equilibrium with their inputs assuming that the driving variables reach an equilibrium as well. Equilibrium river channels, for example, evolve into a form (herein referred to as morphology) where the erosive forces are balanced by resistance to erosion, and the sediment supplied to the river from upstream can be transported through, by the available forces, to downstream reaches of the river network, with no net accumulation or loss over decadal time scales.

Climate change represents a disturbance to the driving variables. Physical systems respond to a disturbance by altering their morphology to accommodate the new driving forces. But, this response does not happen instantaneously. Think of a pot of water simmering on the burner of an electric stove. It we turn up the heat, there will first be a *reaction time* as the burner heats up, adjusting to the new rate of electrical energy dissipation. This represents the physical or thermal *inertia* of the burner, which has finite mass and cannot change temperature instantaneously. Then, there is an adjustment or *relaxation time* as the pot of water adjusts to the new burner temperature with changes to its patterns of bubbling, turbulent motions, release of steam, etc. Finally, the pot/burner/stove system reaches a new state of temperature and motion (*equilibrium form*), which can be sustained until the driving variables change once again.

Surface features of the earth respond in the same manner, with a time lag in response to a change in driving variables. This lag time (reaction time plus relaxation time) is generally a period of instability. The term *instability* indicates rapid morphological change, increased movement of sediment (erosion, mass wasting, deposition), shifts in vegetative cover or type, accelerated change in hydrologic processes (such as from snow to rain or glacial ice to snow), and/or rates of change that are in excess of what can be sustained in the long-term. Processes such as accelerated channel migration, streambed aggradation (deposition) and degradation (scour and downcutting), and accelerated mass wasting are some of the characteristics of this unstable period. Eventually, a new morphology is reached that is in dynamic equilibrium (over the long-term) with the new climate. Again, this assumes that the new climate stabilizes into an equilibrium condition as well.

Unlike some natural disturbances, such as forest fires or extreme floods, which are sudden or “impulse-like,” the current episode of climate change is a “ramp-like” disturbance. That is, the driving variables change gradually over decades and centuries, which is still rapid by geologic standards, but gradual in relation to the patterns of natural variability we experience as daily, seasonal or annual change. This means that the period of instability is greatly prolonged and that landscape response will be dominated by “threshold-like” behavior. In other words, little change may be observed until some *threshold* is reached, upon which a period of rapid response and instability will follow. For example, a glacier may shrink gradually until its accumulation zone reaches some critically small area, upon which the glacier can no longer sustain itself and may break up and melt quickly, perhaps within just a few years. The river downstream from this glacier will then shift rapidly from an ice-melt hydrology to a snowmelt hydrology, with consequently large changes to downstream habitat type and availability. This process is already happening in some parts of Washington State.

How a system responds to change also depends on the presence of positive or negative feedback processes. A *negative feedback* process is one that tends to restore the system to its previous state when it is disturbed, while a *positive feedback* process tends to accelerate the disturbance. Hence, systems with negative feedback tend to be stable, while positive feedback systems are unstable. For example, a gravel bed river can form a coarsened surface layer on its bed, which allows the channel to respond to changes to its sediment load without aggrading or degrading, at least within certain limits. If the sediment load increases, the surface layer becomes finer and its particles more easily entrained, which increases the rate of transport of the streambed sediment to match the increased input. Conversely, if the sediment load decreases, the surface becomes coarsened, which increases the resistance to sediment mobilization. This negative feedback is built into the dynamics of the streambed surface to allow a stable channel form to persist despite varying sediment input. However, substantial increases in flood magnitude (such as from climate-induced hydrological changes) can overwhelm the ability of the streambed to resist massive sediment mobilization. Once this happens, the streambed degrades, and the flood water can no longer spread out over a floodplain, but rather is confined to the incised channel. Thus, the amount of hydraulic force concentrated on the streambed at a given water discharge increases, resulting in even greater degradation. This is positive feedback. The original scour event that mobilizes the coarsened surface layer represents a *geomorphic threshold*.

Different parts of the landscape differ in their sensitivity to changed input forces. *Sensitivity* is a concept somewhat analogous, but opposite in meaning, to *resilience*. Sensitive parts of the landscape or the river network tend to be areas composed of fine textured material (which is easily mobilized), areas that are close to geomorphic thresholds, areas where recovery processes are slow, areas prone to positive feedback, or areas where the ratio of disturbing to resisting forces is large. In river systems, these would be the *response reaches*. The most sensitive of all are those areas where a large amount of material needs to be mobilized in order to reach an equilibrium with the altered forces. For example, a river eroding into fine textured terrace deposits (deposits formed by processes no longer active, such as Pleistocene glaciation) may need to move tremendous amounts of material in order to reach a new equilibrium geometry in balance with new hydraulic forces imposed by the altered climate.

Predicting the actual duration of the period of instability, in other words, the response and relaxation time, is very difficult. This depends largely on the size of the input forces relative to the amount of material that ultimately must move before stability is reestablished. One can look to the literature from historic geomorphic reconstructions to gain some idea. For example, increased rates of landslides and rockfall in northern Europe in response to a climate change event known as the “Little Ice Age" (which lasted from the 17th to 19th centuries) persisted for about 100 years (Knighton, 1998). After the eruption of Mt. St. Helens, parts of the Toutle River reached new equilibrium morphology within approximately 12 years (Simon, 1992). At the other extreme, there is evidence that rivers in British Columbia have still not reached equilibrium in their relaxation or recovery from the last glacial advance more than 10,000 years ago (Church and Slaymaker, 1989). Given that climate change is fundamentally altering physical systems, and that the length of time during which climate change will continue to occur is unknown, it should be expected for the foreseeable future that stream system instability and adjustment will increase.

B. General concepts for interpretation of physical modeling

With the exception of historical studies, virtually all of the climate change literature relies on modeling. *Physical modeling* uses a simplified representation of the earth as a series of spatial elements or “cells,” and uses the equations of mass transfer, energy transfer, and fluid dynamics to link these cells into a dynamic model which can then be solved numerically on a computer. Model output will depend on not only the laws of physics, but the choice of values for input parameters, some of which are known more accurately than others. *Statistical modeling*, by contrast, uses the existing data on climate and/or hydrology, without regard to the physics of how “climate" or "hydrology" comes about, and involves adjustments to these data in ways that match certain expectations or assumptions about how the climate will change.

There are certain limitations to modeling which should be understood in order to interpret the climate change literature. First is the issue of probable range of future condition, such as a future average annual temperature. There are numerous physical models in use, each based on somewhat different assumptions, numerical techniques, or representation of the Earth's surface and atmosphere. Output is often taken from numerous models and averaged, while the differences between the various model outputs are treated as a measure of the variability in the probable range of future condition. Strictly speaking, this is incorrect because it assumes that each of the model outputs are equally likely, ignoring the issue of which models work better, or are better suited for a particular region or application. For non-experts, multi-model comparisons are more appropriately interpreted as a way to describe the overall range of conditions treated in the literature. By contrast, for comparison of alternate socio-economic scenarios, with differing implications for greenhouse gas release, the same model should be used, in multiple runs, with differing input data sets.

Output variability should be assessed by choosing a well-calibrated, tested model that fits a chosen set of assumptions and then performing a sensitivity analysis with that model. Such a model might be, for example, the one which best predicts the existing twentieth century record for the Pacific Northwest. A *sensitivity analysis* involves testing the model with various reasonable combinations of input parameters. In this way, it is determined that model output is more sensitive to certain parameters than others. By exploring the range of model outputs under various physically tenable combinations of the sensitive input parameters, the probable range of future condition can be estimated.

The second issue that arises in modeling is termed *downscaling* (Lettenmaier, 2001, Salathé, 2005, Salathé, Mote, and Wiley, 2007, Maurer et al., 2007). Generally, the physical climate models (called General Circulation Models or GCM's) used to study global warming divide the earth into cells which are about 2.5 degrees of latitude (~300 km) on each side. For use in regional studies, these results must be interpolated to a grid that is a maximum of 1/8 degree (~15 km) or finer. This represents an artificial enhancement of spatial resolution, which gives the appearance of greater accuracy than actually exists.

A more serious issue is downscaling of temporal resolution, more properly termed *disaggregation*. The global climate models provide output in the form of monthly and annual averages. Yet, what is needed for assessment of geomorphic change, flood magnitudes, and hydraulic aspects of habitat are instantaneous water discharges. There is no scientifically tenable way of bridging that gap in resolution. Currently, the best scenario is to examine relative changes to the extreme values predicted and assume that these relative changes are preserved at all timescales (Hamlet and Lettenmaier, 2007). This almost certainly underestimates the changes to magnitudes observed at short time scales due to the loss of variance that happens with averaging. Statistical models get around this problem by using an actual time series of climatic or hydrological measurements, usually daily mean values, and adjusting these in ways predicted by the GCM's for larger timescales, or in ways that isolate precipitation from temperature, for example. In this manner, the full variance of the data is preserved. Yet for certain types of studies, such as flood magnitude predictions, this approach is inadequate because of the use of daily mean values as opposed to instantaneous values. The latter is expected to have higher variance than the former. Furthermore, it is likely that the variance of future temperature or precipitation records will increase.

Best professional judgment of climate change scenarios is a combination GCM predictions tempered by careful scrutiny of the statistics of recent historical records and physical reasoning. Conclusions based solely on downscaled GCM results are incomplete, not to mention very uncertain.

C. River (fluvial) systems

Moving water, derived from rain and snow melt, is the "engine" that drives all physical processes in rivers. The water discharge rate determines the rate of transport of organic material, including large wood, and sediment, and determines the balance between deposition and erosion of sediment. In general, the same volume of runoff occurring over a shorter period of time can do more geomorphic work (i.e. move more material). This is because energy dissipation increases exponentially with water velocity. For example, an intense, brief storm can move orders of magnitude more sediment than a long drizzle, and a single large storm can move more sediment than a series of smaller storms, even though the volume of water involved may be the same.

Thus, the style of peak flow or flood runoff determines the magnitude and duration of energy available in a river to erode and transport sediment. Rain storms generate short duration, but intense runoff events. If there is additional water available from snowmelt (rain-on-snow), the flood event will be even more intense. Snowmelt alone, however, tends to be a more gradual flood -- longer in duration but lesser in magnitude. The snowmelt flood will be spread over days or even weeks, since there is only a fixed amount of energy available in each square meter of sunlight to melt the snow pack.

Rivers will transport more sediment, erode their banks, and scour their beds more readily as the hydrologic patterns change from snowmelt to rainfall, and as the intensity of storms increase. This shift in hydrology will alter the dynamic state of the river, and will induce morphological changes even if total annual precipitation remains unchanged.

As rivers change the amount of sediment in motion, they must accordingly adjust their morphology in order to accommodate both the movement of water and the additional sediment. Rivers accomplish this by evolving from one morphology or channel type to another, and from one set of physical dimensions (cross section, width, depth) to another. This is part of the way physical systems, rivers included, come into equilibrium with the driving forces. As the river evolves from one morphology to another, it is in a state of disequilibrium or *geomorphic instability*. The amount of time it spends in an unstable state depends on the available hydraulic energy in the river in comparison to the amount of sediment it must move in order to reestablish an equilibrium condition. Thus, a river that is incised into its valley must move a tremendous amount of sediment in order to widen out into a stable alluvial channel form, which may take a long period of time. Evolution of a river to a new channel morphology typically lags a change in climate, land use, or sediment often by many years or decades (Orr et al., 2008). Thus, although the pace of global climate change represents a moderate disturbance (in comparison to more abrupt disturbances such as landslides, forest fires, or extreme floods), river channel adjustment will occur more slowly, and we can expect a protracted period of unstable or disequilibrium rivers.

Different places in the river network have varying degrees of sensitivity to changes in the amount or temporal distribution of hydraulic energy. The most sensitive portions of the network are areas where sediment tends to deposit over long periods of time. These are the *response reaches*, which include alluvial fans, transitional areas from confined to unconfined valley settings, places where the channel or valley slope flattens, portions of the channel in the transition zone between gravel and sand substrate, and so forth. These are areas where the equilibrium between deposition and erosion of sediment is easily shifted by relatively small changes in hydraulic energy or sediment volumes. By contrast, disequilibrium is less likely where the channel tends not to have accumulations of alluvially-deposited sediment and where the hydraulic energy is sufficiently large that sediment is transported through.

A prolonged period of river channel instability is expected as rivers adjust to new patterns of flooding and sediment load. Depositional or response reaches will be the most severely impacted.

D. Upslope processes (landslides, etc.)

Upslope areas are the source of sediment and water to fluvial systems. Climate, and thus climate change, influences upslope processes by influencing soil moisture, routing and accumulation of subsurface water, weathering rates of rocks and minerals, decay rates of organic matter, and the type and properties of the rooted vegetation which substantially reinforces soil strength and influences the soil erosion regime and soil moisture content.

Certain parts of the landscape effectively act as sediment source areas and accumulation zones. The most important of these source areas are foci of mass wasting. These focal areas or "*unstable landforms*" are generally places where gravitational forces are large (e.g. steep topography) and were subsurface water tends to concentrate, contributing to a reduction in soil strength and destabilization of slopes. Mass wasting, which refers to movement of soil, rock or poorly consolidated sediment *en masse* rather than a particle at a time, can involve shallow planes of slippage, within or near the rooting zone. The edges of Pleistocene bluffs and terraces, convergent headwalls, inner gorges, bedrock hollows, toes of deep-seated landslides, outside meander bends on rivers, make up the majority of these focal sites for "shallow-rapid" landslides. Deep-seated landslides, by contrast, are large blocks of weathered rock or sediments which sporadically move along planes of weakness situated well below the rooting depth. These features evolve over much longer time spans (millennia), but they, too, are affected by altered hydrology in that increased subsurface moisture, or longer periods of moist conditions, accelerate their movement.

As with fluvial systems, upslope areas will respond to imposed changes by gradual shifts towards new equilibrium conditions. A long-term equilibrium can be said to exist between weathering rates, which “load” the hillslope with unconsolidated material, and erosion rates, which “unload” that material, ultimately depositing it in rivers. Time lags between imposed climate change and response of this *landscape system* are expected.

Sediment transport from source areas to downslope accumulation zones and river channels is very episodic, recurring on time scales of decades to centuries. Over many decades, conditions on an unstable landform gradually mature towards heavier sediment load accumulation on the landform and development of zones of subsurface weakness. Constant exposure to groundwater accelerates weathering of rock and soil particles along potential planes of slippage. Surface erosion and small mass movements bring in soil from adjacent slopes, adding weight to the increasingly unstable feature. Simultaneously with this increase in the load or weight, the probability of a weather event generating extensive conditions of saturated, weakened soil becomes more certain.

Global warming increases the rate of mineral weathering and organic material decomposition, thus speeding up this cycle of erosion. Increasing the intensity of winter storms also speeds up the cycle, by reducing the interval between episodes of saturated soil and increasing the magnitude of the soil water buildup (pore water pressure). The slow movement of deep-seated landslides thus becomes more frequent. Greater flooding magnitudes or flood frequencies in rivers can remove buttressing sediment accumulations at the bases of hills, river terraces and deep-seated landslides, causing renewal or *rejuvenation* of mass wasting. Increases in the frequency or intensity of wildfires can lead to increased occurrence of times when root strength (and hence, soil strength) is at a minimum, making upslope systems more prone to mass wasting.

Although there is little definitive literature linking increased storm intensity to global warming, increased temperatures do result in more moisture and energy in the atmosphere, which in turn causes more intense turbulence and reinforces the processes generating intense storms (Milly et al., 2002, Hamlet and Lettenmaier, 2007). The climate record from the past 40 years supports this conclusion as well (e.g. Allan and Komar, 2000, Graham and Diaz, 2001).

Currently, there is no literature on the effect of global climate change on mass wasting processes specific to the Pacific Northwest, however, there is a growing body of literature from other parts of the world, particularly the Alps. This literature documents the linkages between climate induced changes in groundwater levels and landslide rates. It also supports the concept that any period of shifting climate is punctuated by a period of increased slope instability. This latter concept is further supported by long-term (e.g. >1000 years) historical studies based on geological interpretation of surface deposits and landforms in the continental United States and elsewhere (e.g. Wegmann and Pazzaglia, 2002, Eppes and McFadden, 2008).

Mass wasting frequencies will probably increase in the Pacific Northwest as climate change proceeds. In other parts of the world where the climate becomes drier, mass wasting frequencies may decrease.

E. Coastal systems

Morphology of beaches, coastal wetlands, estuaries, and nearshore bathymetry depend on a balance between sediment deposition and erosion processes. Sediment enters the nearshore system from rivers and from erosion of coastal landforms, such as Pleistocene terraces. The sediment moves along the beach mainly through wind- and wave-driven longshore currents during the winter storm season. Anything altering either the input rate of sediment or the energy available in longshore currents will upset the balance between erosion and deposition, and alter the sizes of particles being transported. This will potentially alter the morphology and surface material composition of the beach and nearshore, as the system adjusts to new driving variables.

Global climate change imposes at least three disturbances on coastal systems. First and foremost, regional increases in sea level will push the zone of wave action further up the beach. This will eliminate beaches in some areas, and will contribute to destabilization of Pleistocene terraces by eroding the buttressing toe of those landforms, making them more prone to mass wasting. Secondly, increases in storm intensity will increase the energy available for erosion and also increase the rate of nearshore sediment transport. Finally, sea level rise will increase, in many cases, the volume of tidal prism in estuary systems. This will increase the energy available for transporting sediment out of such systems, leading to disequilibrium and a period of morphological adjustment. As in the case of fluvial and upslope areas, this disequilibrium will lag the period of disturbance, and may take many years to evolve towards a new steady state.

Coastal erosion rates will increase, beaches will shrink or disappear entirely, and nearshore bathymetry will shift in morphology, slope, and sediment texture, all of which will alter habitat conditions substantially.

2. Summary of relevant literature

Adequate summaries of the literature on effects of global climate change already exist, and that work will not be duplicated here. Mote et al. (2005) provide an excellent review specific to the Puget Sound region of Washington, including the effects on air and water temperature, precipitation, river hydrology, nearshore habitat, and water quality. Dragoni and Sukhija (2008) review the effects on groundwater, including potential influence on mass wasting processes via changes to groundwater levels. Goudie (2006) provides a qualitative review of the effects on fluvial geomorphology. A somewhat broader review of the fluvial geomorphology aspect, written for teachers, is given in Vandeberg (2007). No good review exists for the impacts on slope stability in the Pacific Northwest. However, the salient aspects of how slope stability processes are influenced by climate change are discussed in Dehn and Buma (1999) and in Dikau and Schrott (1999). Hamlet and Lettenmaier (2007) provide a state-of-the-art study on changes to flood risk. However this study does not incorporate the effects of concomitant geomorphic change due to increased sediment loads (e.g. Lane et al., 2007; Orr et al., 2008).

As part of this investigation, several researchers working on climate change effects specific to the Pacific Northwest were contacted and a request for literature and information about ongoing research was sent to the IAG-GEOMORPHLIST (International Association of Geomorphologists), http://earth.boisestate.edu/home/dwilkins/geomorphlist/geomorph-l.htm, which is widely read by most professional geomorphologists. Twenty responses were received from all over the world. The conclusion drawn from this informal survey is that little work is currently available which links current global climate change with geomorphic response, other than a few very qualitative review papers. However, proposals are currently in process for further research on topics such as changes to sediment dynamics in watersheds, increased soil erosion, and increased flooding potential.

Although the foregoing discussion was organized according to physics and geomorphology, it is helpful to provide a brief summary of the literature in the form of a broad list of processes that are likely to become altered as a result of global climate change. This list is developed in Table 1.

Table 1: Outline of effects expected due to specific physical processes documented in the literature

Physical process:	Potential physical and biological impacts:
Change in balance between snow and rain	a. Reduction in long-term snowpack b. Earlier snowpack melt c. Conversion of permanent snow zone to transient snow zone d. Altered flood mechanism & timing (snowmelt to rain-on-snow) -Shift from spring flood maxima to fall-winter flood maxima e. Reduced summer base flows, loss of headwater perennial habitat -Impact dependent on geological structure, soil thickness
Increased storm intensity, including intensity of precipitation	a. Surface erosion increase b. Possible long-term increase in mass-wasting frequency -Era of increased mass wasting as landscape adjusts to new hydrological conditions -Altered long-term pattern of mass wasting dependent on geological structure, specific changes to hydrology and vegetation c. Shifting of moderate landslide hazard areas into high hazard category d. Increased magnitudes and variability of peak flows, even in rain-dominated flood hydrology e. Era of increased sediment load to rivers f. Aggradation, channel morphological adjustments -Influence of geomorphic setting: response reaches affected, conversion of some transport reaches to response reaches g. Translation (longitudinal movement) or expansion of geomorphic process zones including response reaches to different positions on landscape
Changes to total annual precipitation amount and seasonal distribution	a. Moderate increase in winter precipitation b. Moderate decrease in summer precipitation c. Increased average runoff in winter and spring months d. Decreased summer baseflow
Increased flood risk and resultant channel instability	a. Increased flood risk in response to increased peak flow magnitudes b. Increased flood risk in response to aggradation

Physical process:	**Potential physical and biological impacts:**
	c. Shifts in location of channel migration zone and 100 year floodplain boundaries d. Increased rates of channel migration and associated streambank erosion
Melting of glacier ice	a. Altered summer hydrology, sediment and thermal regime of glacial rivers b. Altered sediment load: period of high sediment loading due to recently exposed or destabilized glacial deposits c. Reduction in summertime suspended sediment load
Increase in average water temperature	a. Shifts in habitat type and shrinkage of useable habitat for cold water species, including loss of mid-elevation habitat b. Disproportionate importance of groundwater-fed systems to cold water obligate species. High groundwater-influence sites include: Recent volcanic lithology Wall-based tributaries in glacial terraces Streams originating in glacial drift lithology c. Lower dissolved oxygen d. Higher surface water salinities in summer and decreased salinities in winter, especially in estuaries and salt marshes e. Altered density stratification patterns in lakes (longer summer stratification period), and Puget Sound (stronger winter-time stratification) f. Increased algal blooms, including toxic ("red tide") species
Increased evapotranspiration & loss of soil moisture	a. Reduced summer baseflow in rivers b. Reduced groundwater recharge c. Loss of wetland area d. Conversion of perennial to seasonal wetlands
Sea level rise	a. Altered coastal sediment recruitment and transport b. Upstream translation of deltaic areas, depositional/response zones c. Increased tidal prisms resulting in increased energy in estuaries and tidal marshes d. Morphological and substrate changes in beaches and nearshore zones e. Altered coastal upwelling patterns f. Altered patterns of water circulation g. Loss of some beaches, potential formation of new beaches in other areas

Physical process:	**Potential physical and biological impacts:**
Increase in sea water pH	a. Altered plankton communities, affecting marine food web b. Altered disease occurrence and severity among fish and shellfish
Increase in fire frequency, intensity (due to drought, type vegetation conversion)	a. New disturbance regime: disturbance-dominated channel morphology (unstable channel types), in systems where fire interval is less than recovery time b. Sediment load increase due to increased surface erosion and mass wasting, leading to aggradation of river channels
Changes in vegetation cover and species composition brought about by temperature and precipitation change	a. Potential expansion of invasive riparian species b. Altered erosion rates c. Changes to long-term large wood dynamics (input, persistence)
Effects of elevated levels of carbon dioxide on plant physiology, transpiration and water use	a. Altered competitive relationships among plants, leading to altered recovery form floods, fire, human disturbance b. Increased growth rates
Changes to human management of land and natural resources in response to climate change	a. Increased demand for structural streambank protection b. Increased demand for structural shoreline protection c. Increased groundwater withdrawals in response to declining surface water resources d. Increased demand for irrigation water e. Increased demand for surface water storage reservoirs (e.g. dams) f. Increased renewable energy development, impacting new areas on landscape

3. Discussion: Implications to species recovery, habitat restoration and conservation of aquatic resources

This section contains a discussion, from a physical science point of view, of several key issues relating climate change science to management and conservation of aquatic resources. Although the examples used in this discussion pertain to river habitat, the key principles are more generally applicable.

The first key issue is the concept of ***resilient habitat***. In the physical sciences and engineering, resiliency refers to the ability of a system to quickly and completely return to its original condition after being disturbed. In the ecological literature, resiliency carries the additional meaning of how much disturbance a system can "absorb" without crossing a threshold and entering an entirely different state of equilibrium (e.g. distinctly different physical habitat structure or conditions; see Gunderson, 2000, Holling, 1973, and Scheffer and Carpenter, 2003)**.** In regard to recovery, habitat restoration, and conservation of at-risk aquatic species, **r**esiliency also requires that certain key habitat characteristics or processes will change little, or not at all, in response to climate change. When it comes to aquatic fluvial habitat, the most important elements to remain steady are *temperature* and *disturbance regime*.

Rivers and streams resilient to temperature change include those dominated by groundwater input. Important requisite geological conditions include a highly permeable surface layer with a low density of stream channels, and an aquifer with great storage volume but intermediate hydraulic conductivity, such that the stored water does not rapidly drain. These characteristics occur in terrains dominated by extensive recent volcanic processes, such as the high Cascades region (Grant, 2007), which includes the eastern portion of the Cascade Range in Oregon and Northern California, and extends northward into Washington between the Columbia River and the Mount Adams/Mount Saint Helens area (Grant, 2007). Unfortunately, no other physiographic provinces have been investigated for these properties within Washington state. However, likely candidates include streams originating entirely within the glacial drift comprising the Puget Sound lowlands and the rim of the Olympic Peninsula. This area is likely to be intermediate in character between the extreme groundwater dominance of high Cascades streams and runoff-dominated streams elsewhere.

A quick review of stream gage records in Washington confirmed this hypothesis. Out of 582 stream gauges analyzed (based on statistics developed in Sinclair and Pitz, 1999), 67 (14%) were shown to have high August base flow (defined herein as greater than 2.4 $ft^3/s/mi^2$). Of these, 54 were glacial streams, and 13 were evidently streams of high groundwater input located both in areas of glacial drift deposits and recent volcanic (i.e. High Cascades) lithology. This preliminary analysis is biased by the availability of stream gauge records, but does support the hypothesis that smaller streams originating entirely within glacial drift deposits could function as cold water refugia. Further study of this possibility is warranted.

A resilient disturbance regime would be one in which the peak flow (flood) mechanism and available sediment sources do not become altered. Rivers and streams likely to be resilient to changes in disturbance regime would include those with flow dominated by groundwater. This is because large groundwater aquifers tend to buffer the movement of water, averaging out the extremes in precipitation, and producing a hydrological pattern characterized by fairly constant flows and much smaller differences between peak flows and base flow than streams dominated by runoff. For runoff-dominated streams, from most to least severe, changes to disturbance regime would occur in:

1. Glacial streams which entirely lose their glacial ice, becoming snowmelt streams or rain-on-snow streams (large portions of the non-volcanic North Cascades);
2. Glacial streams experiencing ice retreat which rejuvenates or exposes large volumes of unstable sediments (streams on major volcanoes, especially Mt Rainier);
3. Snowmelt streams that transition to rain or rain-on-snow hydrology (streams with significant headwater areas currently above the transient snow zone);
4. Rain-dominated streams in landscapes prone to mass wasting; and,
5. Rain dominated streams in relatively stable landforms.

Even in rain dominated streams, potential increases in storm intensity may bring about larger, more frequent floods, but without the changes in timing of flood and base flow hydrology which will occur in the other three types.

It should be noted that resiliency is temporally dependent. Given enough time, large disturbances are virtually certain to occur on the landscape and to the climate. Thus, resiliency can only function on a landscape scale -- there must be enough individual rivers available with the appropriate habitat and connectivity so that a disturbance to one system allows the others to support the sensitive populations through the recovery and recolonization period. In the long term, there is no substitute for a landscape that offers redundancy of habitat opportunities. Many of the features that make up high-quality salamonid habitat, such as buried organic matter, large gravel deposits, side channels and logjams, for example, are relics of the legacy of past disturbances. The issue is not to shun stream reaches that are more prone to disturbance, but to identify and work with stream reaches that are likely to have a consistent disturbance regime as opposed to ones that will drastically change as the climate continues to change. This will assure that the habitat identified retains its physical morphology and patterns of cyclic evolution rather than shifting to some different, and presumably less stable, habitat type. In essence, the strategy suggested here is to provide multiple interconnected refugia which undergo severe disturbances at differing periods of time.

Refugia are places in the landscape where organisms can go to escape extreme conditions. Usually, this refers to short-term conditions such as floods or high water temperatures. But in the context of climate change, *refugia* can also be places where a population may persist through decades and centuries of unfavorable climate conditions and instability.

With regards to refugia, some researchers (e.g. Battin et al., 2007) have suggested that headwater reaches of rivers, traditionally considered the best possible candidates due to their colder temperatures, will become less available due to reduction in the summer base flow as the hydrologic pattern changes from snowmelt- to rain-dominated. This would appear to push the emphasis on identification of refugia and restoration efforts to lower elevation reaches where summertime hydrology is expected to be less affected.

However, for coldwater obligate fish species, refugia will continue to be areas where groundwater emergence influences water temperature and volume. These refugia will exist on several scales: local areas of cool water emergence within a reach otherwise insufficiently cool, and entire streams or reaches where groundwater hydrology is dominant. Local zones of groundwater emergence include springs in settings where springs occur adjacent to streams. Two of the most important settings have already been mentioned, namely, streams running through Pleistocene glacial deposits in the Puget Sound lowlands and rim of the Olympic Peninsula, and the recent volcanic terranes of the Southern Cascades. In addition, high elevation sites that retain their permanent snowpack in the face of global climate change will continue to serve as important refugia. Some watersheds of the North Cascades, streams draining the large glaciers on Mount Rainier and high elevation parts of the Interior Columbia Basin (see Martin and Glick, 2008, Rieman and Isaak, 2007), are expected to retain late-season cold water flow. Connectivity of these watersheds to other refugia and to the downstream migration corridors will be crucial for them to adequately serve as refugia (Martin and Glick, 2008)**.**

Rivers that have floodplains will also have emergence zones for subsurface water, which form cool water refugia. This will include hyporheic water, or mixtures of hyporheic and groundwater which may be flowing through subsurface pathways such as relic, buried channels (Burkholder et al., 2008, Lambs, 2004, Woessner, 2000). Hyporheic water is water which originates as stream flow, then enters the subsurface, flowing through the shallow sediments beneath or near a river channel, to emerge again downstream. Tributaries flowing across the floodplain may go partially or entirely subsurface, emerging as cooler water in the side or bottom of the main channel. Alluvial fans associated with tributaries are generally places where surface water is lost into the ground, emerging down gradient where the main channel abuts against the alluvial fan. The degree of cooling depends on the amount of time the water spends flowing through the subsurface, and the degree to which it mixes with cold groundwater. Finally, some geomorphic settings produce upwelling of cool subsurface water, which may be a mixture of hyporheic and groundwater. For example, if the river enters a valley which initially widens, and then constricts in the downstream direction, the constriction zone will be a zone of upwelling. Water which entered the subsurface in the upper portions of the valley, which has been flowing as hyporheic water and mixing with groundwater, must reemerge as the cross-section of shallow alluvial deposits constricts (Baxter and Hauer, 2000).

Thus, the same set of circumstances producing cool water conditions in the current landscape may to varying degrees produce thermal refugia against global warming. Maintaining connectivity amongst these refugia will be difficult. It will be increasingly important to protect these areas and in some cases to enhance them or improve their connectivity.

Enhancement of connectivity will be a vitally important form of ***restoration*** in any strategic response to climate change. Here, the term *restoration* is used very broadly, referring to all forms of enhancement of habitat and habitat forming processes, not restricted to actions which return the system to pristine or aboriginal conditions. Restoration has traditionally been driven by a combination of political and biological considerations. If scarce restoration funds are to be targeted for species recovery in the face of climate change, it is highly important that a site-selection hierarchy based on resource values, and a hierarchy of priority actions based on sustainability be followed. *Sustainable restoration* includes activities which reestablish the structure and function of the stream ecosystem in a manner that the ecosystem will become *self-maintaining*. Site selection should prioritize areas of high resource value, tempered by considerations of resiliency to climate change. Areas of high resource value would include strongholds and refugia. Highest priority actions in these areas would be protection of good habitat, improving connectivity and access to existing habitat not currently occupied, and only then followed by process-based restoration of lesser-quality habitat. All actions should be analyzed in relation to sustainability, and to resiliency and threats from climate change. In regard to Bull trout, the current strongholds may also be the most resilient places (assuming that total loss of current hydrological process does not occur, such as complete loss of a glacier).

When river restoration is performed, or when "fish-friendly" river engineering is necessary, the dynamic nature of climate change effects makes redundancy of actions desirable (J. Park, personal communication). Redundancy can be applied in both horizontal and vertical dimensions. Using engineered log jams as an example, vertical redundancy would include building these structures higher and bulkier than current design practice would dictate, in order to accommodate larger peak flows in the future. Horizontal redundancy would include the placement of structures in currently inactive side channels to assure function in the event of channel avulsions or accelerated channel migration.

In addition, restoration site selection will need to incorporate thinking about geomorphic instability. Unfortunately, some of the most productive spawning areas for fish are in sensitive response reaches, which are likely to undergo an episode of geomorphic instability, making successful active restoration measures difficult. For example, the depositional reaches of some of the large rivers, such as the Nooksack and Lewis, may possibly expand upstream or downstream and experience greater rates of channel avulsions and bank erosion, thus suffering increased human intervention as a result. Passive restoration, such as establishment of wider riparian buffers, is a more sustainable alternative in light of increased geomorphic instability. If active restoration, such as enhancement of instream habitat with large wood, is to be performed in potentially unstable settings, it will be important to design these projects with the appropriate level of redundancy and recognize that the river may move or evolve away from the project at some time. This potential needs to be incorporated into discussions of definition of success, long-term sustainability, and cost of the project.

Human Response to Climate Change

Humans often see themselves as existing outside of "natural" changes occurring in the environment. However, effective management decision-making needs to overlay the footprint of human activity together with external processes, in order to anticipate, rather than merely react to, the way human management alters the natural trajectory. Human response is difficult to predict, because it involves choices made in a larger social and economic context. And with all the uncertainty surrounding the effects of climate change, strong assumptions about human response run the risk of becoming self-fulfilling prophecies, thereby prematurely limiting management options.

Climate change will no doubt incite calls for further human interventions and modifications of watersheds and river systems. Although we can anticipate that the demand for flood control, streambank and shoreline armoring, and water withdrawals may increase because of climate change, the degree to which these activities will be carried out, and the methods used to implement them, are highly uncertain. Future predictions based on past trends along with worst-case assumptions about human behavior and lack of social adaptability to change suggest significant decline in habitat quality and availability (Lackey, 2003), and decline in human quality of life as well (e.g. Bates et al., 2008).

As tempting as it is to adopt a pessimistic determinism over future conditions and our current ability to influence natural resources stewardship, history has demonstrated both the fallibility of future projections and that profound social and psychological change does happen, albeit slowly (Berry, 1999; Curry, 2005). A more fruitful approach is for resource managers to take the time to reflect on long-term desired conditions in river basins, and to be able to articulate a long-term perspective on system resilience, sensitivity, refugia and restoration opportunities. Anticipation of possible future land-use changes that would alter habitat and habitat-forming geomorphic processes should be considered in light of these concepts, in order to facilitate participation in a constructive dialogue that is proactive instead of reactive. This geomorphic perspective will be vital to understanding the direction and magnitude of potential change, and as a counterpoint to proposals which may incur large trade-offs of long-term cost and resource viability for short-term status quo.

Summary

To fully understand the biological impacts of climate change and to properly interpret the climate change literature, knowledge of certain general characteristics of physical systems and system response is essential. Some of these physical concepts include equilibrium, positive and negative feedback, reaction and relaxation times, geomorphic thresholds, geomorphic instability, sensitivity, and resilience in the physical context. Important aspects of climate modeling, which are common to all physical modeling, include spatial downscaling and time disaggregation, as well as the differences between physically-based models and statistical models.

Currently, there is little information in the literature on geomorphic effects of climate change in the Pacific Northwest. Most of the existing research work has focused on the impacts to climate itself and to gross-scale hydrological change. No tools currently exist for predicting geomorphic impacts at specific locations. However, the general principles discussed in this document can be used to suggest ways to screen the landscape for potential geomorphic and hydrological impacts. Development of such screening tools may ultimately provide a systematic and consistent way to address recovery, restoration, and conservation in the context of global climate change.

Supplementary information

The findings and conclusions in this article are those of the author and do not necessarily represent the views of the U.S. Fish and Wildlife Service. Please cite this work as follows: Bakke, P. 2008. Physical processes and climate change: A guide for biologists. Department of Interior, U.S. Fish and Wildlife. Unpublished report. 28 pp.
Copies are available online from the STREAM website: http://www.stream.fs.fed.us/publications/index.html.

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