STREAM SYSTEMS TECHNOLOGY CENTER

STREAM NOTES

Rocky Mountain Research Station

April 2009

Physical Science and Climate Change: A Guide for Biologists (and others)

by Paul Bakke

Global climate change, and the related warming of global climate, has been well documented (e.g., IPCC 2007). Evidence of global climate change/warming includes widespread increases in average air and ocean temperatures, accelerated melting of glaciers (fig 1.), and rising sea level. Given the increasing certainty that climate change is occurring and accelerating, 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 a 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 paper, ***Physical Science and Climate Change: A Guide for Biologists*** (Bakke 2008), reviews basic geomorphic principles, assumptions and limitations of global climatic models, and the potential response of fluvial systems and aquatic ecosystems to climate change.

Here I summarize various aspects of the paper by Bakke (2008) with an emphasis on the potential implications of climate change on river dynamics and stability, aquatic species recovery, aquatic habitat restoration, and conservation of aquatic resources.

General Concepts of Geomorphic Equilibrium

Geomorphic equilibrium implies the existence of stable forms on the landscape which persist over decadal time scales. However, the equilibrium is dynamic, meaning that change does occur, and that movement of water, rock, and organic matter take place although the underlying form is constant. For example, a river channel will erode its banks, deposit sediment, and migrate across its floodplain even though the equilibrium form of the channel, that is, its relative proportions, size, pattern, and overall appearance, remains the same.

Dynamic equilibrium is an idealization which does not exist at

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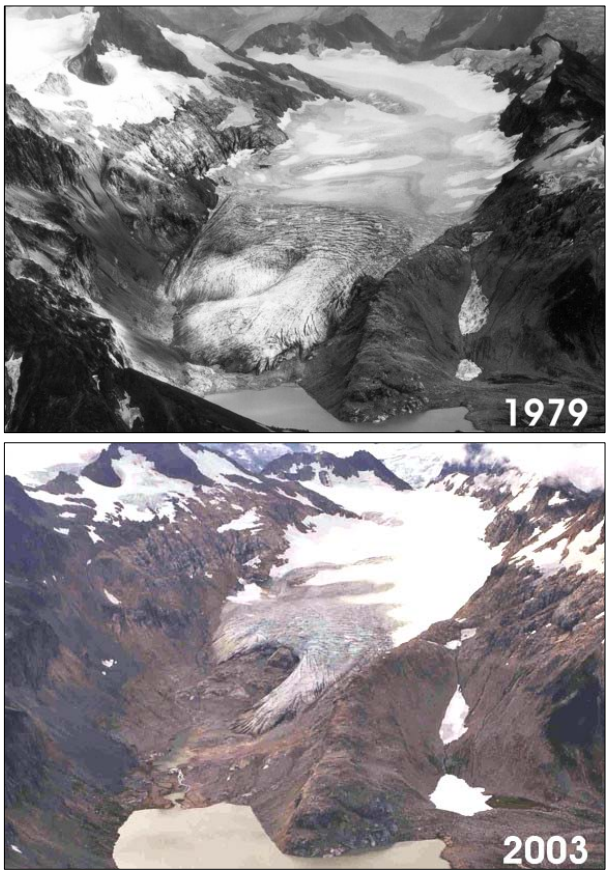

Figure 1. Retreat of the South Cascade Glacier, Washington, between 1979 and 2003. Photos courtesy of U.S. Geological Survey.

some places on the landscape, nor at long time scales. However, it is a very useful concept in physical modeling, and a convenient way to frame the discussion of climate-driven geomorphic change. Climate change associated with global warming represents a disturbance to the driving variables that create and maintain fluvial systems. Physical systems respond to a disturbance by altering their morphology to accommodate the new driving forces. But, this response does not happen instantaneously. 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 (fig. 2). 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 in just a few years. The river downstream of the glacier will then shift rapidly from an ice-melt hydrology to a snowmelt hydrology, with consequently large changes to downstream habitat type and availability.

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 (fig. 2). Hence, systems with negative feedback tend to be stable, while positive feedback systems are unstable. Different parts of the landscape differ in their sensitivity to changed input forces. Sensitive parts of the landscape or the river network tend to be areas composed of fine-textured materials that are easily mobilized, that are close to geomorphic thresholds, where recovery processes are slow, prone to positive feedback, or where the ratio of disturbing to resisting forces is large. These are response reaches in river systems.

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. The length of any period of instability and the trajectory of change, that is, the probable new equilibrium form, are the subjects of interest to geomorphologists studying climate change.

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.

The limitations of the modeling need to be kept in mind as one uses the literature to interpret multi-model comparisons, probable future condition, and perhaps most importantly, model resolution in time and space. The latter issue arises because the General Circulation Models 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 or downscaled to a grid that is a maximum of 0.125 degrees (~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 at present no scientifically accurate way of bridging that gap in resolution to study the statistics of extremes, as opposed to averages. More sophisticated ways to downscale and disaggregate model output in ways that preserve realistic statistical variance of precipitation, streamflow and temperature at all time scales is a current challenge.

Specific Geomorphic Systems

The literature on probable changes to geomorphic systems because of climate change and global warming is limited. However, deductions based on physical geomorphological principles are possible. For example, rivers will transport more sediment, erode their banks, and scour their beds more readily as the hydrologic patterns change from snowmelt to rainfall (fig. 3), and as the intensity of storms

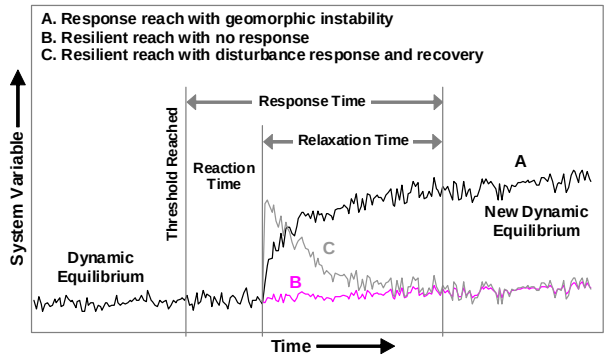

Figure 2. Schematic diagram showing potential responses of the fluvial system to climate change. Sensitive systems will undergo a period of instability in response to climate change before adjusting to a new equilibrium state (A). Resilient systems may show little change to a change in climate (B) or may undergo a period of instability before recovering to its previous equilibrium state (C).

increases. This shift in hydrology will alter the dynamic state of the river, and will induce morphological changes even if total annual precipitation remains unchanged. A prolonged period of river channel instability is expected as rivers adjust to new patterns of flooding and sediment load. Different locations in the river network will have varying degrees of sensitivity to changes in quantity or temporal distribution of hydraulic energy caused by climate change (fig. 2). Depositional or response reaches will be the most severely impacted as these areas are where equilibrium between deposition and erosion of sediment is easily altered by relatively small changes in hydraulic energy or sediment volumes. In contrast, bedrock reaches and confined, coarse-grained transport reaches will be less impacted by climate change as these areas are less sensitive to changes in hydraulic energy and sedimentation.

As with fluvial systems, upslope areas will respond to climate change and global warming by gradually shifting 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 delivering sediment to rivers. Time lags between imposed climate change and response of upslope areas are expected. In some areas, an increase in the frequency and intensity of precipitation will increase the frequency of mass wasting and

sediment delivery to the downstream system. In contrast, a decrease in the frequency and intensity of precipitation in some areas will reduce the frequency of mass wasting and delivery of sediment to the downstream channel.

Global warming imposes at least three disturbances on coastal systems. First and foremost, higher sea levels will cause marine inundation of the near-shore environment and push the zone of wave action further up the beach. This will eliminate existing beaches in some areas, cause beaches and barrier islands to shift inland, and destabilize many marine terraces and coastal dune areas by eroding the buttressing toe of those landforms. Second, increases in storm intensity will increase the energy available for erosion and also increase the rate of near-shore sediment transport. Finally, sea-level rise will increase, in many cases, the volume of water exchanged during each tidal cycle (the 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, which in turn will alter near-shore habitat conditions.

Implications to Species Recovery, Habitat Restoration and Conservation of Aquatic Resources

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 ecology, 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). In regard to recovery, habitat restoration, and conservation of at-risk aquatic species, resiliency 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 stream aquatic 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

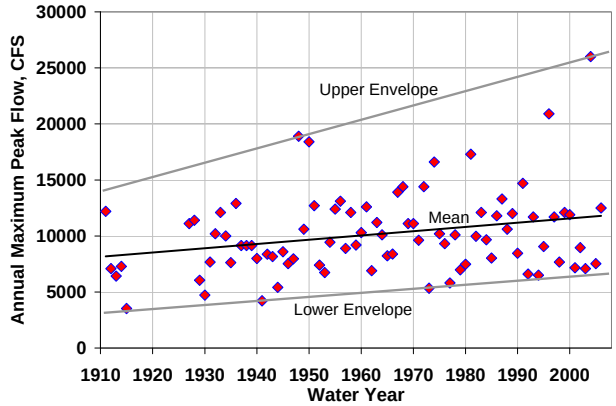

Figure 3. Upward trend in annual maximum flood magnitudes and variance in a river basin in which hydrological processes causing large floods has changed from primarily snowmelt runoff to rain-on-snow events. The Stehekin River, Washington, lies mostly within a national park, and has not experienced land-cover changes.

highly permeable surface layer with a low density of stream channels, and an aquifer that stores a large volume of water and has a moderate hydraulic conductivity rate so that the stored water does not rapidly drain from the aquifer.

A resilient disturbance regime would be one in which the peak flood flow mechanism and available sediment sources do not become altered. Downscaled global climatic model output can be used with geographic information system (GIS) analysis to identify river segments likely to transition from snowmelt to rain or rain-on-snow hydrology (fig. 3). Altered sediment sources or mass wasting rates can be predicted to occur in watersheds having a high landscape density of unstable landforms as well as in cases where glacial retreat or other predicted events will rejuvenate or expose large volumes of unstable sediments. In this way, knowledge of geological conditions, topography, and climate can be integrated to spatially identify resilient habitat, and, conversely, habitat unusually prone to destabilization (fig. 2).

Resiliency is temporally dependent and given enough time, large disturbances are virtually certain to occur on the landscape and to the climate. 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 portion of

the system has a minimal impact on at-risk aquatic species because other parts of the system are able to support 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

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 Pacific Northwest 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 summer 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 stream systems where groundwater hydrology is dominant or snowmelt hydrology is preserved due to high elevations.

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 important to protect these areas and in some cases to enhance them or improve their connectivity.

Restoration

Enhancement of connectivity will be a vitally important form of restoration in any strategic response to climate change. 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 long-term 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 lower-quality habitat. All actions should be analyzed in relation to sustainability, resiliency, and threats from climate change.

When river restoration is performed, or when “fish-friendly” river engineering is contemplated, the dynamic nature of climate change effects makes redundancy of actions desirable. Redundancy can be applied in both horizontal and vertical dimensions. Building engineered log jam structures higher and bulkier than current design practice to accommodate larger peak flows in the future would be an example of vertical redundancy. 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 consider geomorphic instability. Some of the most productive spawning areas for many fish are in sensitive response reaches, which are likely to undergo an episode of geomorphic instability because of climate change (fig. 2). 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 to accommodate greater rates of channel migration and flood magnitudes. This potential needs to be incorporated into discussions of the definition of success, long-term sustainability, and cost of the project. Passive restoration techniques, such as establishment of wider riparian buffers, may be a more sustainable alternative in light of increased geomorphic instability caused by global warming.

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. It is important that resource managers take the time to reflect on long-term desired conditions in river basins, and anticipate future land-use changes that will alter habitat and habitat-forming geomorphic processes in order to participate in a constructive dialogue that is proactive instead of reactive. Articulation of a long-term perspective on system resilience, sensitivity, refugia, and restoration opportunities will be vital counterpoints to land-management proposals which may compromise long-term ecological and resource viability for short-term economic benefits and support of the status quo.

Summary

Currently, there is little information in the literature on the geomorphic effects of climate change. Most of the existing research has focused on the impacts to climate itself and to gross-scale hydrological change. Tools for predicting geomorphic impacts at specific locations are possible, but poorly developed. However, the general principles discussed in this document can be used to suggest ways to screen the landscape for habitat that is potentially resilient or sensitive to climate change. 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.

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. For additional information and references, please refer to the following publication: Bakke, P. 2008. Physical processes and climate change: A guide for biologists. Unpublished report. U.S. Fish and Wildlife Service. Copies are available online from the STREAM website: http://www.stream.fs.fed.us/publications/documentsNotStream.html.

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Ask DOCTOR Hydro

Dear Doc Hydro: I am interested in obtaining better estimates of peak discharge on ungaged streams. Regional regression equations for predicting flood discharge have large standards of error and typically were not developed on streams with small drainage areas. Are there simple, inexpensive techniques for directly determining peak discharge at a stream?

Yes. The crest-stage gage (figs. 1 and 2) is a relatively simple and inexpensive device developed by the U.S. Geological Survey (Buchanan and Somers 1968) for directly obtaining reliable water-surface elevations of flood crests in streams. A crest-stage gage consists of a two-inch pipe containing a wood or aluminum measuring stick held in a fixed position (fig. 1). The arrangement of the six intake holes in the bottom cap are positioned as such to minimize non-hydrostatic pressure drawdown inside the pipe. A perforated tin or plastic cup is attached to the lower portion of the measuring stick to store cork flakes. As water rises

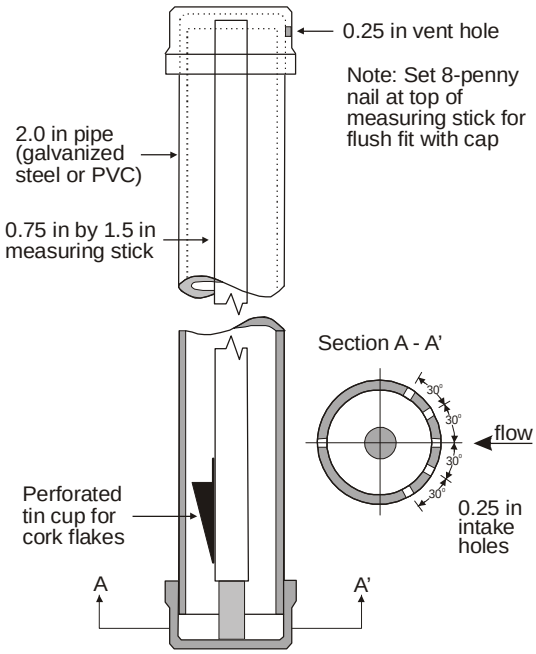

Figure 3. Crest-stage gage diagram and specifications (modified from Buchanan and Somers 1968).

Figure 2. A photo of a typical crest-stage gage.

inside the pipe the cork floats to the water surface. When the water reaches its peak and starts to recede the cork adheres to the stick inside the pipe, leaving a distinct mark of the flood crest or maximum water-surface elevation. The height of the peak is obtained by measuring the length between the base of measuring stick (reference point) and the flood crest mark. Once measured, the gage should be reset by washing cork from the measuring stick. The gage should be strategically placed in a location on the bank margin that protects it from direct flow (fig. 2) and can be readily accessed for measuring and resetting of the cork. The gage should be built to a height so that all ranges of peak flows are recorded.

A channel cross section surveyed at or in close proximity to the crest-stage gage can be used to indirectly obtain the discharge of the flood by using a simple hydraulic model such as WinXSPRO (Hardy et al. 2005). The channel cross section and crest-stage gage need to be related to a common elevation datum so that the flood crest elevation obtained at the crest-stage gage can be delineated at the cross section. WinXSPRO uses a resistance-equation approach and basic continuity to calculate discharge and flow hydraulics at a single cross section. Refer to Hardy et al. (2005) for guidelines on collecting cross section and slope data, selecting channel roughness values, and using WinXSPRO.

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