Understanding Dynamic Relationships and Process Linkages in Earth Surface Systems
As We Respond To Climate Change and Develop Successful Strategies for Watershed Restoration

R. Craig Kochel, Bucknell University

Journey of the Universe Conference – Yale University, March 2011

The extraordinary evolutionary journey of the universe produced our tectonically active planet characterized by magnificently regenerative and diverse marine and terrestrial environments. Terrestrial ecosystems on Earth are intimately linked to the complex physical dynamics of watersheds. Watersheds are self-organized units of terrestrial landscapes, that regulate the flow of water, sediment, and nutrients at the surface (and shallow subsurface). Even in the driest areas of Earth, like the Atacama Desert in Chile (which NASA uses to represent the limits of life), the movement of water has inexorably shaped the landscape for countless millenia. Watershed hillslopes are battlegrounds between resisting forces trying to hold onto gains imparted to them from powerful tectonic forces which uplifted them from positions below sea level to towering prominence, and the relentless attack of weathering forces dutifully reducing them to fragments small enough so that rivers can transport them back to the sea, continuing a spectacular journey of sedimentary recycling that occurs in Earth surface systems. Hillslopes bear witness in this journey to lengthy periods of relative stability punctuated by episodic cataclysms as geomorphic thresholds are crossed during the addition of water from intense rainfall or snowmelt. Then, slopes yield to the omnipotent power of gravity as massive volumes of material move downslope toward rivers in spectacular landslides and debris flows. Gravity also operates on these same slopes in less flamboyant, but equally effective fashion to move material downhill bit by bit in more frequent gradual processes such as creep. In this way, watershed slopes establish the linkage between resistant upland terrains and lowland river channels. Once in the stream channel, sediments are again redistributed gradually by frequent flows and catastrophically during less frequent floods.

Throughout the upland parts of the watershed, a network of tributaries collects water and sediment from slopes and delivers them to mainstream channels. Geomorphologists in the mid 20th century discovered that watershed networks had magnificently organized structure, in ways not dissimilar to the self-organized structure of nearly everything in the universe. Amazingly, this structure can be mathematically characterized and replicated in most climates and diverse terrains around the planet. Likewise, river channels are not random, but are highly structured and adjusted to a delicate balance, a constantly adjusting dynamic equilibrium, dictated by the sediment and water delivered from upstream parts of the watershed. Whether rivers display single meandering channels or spectacular systems of constantly shifting channels (braided streams) across their floodplains depends on the nature of sediment and water supplied to them – chiefly sediment volume, delivery frequency, and size. Rivers are remarkably well adjusted in this dynamic equilibrium as sediment enters their channel reaches from upslope and simultaneously discharges downstream into more permanent resting places, deposited through deltas into lacustrine or marine systems. Because of this delicate balance, any change in sediment or water delivery from the upstream watershed (hillslopes) is likely to result in adjustment in the downstream river channel system. Changes in sediment and water delivery occur in response to a variety of natural influences, including: slope, weathering rate, bedrock type, vegetation cover, tectonics (i.e. an episode of renewed uplift), and climate change (annual total, intensity and/or frequency of precipitation events). The shape of river channels (morphology) is a dynamic system regulated by a large number of interrelated variables, such as: streamflow (discharge), channel slope, channel geometry (width, depth), water velocity, and sediment load (size and volume of coarse bedload, and concentration of finer sediment in suspension), just to name a few. It is not always easy to predict exactly how a river will respond to changes in sediment and water from upstream, but adjust they will. Rivers may adjust in one or more ways. Rivers may change their channel geometry, i.e. their width to depth ratio. Alternatively they may change their gradient (slope). Or, rivers may change their entire pattern or regime (i.e. from meandering to braided). The precise nature of the change isn't always predictable, but it is certain that there will be adjustments in the river channel to watershed changes. Often, these adjustments result in disruptions to human infrastructure in catastrophic ways. Imagine the chaos if overnight a normally well-behaved 30-m wide single-channel meandering stream suddenly changed to a 300 m wide complex of dynamically shifting braided channels. Bridges would be stranded, homes and businesses would suddenly be in the channel rather than on a terrace safely above the floodplain, and farms with formerly fertile topsoil would find their fields replaced with sterile gravel. This is exactly what happened in the 1980's to streams in southern Illinois (in response to complex landuse changes).

Such disruptive scenarios have occurred in many places, some in response to temporary oscillations of the climate such as El Nino, and in other cases due to longer-term climate shifts such as deglaciation in response to global warming. A couple of examples may help illustrate the kinds of physical changes to be expected in watersheds as the dynamic balance of sediment and water in Earth surface systems is altered by climate change. 1) Catastrophic watershed adjustments to climate change are now visible in high alpine areas undergoing rapid deglaciation. Extreme hillslope instability is occurring in areas where high-level icecaps have recently become decoupled from lower valley glaciers. Extraordinary increases in avalanching and mass wasting have occurred as these newly-exposed unstable hillslopes rapidly disintegrate. At one of these locations in southern Alaska, we documented nearly 300 major avalanches, rockfalls, and icy debris flows within just a week. Similar observations in the Southern Alps of New Zealand show that this phenomenon is common in alpine areas experiencing rapid deglaciation. This period of highly unstable landscape activity is known as the paraglacial, and accompanies deglaciation. Landscape instability and erosion rates during this short interval of time may be orders of magnitude higher than experienced for thousands of years following. A notable increase in geohazards coincides in these mountainous watersheds. 2) Global fluctuations in sea surface temperatures known as ENSO events (El Nino Southern Oscillation) in the Pacific Ocean basin have long been known to cause quasi-periodic fluctuations in precipitation at many terrestrial locations, including California. San Diego County's climate is seasonal (mostly dry with moist winters). Overall they experience relatively dry conditions for decades, punctuated by shorter wet and stormy intervals caused largely by ENSO fluctuations. The stability of southern California hillslopes and associated watersheds is dramatically different between these extremes. During dry intervals, the landscape is relatively quiet and stable – encouraging human growth and development. During wet intervals, typically lasting just a few years, major instability can result – marked by frequent catastrophic debris flows, flash floods, and coastal erosion. This alone is significant with regard to hazards, but our studies of a recent wet interval (1978-1983) illustrated that landscape response to the same change in rainfall can be very complex across the region. The wet interval saw a rise in annual rainfall over 100%. Extreme erosion occurred along the coast because of increased storm wave action. Inland areas however had mixed response. Inland low regions west of the Peninsular Ranges did little. Increased precipitation in the mountains resulted in thicker vegetation and relative stability. Desert basins to the east, however, experienced major instability manifested by frequent flash floods and debris flows on alluvial fans that had been stable since the 1940's, which was the last period of major increases in rainfall. Geomorphic studies of alluvial fan stratigraphy revealed that episodes of desert instability corresponded to these major wet intervals, with relatively quiescence marking decades in between. The complex nature of response to the wet period depended on the location. Theoretical studies by geomorphologists in the 1950's may have allowed us to anticipate the distribution of differing responses to precipitation changes. Their work suggested that erosional instability is highest for semi-arid regions (~ 12-15 in. effective annual precipitation). Desert areas with antecedent rainfall ~ 5-7 in. increased to the peak of instability during the change, while wetter areas (at or beyond the peak) became more stable. To add to this complexity, some transitional regions experienced major land surface aggradation burying fences and bridges years after the cessation of the wet interval. Alluvial fans apparently acted as extensive sponges absorbing water during the wet interval until a critical threshold was reached and stored water was gradually released for years. Complex response of watersheds, often marked by non-synchronous erosion and deposition, both spatially and temporally, is not uncommon.

Just as commonly, however, rivers have made similar adjustments in response to changes in sediment and water yield from watersheds caused by anthropogenic disturbance – changes in land use. Changes in land cover caused by humans, such as clearing the forest in logging operations, hydraulic mining in floodplains, shifting from forest to agriculture, and wholesale disruption of infiltration/runoff processes in developing urban centers. Anthropogenic disturbances in watersheds often overshadows the more gradual pace of natural changes in water and sediment delivery. Not only are the anthropogenic changes significant, but they can result in a complex protracted legacy that extends for decades or even centuries in rivers. The legacy of clear-cutting of eastern USA forests in the late 19th- early 20th centuries is a prime example of how anthropogenic change can affect river channel response today. Widespread clearcutting of watershed slopes released coarse sediments to downstream channels, causing major aggradation. After forests were clearcut, and of little use economically, they were acquired by government as public lands. After a few decades of resforestation, these upland slopes delivered clear water to downstream reaches of the watershed. Streams use energy to transport sediment, thus, clear water is naturally aggressive, with more capacity to erode sediment. Clear water began to erode the sediments previously deposited in downstream channels during clearcutting. This is still happening today in many places, sending pulses of newly-eroded gravel from streambanks downstream, clogging river channels and causing single-channel streams to become braided, disrupting floodplains which have been settled by farmers and other inhabitants. Bridges are now being buried, as streams simultaneously erode logging legacy sediments and deposit them further downstream -- all this happening nearly 100 years after the anthropogenic disturbance that is driving the change. A third example of anthropogenic impact on watersheds was extensive degradation of upland water courses on the western slopes of the California Sierras in the Sacramento River – San Francisco Bay system. Widespread aggradation affected upland rivers, the delta region around Sacramento, and into the Bay during the late 18th – early 19th century. Rivers shallowed and floods became common as channel capacity was reduced. Major parts of the Bay shallowed. By the late 20th century, the uplands recovered and sediments began rapidly moving out of the Bay owing largely to tidal circulation. Recent years have been characterized by eroding shorelines and disappearance of tidal marshes in response to lower delivery of sediment to the Bay (exacerbating impacts of rising sea level). Not understanding the complexity of watershed responses can lead to absolute chaos in attempts to manage and restore these ecosystems.

During the short tenure of anthropogenic activity in Earth's watersheds, we failed to recognize the dynamic nature of these systems and how the very existence of delicate ecosystems depends on the dynamic functioning of physical watershed processes. The result of our ignorance was a period of devastating disruption to river systems world-wide by a wide variety of channelization strategies that treated rivers as mechanistic avenues to rid our human domains of unwanted stormwater. This unethical environmental abuse of our waterways resulted in enormous devastation to aquatic ecosystems and physical diversity alike. Fixing river channels with concrete and other hardened structures resulted in enormous reductions of biodiversity, reducing channel diversity and preventing the migration of channel systems so critical in the creation of new habitat for aquatic organisms. In the past few decades, we have awakened to the realization that physical and biological systems in watersheds are intimately linked in a complex dynamic equilibrium. Healthy ecosystems cannot be maintained without diverse physical underpinnings.

Ecosystem restoration has gained enormous momentum in recent decades as scientists and engineers attempt to undo the wrongs of centuries of ignorance of natural watershed systems with a goal to restore watersheds to healthy ecosystems. Significant effort and resources have been invested in restoration, but with mixed results at best. Stream restoration is a good example of the nature of this dilemma. Stream restoration in the USA has become a multi-billion dollar industry conducted largely by consulting firms, government agencies, and citizen watershed groups with good intentions. Recent regional scientific surveys in North Carolina and Pennsylvania, however, have shown that many of these efforts have failed miserably. Our studies showed that in more than half of the projects, stream restoration structures failed after the first significant flood. Few, if any, examples of success with restoration of aquatic habitat have been reported. All the while, we are throwing billions of dollars at stream restoration annually. The primary method used in stream restoration, in the USA, is referred to as "natural channel design" (NCD). The only thing "natural' about this approach is the use of geological materials (big rocks) and biological materials (tree stumps called rootwads) to stabilize stream channels. There are major problems with this NCD approach. First, the approach assumes that stream channels are naturally stable and fixed in one location. In nature, the only channels fixed for any significant time are bedrock channels. Meandering streams migrate by depositing sediment on the inside of meanders and eroding sediment from the outside of the bends. Lateral migration is the natural mode of channel evolution in this most common river type. In braided rivers, nothing is stable. Braided channels avulse and move about on a daily basis with frequent changes in streamflow in their non-cohesive channels. Second, the natural channel design approach assumes that channel morphology can be described and categorized. This of itself is not a problem. However, the method goes on to presume that these cookbook descriptions can be used in a prescriptive manner to predict future channel behavior and evolution. That usually results in chaos. Thirdly, the natural channel design method, using its arsenal of channel-hardening structures such as cross-vanes, J-hooks, and rootwads, really only functions well at flows below bankfull discharge. In low flows, structures perform relatively well by deflecting the primary flow (the thalweg) away from the outside of bends. Many of the vanes also provide some measure of grade control. However, during overbank flows, these structures become mere roughness elements on the bed and do little to regulate flow behavior. In many cases, straight vanes along the bends even serve to amplify flow up onto the floodplains, disrupting the structures placed at the bends. More importantly, even though the trend is to use huge boulders which are unmovable by rivers, the structures are typically bypassed as the stream erodes around them, leaving structures as unsightly boulder islands when the stream migrates, providing neither bank protection or grade control. Gravel deposited by floods on the insides of the bars deflects the flow into structures such as rip-rap on the outside of the bends, undercutting them and resulting in their failure. This is simply a stream doing what is natural in its physical operation. In other cases, stream restoration projects are constructed to try to reduce bank erosion and stabilize streambanks. These structures also typically fail after a few floods, largely due to undercutting and collapse. These problems illustrate the fourth major fallacy of most stream restoration approaches – the reach-focused approach. Restoration projects typically focus on "fixing" the local problem, such as bank erosion, with the application of some bank stabilizing method. The reach approach typically fails because it doesn't address the root cause of the problem – the adjustments at the reach in question are really taking place because the upstream watershed system is out of equilibrium due to some natural or anthropogenic change in sediment and/or water supply. In the eastern USA, most streambanks are eroding in response to adjustments to the legacy of logging more than a century ago. This example of complex response demonstrates that in order to understand how to respond to bank erosion, restoration projects need to study stream channel behavior on a watershed scale. Nothing can be done at the reach scale to correct a problem driven by changes originating upstream in the watershed.

It is now becoming clear that in order to develop successful strategies for effective ecological restoration in watersheds, scientists and engineers must understand the complex dynamic equilibrium in Earth surface systems. Only then will we be able to funnel resources toward sustainable approaches to stream restoration. Fluvial geomorphologists, trained in understanding the interplay between the many variables of river systems, will lead the charge in providing a sustainable framework for watershed restoration. Likewise, we now understand that the impacts of global climate change on Earth surface systems will include alterations that will be manifest in complex ways spatially and temporally across diverse terrestrial watersheds. Applying the knowledge we now have of the dynamic balance between water and sediment yield on watershed slopes and stream channels will enable us to anticipate the nature of future changes and to better manage watershed development patterns. As the journey of the universe continues to unfold, the success of human activity on Earth's dynamic landscape as well as the success of our strategies for ecological restoration of watersheds requires an approach fully grounded in understanding the nature of dynamic equilibrium in rivers. This approach recognizes the rights of watersheds and rivers in their physical being as well as the ecosystems so fully dependent upon them.