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Post-Flood Cleanup Alternatives along Stream Corridors in Central Pennsylvania Helping Resolve River and Land Use Conflicts in an Economically and Ecologically Sustainable Manner

Benjamin R. Hayes
Bucknell University, brh010@bucknell.edu

R. Craig Kochel
Bucknell University, kochel@bucknell.edu

Jessica Newlin
Bucknell University, jtn003@bucknell.edu

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A Scientific and River Engineering Perspective

"Stream cleaning" efforts underway shortly after the devastating floods of Tropical Storm Lee in September 9-11, 2011. Big Bear Creek, a tributary to the Loyalsock Creek in the West Branch of the Susquehanna River in north-central Pennsylvania.

Since 1990, over one million dollars of state and federal funding and countless hours by volunteers have been spent trying to improve the trout habitat improvement in this steep, narrow watershed.

Benjamin R. Hayes, Ph.D. - Susquehanna River Initiative Director, Bucknell University

Watershed hydrology, fluvial processes and habitat restoration

R. Craig Kochel, Ph.D. - Professor of Geology, Bucknell University

Fluvial geomorphology, flood hydrology, stream restoration

Jessica T. Newlin, Ph.D., P.E. - Professor of Civil and Environmental Engineering, Bucknell University

Fluvial hydraulics, sediment Transport, Bridge and River Engineering

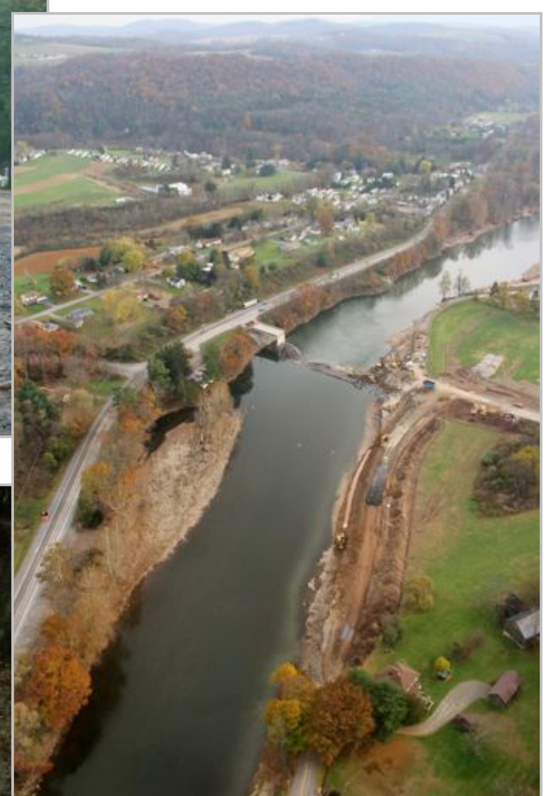
Post-Flood Alternatives for River Corridor Management in Central Pennsylvania

Helping resolve river and land use conflicts
in an economically and ecologically sustainable manner

Like many other states, Pennsylvania finds itself in an unending and escalating cycle of spending millions of dollars to maintain its stream and river channels, repair and rebuild flood damaged roads and bridges, and protect adjacent land uses from destruction by erosion or flooding, only to see these river management investments:

- fail during the next flood; or
- result in increased damage elsewhere, usually downstream.

To complicate the problem, riparian landowners are increasingly strident about real and perceived failures of the state's river management policies to address their concerns as they lose valued property with every significant runoff event.



Tropical Storm Lee delivered over 18 inches of rain to steep, narrow watersheds in north-central Pennsylvania, devastating homes, roads, and bridges in the Muncy, Loyalsock, Fishing Creek and Lycoming creek watersheds.

At the same time, stream erosion is increasingly cited as one of the most significant statewide water resource concerns, as evidenced by physical and biological indicators of aquatic ecosystem health. The EPA still ranks suspended sediment as the number one pollutant from the Susquehanna River to the Chesapeake Bay (EPA, 2010).

Suspended sediment-laden flood waters from Tropical Storm Lee at the confluence of the North and West Branches of the Susquehanna River at Sunbury, Pennsylvania. September 9, 2011.

Tropical Storm Lee delivered record amounts of suspended sediment to the Chesapeake Bay. Erosion of sediments accumulated behind old mill dams and modern hydroelectric dams is of major concern in these events.

1. Key Concepts for Managing River Corridors in Sustainable Manner

It is important to recognize that:

- Over the past two centuries, a significant percentage of Pennsylvania streams and rivers have undergone channelization and modification (Hayes and Field, 2008; 2009). This began in earnest during the log drives in the mid- to late-1800s, but continues today, albeit at a much smaller scale, and primarily for road and highway construction. Typically, channelized streams are straighter, steeper, wider, and largely devoid of the instream and riparian features that maintain natural channel stability and provide a diversity of aquatic and riparian habitats.

Channelization and straightening of stream remains a common practice by homeowners in Pennsylvania as a immediate response to flooding.

- Channelization practices that were started over 100 years ago to accommodate early settlement, roads, railroads, logging, farms, mills, and other "human investments" have been periodically maintained through gravel removal, realignment, channel armoring, and post flood remediation projects (Hayes and Field, 2009).
- Many channels have incised, eroding downward, losing access to floodplains which are essential to maintaining natural channel stability over time. Many miles of rivers have lost access to their floodplains during frequent run-off events (1-10 year floods) and in some cases even rare events involving very large discharges (50-100 year floods) resulting in a tremendous increase in channel adjustment and erosion.
- Adjacent to incised and adjusting channels, land uses, including agriculture, residential and commercial development, and transportation infrastructure, have encroached into the lands previously used by river meanders and flood water.
- While some channelization continues today, many straightened, incised reaches are now widening and aggrading (building up with sediment transported from upstream). Recent major storm events have energized these channelized stream systems with inputs of water and sediment and, in so doing, have accelerated these physical adjustment processes (widening and aggradation), as new flood plains develop along the rivers.
- The physical adjustment processes (most commonly observed as stream bank erosion) lead to the planform or meander changes that are imperative for the river system to attain a natural balance within its watershed. These adjustments cause property damage that, in many cases, have become increasingly intolerable for current landowners.

2. Options for Managing the Conflict between Nature and Man

Managing the conflict between people's land use expectations and river dynamics should be based on an examination of alternatives and cost-benefit analyses, in both the short and long-term, to both private and public interests. To avoid the growing conflict between the changing course of Pennsylvania rivers and our land use expectations, the environmental agencies (Pennsylvania Department of Environmental Protection), fisheries agencies (U.S. Fish and Wildlife and Pennsylvania Fish and Boat Commission), and U.S. Army Corps of Engineers (USCOE) in collaboration with its partners must:

(A) acknowledge these on-going physical processes and the circumstances leading to the conflict between nature and man today;

(B) understand and be able to articulate the implications and consequences of different conflict management options; and

(C) develop the ability to effectively address conflicts with riverine systems through the application of one or a combination of the following alternatives.

There are generally four different river corridor management alternatives for resolving historic and ongoing conflicts between river dynamics and land use expectations (Kline and Cahoon, 2010):

A. Channelization: Maintain rivers in a channelized state through dredging and bank armoring applications. Active revegetation and long-term protection of a wooded riparian buffer is important to this alternative.

B. Active Geomorphic: Restore or manage rivers to a geomorphic state of dynamic equilibrium through an active approach that may include human-constructed meanders, floodplains, and bank stabilization techniques. Typically, the active approach involves the design and construction of a management application or river channel restoration such that dynamic equilibrium is achieved in a relatively short period of time. Active riparian buffer revegetation and long-term protection of a river corridor is essential to this alternative.

C. Passive Geomorphic: Allow rivers to return to a state of dynamic equilibrium through a passive approach that involves the removal of constraints from a river corridor thereby allowing the river, utilizing its own energy and watershed inputs to re-establish its meanders, floodplains, and self maintaining, sustainable equilibrium condition over an extended time period. Active riparian buffer revegetation and long-term protection of a river corridor is essential to this alternative.

D. Combinations of the Above Alternatives: Use a combination of alternative approaches to accommodate the varying constraints that typically occur along a project reach.

Defining and protecting the meander belt or stream width corridor that will accommodate equilibrium conditions may be the most important objective in any stream restoration and flood recovery project.

3. The Physical Imperatives of River Systems

Changes to the shape of a river channel or changes in the inputs of water and sediment often lead to imbalance, and cause adjustments in river and floodplain geometry until balance is re-established. Natural adjustments to the river channel occur continually, but often dramatically manifest themselves during large flood events. These adjustments, however, have been overshadowed or largely magnified during the past two centuries by those resulting from human- imposed changes to the depth and slope of rivers related to intensive watershed and riparian land uses.

Nearly every central Pennsylvania watershed has streams “in adjustment” from the following sequence of events:

A. **Deforestation** – led to dramatic increases in the volume of water and sediment runoff;

B. **Snagging & ditching** – clearing boulders and woody debris for logging and flood control, and ditching poorly drained land for agricultural improvements increased the rate of water and sediment runoff;

C. **Villages, roads, and railroads** – early settlements led to the first attempts to straighten rivers and streams which resulted in increases in channel slope, stream bed degradation, and floodplain encroachments;

E. **Mills, dams, and diversions** – led to alterations in the amount and rate of water and sediment runoff. While dozens of dams are in place in each Pennsylvania watershed today, historically there were hundreds;

F. **Floods and flood works** – each major flood event brought enormous loads of sediment into channels that were already aggrading or degrading, causing damage to human infrastructure which in turn led to new efforts to straighten and deepen the rivers;

G. **Gravel removal** – advocated as a way to maintain straighter, deeper channels; large-scale commercial gravel mining resulted in bed degradation, head cutting, channel over-widening, and severe bank erosion;

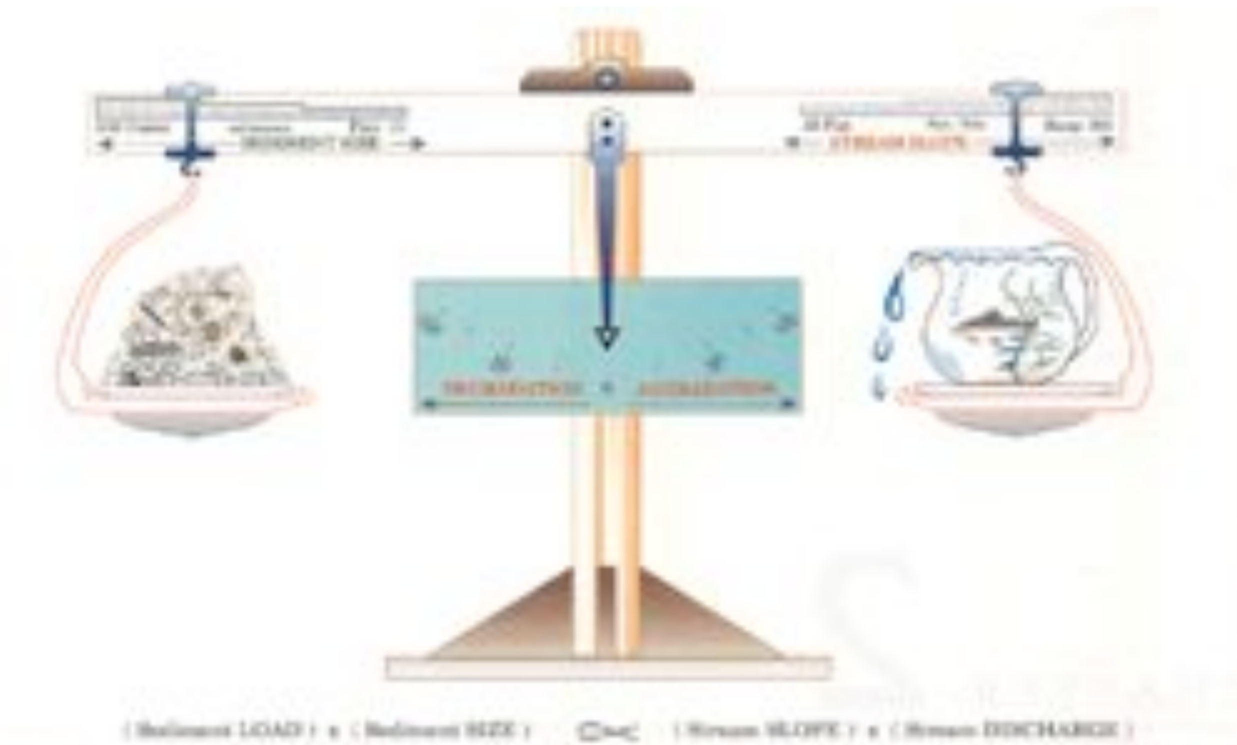
H. **Encroachment** – investments on lands previously occupied by river meanders or inundated during floods created unrealistic and unsustainable human expectations in the absence of continuous or periodic channel management activities; and

I. **Stormwater and urbanization** – increases in impervious surface and ditching to support economic development and land use conversion increased the rate and volume of water and sediment runoff entering stream systems.

During the peak of the logging boom in the 1880s, watersheds such as this one - Pine Creek in the West Branch of the Susquehanna River - were completely denuded; their hillslopes were stripped bare of protective forests. Stream channels were straightened, snags removed, and temporary “splash dams” constructed to float the logs downstream to the saw mills and log booms of the Susquehanna. As a result, millions of tons of sediment were washed into the rivers, destabilizing the streams for decades. Geomorphic and hydrologic studies are showing that over the past 100 years, these logging legacy sediments are being flushed downstream with each major flood.

4. Dynamic Equilibrium of Streams and Anticipating Adjustments in the Future

Rivers are in a constant balancing act between the energy they produce and the work that must be done to convey the runoff of sediment and woody debris produced in their watersheds (Leopold, Wolman and Miller, 1964; Schumm, 1970). The slope and depth of a river determine how much transporting energy it has. For example, a wide and shallow river will have less energy than one that is narrow and deep, resulting in a lower capacity to move sediment. During large runoff events, the shallow river channel may aggrade or fill with gravel (Baker, Kochel, and Patton, 1988). On the other hand, a steep or high gradient river will have more energy and a greater capacity to move sediment.   River channels that have become steeper will often degrade, eroding bed and banks, then widening and aggrading until the meanders and floodplains necessary to expend the excess energy have been established.



It is a physical imperative within river systems that over time, **an energy balance with watershed inputs is achieved and maintained.** This balance is achieved through adjustment of channel dimensions and longitudinal slope, and its elevation relative to the floodplain (Ritter, Kochel, and Miller, 2011).

When a natural stream achieves a depth and slope in balance with its water and sediment loads, the channel and flood plain geometry are primarily maintained by the boundary conditions established by coarse sediment on the bed and/or the soil cohesiveness and soil binding attributes of vegetative root systems on the banks. When these stabilizing influences are disturbed, the resistance of the bed and bank to erosion is largely diminished.

Grade control structures and rip-rap have been used on streams to replace boulder steps, cobble riffles and the deep, soil binding roots of trees and shrubs. These structures work but are not self-maintaining or replenishing like the boundary materials of naturally stable streams, and thus, must be periodically maintained.   Human-placed boundary conditions may work for many years where the channel and floodplain geometry are in equilibrium, but typically **initiate other channel adjustments** or **fail with the next flood** when placed on channels that are in adjustment through stages of aggradation, degradation or seeking balance through longitudinal slope adjustment and plan form change (Thorne, Hey, and Newson, 1998).

Aerial view of staggering amount sediment deposition in the channel and adjacent floodplain areas in the lower reaches of Loyalsock Creek during the record floods of Tropical Storm Lee on September 9-11, 2011. The river is adjusting its channel and floodplain corridor as it tries to accommodate enormous quantities of sand and gravel delivered to the headwater regions of the watershed during the logging era. The meandering low-flow channel is visible (note excavators and pickup trucks for scale), with gravel bars and braided high-flow channels visible across the forested floodplain corridor. Loyalsock Creek and most other streams in the north-central Pennsylvania remain in a protracted phase of adjustment from the complete deforestation of these watersheds 100 years ago. Enormous quantities of sediment were delivered to the river and pulses of gravel continue to work their way downstream during floods such as this one. Attempts to dredge, channelize, or realign streams in this condition are unsustainable and usually only increase flooding and channel erosion further downstream.

Try to minimize development in the entire river corridor is the most inexpensive and sustainable alternative in situations such as this. Efforts to rebuild homes or farm within the floodplain corridor stand a high likelihood of being damage by floods in the future as well - Loyalsock Creek needs this space to move the gravel through its system as seeks a new equilibrium state in the future.

5. The Conflict: Today's Accounting

Conflict between river corridor land uses and riverine flooding and erosion is as old as our imprint on the landscape. Traditional floodplain and channel management practices implemented to reduce or manage these conflicts have largely worsened the problem, or transferred it to an adjacent landowner, out of a lack of respect for or understanding of the physical imperatives of river systems.

Each time a river has been straightened, dredged, bermed, and armored to mitigate flood damage without respect for the physical form and function of its channel and floodplain, adjustments were set in motion that, more often than not, led to further erosion.

This property, located in the headwaters of the Muncy Creek watershed, has experienced increased erosion over the past forty years, since Hurricane Agnes in June 1972. Upstream, the channel was been straightened and bermed for log drives eighty years ago. Well-intended efforts and expenditures by the home owner to dredge the channel on the upstream end of the property have not been effective. In fact, the channel is returning to its braided, multithreaded condition it was in before European settlement and logging in the watershed took place. Efforts to constrain the channel to one static location will be unsustainable over the long term.

The decades that often intervene between major floods have given people the misperception that their channelization projects actually worked. Generations have passed and people have forgotten that the rivers have been altered multiple times to "protect" human investments.

In central Pennsylvania, there are many rivers and streams that were channelized with little thought to how river systems work. As rivers adjust to regain a balance between their form and function, they are likely to undergo a period of significant bank erosion. This period will be particularly painful for people to watch or experience. Especially as our population and global economy grow, the conflict between what is a physical imperative of the river system and our land use expectations becomes more and more intractable.

The Tropical Storm Irene flood of September 8-9, 2011 resulted in tens of millions of dollars in mostly erosion-related damages, especially in the narrow, steep tributaries to Fishing Creek, Muncy Creek, Loyalsock Creek, and Lycoming Creek. Areas near Towanda and Bradford County were also devastated. Within weeks following the storm, a number severely aggraded channels began to be dredged, channelized, and cutting up or burning of the large woody debris jams. Streams were straightened and armored with rip-rap near bridges and roads.

Stream ecosystems in Pennsylvania rely upon a complex cascade of water, nutrients, and woody debris for their health and survival. Flooding is a natural part of maintaining the stream, providing energy for the channel to rework its bed and bank and create new habitat for aquatic life. Trees washed into the channel provide fresh wood and organic material, complexity and refuge for trout, salamanders, and all life in the river.

These floods - essential for the natural system - are damaging to homes and cabins built along the edge of the streams. To the homeowners, floods are a "disaster" and destructive to their built property. Our first inclination is to cut up the log jams, sell the logs for timber and snag and even burn the root wads and smaller woody debris. The old way of thinking - remove logs and debris from the stream and straighten the channel to convey the water out of the watershed remain, even though science, engineering, and decades of observation have proven that not to be the case.

By removing the wood delivered to the stream, digging out the flood gravel and sediments, such stream "cleaning" efforts end up destroying the fresh aquatic habitat created by the flood. Floods resort the channel sediments and scour out new pools and riffles that are compacted or flattened by the earth working machines. More intensive efforts to straighten the channel or return the stream to its previous channel are often futile, because the post-flood slope, channel width and depth, and other conditions are not the same as before.

But unlike the damaging floods of the 1970's, when commercial gravel mining was in its heyday, the rivers were not dredged and bermed as extensively during the 1990's. This has caused great concern for some interests, because, although the rivers have begun the adjustments necessary to reach equilibrium, the erosion and changes in planform are threatening current day investments in lands adjacent to the rivers.

6. Cost-Benefit Analyses

Today's accounting shows a significant amount of the Central Pennsylvania land base to be threatened by flood-related erosion due to historic channel management, changes in watershed hydrology and sediment regime, and riparian land use practices and encroachments. **The expenditure of millions of dollars will be necessary to restore or manage rivers and property after future floods.** The high cost of restoration or management may be mitigated over time at a watershed scale where an understanding of the physical processes of rivers (fluvial geomorphic science) is used to restore both channel and floodplain function and protect riparian corridors from future ill-advised developments. Since 1970s, over $13 million dollars of state and federal funds have been spent on stream habitat improvement projects in the seven counties in north and central Pennsylvania (Hayes, Kochel, and Kassab, 2009). The long term efficacy of this investment is threatened to being destroyed by channelization and gravel mining proposed as part of the Tropical Storm Irene cleanup effort.

Where there is neither the will nor the means to compensate people for their current investments, the cost of post- flood remediation and property protection will remain high in perpetuity (Cahoon and Kline, 2003).

On another part of the ledger, the cumulative impact of human actions have degraded physical habitat necessary to support healthy populations of some fish species and other aquatic life. Repeated channelization reduces the river bed and riparian structures upon which aquatic biota rely for shelter, food, and reproduction. Worldwatch Institute research (Abramovitz, 1996) cited **dams and channelization as the two most pervasive threats to freshwater ecosystems today,** with dramatic effects on species abundance and diversity.

Unfortunately the growing conflict with river dynamics can not be treated as a one-dimensional economic problem to be solved for short term gain. The social, economic, and ecological return for implementing river corridor management practices that work toward equilibrium at the watershed scale will be largely enjoyed by generations to come. The long term challenge is to have more predictable investments with less erosion and healthier aquatic ecosystems, while minimizing short term economic losses along the way (Hermans, et. al., 2007).

7. Short vs. Long Term Solutions: A Choice of Management Scenarios

For the straightened river, it is only a matter of time before a flood drops a very large load of sediment at some point along its course. The wedge of sediment that builds in the channel during the recession of the flood may cause the river to avulse, or leave the channel, and head cut back through the landscape from the point where it returns to the channel further downstream. These events can erode river banks tens of feet and sometimes create whole new channels through adjacent lands, often someone's farm field.

A common, understandable response from landowners is to get the gravel out, return the river to where it was, and repair the eroded river bank with rock. This “dredge and armor” response should be used with great caution. We can all agree and recognize that the current pattern of land use investment and expectation along river corridors is not sustainable without some level of intervention or channel maintenance. The key is to assure that the maintenance is done in an informed way through acknowledgment of past mistakes and moves us all toward a more economically and ecologically sustainable relationship with the river.

Success, in the long term, will primarily be measured by our ability to solve problems at the watershed and river corridor scale; and secondarily, by how we resolve conflicts at individual erosion sites. From a geomorphic standpoint, this means recognizing that rivers transport and deposit sediment; and that natural stability and balance in the river system will depend on the river’s opportunity to build and access a floodplain and create depositional features such as point bars, steps, and riffles to evenly distribute its energy and sediment load in a sustainable manner (Ritter, Kochel, and Miller, 2011).

8. “Stream Cleaning” - allow gravel removal or “do nothing”?

As with the “dredge and armor” response, the “do-nothing” response has limited application, and should be used with caution and consensus. Projects that would restore and enhance aquatic habitat, aesthetics, and/or river recreation as primary objectives, in the absence of river and land use conflicts, should strongly consider the do nothing alternative. Where river and land use conflicts exist, the do-nothing response is rarely a viable alternative. Watersheds and river corridors freed of human encroachment would heal themselves in time, but unresolved conflict at one location may create more conflict and unintended consequences for both the river and adjacent landowners. Sometimes, the river management practices that must be implemented after a period of doing nothing (as the conflicts have worsened) may, in the end, be worse than those avoided in the first place.

Understanding that **river and riparian habitats are formed and maintained by fluvial processes at the watershed scale** is essential to resolving conflicts and carrying out river corridor management activities that, while seemingly detrimental to an existing habitat feature, nevertheless represent meaningful long-term solutions that support the river’s ecological potential. In the end, the riparian corridor and floodplain functions provide the basis for instream habitat-forming processes. Opportunities to establish long-term buffer agreements that minimize future corridor encroachments and support riparian woodlands should be supported even where site-specific habitat features may be compromised in the short-term. The major exception to such a policy would be that a long term solution should not compromise habitat that is critically limited in geographical extent, especially rare, threatened or endangered species habitats.

Impact of gravel removal on the homeowner's property

Removal of gravel bars is often used in an attempt to reduce flooding and widen the active stream channel. This way of thinking has its roots in canals and irrigation ditch design - make the channel wider to increase its conveyance and straighten the bends to get the water through the system quicker." However, streams and rivers are orders of magnitude large and more complex than canals and drainage ditches, and respond very differently. The data and years of observation confirm that stream dredging and reworking can actually *worsen* the situation in the event of a large flood. Increasing the channel depth and removing gravel bars and woody debris creates a stream with *more* concentrated energy and greater erosional forces that can increase damage and loss of property. Those who have removed point bars can attest that these features almost always return, supplied by fresh sediment during the next high flow event .

1. Immediately after the Tropical Storm Lee flood of record, September 9-11, 2011.

2. Snagging and burning of woody debris, gravel, realignment of channel, and installation of rock veins. (mid to late September, 2011)

3. Removal of gravel point bar, realignment of main flow channel, regrading of channel slope and width. (late September 2011).

4. Reworking of channel banks, installation of rock veins on meander bend, regrading and armoring of channel banks. (October, 2011)

Impact on Neighbor’s Property

Any excavation of gravel from a stream effects areas both upstream and downstream of the reach. Increased erosion often ensues, leading to excess sediment deposition downstream while headcutting can occur upstream of the reach. The bottom line is that **the stream system as a whole must be taken into account before conducting many site specific projects.** Gravel bars are likely to end up either returning or simply moving the problem up or downstream if proper stream morphology is not considered.

The Pennsylvania Emergency Management Agency (PEMA, 2011) emphasizes in their *Emergency Stream Stabilization Guide* that the “dredge and armor” or “stream cleaning” approach has a profoundly negative consequences:

- **increases flooding** downstream
- **increases bank erosion** upstream
- **increases gravel bar formations**
- **destroys aquatic habitat** by compaction, siltation, loss of wood and rocks, etc.

In some situations, the “dredge and armor” and “do nothing” approaches may support positive land use and/or habitat- related outcomes for a certain period of time. **When the alternatives are not well known, articulated or understood, it is human nature to seek out or repeat solutions that protect the status quo, even if that same solution just failed**. It would be wrong though, to pursue a short term “dredge and armor” approach that is doomed to failure and/or did not resolve the conflict between nature and man at the expense of long-term solutions. A guide to both the short and long term costs and benefits associated with the four different management alternative and examples of how each alternative might be pursued as a river management project are offered in an appendix to this paper.

> “ *They may be thinking only of protecting their property, but by digging out the gravel and widening the banks, they're just moving the problem to me and other homeowners.*
>
> *Now a head cut is working it’s way upstream to my place, undermining my stream banks, washing more gravel downstream to fill in the hole they just created. I’m losing even more property.*
>
> *Something better needs to be done. A better understanding is needed. Maybe we should just take all this flood recovery money and instead of wasting it on digging out the stream, use it to buy our property or just move our cabins further away from the creek so it can do its own thing.* ”
>
> - Quotes from a discussion with a resident whose home is located along Fishing Creek, regarding complications to his property after a downstream neighbor snagged, dredged, and realigned the stream following Tropical Storm Lee flood.

9. Informing the Alternatives Selection Process

The decision to armor an eroding bank or dredge a river to protect investments in the land becomes easy if you focus only on the short term costs and benefits. While one armoring or gravel removal project to stop erosion may be relatively benign, the problem arises from the cumulative effects of dredging and armoring up and down a river valley. At some threshold, bank armoring, post flood channelization, and changes in stormwater runoff combine to move a river out of equilibrium. In Central Pennsylvania over the past century, a high percentage of riparian landowners, with government assistance, have considered and applied the dredge and armor approach. Meanwhile, commercial and residential development, transportation infrastructure, logging, and agricultural practices have altered the quantity and rate of water and sediment runoff. The resulting watershed-level instability places the viability of individual, seemingly benign, bank protection projects in jeopardy where significant channel adjustments are now underway. Even so, gravel removal and bank armoring may be the necessary short-term "band-aid" solutions that are applied in areas of irresolvable conflict until significant watershed problems can be documented through geomorphic assessment and addressed through the application of best management practices.

10. Managing Sustainably

Fluvial geomorphologists and civil engineers at Bucknell University have been studying the impact of floods on Pennsylvania streams, bridges, dams, and roads for decades. We are partnering with our colleagues in the Susquehanna River Heartland Coalition for Environmental Studies (a Kings College, Bloomsburg University, Susquehanna University, Lycoming College, and Lock Haven University) to explore new management alternatives to post-flood cleanup. We are also. sharing our findings with the public and our partners at DEP, DCNR, and U.S. Fish and Wildlife Service.

Our goal is to to focus on the long term benefits of a **geomorphic corridor management approach which can benefit both property owners and riparian ecosystems.** The largest challenge will not be in applying the science to understand the river's slope and planform requirements, but rather **how to redefine the relationship of public and private investments with fluvial dynamics in an equitable manner over time within a watershed.**

The larger short term costs associated with using a geomorphic-based approach, where land conversion is necessary, become **more acceptable** and **economically justifiable** where channelization projects have failed repeatedly or in post flood remediation where major erosion, property damage, and channel avulsions have occurred. **A passive geomorphic approach may be the most desirable alternative due to its lower maintenance costs** but is highly dependent upon landowners willing to accept what may be significant changes in land use expectations. It is extremely important that State and Federal agencies involved with river resource management work together to provide economic incentives and technical assistance to towns and landowners to make decisions that resolve immediate conflicts with the long term watershed solutions in mind.

Watershed planning and the year-to-year implementation of management / restoration projects will require information about the geomorphic condition of the watershed. Using the protocols and assessment strategies, the SRHCES and its partners will gain critically important information on:

- stream condition or the current degree of departure of the channel, floodplain, and valley conditions from the reference (natural or equilibrium) condition for parameters such as channel dimension, pattern, profile, sediment regime, and vegetation;

- sensitivity or the likelihood that a stream will respond to a watershed or local disturbance caused by natural event and/or anticipated human activity; and
- adjustment process or type of change that may be underway due to natural causes or human activity that has or may result in a change to the valley, floodplain, and/or channel condition (e.g., vertical, lateral, or channel plan form adjustment processes).

The assessment of stream condition, sensitivity, and adjustment process is an ideal tool for problem solving in a watershed context because it will not only show the proximity of river reaches undergoing channel adjustment, but will explain how one reach may be affecting the geomorphic condition of another. The physical stream condition is largely a function of the type and magnitude of channel adjustments that are happening in response to changes in runoff patterns and the channel and floodplain modifications that have occurred in a watershed.

Ideally, watershed plans involving all stakeholders would articulate how public and private land use and infrastructure investments would be balanced with the goal of achieving an equilibrium condition in the river. In addition to that, an incentives-based, multi-agency river management program that seeks incremental progress with each landowner toward protecting, managing, and restoring the river corridor should be established. Either way, real progress will be measured over decades.

11. References

Abramovitz, J. 1996. *Imperiled Waters, Impoverished Future: The Decline of Freshwater Ecosystems*. Worldwatch Institute, Worldwatch Paper 128. Washington DC.

Baker, V. R. , Kochel, R. C., and Patton, P., 1988. *Flood Geomorphology*, (1st edition) Wiley-Interscience, 528 pgs.

Cahoon, B. and Kline, M., 2003. *Alternatives for River Corridor Management Vermont DEC River Management Program*, Vermont Department of Environmental Conservation, used with permission.

Fischenich, J.C. 2003. T*echnical Considerations for Evaluating Riverine/Riparian restoration Projects*. ERDC/EL TR-WRAP-03-XX, April 2003, U.S. Army Engineer Research and Development Center Environmental Laboratory, Vicksburg, MS.

Hayes, B. R. and Field, J., 2008. *Stream Restoration Efforts Must Consider Ecological Connectivity, Watershed-Scale Processes, and Historic Land Use Changes,* Paper No. 5 in Pardee Keynote Symposia: River Restoration: Environmental Success or Strategic Failure?, 2008 Joint Meeting of The Geological Society of America, Soil Science Society of America, American Society of Agronomy, Crop Science Society of America, Gulf Coast Association of Geological Societies with the Gulf Coast Section of SEPM.

Hayes, B. R. and Field, J., 2009. *Restoration of Fluvial Process and Aquatic Habitat in the Sandy River and Tributaries to the Kennebec River, Maine*, Session No. 29: Habitat Restoratino in North Atlantic Watersheds,Geological Society of America Abstracts with Programs, Vol. 41, No. 3, p. 101.

Hayes, B. R., Kochel, R. C., and Kassab, 2009. *Assessment of stream restoration structures in streams of north-central Pennsylvania*, Report to the Cora Brooks Foundation, Bucknell University, 65 pg.

Hermans, C., Erickson, J., Noordewier, T., Sheldon, A., and Kline, M., 2007. *Collaborative environmental planning in river management: An application of multicriteria decision analysis in the White River Watershed in Vermont*. Journal of Environmental Management, v. 84, p. 534-546.

Kline, M. and Cahoon, B., 2010. *Protecting River Corridors in Vermont,* Journal of American Water Resources Association, v. 46, no. 2, p. 227-236.

Leopold, L. B., Wolman, M.G., and Miller, J. P., 1964. *Fluvial Processes in Geomorphology*, W.H. Freeman, 522 pgs.

Pennsylvania Emergency Management Agency (PEMA), 2011. *Emergency Stream Stabilization Guide*, 2 pgs.

Ritter, D., Kochel, R. Craig, and Miller, J., 2011. *Process Geomorphology* (5th edition), Waveland Press, Inc., 652 pgs.

Schumm, S. A., 1977. *The Fluvial System*, John Wiley and Sons., 338 pgs.

Thorne, C. R., Hey, R. D., and Newson, M. D., editors, 1998. *Applied Fluvial Geomorphology for River Engineering and Management*, John Wiley and Sons, 384 pgs.

U.S. Environmental Protection Agency (EPA), 2010. *Chesapeake Bay Total Maximum Daily Load (TMDL) for Nitrogen, Phosphorus and Sediment*, Region 3 Water Protection Division, Philadelphia, Pennsylvania. 75 pgs.

Glossary

Aggradation: Raising or building up of the channel bed or flood plain through the deposition of sediment transported from upstream.

Armoring: Increasing the erosion resistance of the channel bed and banks through structural treatments such as rock rip rap or gabions.

Avulsion: Catastrophic relocation of the channel, typically across a peninsula-shaped flood plain or through a flood chute usually during a major flood event.

Channelization: Channel and flood plain alterations that typically straighten and increase the longitudinal slope, raise the elevation of the banks or lower the elevation of the bed and often includes bank armoring.

Degradation: Lowering of the streambed typically due to an imbalance between a) sediment supply and transport capacity or b) resistance of the bed materials and the energy of flowing water.

Dynamic Equilibrium: A state of balance whereby a stream, over time and in the present climate, transports the flow, sediment, and debris of its watershed in such a manner that it maintains its dimension, pattern, and profile without aggrading or degrading.

Fluvial: Related to the river system

Geomorphic: 1) Refers to a condition within which a fluvial system is in dynamic equilibrium or 2) refers to the complex interaction of physical landscape parameters that influence river form and function.

Incise: See Degradation.

Longitudinal Slope: The profile of the river or the rate at which it drops in elevation in relation to the horizontal length it travels.

Physical Adjustment Process: If a stream reach is forced out of a state of dynamic equilibrium (generally as a result of channel, floodplain or watershed disturbances), it will adjust its dimension, plan form and profile until balance between the watershed inputs and its ability to transport those inputs is re-established.

Plan Form: Channel geometry in plan view; meander pattern. Riparian: Relating to the river or in geographic proximity to river.

Sediment: Soil materials ranging from boulders to clay particles that may be transported or deposited in the channel or flood plain.

Structure: Natural or human-introduced materials, typically wood or rock, that create physical features along the bank or bed.