A NATURAL CHANNEL DESIGN APPROACH TO STREAM RESTORATION ON RECLAIMED SURFACE MINE LANDS[1]

William A. Harman, Suzanne J. Unger, and Ronald H. Fortney[2]

Abstract. Natural channel design methods are being considered for the purpose of re-establishing stable stream channels and valleys on reclaimed surface mine lands. Natural channel design is the process of applying fluvial geomorphic principles to transform unstable stream corridors into stable channels that maintain their dimension, pattern, and profile over time. Additional goals include improving aquatic habitats and restoring native riparian vegetation. Natural channel design concepts are reviewed in the context of their application to reclaimed mine lands. A tributary to the Mitchell River in the Blue Ridge Mountains of North Carolina is used as a case study demonstrating techniques that may be applied to reclaimed surface mine land sites.

Additional Key Words: fluvial geomorphology, surface mining, revegetation, channel stabilization, mine land reclamation.

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[1]Paper was presented at the 2004 National Meeting of the American Society of Mining and Reclamation and The 25th West Virginia Surface Mine Drainage Task Force, April 18-24, 2004. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.
Proceedings America Society of Mining and Reclamation, 2004
DOI: 10.21000/JASMR04010791

[2]William A. Harman is Principal of Buck Engineering, Cary NC 27511. Suzanne J. Unger is an Environmental Engineer at Buck Engineering. Ronald H. Fortney is Research Professor of Civil and Environmental Engineering, West Virginia University, Morgantown WV 26505.
Proceedings America Society of Mining and Reclamation, 2004 pp 791-810
DOI: 10.21000/JASMR04010791
https://doi.org/10.21000/JASMR04010791

Introduction

The effects of surface mining on streams are well documented and include hydrologic modifications, erosion and sedimentation, fish and wildlife disturbances, water quality deterioration, and floodplain degradation (USACOE et al., 2003; USGS, 2001; PADEP, 2001; Wiley et al., 2001). Restoration practices on reclaimed lands attempt to reconstruct topography, soil profiles, hydrologic patterns, and vegetation in order to improve water quality and return the landscape to a usable condition. Natural channel design methods are now being investigated for the purpose of re-establishing stable stream channels and valleys on reclaimed mine lands (USACOE et al., 2003). Natural channel design is the process of applying fluvial geomorphic principles to transform unstable stream corridors into stable channels that maintain their dimension, pattern, and profile over time (Leopold, 1994; Rosgen, 1994). Typical goals include designing channels with natural materials (e.g., without the use of concrete or rip rap), improving aquatic habitats, and restoring native vegetation along stream corridors. This paper is a review of natural channel design concepts and surface mining impacts on stream morphology, along with a series of guiding principles for the application of natural channel design practices on reclaimed mine lands. A tributary to the Mitchell River in the Blue Ridge Mountains of North Carolina is used as a case study demonstrating techniques that may be applied to reclaimed surface mine land sites.

Background

A stream and its floodplain comprise a dynamic environment where the floodplain, channel, and bedform evolve through natural processes that erode, transport, sort, and deposit alluvial materials. The size and flow of a stream are directly related to its watershed area. Other factors that affect channel size and stream flow are geology, land use, soil types, topography, and climate. The morphology, or size and shape, of the channel reflect all of these factors (Leopold et al., 1992; Knighton, 1984). The result is a dynamic equilibrium, where the stream maintains its dimension, pattern, and profile over time, neither degrading nor aggrading. Land use changes in the watershed, including increases in imperviousness, channelization, and removal of riparian vegetation, can upset this balance. A new equilibrium may eventually result, but not before the occurrence of large adjustments in channel form, such as extreme bank erosion or incision (Lane, 1955; Schumm, 1960). By understanding and applying natural stream processes to stream restoration projects, a self-sustaining stream can be designed and implemented that maximizes stream and biological potential (Leopold et al., 1992; Leopold, 1994; Rosgen, 1996).

In addition to transporting water and sediment, natural streams also provide the habitat for many aquatic organisms including fish, amphibians, insects, mollusks, and plants. Trees and shrubs along the banks provide a food source and regulate water temperatures as well as stabilize stream banks. Channel features such as pools, riffles, steps, and undercut banks provide diversity of habitat, oxygenation, and cover (Dune and Leopold, 1978). Stream restoration projects can repair these features in concert with the return of a stable dimension, pattern, and profile. The following sections provide an overview of the dominant channel forming process and typical stream morphology. Understanding basic aspects of stream processes and form are important to discern use of principles of natural stream design on surface mined lands.

Channel Forming Flow Theory

The most important stream process is the channel forming discharge, also referred to as bankfull discharge, effective discharge, or dominant discharge (Leopold et al., 1992; Leopold, 1994). Channel forming discharge theory states that there is a unique flow that over a long period of time would yield the same channel morphology that is shaped by the natural sequence of flows. At this discharge, equilibrium is most closely approached and the tendency to change is the least (Inglis, 1947). Uses of the channel forming discharge include channel stability assessment, river management using hydraulic geometry relationships, and natural channel design (Soar and Thorne, 2001).

Proper determination of bankfull discharge in the field is vital to the natural channel design process. The bankfull discharge is the point at which flooding occurs on the floodplain (Leopold 1994). This may or may not be the top of the streambank. On average, bankfull discharge occurs approximately every 1.5 years (Leopold 1994; Harman et al., 1999; Harman et. al., 2000, McCandless 2003). If the stream has incised due to changes in the watershed or streamside vegetation, the floodplain stage may be a small bench or scour line on the streambank (Harman et al., 1999). In this case, the top of the bank, which was formerly the floodplain, is called a terrace. A stream with terraces near the top of its banks is an incised stream.

Channel Bedform

Gravel bed streams in alluvial valleys have sequences of riffles and pools that maintain channel slope and bed stability. The riffle is a bed feature composed of gravel or larger size particles. The water depth is relatively shallow and the slope is steeper than the average slope of the channel. At low flows, water moves faster over riffles, providing oxygen to the stream. Riffles control the streambed elevation and are found entering and exiting meander bends. Pools are located on the outside bends of meanders between riffles (See Figure 1). Pools have a flat slope and are much deeper than the average depth of the channel. At low flows, pools are depositional features and riffles are scour features. At high flows, however, the pool scours and bed material deposits on the riffle. This occurs because a force applied to the streambed, called shear stress, increases with increasing hydraulic radius and slope. The inside of the meander bend is a depositional feature called a point bar, which also helps maintain channel form (Knighton, 1984).

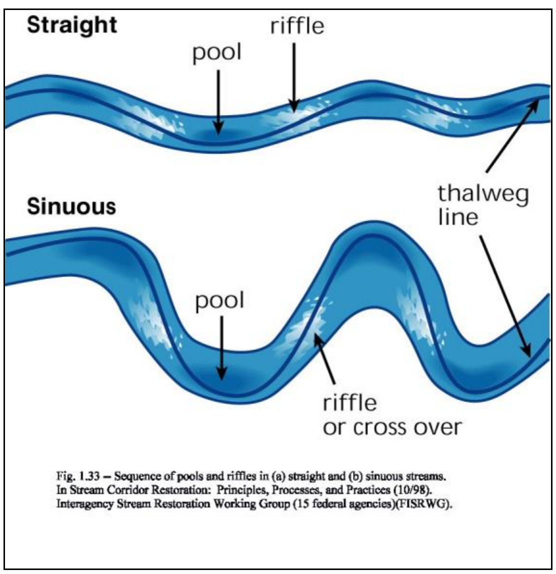

Figure 1. Riffle and Pool locations in straight and meandering streams.

Steep mountain streams demonstrate step/pool morphology as a result of their episodic sediment transport mechanisms. Sediment supply in colluvial valleys is controlled by hillslope erosion and mass wasting processes (Whittaker, 1987). As a result, colluvial valleys are often bowl-shaped with sediments that are poorly sorted and angular. As a result of the energy associated with the slope of the channel, step/pool streams are influenced by particles with significantly larger diameters than streams in alluvial valleys. Steps form from accumulations of boulders and cobbles that span the channel, resulting in a backwater pool upstream and plunge pool downstream. Smaller particles collect in the interstices of the step, creating a stable, interlocking structure (Knighton, 1984).

Channel Stability

A naturally stable stream must be able to transport the water and sediment load supplied by its watershed while maintaining dimension, pattern, and profile over time so that it does not degrade or aggrade (Rosgen, 1994). Stable streams migrate across alluvial landscapes slowly over long periods of time while maintaining their form and function. Instability occurs when scouring causes the channel to incise (degrade), excessive deposition causes the channel bed to rise (aggrade), or lack of streamside vegetation allows rapid channel migration. A generalized relationship of stream stability proposed by Lane (1955) is shown as a schematic drawing in Figure 2. The drawing shows that the product of sediment load and sediment size is proportional to the product of stream slope and discharge or stream power. A change in any one of these variables causes a rapid physical adjustment in the stream channel.

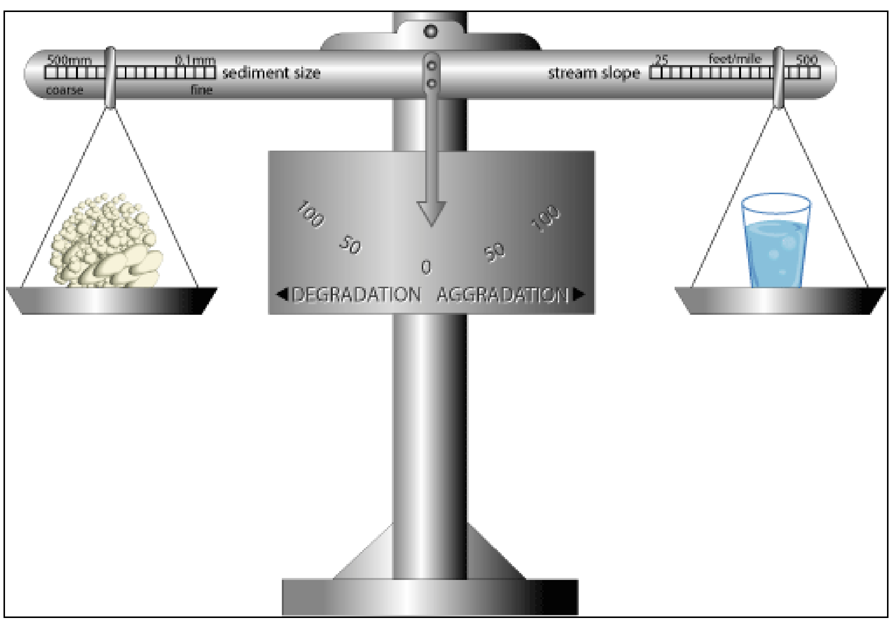

Figure 2. Factors Influencing Stream Stability (after Lane, 1955).

A common sequence of physical adjustments has been observed in many streams following disturbance. This adjustment process is often referred to as channel evolution. Disturbance can result from channelization, increase in runoff, removal of riparian vegetation, as well as other changes that negatively affect stream stability. All of these disturbances are common in the surface mining environment.

The channel evolution process is initiated once a stable, well-vegetated stream that interacts with its floodplain frequently is disturbed. Disturbance commonly results in an increase in stream power that causes degradation, often referred to as channel incision (Lane, 1955). Incision eventually leads to over-steepening of the banks and when critical bank heights are exceeded, the banks begin to fail and mass wasting of soil and rock leads to channel widening. Incision and widening continue moving upstream in the form of a head-cut. Eventually the mass wasting slows and the stream begins to aggrade. A new low-flow channel begins to form in the sediment deposits. By the end of the evolutionary process, a stable stream with dimension, pattern, and profile similar to those of undisturbed channels forms in the deposited alluvium. The new channel is at a lower elevation than its original form with a new floodplain constructed of alluvial material (FISRWG, 1998).

Several models have been used to describe this process of physical adjustment for a stream, including the Simon (1989) channel evolution model. Simon characterizes evolution in six steps: 1) sinuous, premodified, 2) channelized, 3) degradation, 4) degradation and widening, 5) aggradation and widening, and 6) quasi equilibrium. These steps or classes are shown in Figure 3.

Stream Impacts from Surface Mining

Surface mining temporarily eliminates surface vegetation, changes topography, modifies soil and subsurface materials, and alters the equilibrium between ground and surface waters (PADEP, 2001; Wiley et al., 2001; USEPA 2001; USACOE et al., 2003). These landscape changes can significantly impact stream channel morphology due to changes in flow, loss of riparian vegetation, removal of bedform features, and changes in the composition of channel material. Often, stream channels are relocated entirely.

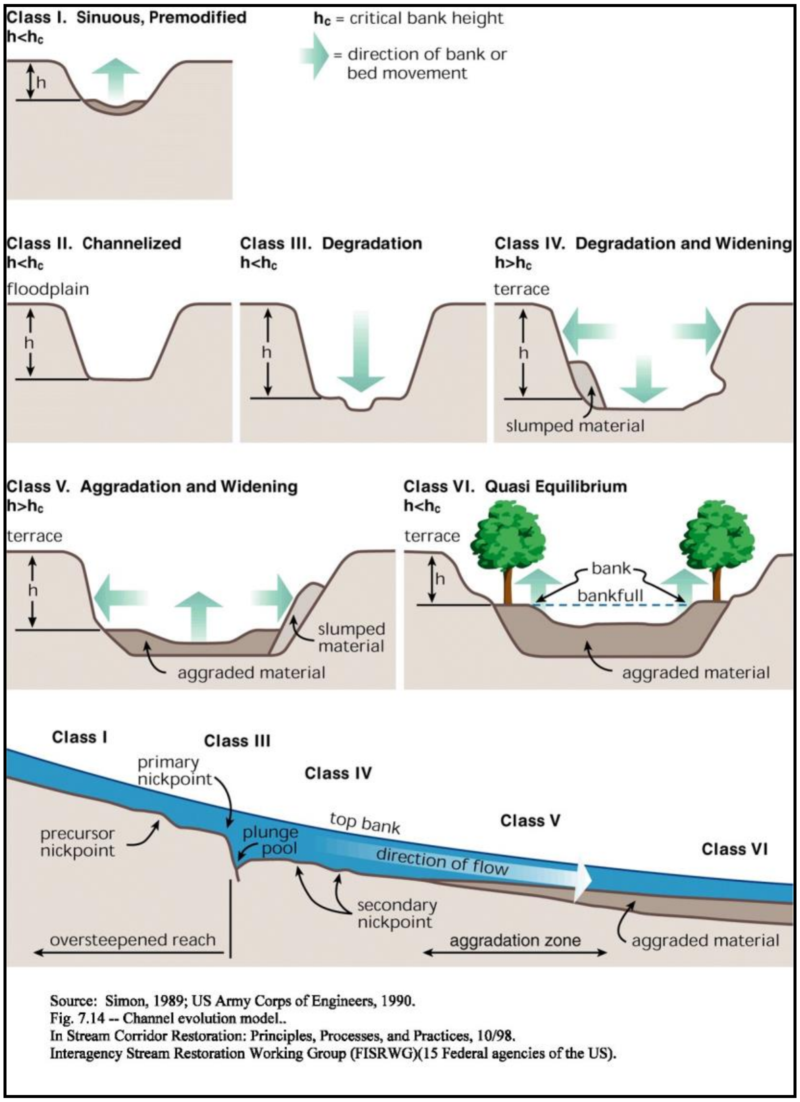

Figure 3. Channel Evolution Model (Simon, 1989).

Excess spoil from surface mining is typically disposed adjacent to the mine site, frequently in lower lying areas called valley fills or replaced as mined lands and reclaimed back to approximate original contours. Forested areas with layered sedimentary rock are typically transformed during this disposal process to grass-covered landscapes with poorly sorted, porous rock fragments (Wiley et al., 2001). Water can percolate through these unconsolidated sediments more readily, affecting runoff and recharge characteristics.

When mining activities completely bury channels, the invertebrates and microbiota present in headwater streams are removed from the ecosystem. While these organisms represent a small amount of biomass, they play an important role in the food chain because of their ability to convert leaf litter to coarse and fine particulate organic matter. Fish use these materials as a food supply. Subsequently, the loss of invertebrates and microbiota headwater streams reduces the amount of biomass and energy transferred downstream (USACE et al., 2003).

Application of Natural Channel Design Principles to Reclaimed Surface Mine Land

Application of natural channel designs to a stream on reclaimed surface mine land will require a thorough understanding of fluvial processes and completion of the following tasks: watershed characterization, existing condition survey of the project reach, bankfull verification, design criteria selection, and new channel design. These tasks are common to all natural channel designs. Once a design is in place, permitting must be secured, construction may begin, and evaluation should be documented.

Watershed Characterization

The watershed characterization includes watershed delineation; collection of topography, soils, and geology information; determination of impervious cover; and land use trend analysis. Delineation of drainage area is used for a number of purposes, including estimations of bankfull discharge and dimensions using regional curves, regional regression equations for flood flows, and geomorphic analysis. Watershed topography, geology and soils information are to determine the effects of the project on hydrology and geomorphology.

Existing Condition Survey

The existing condition survey includes a detailed topographic and planimetric survey of the project reach. A geomorphic assessment is completed to determine channel stability and the potential for recovery. For mine land reclamation, this assessment would include historical aerial photography and topographic analyses to determine pre-mining channel geometry. If reaches upstream and/or downstream of the mining area are still intact, a detailed survey, geomorphic assessment, and biological inventory should be completed to verify bankfull geometry and develop design criteria.

Channel stability is often determined using the Rosgen (2001a) stream channel stability assessment methodology. This assessment includes the following measurements and determinations:

- Rosgen stream classification (Rosgen, 1994)
- Vertical stability (degradation or aggradation)
- Lateral stability (bank erosion)
- Channel pattern assessment
- Bed profile and feature assessment
- Channel dimension relations
- Scour/deposition assessment
- Channel evolution stage (Simon, 1989).

These measurements are determined through cross sectional and longitudinal profile surveys of the bankfull channel, bed material analyses (pebble count or bulk sampling), floodplain hand auguring, and analysis of photographs. All measurements are determined for the bankfull stage.

The data are transformed into ratios and compared to reference reach streams in the same physiographic region to determine the departure from stability and the potential for restoration. For incised channels, the restoration potential follows a priority approach (Rosgen, 1997) with the overriding objective of re-establishing contact between the channel and its floodplain. The four Rosgen restoration approaches are defined below:

- Priority 1 – Re-establishes the channel on a previous floodplain (i.e., raises channel elevation); meanders a new channel to achieve the dimension, pattern, and profile characteristic of a stable stream for the particular valley type; and fills or isolates existing incised channel. This option requires that the upstream start point of the project not be incised.
- Priority 2 – Establishes a new floodplain at the existing bankfull elevation (i.e., excavates a new floodplain); meanders channel to achieve the dimension, pattern, and profile characteristic of a stable stream for the particular valley type; and fills or isolates existing incised channel.
- Priority 3 – Converts a straight channel to a different stream type while leaving the existing channel in place by excavating bankfull “benches” at the existing bankfull elevation. Effectively, the valley for the stream is made more bowl-shaped. In-stream structures are used to dissipate energy through a step/pool channel type.

- Priority 4 – Stabilizes the channel in place using in-stream structures and bioengineering to decrease streambed and streambank erosion. This is typically used in highly constrained environments.

Bankfull Identification and Verification

During the existing condition survey, bankfull indicators are identified and included in the survey. A longitudinal profile is produced that compares the existing channel thalweg, existing water surface slope, bankfull stage, and top of bank. This profile can be used to calculate existing facet slopes and to validate the bankfull stage. A common bankfull verification technique is to compare stable riffle cross sectional areas from the project reach with a published regional curve. Regional curves are bankfull hydraulic geometry relationships that relate bankfull channel dimensions (width, mean depth, and cross sectional area) and discharge to drainage area. They were first developed by Dunne and Leopold (1978). A primary purpose for developing regional curves is to aid in identifying bankfull stage and dimension in un-gaged watersheds. They also help estimate the bankfull dimension and discharge for natural channel designs (Rosgen, 1994). The determination of bankfull discharge and dimension for a project reach is the single most important step in the natural channel design process.

A second approach to bankfull verification uses the Hydrologic Engineering Center River Analysis System (HEC-RAS) and watershed runoff models, such as an appropriate US Geological Survey logistic regression equation or TR-55 (USDA, 1996). HEC-RAS is a water surface profile model developed by US Army Corps of Engineers. TR-55 was developed by the US Department of Agriculture Natural Resources Conservation Service as a simplified method to compute storm runoff in small watersheds. Bankfull discharge can be estimated from regional curves and watershed runoff models and then input into HEC-RAS. The resulting bankfull water surface elevation can then be compared to the field observed bankfull indicators.

Design Criteria Selection

There are numerous methods for determining the criteria for a natural channel design. Some of the more common techniques include analog, empirical, and analytical approaches (Skidmore et al., 2000). Analog approaches replicate the condition of historic or adjacent channel characteristics. The most common analog approach is the reference reach survey, which requires a detailed survey of the bankfull channel dimension, pattern, and profile of a stable stream (Rosgen 1998). The information collected is converted into dimensionless ratios that are used to develop designs for streams with different drainage areas. For example, a common pattern measurement is the meander wavelength, which is the length from the apex of one meander bend to the apex of the next bend on the same side of the valley. This length is divided by the bankfull width to create a dimensionless ratio. A common range for the meander wavelength ratio is 10 to 14 times the bankfull width (Leopold and Wolman, 1960; Carlston, 1965; Schumm, 1968). However, in the eastern United States the range is much lower with reported values between 2.9 and 7.7 times the bankfull width (Rinaldi and Johnson, 1997). A common list of ratios is provided below in Table 1.

Table 1. Common reference reach ratios. (All measurements are made at the bankfull stage.)

Dimensionless Ratio	Description
Wr/Dbkf	Riffle width / Riffle mean depth†
Dmax / Dbkf	Riffle max depth / Mean riffle depth†
Bhlow / Dmax	Low bank height / Riffle max depth†
Wp / Wr	Pool width / Riffle width†
Dp max / Dbkf	Pool max depth / Mean riffle depth†
Rc / Wr	Radius of curvature / Riffle width‡
Lm / Wr	Meander wavelength / Riffle width‡
Wblt / Wr	Belt width / Riffle width‡
CL / VL	Channel length / Valley length (sinuosity)
Srif / S	Riffle slope / Average slope*
Spool / S	Pool slope / Average slope*
Pspacing / Wr	Pool to pool spacing / Riffle width*

† Riffle and Pool Dimension Ratios.

‡ Pattern Ratios.

* Profile Ratios

Empirical designs use equations that relate channel characteristics derived from databases of reference reach information. These equations rely on data from watersheds and channels that are stable and unchanging. The most significant problem in application of empirical relationships is that they are only applicable over the range of conditions from which they were derived (Wharton, 1995) and most are from systems much larger than typical stream restoration sites.

Analytical designs utilize the continuity equation, roughness equations, hydraulic models, sediment transport, and other modeling techniques to derive equilibrium channel conditions. These approaches require careful consideration of the applicability of the chosen equation to the particular project (Skidmore et al., 2000).

Natural Channel Design

The natural channel design determines a dimension, pattern, and profile that can transport the bankfull discharge without degrading or aggrading. This design objective is tested for stability by considering the channel’s ability to move water and sediment, which is accomplished through HEC-RAS modeling and sediment transport competency and capacity analysis. Once the analysis demonstrates that the channel will not aggrade or degrade, in-stream structures are incorporated to provide further stability. These structures include cross vanes, J-hook vanes, root wads, and bioengineering techniques. A vegetation plan is also prepared to provide long-term stability and floodplain functionality. All of this information is conveyed through a set of plan sheets and specifications that can be used to hire a contractor to build the project.

In-Stream Structures

In-stream structures are often used to improve aquatic habitat functionality and provide bed and bank stability. These structures include a combination of large rock vanes and the root masses and trunks from downed trees. Common structures include cross vanes and J-hook vanes. Cross vanes decrease near-bank shear stress, velocity, and stream power, but increase the energy in the center of the channel (Rosgen, 2001). They are constructed from large boulders or logs and shaped to form a structure with two arms and an invert weir. The invert weir is typically one-third of the channel width. The vane arms start at the bankfull elevation and slope down (upstream) into the channel bed at a 2 to 7% slope. The arms extend at an angle of 20 to 30 degrees off of the channel bank to the streambed invert. Footer boulders are placed under header boulders to ensure that the pool scour does not undermine the structure. The structures also provide additional stability to protect banks from erosion. Transplants, erosion control matting, and vegetation planting are used to prevent erosion and provide long-term stability.

J-hook vanes reduce bank erosion by reducing near-bank slope, velocity, velocity gradient, stream power and shear stress (Rosgen, 2001). They are constructed from a combination of natural materials such as boulders, logs, and tree roots. J-hook vanes have gentle slopes and point upstream. They are located on the outside of meander bends where stream forces generate high stress in the near-bank region. The arm portion of the structure occupies one-third of the bankfull width of the channel, while the "hook" occupies the center third (Rosgen, 2001). Boulder clusters can be installed downstream of the J-hook to improve fish habitat. An example of a J-hook is shown in Figure 4 (stream flow is left to right).

Root wads divert high-energy flows away from streambanks, providing bank stabilization and preventing further bank erosion. A root wad consists of a tree trunk with an attached root mass. Root wads are buried in the streambank so that only the root mass protrudes from the bank. In addition to providing bank stabilization, root wads also offer fish habitat for feeding, resting, and security cover. A root wad example is shown in Figure 5.

Figure 4. J-hook vane with boulder cluster

Figure 5. Root wads cluster in bend apex

Maintenance

The newly constructed channel is most vulnerable immediately after construction. Restoration projects often require significant grading and leave the channel and floodplain devoid of vegetation. As the vegetation becomes established, the channel and floodplain become less vulnerable to disturbance. Typically, within one to two growing seasons, the channel is completely stable. At this point, most visitors cannot tell that the channel was constructed and the goal of "natural" channel design is accomplished.

Un-Named Tributary to the Mitchell River (Mickey Reach) – Case Study

In 2002, Buck Engineering implemented a natural channel design restoration project on the Mickey Reach, an un-named tributary of the Mitchell River in Surry County, North Carolina. The drainage area is 0.45 square miles just upstream of the confluence of the project reach with the Mitchell River. At a broad scale, the project site is located along the Blue Ridge escarpment. This area of the Blue Ridge Belt is underlain with gneiss that is finely laminated to thin layered. The gneiss contains micaceous granule conglomerate, schist, phylite, and amphibolite. At a reach scale, the upper section is moderately confined within a colluvial valley. An inactive alluvial fan joins the colluvial valley with the floodplain of the Mitchell River. The overall reach average slope is 3.3% and is consistent between the colluvial valley section and the alluvial fan. The bed material is predominantly gravel and cobble with a median value of 31 mm.

The existing bedform diversity for the Mickey Reach was poor with a pool-to-pool spacing range of 3.0 to 14.5. Literature values for pool-to-pool spacing in stable step/pool mountain streams range from two to three times the bankfull width for streams with a channel slope between 3 and 5% (Whittaker, 1987). Grant et al. (1990) found a higher average pool-to-pool spacing range of two to four times the bankfull width in Oregon. A reference reach in the Blue Ridge Mountains of North Carolina provided a broader range than the literature values with a pool-to-pool spacing range of 1.5 to 5.7 times the bankfull width. However, these are values for one site and are not averaged over many sites, as are the literature values.

The absence of pools on the Mickey Reach was caused by a combination of livestock grazing and timber harvesting. Livestock access to the stream channel denuded the streambanks of vegetation and caused localized bank erosion. Hoof shear and trampling of the streambed displaced most of the steps, thereby removing the pool forming process. The result was a nearly plane bed channel devoid of pools. Timber harvesting in the watershed increased sediment yields and further reduced depth due to aggradation in the pools.

The impacts to channel stability and function were not caused by mining. However, the results of the impact are similar to those associated with surface mining. A general comparison of stream impacts between the Mickey Reach and streams on surface mine lands include the following similarities and differences.

Similarities:

- Surface mining most often impacts headwater gravel bed streams with slopes greater than 3%,
- Surface mining impacts often create channels with unnatural bedform diversity, and
- Mining impacts often lead to channels that are laterally and sometimes vertically unstable.

Differences:

- Design constraints imposed from unconsolidated sediments associated with mine lands.
- Mine lands often have soil and substrate with low pH values, high metal concentrations, and low in organic carbon.
- As a result, offsite soil material is often required for the restoration of mine land, including riparian corridors.

The natural channel design goal for the Mickey Reach was to restore a stable channel that maximized geomorphologic and biological function. This was accomplished by restoring the natural bedform diversity of the reach with a step/pool channel configuration, removing livestock access to the stream, and acquiring a conservation easement on the property. The step/pool channel configuration was restored by modifying the bankfull cross-section where necessary and installing cross vanes (Rosgen, 2001) using the pool-to-pool spacing guideline from an appropriate reference reach. Examples of the cross vanes used on the Mickey Reach are shown in Figures 6 and 7.

Figure 6. Constructed step/pool channel

Figure 7. Cross vane with log double drop.

In some cases, large woody debris were incorporated into the cross vane to improve fish habitat. Figure 7 shows an example of a log used to create a second step in the structure. Once the step/pool configuration was installed and livestock were excluded from the channel, a riparian buffer was planted with native grasses and trees. The project has remained stable after numerous bankfull events and the bedform diversity has remained. Ongoing monitoring will show the long term functionality of the site.

Conclusions

Natural channel design technologies offer the mining community tools for restoring a natural morphology to degraded streams along with improved biological function. Few projects have been completed on reclaimed mine land, however, and the need for improved design equations and techniques remain. For areas of the country that have strong stream restoration programs, the transition to natural channel design on mine lands will be simpler. For other areas, state agencies and universities should begin developing regional curves, a reference reach database, regime equations, and sediment transport competency and capacity equations applicable to watersheds where surface mined operations influence stream flows.

Literature Cited

Carlston, C. W. 1965. The relation of free meander geometry to stream discharge and its geomorphic implications. American Journal of Science 263, 863-865. http://dx.doi.org/10.2475/ajs.263.10.864.

Clinton, D. R. 2001. Stream morphology relationships from reference streams in North Carolina. Thesis (M.S.) - North Carolina State University.

Dunne, T. and L. B. Leopold. 1978. Water in Environmental Planning. New York: W. H. Freeman and Company.

Grant, G.E., F.J. Swanson, and M.G. Wolman. 1990. Pattern and Origin of Stepped-Bed Morphology in High Gradient Streams, Western Cascades, Oregon. Geological Soceity of America Bulletin, 102. pp 340-352. http://dx.doi.org/10.1130/0016-7606(1990)102<0340:PAOOSB>2.3.CO;2.

Harman, W. A., G. D. Jennings, J. M. Patterson, D. R. Clinton, L. O. Slate, A. G. Jessup, J. R. Everhart, and R. E. Smith. 1999. Bankfull Hydraulic Geometry Relationships for North Carolina Streams. Wildland Hydrology. AWRA Symposium Proceedings. Edited by: D. S. Olsen and J. P. Potyondy. American Water Resources Association. June 30-July 2, 1999. Bozeman, MT.

Harman, W.A., D.E. Wise, M.A. Walker, R. Morris, M.A. Cantrell, M. Clemmons, G.D. Jennings, D. Clinton, and J. Patterson, 2000. Bankfull Regional Curves for North Carolina Mountain Streams. AWRA Proceedings: Water Resources in Extreme Environments. Edited By D. L. Kane. May 1-3, 2000. Pp185-190.

Inglis, C.C. 1947. Meanders and their Bearing on River Training. Institution of Civil Engineers, Maritime and Waterways Engineering Division, Paper No. 7, 54 pp.

Knighton, D. 1984. Fluvial Forms and Processes. Rutledge, Chapman, and Hall, Inc. New York, NY.

Lane, E. W. 1955. Design of stable channels. Transactions of the American Society of Civil Engineers. Paper No. 2776. pp. 1234-1279.

Leopold, L. B. and M. G. Wolman. 1960. River meanders. Bulletin of the Geological Society of America, 71, 769-794.

Leopold, L. B. and M. G. Wolman. 1960. River meanders. Bulletin of the Geological Society of America, 71, 769-794. http://dx.doi.org/10.1130/0016-7606(1960)71[769:RM]2.0.CO;2

Leopold, L. B., 1994. A View of the River. Harvard University Press, Cambridge, Mass.

Pennsylvania Department of Environmental Protection (PADEP), Bureau of Mining and Reclamation, and Earth Sciences Consultants, Inc. 2001. Study of the Effects of Longwall Mining on Streams, Wetlands and Riparian Areas. Contract No. BMR-00-01. Project No. 5904.

Rinaldi and Johnson. 1997. Stream Meander Restoration. Journal of the American Water Resources Association 33(4):855-866. http://dx.doi.org/10.1111/j.1752-1688.1997.tb04110.x.

Rosgen, D. L. 1994. A Classification of Natural Rivers. Catena 22:169-199. http://dx.doi.org/10.1016/0341-8162(94)90001-9.

Rosgen, D. L. 1996. Applied river morphology. Wildlife Hydrology, Pagosa Springs, CO.

Rosgen, D. L. 1998. The Reference Reach : A Blueprint for Natural Channel Design. American Society of Civil Engineers Conference 1998, Denver, CO. http://dx.doi.org/10.1061/40382(1998)166.

Rosgen, D. L. 2001a. A Stream Stability Assessment Methodology, Federal Interagency Sediment (FISC) Conference 2001, Reno, NV, March, 2001.

Rosgen, D. L. 2001b. The Cross-Vane, W-Weir and J-Hook Vane Structures…Their Description, Design and Application for Stream Stabilization and River Restoration. Published By: ASCE conference, Reno, NV, August, 2001.

Schumm, S. A. 1960. The shape of alluvial channels in relation to sediment type. Geological Survey Professional Paper 352-B, Washington DC.

Schumm, S. A. 1968. River adjustment to altered hydrologic regime – Murrumbidgee River and Paloacochannels, Australia. U. S. Geological Survey Professional Paper, 598.

Simon, A. 1989. A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms 14(1):11-26. http://dx.doi.org/10.1002/esp.3290140103

Skidmore, P. B., F. D. Shields, M. W. Doyle, and D. E. Miller. 2000. A Categorization of Approaches to Natural Channel Design. Published By: ASCE conference, Reno, NV, August, 2001.

Soar and Thorne, 2001. Channel Restoration Design for Meandering Rivers. U.S. Army Corps of Engineers, Engineering Research and Development Center. Coastal and Hydraulics Laboratory, ERDC\CHL CR-01-1. September, 2001.

US Army Corps of Engineers (USACOE), US Environmental Protection Agency, US Department of Interior's Office of Surface Mining, US Department of Interior's Fish and Wildlife Service, and West Virginia Department of Environmental Protection. 2003. Mountaintop Mining/Valley Fill Draft Environmental Impact Statement.

US Department of Agriculture (USDA) Natural Resources Conservation Service, Conservation Engineering Division. 1986. Urban Hydrology for Small Watersheds: TR-55. Technical Release 55, Second Edition. NTIS # PB87101580.

US Environmental Protection Agency (USEPA). 2001. Performing Flow Measurements at Mine Sites. Prepared by SAIC, Idaho Falls, ID.

US Geological Survey (USGS). 2001. Coal mining, fecal bacteria, and radon are water-quality issues for the Kanawha River basin. 4 May 2001. News release.

Wharton, G. 1995. Information from channel geometry-discharge relations. In: Changing River Channels. A. Gurnell and G. Petts (eds.). John Wiley and Sons Ltd.

Whittaker, J.G. 1987. Sediment transport in step-pool systems. Sediment Transport in Gravel Bed Rivers, edited by C.R. Thorne, J.C. Bathurst, and R.D. Hey. John Wiley and Sons, pp545-579.

Wiley, J. B., R. D. Evaldi, J. H. Eychaner, and D. B. Chambers. 2001. Reconnaissance of Stream Geomorphology, Low Streamflow, and Stream Temperatures, in the Mountaintop Coal-Mining Region, Southern West Virginia, 1999-2000. US Geological Society, Water Resources Investigation Report 01-4092.