APPLYING GEOMORPHOLOGIC PRINCIPLES TO RESTORE STREAMS IMPACTED BY SURFACE MINING[1]

by

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ABSTRACT. The combination of geomorphic principles and native material restoration techniques provides a viable alternative to traditional engineering approaches to restore rivers and streams affected by surface mining. Channels can be designed to reflect ranges of stability known to occur in natural streams for measurable parameters such as bankfull width, depth, gradient, meander radius, sinuosity and entrenchment. Stable channel geometry reduces stresses on the stream bed and banks and eliminates the need for channel lining. Methods to utilize native materials have been developed and refined to stabilize stream channels constructed to appropriate dimensions until planted riparian vegetation develops mature root systems. These native materials include root wads, willow bundles, and boulders. These methods result in improved wildlife habitat in and around channels that maintain equilibria between sediment supply and sediment transport, and between erosional and depositional rates and patterns. Two streams in Baltimore County, Maryland were disturbed during mining operations and are being restored using this approach. Goodwin Run had been channelized to allow quarrying of the Cockeysville Marble. Approximately 1100 feet of stream were restored in the fall of 1992. White Marsh Run has been channelized and relocated several times to facilitate sand and gravel mining between an urbanized area and sensitive habitats of the Chesapeake Bay. The design of the White Marsh Run Restoration Project incorporated refinements to techniques used at Goodwin Run, and entails the restoration of over 5000 feet of stream and adjacent wetland habitat.

Additional Key Words: Stream Classification, Channel Geometry, Native Materials.

Introduction

Stream channel morphology is a sum of function and process that reflects the influence of physical laws. The organized nature of stream morphology is expressed by natural stream channels, and the consistent relationships among measurable variables allow streams to be classified based on delineative criteria. The classification system developed by Rosgen (1994) allows predictions of a river's response to changes in its watershed that may result from surface mining.

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Prior to passage of the Surface Mining and Reclamation Control Act of 1977 (SMCRA), rivers were frequently relocated to acquire access to mineral deposits. While the current regulatory climate discourages this practice, streams continue to be impacted by surface mining operations. The cumulative effects of increased runoff, decreased infiltration, and increased sediment load, disturb the dynamic equilibrium of stable streams, resulting in adjustments of channel geometry and pattern.

Recognition of the potential effects to streams from increased discharge and sediment load requires an understanding of the normal characteristics of channels, fluvial processes, and probable reactions to imposed changes (Dunne and Leopold, 1978). Given such an understanding, measures can be prescribed to restore river function and process. By applying proven geomorphologic principles, the river environment can be returned to a more natural state.

English units of measure are used herein for two reasons. First, all of the river measurements published by the U.S. Geological Survey, and therefore the vast majority of the literature, are published in English units. Second, as a result, most of the hydrologists involved in stream restoration are more accustomed to this system.

The Nature of Streams

A river or stream functions as a conveyance system for water and sediment. The system is powered by the process of energy transformation in which the potential energy of elevation is transformed into the kinetic energy of flowing water and sediment. In a natural state, a condition of dynamic equilibrium exists in which the sediment supplied by the watershed is efficiently carried by the stream, and erosion rates within the active channel are balanced by approximately equal rates of deposition. Owing to the universality of physics, channel morphology is highly organized and similar for streams of the same size in comparable climates (Dunne and Leopold, 1978).

Bankfull flow corresponds to the stage that shapes and maintains channels, and has been shown to have a recurrence interval of 1.5 years (Leopold et al, 1964). It is the most effective discharge in that it transports the largest amount of sediment. Larger flood events may move more material, but they occur so infrequently that, over time, they do not accomplish as much as bankfull flows (Leopold, 1994). It is the bankfull flow that is most responsible for forming or removing bars, forming or changing bends and meanders, and generally doing the work that results in the average morphologic characteristics of rivers (Dunne and Leopold, 1978). These average morphologic features, which can be identified and measured, are the manifestations of the physical processes which must be understood in order to understand of a given reach of stream.

Channel geometry describes the physical size, shape, and characteristics in relation to the hydraulic factors of velocity, roughness, slope, and flow frequency (Dunne and Leopold, 1978).

Shear stress is the eroding force per unit area exerted by streamflow. The form assumed by a stable channel is such that shear stress at every point on the wetted perimeter is approximately balanced by the resisting forces of the stream bed or bank (Leopold, 1994).

Stream pattern morphology refers to the form taken by a river in its valley and is directly influenced by eight variables: channel width, depth, velocity, discharge, slope, roughness of channel materials, sediment load, and sediment size. The independent variables are discharge and sediment load. A change in any one of these variables sets up a series of channel adjustments which lead to a change in the others, and the result is an alteration in stream pattern morphology (Rosgen, 1994). The response among the dependent variables to changes in discharge or load is highly consistent from one location to another in a given river system, and from one river to another, and are all factors related to the dissipation or conservation of energy, and to the distribution of energy expenditure (Leopold, 1994).

One of the most obvious morphological features is the stream meander, and the lateral migration of stream meanders is a very important and readily observed process. Meandering represents the condition that channels approach as erosion and deposition proceed. Stable channels maintain a constant cross section as lateral migration occurs, with the quantity of material eroded from the cut bank being approximately equal to the amount of deposition on the next point bar downstream on the same side of the channel (Leopold, 1994).

Meanders are a good example of the predictability of river behavior that is so important in the restoration of disturbed systems. The relation of bankfull width and radius of curvature to meander wavelength is linear through five orders of magnitude (Leopold, 1994). Rosgen (1993) has demonstrated that the meander radius of stable streams is 2.2 to 2.8 times the bankfull width. Leopold (1994) states that the meander radius of 2.3 times the bankfull width is the ratio of least friction loss, and manifests the conservation of energy or tendency toward minimum work. Having once established a meandering pattern, a stream will not change to a straight pattern as long as the climate does not change (Dunne and Leopold, 1978). Therefore, the relationships between bankfull width and meander radius and wavelength must be maintained or re-established for effective restoration.

Stream Classification

Scientists have long sought to define a categorical order for streams, and a multitude of descriptive and theoretical schemes are documented in the literature. One of the more recent classification systems is that of David Rosgen, who analyzed data from over 450 rivers in the United States, Canada, and New Zealand and developed a methodology based on the concept that current channel morphology is governed by the laws of physics through observable stream channel features and related fluvial processes (Rosgen, 1994). Because Rosgen brought together quantitative relationships into a readily understood, meaningful framework, his system has gained rapid acceptance across a variety of disciplines. The Rosgen Classification System is now the most widely accepted manner of describing a channel (Leopold, 1994).

Rosgen provides a staged classification scheme with four levels of detail that can be applied commensurately with the objectives and skills of the user. The system organizes data from measurable stream features into combinations of delineative criteria (Figure 1), while at the same time recognizing a continuum within and between the various stream types. The end result is 42 major stream types determined by (in order) entrenchment ratio, width/depth ratio, sinuosity, slope range and channel material particle size (Figure 2).

The entrenchment ratio provides a quantitative means of describing the interrelationship of a stream to its

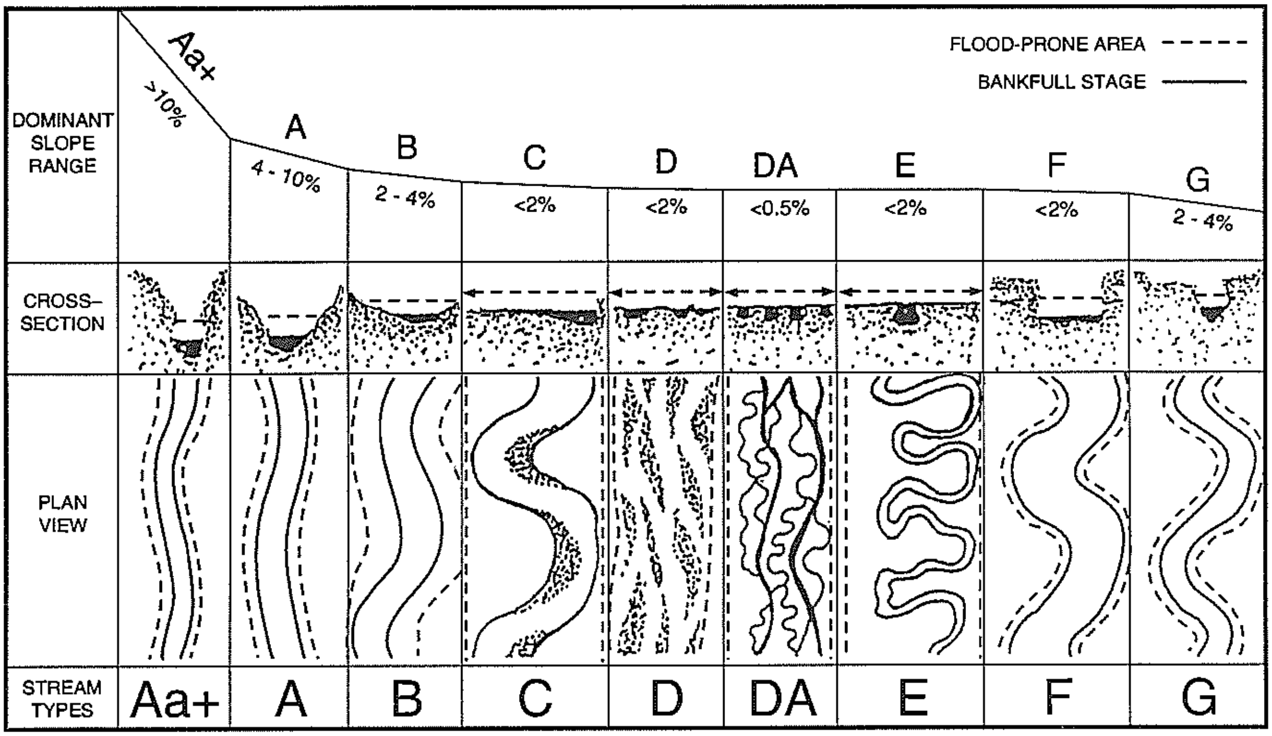
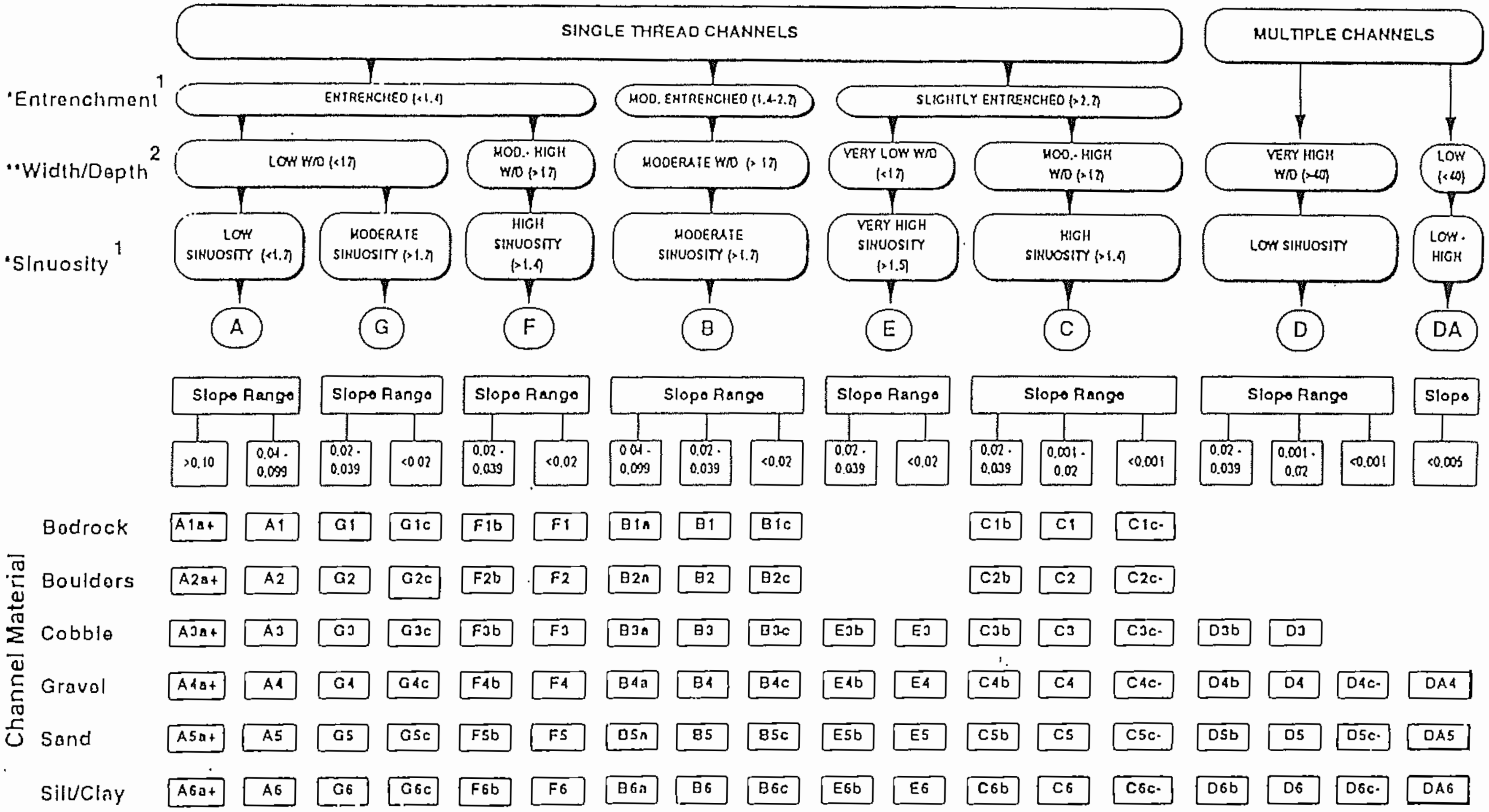


Figure 1. Longitudinal, cross-sectional, and plan views of major stream types (from Rosgen, 1994).

valley and/or adjacent landforms. It is the ratio of the width of the floodprone area to the bankfull width of the channel (Rosgen, 1994). Rosgen defines the floodprone area as the width measured at an elevation which is determined at twice the maximum bankfull depth (Figure 3). This is a relatively frequent flood elevation (50 year return period or less) and helps distinguish whether the flat adjacent to a channel is active floodplain, terrace, or outside a floodprone area.

The width/depth ratio is simply the bankfull width divided by the average bankfull depth, and is usually calculated from field measurements. Sinuosity is the quotient of channel length divided by valley length. Slope refers to the water surface slope in the center of the channel at the bankfull stage, and should be measured over a length of at least twenty channel widths. Channel material particle size is the median intermediate diameter of particles in the bed and banks of the active



[1] Values can vary by ± 0.2 units as a function of the continuum of physical variables within stream reaches.
[2] Values can vary by ± 2.0 units as a function of the continuum of physical variables within stream reaches.

Figure 2. Streamtype delineation key (from Rosgen, 1994).

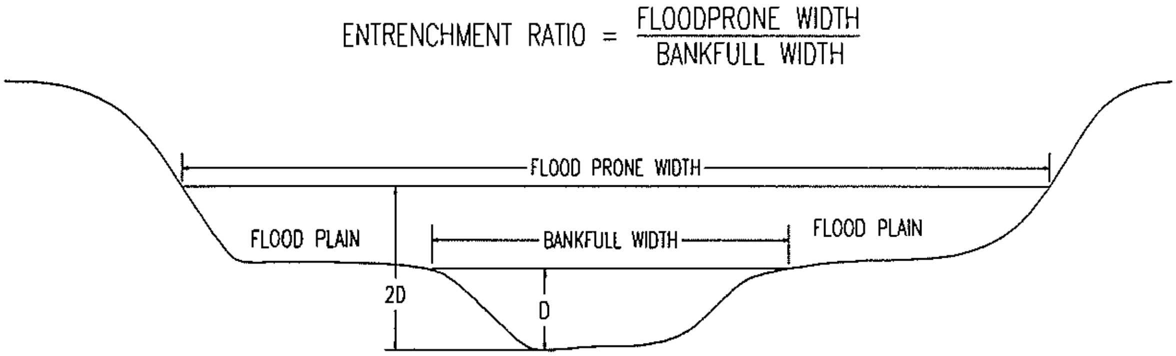


Figure 3. Determination of Entrenchment Ratio.

channel.

One of the primary objectives of this classification system was to be able to predict a river's behavior from its appearance, with a major application being the restoration of disturbed streams (Rosgen, 1994). The system was designed to allow interpretations regarding modes of adjustment-- either vertical, lateral, or both-- and energy distribution to be inferred through stream types (Rosgen, 1994). Rosgen and others have used this system to evaluate changes in channel geometry that have resulted, or would most probably result, from hydrologic and sediment load changes within watersheds.

Since its adoption by the USDA Forest Service, U.S. Fish and Wildlife Service, and many state and local government agencies, the Rosgen system has been successfully applied to many hundreds of streams across North America and found equally valuable for the evaluation of ephemeral, intermittent and perennial streams. Rosgen's system is a Classification of *Natural* Rivers (emphasis added) intended for use on individual reaches rather than entire stream systems or watersheds. Under natural conditions a given stream may vary in character, and therefore class, even through short distances downstream, as a result of passage from one lithologic type to another, tributary entrance, or change in landscape character (Leopold, 1994).

Stream Disturbance from Surface Mining

The overwhelming consensus in the literature is that surface mining increases the runoff and sediment supply to receiving streams, which, as discussed above, will initiate alterations in channel pattern. Changes in vegetative cover are a primary cause of the changes in hydrologic and sediment regimes that destabilize streams. In addition, alterations to soils, geology, and topography all contribute to erosion and affect the amount, timing and location of water reaching streams. Channel relocations to facilitate mining operations are another major cause of river instability, and will be discussed in a subsequent section.

Clearing vegetation increases runoff volume and decreases lag time, thereby increasing peak flows from a given storm event (Dunne and Leopold, 1978). Drainage diversions around active mine sites can result in the premature channelization of runoff from upslope undisturbed areas, increasing times of concentration. Toy and Hadley (1987) describe higher peak flows in mined watersheds compared to unmined watersheds, and discuss increases in volume, depth, and velocity of runoff, as well as increased rates of delivery to receiving streams as a result of reduced soil infiltration capacity.

Elliott (1990) and others have correlated increased bulk densities in reclaimed soils with reduced infiltration rates. Toy and Hadley also provide a good synopsis of several studies that compared erosion rates and sediment yield from surface mined lands to natural sites.

Elliott (1990) studied areas reclaimed under current SMCRA regulations that were still affected by relatively rapid erosion rates several years after conclusion of reclamation activities. He found erosion rates can remain high after establishment of vegetation due to steep slopes or narrow valley floors. Elliott identified two geomorphologically distinct areas of erosion: rills with occasional gullies on hillslopes, and gullies/unstable stream channels on valley floors. While both conditions can provide excess sediment to streams, gullies on reclaimed valley-floors have the potential to rapidly mobilize substantial volumes of soil and spoil, thereby inducing channel instability downstream. In addition, local base-level lowering can propagate headcuts upstream and into nearby tributaries (Elliott, 1990).

Surface mining also tends to remove lithologic and structural controls on the drainage network as consolidated lithologic units are fragmented, removed, and replaced when operations proceed across valleys (Elliott, 1990). The destruction of bedrock also results in decreased material strength and resistance to erosion and mass wasting (Toy and Hadley, 1987). Because geomorphic process rates are accelerated during and for some time after mining operations, valley geometry and hillslope stability become important factors in long term stream stability.

In evaluating stream impacts from mining, the elements of proximity and direction need consideration. Due to the interconnected nature of drainage networks, many effects may not be fully observed for some great distance from where change occurred (Dunne and Leopold, 1978). Different stream types adjust to stress in different ways, and some, such as most "A" type and some "B" type channels, are more forgiving of hydrologic changes, and significant channel disturbance may not be manifest until there occurs a change in stream type down valley. Additionally, the concept of headward erosion implies that all impacts may not be downstream of the mine site.

Traditional Remedies: The Engineering Approach

Historically, streams destabilized as a result of mining operations have been neglected. Dredging often occurs when mass wasting or excessive sedimentation cause flooding problems, and various methods of armoring have been applied to protect bridges or other structures threatened by erosion, but, in general, the restoration of river function and habitat is a relatively new concept. This is probably due, at least in part, to the lack of understanding of fluvial processes and the downstream ramifications of disturbance in the watershed.

In addition, the physical relocation of rivers has typically resulted in straight ditches designed for maximum efficiency of water movement and covering the shortest distance possible (Thompson, 1985). This practice, generally referred to as channelization, usually raises the severity of erosion and deposition problems. Without the appropriate channel geometry, a river will not remain passively in its newly assigned place, but will instead respond immediately with alterations among hydraulic variables to return to its pre-disturbed pattern (Dunne and Leopold, 1978).

In addition to the instability

caused by adjustment to imposed conditions, channelization typically has downstream effects, especially increased bank erosion and aggradation or degradation of the bed (Dunne and Leopold, 1978). One example, though unrelated to mining, frequently mentioned in the literature (Dunne and Leopold, 1978; Toy and Hadley, 1987; Leopold, 1994) is the Blackwater River in Missouri. The river was shortened by the elimination of meanders, which increased the slope of the channel and has caused over 60 years of continuous downcutting.

Artificial channels are often sized to contain flood events well in excess of the bankfull flow, and are typically designed to have a wide, relatively flat cross section. These conditions typically cause aggradation because the increase in width/depth ratio reduces the shear stress and entrainment capacity of the stream at any flow (National Research Council, 1992). In addition, the bed and banks are routinely stabilized with rip-rap, gabion baskets, or concrete, which limit the development of aquatic and riparian habitats and are devoid of aesthetic value.

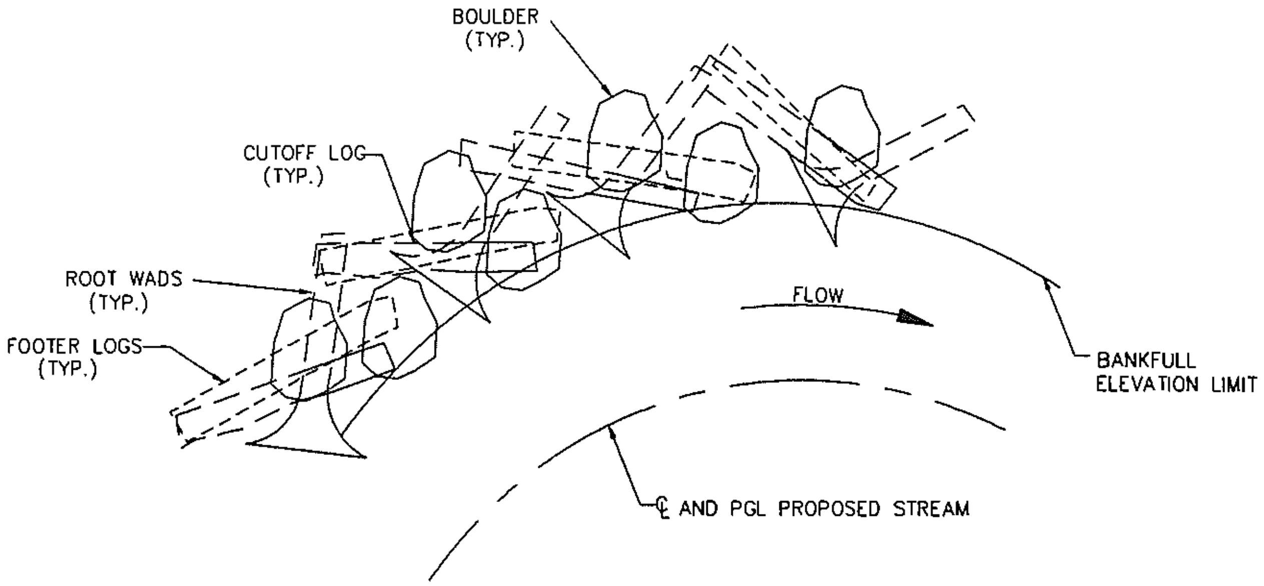
Geomorphology and Native Materials: An Alternative Approach

The objective of stream restoration is to restore the dynamic equilibrium of the physical system, which will establish and support the biological components (National Research Council, 1992). This is accomplished by establishing the channel geometry and pattern that are appropriate for the bankfull discharge and sediment load, and consistent with the morphological features of the valley.

The Rosgen classification system provides a framework for determining the most probable form of a stream. The delineative criteria reflect ranges of stability that can be used to calculate design channel dimensions based on streamtype. The morphology of the valley is the primary determinant of the appropriate streamtype because of the empirical relationships between a stream and its valley. Narrow valleys will dictate moderate to high entrenchment, while broader valleys allow greater sinuosity and a more developed floodplain. In addition, the valley slope divided by sinuosity equals the channel slope, which allows the integration of potential vertical and lateral constraints in the restoration design.

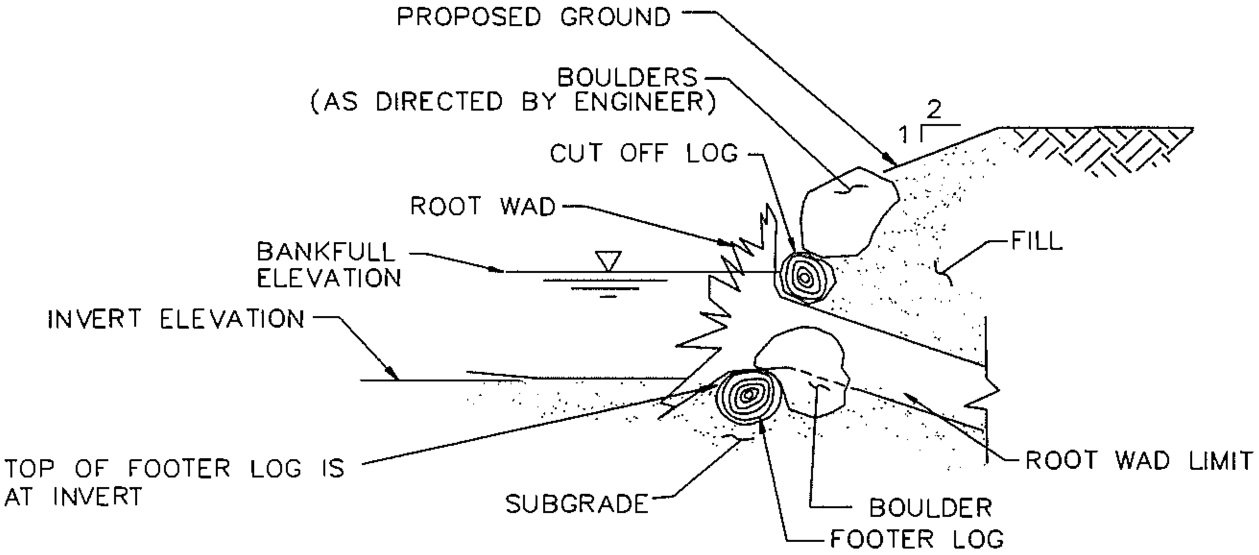
Other relationships between the valley-floor width, valley slope and drainage area are described by Elliott (1990). Elliott suggests that stream channel stability can be significantly improved if these parameters are replaced to appropriate values during the reclamation process.

If the channel geometry of a river is restored to a stable form, shear stress will be minimized and excessive armoring of bed and banks is unnecessary. This eliminates the expense of importing large quantities of rock or concrete. Instead, stream banks can be effectively stabilized using native material revetments such as rootwads and willow bundles (Figures 4 and 5, respectively), which can often be salvaged close to the site. These materials allow the construction of vertical banks on the concave side of meander bends, unlike rip-rap, which must be placed at slopes of 1:1 or less. In addition, they provide organic matter for benthic organisms and can be installed to provide cover for fish. Willow cuttings are typically planted in and around rootwads to provide permanent bank stabilization after the rootwads decay. Native materials facilitate this establishment of riparian habitat to the edge of the active channel, with the end result being a more natural stream in terms of aesthetics and function.



ROOT WAD TYPICAL PLAN

NOT TO SCALE



ROOT WAD REVETMENT TYPICAL SECTION

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Figure 4. Root wad revetment for concave side of restored meander.

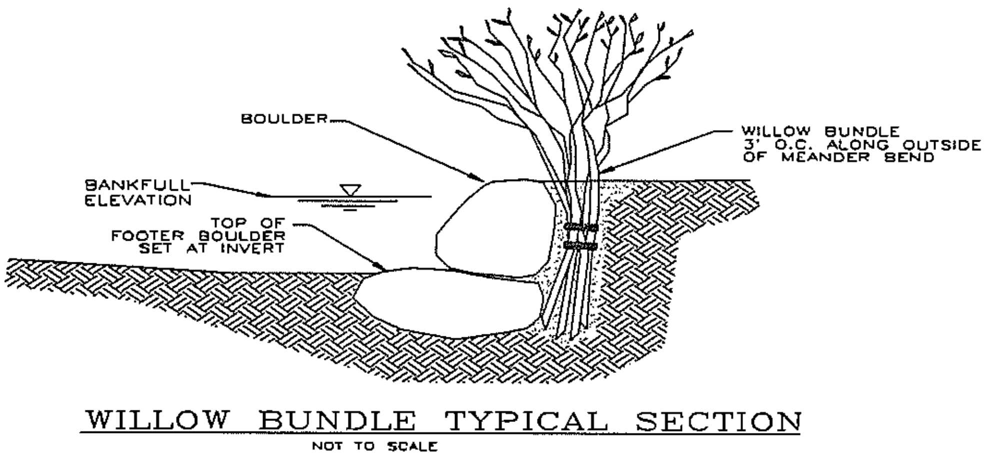


Figure 5. Willow Bundle revetment for concave side of restored meander.

Vortex rock weir structures (Figure 6) were developed and refined by David Rosgen to provide habitat enhancement and grade control without inducing backwater conditions. In addition, the upstream pointing "V" configuration directs flow into the thalweg, thereby reducing stresses on the near bank regions. Footer rocks are set at the channel invert elevation behind the vortex rocks to break the hydraulic jump of flow over the vortex rocks. These structures are typically placed at intervals of about every two to three channel widths, and at the points of curvature in and out of meander bends.

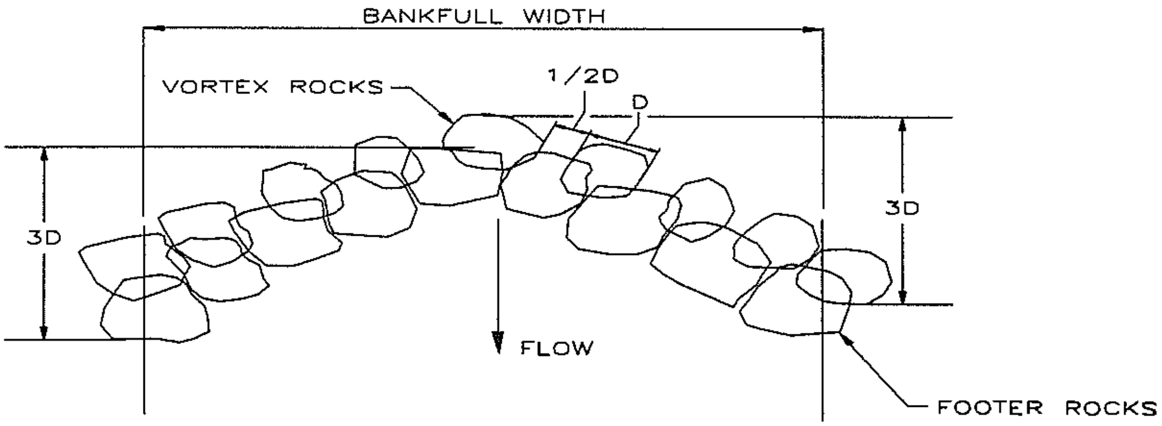
Examples

Goodwin Run

Goodwin Run is a second order tributary to Beaverdam Run, a significant trout fishery in the Piedmont physiographic province of north-central Baltimore County, Maryland. Near the confluence of its two headwater tributaries, Goodwin Run flows through a large quarrying operation where the Cockeysville marble has been extracted for decades. Despite several channel relocations over the years, one of the tributaries sustains a good brook trout population, and brown trout have been known to inhabit the main stem. The stream had been targetted for restoration as part of a county-wide stream improvement program, and funding was aquired when the Maryland State Highway Administration required compensatory mitigation for stream and wetland impacts related to a road project that would cross the stream.

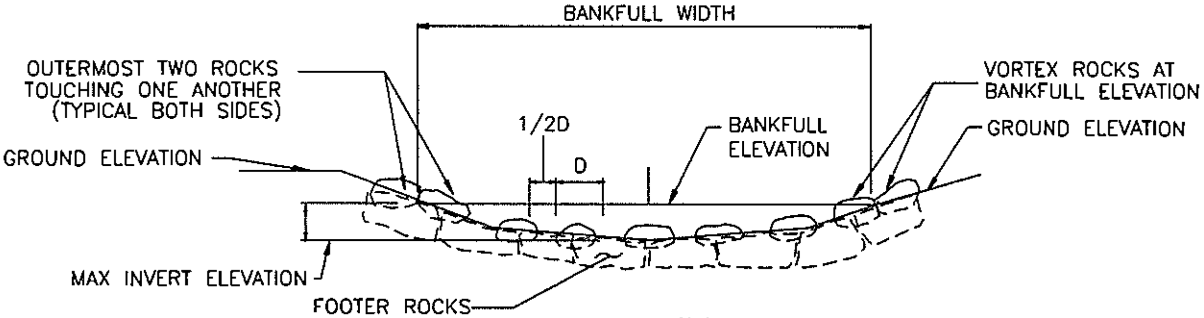
Prior to restoration, the channelized stream was classified using the Rosgen system as predominantly a "G" type channel with some reaches of the "F" streamtype (Gracie, 1995). In addition, some sections of the stream had been lined with rip-rap. Severely eroding banks were providing excess sediment to downstream reaches and to Beaverdam Run, with substantial aggradation occurring near a railroad crossing just upstream of the confluence. The objectives of the restoration effort were to arrest the bank erosion problems by installing natural channel geometry, and to improve fish habitat by using native material revetments.

Measurements of existing conditions were collected to allow determination of the bankfull discharge and other design criteria. The design of the new stream was based on a C4 stream type in the Rosgen classification system (McGill and



VORTEX ROCK WEIR (PLAN)

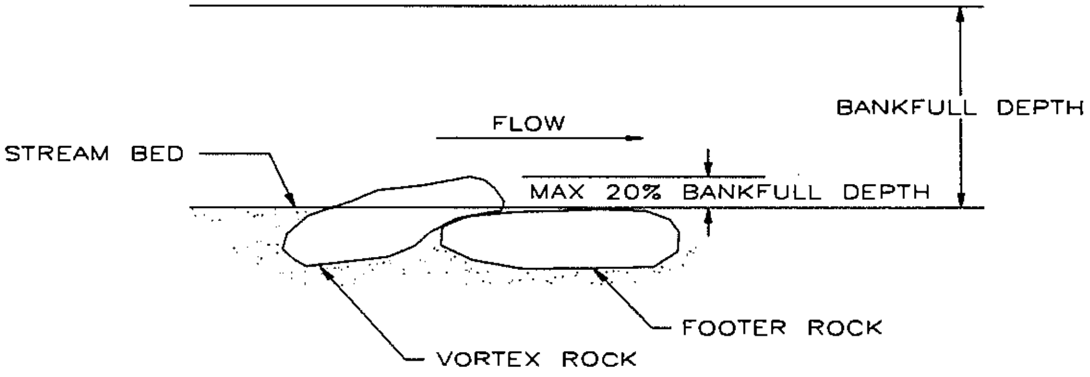
NOT TO SCALE



NOTE: TOPS OF VORTEX ROCKS SET MAXIMUM 20% OF BANKFULL DEPTH.

VORTEX ROCK WEIR (CROSS SECTION)

NOT TO SCALE



VORTEX ROCK WEIR (PROFILE)

NOT TO SCALE

Figure 6. Vortex Rock Weir structure for grade control and habitat enhancement.

Gracie, 1993). The design bankfull width was 28 feet and the average bankfull depth was 2 feet. The maximum depth in pools was 3.6 feet. Rootwads were used to reinforce meander bends and vortex rock weirs to provide grade control and direct flow into the center of the channel. Approximately 1100 feet of river were restored.

Construction was completed in September of 1992, and within a week a tropical storm caused flows to exceed the bankfull stage. The stream has since received several bankfull events and has generally held up well. Monumented cross sections allow consistency in annual monitoring of channel geometry, and sample data are provided in Figure 7.

Since construction, there have been some minor adjustments in the stream that are instructive. First, there has been some erosion of point bars on the inside of meander bends. The primary cause of this was a directive from a regultory authority that required the application of a stabilization seed mix on the point bars within the the limits of the active channel. After the grass was established, channel capacity was reduced and roughness was increased. The river adjusted by eroding enough material from unvegetated portions of the point bars to regain its capacity. The stream was designed to have a width/depth ratio of 14. If a width/depth ratio at the higher end of the stable range for this streamtype had been used, the amount of this erosion would most likely have been less.

Another problem has been aggradation in and around the rock weirs. There probably was not enough displacement to the apex of the weirs; in other words, the distance in the center of the channel from the wide end of the `V' to the upstream-most rock at the point was insufficient. Design modifications by Rosgen now indicate that this displacement should be 2.5 to 3 times the average intermediate diameter of the boulders. In addition, the vortex rocks supplied by the contractor were too big. Although correctly installed with a 0.3 to 0.5 diameter space between rocks, the large gap appears to have inhibited proper functioning of these devices.

The last problem was with the rootwad revetments. Rootwads are installed such that the bole of the tree is oriented parallel with the incoming flow, which usually sets the root fan normal to flow (Figure 4). The cut-off log is placed on top of the bole and oriented downstream and out toward the next rootwad. The cutoff log is secured with a single boulder and backfill material. The purpose of the cutoff log is to break up eddy currents that can develop when bankfull flows come around the meander. To function effectively, it is critical that the elevation of the tops of the cutoff logs be above the bankfull elevation. At Goodwin Run, most of the cutoff logs were only about twelve feet long. The result was that some of the logs were not long enough to be adequately buried in the bank. Of over 100 cutoff logs installed, 3 have been torn out and 4 or 5 others show evidence of buoyancy during high flows.

White Marsh Run

White Marsh Run has been channelized and relocated several times to facilitate extensive sand and gravel mining between a heavily urbanized area and sensitive habitats of the Chesapeake Bay. Due to the mitigation requirements of another highway project, approximately forty acres of wetlands will be created and over 5000 feet of stream will be restored. The existing stream is an F4 streamtype that is fully entrenched by steep banks.

The discharges used for the

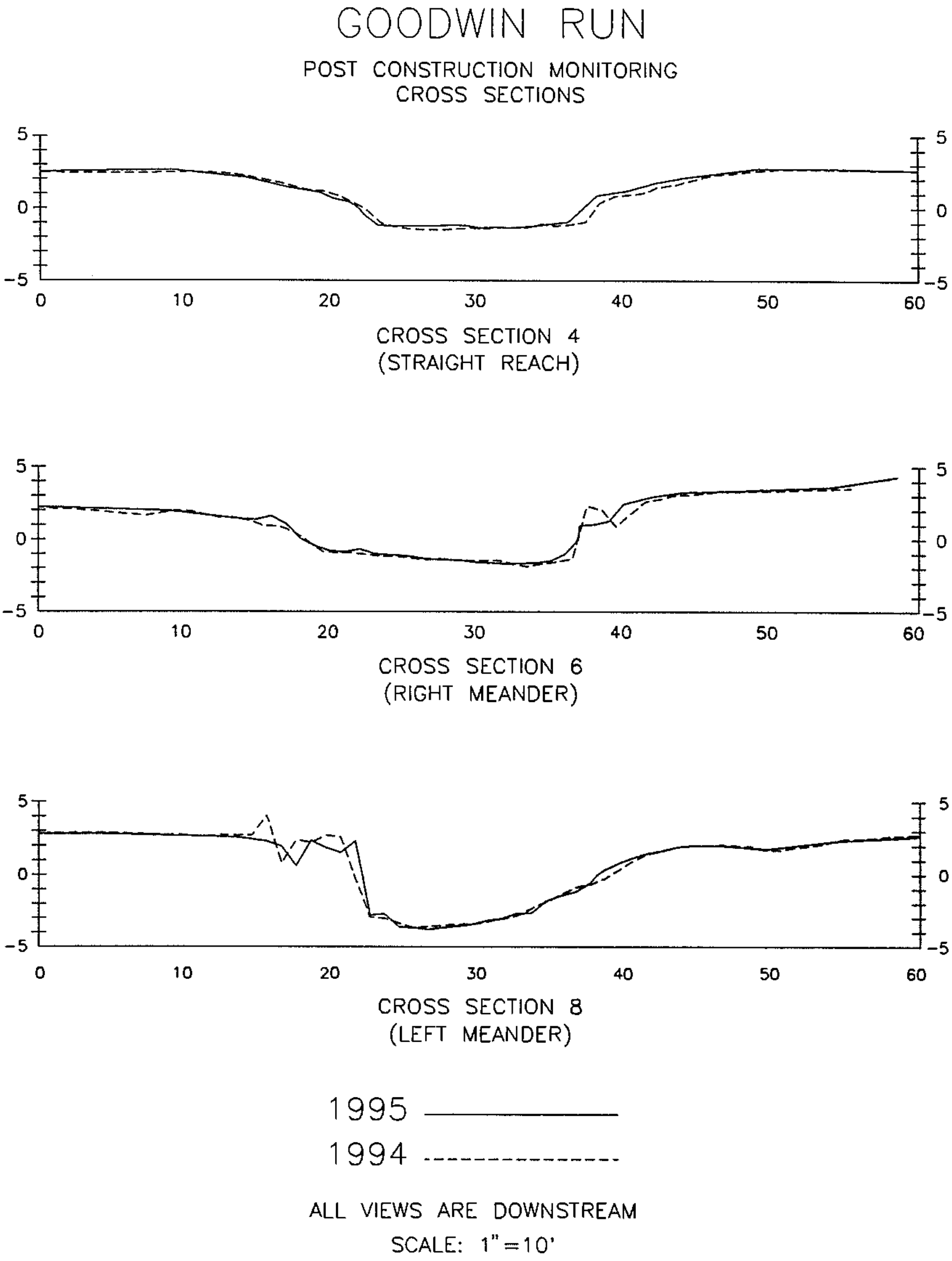


Figure 7. Goodwin Run sample cross section monitoring data.

restoration design were determined from field measurements and checked by stage discharge relations from gage station data. The upstream portion of the project was designed for a bankfull flow of 250 ft^3/second, with 300 ft/second used for the downstream section due to tributary entrance and increased drainage area. The restoration plans again call for a C4 streamtype with rootwad revetments on meander bends. The width/depth ratio will be 22. The cutoff logs are specified to have a minimum length of 16 feet. The plans also include the revised vortex rock weir design shown in Figure 6. Construction was started in March of 1996 and is expected to take 6 months to complete.

Summary

Geomorphologic principles can be applied to streams disturbed by surface mining to restore channel geometry to a stable form. By integrating knowledge of fluvial process, stream pattern morphology, channel and meander geometry, and the natural tendencies of adjustment toward stability, the most effective design for long-term stability and function can be predicted. The Rosgen Classification System provides a methodology for the determination of the design parameters needed for a natural channel design. By defining design parameters within the ranges of stability for natural streams, and by respecting the relationships between the eight variables, streams be returned to a self-maintaining condition of dynamic equilibrium.

By restoring this stable condition, a stream will tend toward uniformity in the rate of energy expenditure and minimum work, therefore exerting the least stress on channel bed and banks. The minimization of stress allows native materials to support and complete restoration to a natural condition.

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