EROSION CONTROL AND USE OF STREAM RESTORATION PRINCIPLES IN THE DESIGN OF CHANNELS AND DIVERSIONS

by

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Abstract. Engineered systems for erosion control in drainage networks have often been used to mitigate the impacts of increased soil erosion from surface disturbance. However, these systems often alter the natural equilibrium in the water and sediment transport regime. Application of the principles of stream restoration and in regime design seek to create diversions and other relocated channel systems that function more like natural channel systems with respect to both the passage of flood events and the preservation of both aquatic and riparion/terrestrial habitat. Although not applicable to all diversion design, where it is possible to apply these principles, the design usually results in channels requiring little or no maintenance, little or no modification at the time of reclamation and abandonment, and typically at a cost equal to or less than that of a conventional hard lined channel. Examples of projects will be presented where designs have resulted in the saving of from $200,000 to $500,000 in riprap costs alone. Other advantages often include reduced maintenance costs, reduced or eliminated cost at the time of reclamation, and greater acceptance by regulatory agencies leading to easier permitting.

Introduction

Mining facilities, by their nature, result in significant areas of ground disturbance and an increase in the amount of surface soil erosion when compared to natural or background levels of soil erosion within the affected drainage basin. These impacts may be either temporary or permanent, depending on the level of reclamation performed within disturbed areas. The magnitude of impact on stream channels and receiving water bodies will depend on the type of mitigation applied both during operations and at the time of final reclamation. Often some of the most long lasting impacts on natural stream channels result from the temporary application of erosion control methods within the channel bed including the use of concrete or riprap channel linings and the construction of sediment detention structures. Channel linings, while effective at limiting bed and bank erosion, can leave a sterile (or at least severely degraded) aquatic habitat and degraded adjacent riparian and terrestrial habitat. Large sediment detention structures on perennial streams can severely disrupt the sediment transport regime within a channel and result in downstream channel degradation. This paper will briefly discuss some of the more commonly used Best management Practices (BMPs) that can affect the performance of channel systems and the use of stream restoration principles in channel and diversion design to minimize impacts on aquatic, riparian, and terrestrial habitats while preserving equilibrium level sediment transport regimes.

Entrainment and the Mechanics of Erosion

Soil erosion within a drainage basin is a continuum of processes from the drainage divide at the watershed boundary to the final point of discharge at the mouth of the drainage basin. However, for purposes of discussing erosion control, these processes will be divided into two broad categories consisting of slope processes and those processes pertaining to flowing water.

Slope Processes

Erosion on a uniformly sloping surface (i.e., no channels) occurs by means of *sheet erosion,* which is the detachment of soil by raindrop impact. The detached soil particles are then transported by overland flow or *sheet flow.* As the size of the area experiencing sheet flow increases, so does the discharge per unit width.

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With increased flow distance, the sheet flow begins to concentrate, forming small, regularly spaced micro-channels called *rills*. A rill is a channel that is sufficiently small to be completely removed by normal tillage of the soil. With further increased flow distance, rills begin to converge and form gullies (now too large to be removed by normal tillage) and gullies may converge and flow into still larger channels ultimately forming the drainage network that will remove both the water and sediment from the drainage basin. The collective sum of the soil volume put into motion in these processes is referred to as the *sediment yield.* However, some of the soil that is detached in one part of the basin may be re-deposited and trapped elsewhere in the basin and never does make it all the way to the mouth of the basin. The ratio of the volume of soil finally discharged at the mouth of the basin to the sediment yield (the total volume of soil put into motion) is referred to as the *sediment delivery ratio.*

Some of the earliest work on quantifying the sediment yield was performed in 1947 by G. W. Musgrave. His work indicated that soil erosion was a function of soil erodibility, runoff length and slope, the maximum 30 minute rainfall amount, and the amount and type of surface cover. This eventually led to the Universal Soil Loss Equation (USLE), a simple multiplicative equation consisting of six factors. The equation was originally developed for use in estimating the soil loss from cultivated fields, but by the 1970's it began to see substantial use in areas not related to agriculture, particularly in the evaluation of erosion on rangeland in the steeper slopes of the North American West and in semi-arid to arid climates.

A revision to the original USLE was developed and published in 1978 to update the factors and procedures to account for the new uses outside the limits of the original database while preserving the structure of the original equation. This new work became known as the RUSLE procedure (Revised Universal Soil Loss Equation). New research is now in progress on better methods for prediction of soil erosion having a solid theoretical, and process-based foundation rather than the purely empirical foundation of the RUSLE procedure (specifically the Watershed Erosion Prediction Project or WEPP). However, the RUSLE procedure is still the most widely used and best practical method available for prediction of sediment yield at the present time.

The sediment delivery ratio is a function of drainage area, drainage density, watershed slope, and runoff. However, it is generally considered that the most important factor is drainage area (the larger the drainage area, the higher the probability of encountering surface features that will trap and hold sediment).

<u>*Flowing Water*</u>

Once the runoff is concentrated into well defined channels, the flowing water can interact with the soil in the channel bed and banks. In 1939, Hjulstrom developed a relationship between mean current velocity, particle size, and process (Figure 1). Examination of this relationship shows that sediment dominated by particle sizes on the order of 0.1 mm. to 0.5 mm. (fine to medium sand) is the most easily entrained into the flow (eroded). Particle sizes coarser than 0.5 mm. become increasingly more difficult to entrain requiring higher mean current velocities as the particle size increases. These coarse particles are also readily re-deposited as the mean current velocity begins to drop. This coarser fraction is commonly referred to as the *bedmaterial* load. For particle sizes less than 0.1 mm., the current velocity required for entrainment starts to increase as the particle size decreases (due in large part to the increasing effects of cohesion within aggregations of finer particles). In other words, clays are more difficult to erode than fine sand. However, the boundary separating transportation and deposition continues to drop steadily with the decreasing particle size requiring lower and lower mean current velocities to initiate deposition of the smaller particle sizes. The significance of this is that once the smallest size fractions (silts and clays) have been entrained into the flow, they can be transported by almost any level of flow, essentially requiring standing water to induce deposition. This finest fraction of the sediment load is commonly referred to as the *washload* (because it tends to wash out through the entire channel system without re-depositing until a standing water body is reached or until the flow dissipates becoming a subsurface or alluvial groundwater flow).

Figure 1 – Hjulstrom Curves

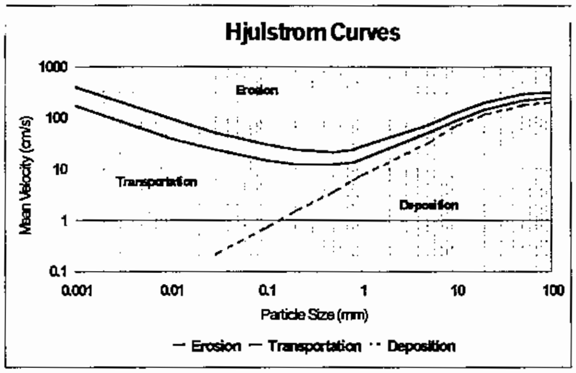
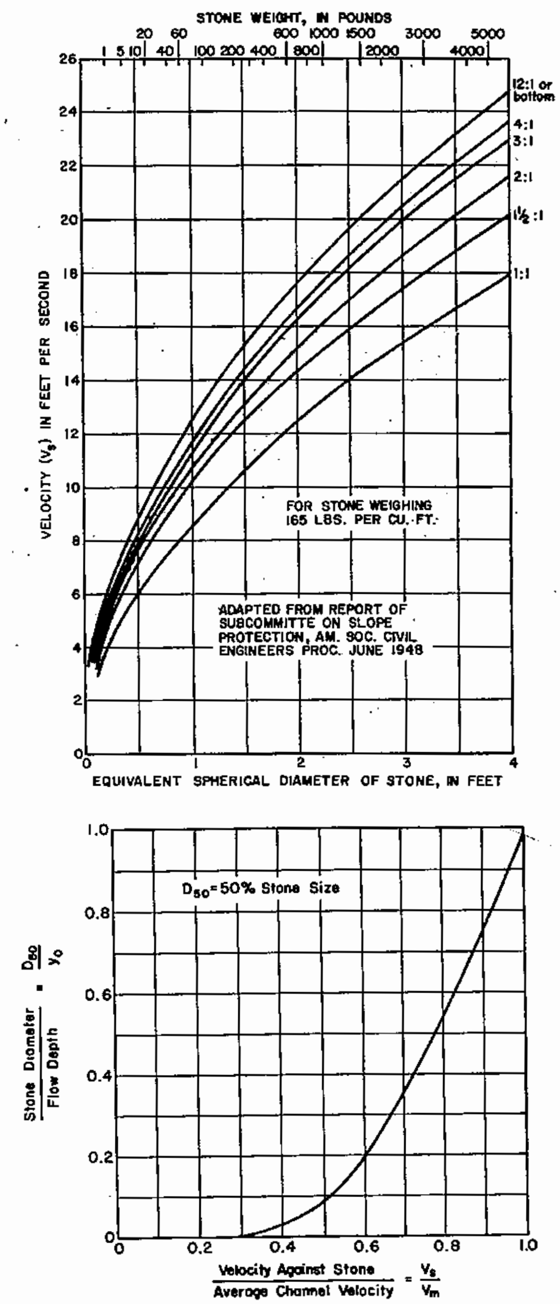


Figure 2 – Curves for Estimation of Riprap Size (from Highways in the River Environment, National Highway Institute, Federal Highway Administration, February 1990).



Conventional Erosion Control and Best Management Practices

The discussion of conventional erosion control measures will be limited to two major categories: roads, and concentrated drainage. A discussion of erosion control procedures on slopes (the third major category) is beyond the scope of this paper.

Roads

Paved roads represent a surface that has minimal opportunity to produce any sediment from erosion. An exception to this statement would be in cold climates where sand or a mixture of sand and salt might be used to improve traction on snow and ice, producing a source of readily entrained sand. Abrasion of the wearing surface on unpaved roads can also produce a significant source of easily entrained fine sand and silt. Roadside ditches are used to carry concentrated flows alongside the roadway itself and to collect runoff and sediment from cut slopes adjacent to the roadway. *Waterbars* are raised linear features periodically placed along the surface of a steep, unpaved road to limit the slope distance along the road surface and turn sediment laden sheetflow into the roadside ditch. Once flows are in the ditch, erosion can be controlled with a number of techniques including various types of ditch *linings* or some form of *check dam.*

Non-erosive lining materials can consist of coarse rock (riprap), vegetation, geosynthetic linings, or some combination of vegetation and geosynthetics. The sizing of rock riprap within a small roadside ditch is a function of flow velocity (Figure 2). With respect to riprap gradation, the D_{100} should be approximately 2 x D_{50} and the D_{20} should be approximately 0.5 x D_{50}. The thickness of the riprap lining should be not less than 1.5 x D_{100}. In order to limit scour damage below the riprap lining at the riprap/soil interface, the filter design criteria between the riprap gradation and the protected soil (base) should be satisfied. The most commonly used criteria are as follows:

D_{50} (riprap)/D_{50} (base) < 40
5 < D_{15} (riprap)/D_{15} (base) < 40
D_{15} (riprap)/D_{85} (base) < 5

If the base is a cohesive soil (clay), then the D_{15} of the riprap should be less than or equal to 0.4 mm. In the event that the filter criteria cannot be satisfied between the riprap and the base, then a filter layer(s) can be placed above the base soil prior to placing the riprap. The filter layer should be about ½ the thickness of the riprap layer but not less than about 15 cm. Geosynthetic filter cloth can also be used in lieu of a graded soil filter.

In wet climates vegetative linings can be very viable. Allowable velocities in vegetated channels vary with the type and nature of the vegetation. The greatest protection will come from tall, flexible grasses that lay down during the passage of design flows, forming a protective mat of vegetation on the channel bed. Resistance to flow is variable with the magnitude of the flow being highest during the passage of low flows when the vegetation remains stiff and erect within the flow and lowest during larger flows capable of bending over the vegetation and opening up the channel section for flow. Resistance to flow can be estimated from retardance curves as a function of the type and condition of the vegetation. Allowable flow velocities in vegetated channels also varies as a function of the type and condition of the vegetation. However, the upper limits of allowable flow velocities are on the order of 1.83 meters per second (6 feet per second) in cohesionless soils (sands and gravels) and 2.44 meters per second (8 feet per second) in silts and clays. Vegetation anchored geosynthetic lining (Enkamat for example) can routinely withstand allowable design velocities in the range of 1.83 to 2.74 mps (6 to 9 fps) and under ideal conditions can withstand velocities in excess of 2.74 mps (9 fps). These materials consist of an open network of stiff plastic wire filaments, typically about 1 cm thick which are initially anchored to the surface with wooden stakes. Vegetation is planted in conjunction with the placement of the lining and ultimately, the root masses provide a more permanent and more uniform anchorage of the liner to the surface.

Check dams are small temporary detention structures most commonly used within ditches or small ephemeral drainages to control velocity and trap and store coarse sediment. In larger intermittent or perennial streams, check dams can cause a significant disturbance in the normal flow and sediment transport regime and can become counterproductive (this will be discussed further in the context of sediment detention structures). Their effectiveness depends on design and routine maintenance. Check dams can be very temporary (such as straw bales anchored to the ditch with driven reinforcing steel and placed immediately below a temporary construction disturbance) or they can be a quasi-permanent installation such as a porous rock check dam. The detention time is typically so short for these structures that they do little to trap any fine sediments (fine sand and smaller) and will trap primarily coarse sand, gravel, and cobble sized particles. The flow capacity of a ditch containing check dams is determined by the overflow capacity of the small broad crested weir formed by the crest of the dam. This is an important design consideration since, if the crest is placed too high, large flows are forced out of the ditch and onto the road surface where they have the opportunity to pick up a much larger volume of fine sediment (Figure 3). If the sediment trapped behind these structures is not cleaned out and disposed of regularly, then they can become ineffective after only one or two significant flow events (Figure 4).

Other erosion control structures sometimes used along roadway ditches include special drainage inlet designs such as sand traps/filters and grease traps. These structures often operate similarly to check dams. They provide room for sediment detention and storage with baffles acting as overflow weirs to slow flows and allow coarse sediment to settle out; however, the elements are completely contained within a reinforced concrete box. In the case of grease traps, the outlet is designed to withdraw flow from the base of the storage area in an attempt to trap floating oil and grease. In general, the structures tend to be very expensive and their effectiveness strongly dependent on regular maintenance and cleanout. Grease traps, in particular, tend to have limited effectiveness, with the oil and grease collected during small storm events being flushed out of the system again during the larger storm events if not maintained during the interim period between storms.

Figure 3– A Check Dam Constructed with the Crest at or above the Road Surface

Figure 4 – Check Dam Completely Filled with Sediment

<u>*Concentrated Drainage (outside of roadside ditches)*</u>

The overriding rule of thumb in all erosion control design is that *as much of the increased sediment yield as possible should be trapped and stored as close to the sediment source as possible.* The removal of excess sediment from flowing water becomes increasingly difficult and more expensive in direct proportion to the distance from the source. Sediment detention structures and constructed wetlands are commonly used for the removal of excess sediment and other pollutants from concentrated flows of water. The majority of these structures represent small earth dams with similar design and safety considerations. The larger the drainage area, the larger the structure and the more significant the safety considerations. Structures can be divided into two broad groups:

- Pond Systems
- Wetland Systems

Ponds rely on simple storage and detention time for the removal of sediment/pollutants. A *conventional dry pond* is simply an empty pond placed in a dry, ephemeral drainage that, during storm events, will fill to the level of its design control structure and provide some time for sediment to settle out in the relatively quiescent environment of the pond. Re-entrainment of deposited sediment during subsequent storm events is a frequent problem in the dry pond systems. A *wet pond* system has the same basic design as the dry pond but is supported by sufficient base flow to maintain a permanent pool. The existence of the permanent pool substantially reduces the problem with re-entrainment of stored sediment.

In general, ponds should have a larger length (the dimension in the flow direction) than width. Short, wide ponds tend to short circuit creating ineffective dead storage zones in the outer wings of the pond. Short circuiting reduces the effective detention time to something less than that which would be indicated by the pond volume alone. If a given site will not permit anything other than a short, wide pond site, then short circuiting can be overcome to some degree with a system of baffles or berms that direct the flow through a greater percentage of the pond footprint.

Some structures will incorporate pretreatment in the form of a small forebay (micropool) which traps coarse sediment for easy cleanout and disposal and optimizes the detention time and removal of fine sediment in the main pool. If a micropool is used, it should be sized to be cleaned out, on average, every one (1) to two (2) years. The main storage area of the pond should be sized to be cleaned out every two (2) to five (5) years.

Wetland systems operate similarly to pond systems but involve more shallow storage and less open water. Wetland systems tend to require more surface area for a given flood flow than do pond systems and also require a strong groundwater/baseflow component to support the wetland vegetation. The strong vegetation component in wetland systems can make them effective at treating other pollutants including phosphorous, nitrogen, and even heavy metals through uptake of dissolved constituents by the wetland plants. Wetland systems have been used effectively for water polishing and the treatment of acid rock drainage (ARD) although they cannot handle large flow volumes or extremely erratic flow rates. *Combination pond/marsh* systems attempt to combine the best aspects of both wetlands and open water pond systems.

Table 1 shows a performance comparison among various BMPs and also provides some information on the relative design life and maintenance requirements. For mining applications, the guiding design principles should emphasize simplicity and rugged durability.

Table 1 – Summary Performance Comparison of BMPs Adapted from ASCE, Urban Watershed Management, Center for Watershed Protection, September 1995

Description	Typ. Drain. Area (hectares)	Mean Pollutant Removal (%)			Design Life	Maint.
		Total Susp. Solids	Total Phosph.	Total Nitrogen		
Filtering Systems						
Sand Filter	0.4 to 20	85	50	35	Variable	High
Grassed Swale	< 2	70	40	25	Mod	High
Biofilter	< 4	80	45	25	Mod	High
Bioretention	< 0.4	90	50	25	Ex	High
Oil/Grit Separator	< 2	10	0	0	Ex	High
Infiltration Systems						
Convent. Infiltration Trench	0.4 to 2	90	60	50	Poor	High
Enhanced Infiltration Trench	0.4 to 2	90	60	50	Mod	Mod
Infiltration Basin	0.8 to 2	90	60	50	Poor	High
Pond Systems						
Conventional Dry Pond	2 to 160	10	0	0	Ex	Low
Dry Extended Detention Pond	4 to 160	30	10	10	Ex	High
Micropool Ext. Detention Pond	4 to 160	70	30	15	Ex	Low
Wet Pond	10 +	76	60	40	Ex	Mod
Wet Extended Detention Pond	10 +	76	65	40	Ex	Mod
Multiple Pond Systems	10 to 160	80	70	45	Ex	Mod
Wetland Systems						
Shallow Marsh	10 +	75	45	25	Ex	Mod
Extended Detention Wetland	4 +	70	40	20	Ex	Mod
Pocket Wetland	< 2	60	25	15	Ex	Mod
Pond/Marsh Systems	10 +	85	60	45	Ex	Mod

Stream Restoration

Stream restoration is an attempt to restore, in so far as possible, most or all of the natural form and function of the original unimpacted stream. Naturally functioning hydraulics can be restored, much of the habitat can be replaced (resulting in improved wildlife diversity), and water quality can be improved. In the absence of these principles, channels are often force fit into a convenient geometry and then held in place through the use of hard linings (riprap, concrete, shotcrete, etc.) and high maintenance.

Basin and stream systems accomplish geomorphic work such as removing water from the basin area during rainfall and snowmelt and the transporting of sediment out of the basin. Every river and stream tends to establish an equilibrium relationship between a critical flow level, referred to as the mean dominant discharge, and the sediment load produced by the basin. The system accomplishes this by adjusting its hydrologic variables (i.e., channel width and depth, velocity, roughness, slope, sinuosity, etc.). This normal fluvial condition is a state of dynamic equilibrium referred to as "quasi-equilibrium" (Rosgen, 1994). The inter-relationship of these variables is extremely complex and the difficulty involved in understanding stream and river behavior is evident when one considers that the water discharge and the sediment load are in a continuous state of flux or change, so that all of the hydraulic variables are always adjusting. A river or stream system will never ultimately reach a final steady state permanent condition, thus the term "quasi-equilibrium". However, a stream system that is approaching this equilibrium state is said to be "in regime".

The total effectiveness of a stream to do geomorphic work (i.e., to transport water and sediment) is a function of both the magnitude of an event and its duration. Although it is true that very large flow events are capable of transporting enormous amounts of sediment, they occur very infrequently and persist only over a very short duration. These are the kinds of storm events often referred to as peak storm events or extreme events. Surface water facilities must still be designed to pass these peak storm events without substantial erosion or damage. However, the vast majority of the geomorphic work and the events that shape the geometry of the channel are associated with the intermediate events that occur every one to two years, referred to as the "mean dominant discharge". This event is usually coincident with "bankfull discharge" which, in a natural and relatively undisturbed stream system that is near its quasi dynamic equilibrium point, is the flow at which the water just fills the bed and banks of the main channel and is about to spill into the active flood plain. A frequent failing of modern drainage system planning and design is that most designers effectively accommodate the delivery of water discharged through the system but often fail to consider the needs of the stream to transport sediment. In a drainage channel that has the ability to change its boundaries (i.e., to either aggrade, degrade, or migrate laterally, which is the definition of a fluvial system), it is critical that provisions be made for the transport of sediment as well as water in order to avoid upsetting the equilibrium of the channel.

A common method to circumvent the need to consider the movement of sediment in addition to water is to invoke the assumption of the "rigid boundary model" (which means to assume that the stream channel is incapable of changing its boundaries, Simons et. al., 1982). The physical reality corresponding to this design assumption is the use of channel armoring such as concrete, riprap, or other forms of artificial erosion protection (in order to prevent degradation and erosion). The other physical manifestation of this assumption is maintenance (dredging) in order to remove the sediments associated with aggradation. When applied properly, the principles of fluvial geomorphology and in-regime design can be used to create a more natural-appearing and naturally functioning stream channel system while minimizing hard-lining forms of erosion protection and with substantially reduced maintenance requirements. Use of stream restoration is commonly intended to address four primary goals:

1. To improve water quality by minimizing bed and bank erosion;
2. To restore riparian vegetation and minimize the need for hard lining materials such as concrete and riprap;
3. To reduce maintenance requirements to the greatest extent possible;
4. To provide a system which in the long term provides the greatest degree of compatibility possible with both aquatic and terrestrial forms of wildlife.

Stream Classification

The physical appearance and character of a stream is a product of the adjustments of its boundaries to the current stream flow and sediment regime. Stream form and fluvial process evolve simultaneously and operate through mutual adjustments toward quasi-equilibrium or self-stabilization (Rosgen, 1994). As mentioned previously, an important concept in fluvial geomorphology is the concept of the channel forming or bankfull discharge which drives or controls channel morphology. This discharge is not an extreme flood event but rather a low-magnitude, high-frequency flood event (the 1 to 2-year return frequency flood). Over the long-term, this discharge moves the greatest total volume of sediment and, therefore, exerts the greatest influence on channel changes and channel geometry. The Rosgen Stream Classification system is an effort to categorize river systems by channel morphology in order to better:

1. Predict a stream's behavior from its appearance.
2. Develop specific hydraulic and sediment relations for a given morphological channel type and state.
3. Provide a mechanism to extrapolate site specific data collected on a given stream reach to those of similar character.
4. Provide a consistent and reproducible frame of reference of communication for those working with river systems in a variety of professional disciplines (Rosgen, 1994).

None of the principles utilized in the Rosgen Stream Classification System are particularly new. In fact, the earliest observations of the importance of mean dominant discharge or bankfull discharge, were published by Leopold and Wolman in 1957. Stream classification systems are nothing new either, with the earliest classifications dating back to Davis in 1899, when he first divided streams into three classes based on relative stages of adjustment which he described as youthful, mature, and old age. Subsequent classification systems based on qualitative and descriptive delineations were developed by Melton in 1936 and Matthes in 1956. Systems based on channel patterns (described as straight, meandering, and braided) were developed by Leopold and Wolman in 1957 and by Lane in the same year. A system proposed by Schumm in 1963 involved delineation partly based on channel stability (stable, eroding, or depositing) and mode of sediment transport (mixed load, suspended load, and bedload). Numerous investigators in the 1960's and 1970's began to develop descriptive classifications that utilize depositional features, vegetation, braiding patterns, sinuosity, meander scrolls, bank heights, levy formations, and flood plain types to discriminate various stream systems. Many of these classification systems are rather academic in nature as might be expected since their use was primarily for research. One of the most compelling characteristics of the Rosgen Stream Classification System is that it was developed by an individual who was not directly involved in the academic role of research, but by one who spent most of his career dealing with practical problems in the river environment and finding practical solutions to those problems. Because of its origin, this particular classification system is, in my opinion, better suited to design oriented problems and to the "application" of in regime design.

The Rosgen approach to stream classification and stream restoration design involves a hierarchy based on level of detail. There are four distinct levels:

Level I is a broad morphological characterization that integrates the landform and fluvial features of valley morphology with channel relief, pattern, and dimension. It combines the influences of climate, depositional history, and life zones on channel morphology focusing largely on basin-wide or watershed conditions.

Level II is a morphological description or determination of stream type. The key parameters will include channel patterns, entrenchment ratio, width-depth ratio, sinuosity, channel materials, and slope.

Level III is the stream "state" or condition. It involves the evaluation of parameters such as riparian vegetation, depositional patterns, meander patterns, confinement features, fish habitat indices, flow regime, stream size category, debris occurrence, channel stability index, and bank erodability. It describes the existing conditions that influence the response of channels to induced change. It provides data on where the stream is at in the evolutionary process and, if the stream is experiencing change, helps to identify the direction of change. This level of study will further assist in the prediction of channel response to man-imposed change in flow regime, sediment supply, geometry, etc.

Level IV is monitoring. Monitoring of a stream restoration effort can involve many facets including changes in channel plan form, profile, or cross section, changes in bed material gradation, in flow regime, in habitat or diversity, vegetation success or survival rate, and so on.

<u>*Diversion Channel Design*</u>

Surface mining results in major earthworks and large areas of surface disturbance. The disturbance will almost always involve the modification or relocation of existing drainage channels. The typical response to this set of circumstances is the engineering design of "channel improvements" taking the form of a new channel design using a simple trapezoidal cross section sized to safely pass a selected extreme flood event (usually the 100 year peak discharge for an "important" channel). An

Figure 5 – Broad Level Stream Classification Delineation (used with permission from Wildland Hydrology, *Applied River Morphology*, Rosgen 1996, Figure 4-2, pg. 4-4).

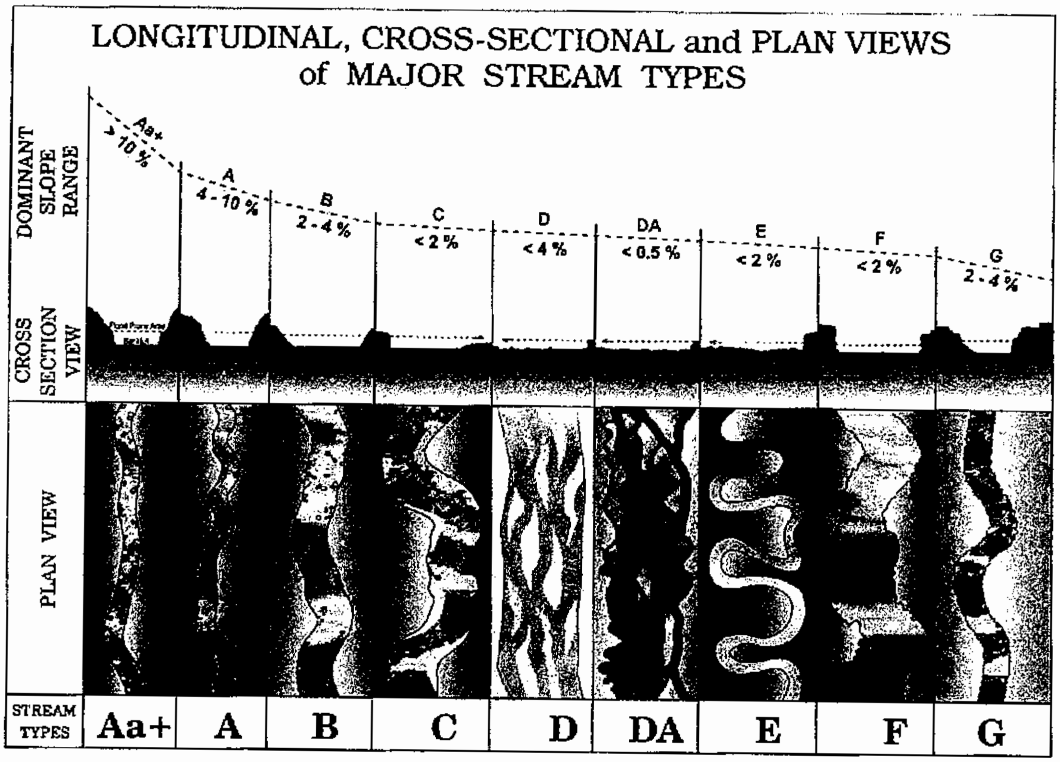
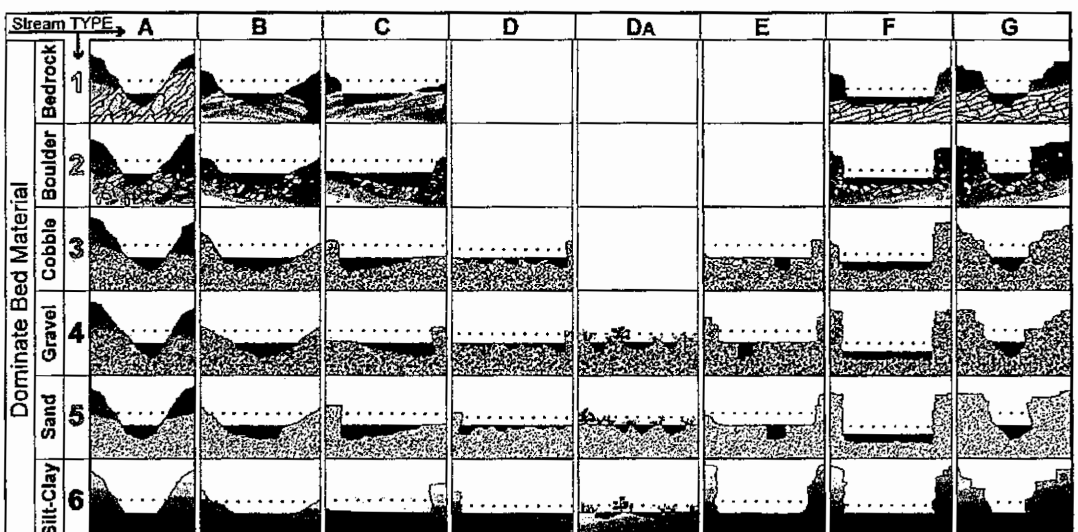


Figure 6 – Primary Delineative Criteria for the Major Stream Types (used with permission from Wildland Hydrology, *Applied River Morphology*, Rosgen 1996, Figure 5-2, pg. 5-5).



	A	B	C	D	DA	E	F	G
Entrchmnt	< 1.4	1.4 - 2.2	> 2.2	n/a	> 4.0	> 2.2	< 1.4	< 1.4
W/D Ratio	< 12	> 12	> 12	> 40	< 40	< 12	> 12	< 12
Sinuosity	1 - 1.2	> 1.2	> 1.2	n/a	variable	>1.5	> 1.2	>1.2
Slope	.04-.099	.02-.039	< .02	< .04	< .005	< .02	< .02	.02-.039

alignment is selected and an associated profile or grade determined. Iterative application of the Manning's equation to calculate normal depth results in final dimensions of the channel cross section (with added freeboard as a safety measure) and estimates are obtained for the channel capacity (discharge) and associated mean flow velocity. The calculated mean velocity almost invariably exceeds the "allowable" velocity of the new channel bed materials and a suitable lining (riprap, concrete, shotcrete, synthetics, etc.) is selected and included in the design. The final channel design has little or no sinuosity, no low flow channel, no functioning floodplain, a sterile, lifeless bed with no aquatic habitat, and a detached, degraded riparian habitat (if any) perched high above the channel bed. The design accomplishes a single, simple goal. It produces a channel that, at the end of construction, is capable of passing the design extreme event without overtopping the banks or producing excessive erosion (at least within the newly constructed reach).

Now let us look at a hypothetical scenario of how the typical extreme event channel design might perform over an extended period of time. A modest flood with a five (5) year return frequency is experienced a year or so after the completion of the diversion channel. The natural channel systems upstream of the diversion are flowing just out of the normal channel bed and banks (the bankfull channel) at a depth of say 40 cm and deliver their water and sediment load to the upstream end of the diversion channel. Since there is disturbance in the basin, they may even be carrying a somewhat higher sediment load than normal, but the sediment transport capacity in the relatively narrow and deep channel section of the natural stream is able to accommodate the moderate increase in sediment load with little difficulty. As the flow enters the wide, flat bottom of the diversion channel, the water spreads and the depth of flow drops from 40 cm. to less than 10 cm. Despite the increased width of flow, the sediment transport capacity is insufficient to carry the sediment load and a thin layer of sediment begins to deposit on the bed of the diversion channel (aggradation). More sediment accumulates on the declining limb of the hydrograph as the flood flow recedes and a 5 cm thick layer of sediment is left behind.

As the flow reaches the end of the diversion channel, it re-enters the natural channel system and begins flowing down the narrower bankfull channel and floodplain section at a depth of 40 cm., but it is no longer carrying the sediment load that it had upstream of the diversion channel. The increased flow depth gives it the same sediment transport capacity that it had at the upstream end so, to satisfy that capacity, it begins to erode sediment from the bed and banks of the natural channel section (degradation) until it restores its original sediment load. The natural channel begins to widen and deepen for some distance downstream of the end of the diversion channel. This scenario is repeated half a dozen times over the next decade with small to moderate floods every year or two resulting in 35 cm or more of aggradation in the diversion channel and 10 cm to 20 cm of degradation in the natural channel downstream extending over a distance three times the length of the diversion channel. The natural channel downstream is becoming detached from its floodplain and each successive flood finds it increasingly difficult to reach the floodplain and spread the flow. The increased depth of flow during even moderate sized floods is starting to accelerate the rate of degradation in the natural channel.

In the tenth year, an extreme flood approaching the 100 year design storm event is experienced. As the peak discharge approaches, the natural channels upstream of the diversion are well out of their banks and water is spread across a wide floodplain. At the entrance to the diversion channel, the flow must now converge to enter the narrower cross section but the channel bed is now 35 cm higher than it was at the time of construction. Although the sediment transport capacity in the narrower and deeper section of the diversion channel is higher than the natural channel at this large discharge, the incoming sediment load is still high and elevated by the impact of the disturbed slopes within the basin and the re-entrainment of sediment on the bed of the diversion channel cannot keep up. The flow is using all of the freeboard and is still spilling over the banks of the diversion. Halfway down the length of the diversion channel it cuts across a slope so that the downslope bank is actually an embankment (levee) and as the flow overtops the embankment, it begins to erode and open up a breach within the embankment. Now most of the flow is released onto the slope below and it begins to scour and cut a new channel (an avulsion), abandoning the remainder of the original diversion channel.

The hypothetical circumstances described above are intended to illustrate some of the potential consequences of failing to consider sediment transport in addition to water discharge in the design of drainage channels. These potential impacts can be mitigated through regular inspection and maintenance after storm events (requiring human intervention on a regular basis over the entire life of the channel). However, a better alternative is an improved design.

The application of stream restoration principles in channel design seeks to mimic the characteristics of stable natural channels in order to maintain the quasi-equilibrium condition in the water and sediment regime. This will eliminate or at least minimize the potential negative consequences from the modification or relocation of a channel and produce a channel that is self sustaining and self maintaining. A discussion of the detailed design procedures is beyond the scope of this paper. However, the remainder of the discussion will attempt to provide the reader with an understanding of the most important aspects of in regime design, the lessons that can be drawn from natural stream systems, the impact of erosion control BMPs placed in a natural stream system, and the limitations of in regime design on mining projects.

The starting point for in regime channel design is usually the mean channel grade or profile of the channel. For example, one cannot create a highly sinuous meandering channel on a valley slope of 6% and expect it to remain sinuous. Most meandering channels form on slopes of less than 2%. Sinuous, meandering channels on gentle grades dissipate much of the kinetic energy of flow through the sinuous, twisting planform of the channel. Sinuosity can be defined in one of two ways. It is the length of the channel divided by the length of the valley, or the slope of the valley divided by the slope of the channel. For example, a meandering channel with a sinuosity of 2.0 flowing in a valley with a mean slope of 1% will have a mean water surface slope in the bankfull channel of 0.5% (1% divided by 2). These highly sinuous meandering channels will have a *riffle-pool* type of profile that is correlated with the planform or meander geometry. Pools will be located at the outside of meander bends and riffles (shallow rapids) will be located at the crossover points between bends. Steeper channels will tend to have substantially less sinuosity and will form a *step-pool* profile geometry which is not correlated with the meander planform geometry. Energy in these steeper channels at the bankfull stage is dissipated by flow over the steps which form low drop structures and create shallow backwater pools between the steps. Spacing of the steps varies with the steepness of the channel ranging from about four (4) to five (5) bankfull widths for channels in the range of 2% to 4% to two (2) bankfull widths or less for channels of 10% and steeper.

The next most critical element of design is the determination of channel geometry. The key to the design of channel geometry is the determination of the bankfull flow and the dimensions of the bankfull channel (i.e., bankfull width and bankfull depth). The bankfull channel performs the important function of regulating the sediment transport regime and channel maintenance (i.e., keeping sediment transport in balance with the watershed's ability to produce sediment and preventing long term aggradation within the channel). Virtually every other aspect of channel geometry can be correlated to the bankfull flood including meander wavelength, meander radius of curvature, beltwidth (the width of valley floor occupied by a meandering channel), entrenchment, and step spacing in a step-pool channel profile. The assessment of an accurate discharge magnitude for the bankfull flood event should probably be given more attention and effort in the design process than any other single design task.

The particle size distribution of the bedmaterial also exerts considerable influence on the character and behavior of the channel. Coarse bedmaterials of gravel, cobble, or boulders tend to produce channels that are armor controlled. Scour in these channels is limited by the presence of an armor layer on the bed formed by the removal of fines during the passage of successive large floods and the accumulation of coarse particles too large to be transported by the flood flow velocities and associated bed shear. It is generally considered that a stable armor layer, for a given flood flow, is one in which the thickness of the armor exceeds two times the diameter of the largest particle that can be transported by that flood flow. In an armor controlled channel, much of the sediment delivered to the channel by the watershed is simply transported through the channel reach above the armor layer with limited interaction with the bed. Finer bedmaterials such as sands, silts, and clays tend to produce channels with a stronger fluvial character (i.e., a stronger interaction between the water and the sediments in the bed and banks). The profile and cross section of the channel will reflect the equilibrium sediment transport conditions.

Although vegetation has a significant influence on virtually all natural channels, the stability of the strongly fluvial channel types tends to be more sensitive to changes in vegetation than the armor controlled channels (particularly the heavily armored channels where boulders and cobbles are dominant). Grasses typically dominate the flat wide floodplain of the gently sloped E type channels, while woody vegetation like willows become more important in the steeper but still highly sinuous C type channels, particularly along the outside of meander bends and the backs of point bars. The deep woody root systems help hold the bank soils together and protect the bank materials from erosive near bank velocities. Vegetation communities that line the channel banks (riparian vegetation) are also responsible for nutrient regulation, filtering of sediments, shade and water temperature control, nesting for birds, cover for fish and for terrestrial wildlife, and food supply for aquatic and terrestrial wildlife. Riparian vegetation is also important as a potential source of woody debris for the support of aquatic in stream habitat and as a wildlife migration corridor. The importance of vegetation to the stability and the ecological health of most channel systems cannot be overemphasized. Since vegetation is so important in the stability of restored channels, the channel is at greatest risk during the first one (1) to two (2) years after construction, before mature vegetation can be established. Risk then decreases steadily over time. Woody vegetation could require five (5) years or more to become significantly effective as bank protection. In the meantime, it may be necessary to install temporary erosion control measures in critical areas of high bank stress such as the outside of meander bends. Depending on the size of the channel and magnitude of the flow, these structures could range from willow mattresses to geosynthetic erosion control mats to timber and rock revetments. In general, the use of natural materials that will decompose and disappear over an extended period of time (after the vegetation has matured sufficiently to take over) is preferable to synthetic materials.

In completing an in regime design, the ideal circumstances would involve locating and documenting the characteristics of a stable channel of the same desired type (a reference reach). The measured characteristics then become design target characteristics for the new channel design. The reference reach might be in the same channel network either upstream or downstream of the new channel reach, or a reach in the same approximate position within an adjoining watershed. In the absence of a suitable reference reach, target design characteristics might be selected from a database of the characteristics of similar stable natural stream types. It is important to recognize that, in the context of stream restoration and in regime design, stability does not necessarily mean no change. Remember that fluvial channels are dynamic systems tending toward a dynamic equilibrium. A stable channel is one which will, in the long term, retain its shape, pattern, profile, and channel features and will neither aggrade nor degrade (i.e., it is self sustaining and self maintaining). Although equilibrium conditions can be temporarily upset by the passage of an extreme event, a stable channel will have the ability to recover over a short period of time, without human intervention. One of the goals of in regime channel design should be to minimize the risk of crossing a geomorphic *threshold* from which there is no recovery (at least not over any reasonable period of time). Examples would include undesirable conversions of stream type such as the conversion of a single thalweg meandering channel system to a highly unstable and unpredictable *braided* system of multiple channels or the initiation of channel rejuvenation (incision) usually caused by a change in the effective base level of the channel.

Armed with a knowledge of the dynamic nature of stream systems from the above discussion, one should now be able to appreciate the risks associated with the placement of erosion control structures within the natural stream channel environment. Structures such as detention pond systems and check dams can significantly alter the flow regime and, in particular, the sediment transport regime of the channel system. A properly designed and maintained system of check dams is entirely appropriate in a roadside ditch below an unvegetated, raveling cut slope. However, the same check dam structures placed in a natural stream channel can result in headward aggradation and the burial of the bankfull channel upstream of the check dam. Subsequent flood flows are then elevated to the level of the top of the check dam and will eventually outflank the structure cutting a new channel around one side of the check dam resulting in a local avulsion with increased erosion and sediment loading (Figure 7). An oversized sediment detention structure can collect the incoming sediment load and release sediment depleted flow to the natural channel downstream

Figure 7 – Outflanked Check Dam Resulting in Substantial Bank Erosion

resulting in increased erosion and degradation of the downstream channel. The risk of inducing an undesirable change in the sediment transport regime of the natural channel system increases in direct proportion to the size of the structure and to the distance downstream from the source of the increased sediment load. This leads us back to the basic principle of applying appropriate sediment controls as close as possible to the source.

If the goal of a system of check dams is to control mean channel velocity and the associated potential for bed and bank erosion, then the design should be modified to provide for an equilibrium level of sediment transport through the bankfull channel in order to avoid headward aggradation and the outflanking of the dam. One way to accomplish this is through the use of the rock vortex weir (Rosgen, 1994). A rock vortex weir is a structure that is designed to mimic the behavior of the natural steps that form within the steeper step-pool profiles of natural streams. The shape of the crest of the structure should conform to the cross sectional shape of the bankfull channel. The crest rock within the bankfull channel portion of the weir should be separated to create spaces between the rock that are about ¼ to $^1/_3$ of the diameter of the rock to permit the passage of sediment through the weir within the bankfull channel. Rock forming the crest of the weir should be keyed against the back of larger rock (referred to as footer rock) that is embedded well into the bed of the channel to prevent undermining by scour. The planform of the rock is laid out in an upstream pointing "V". This serves to center the flow within the channel, create a localized scour hole in the center of the channel, create opposing flow currents for dissipation of energy, and minimize the risk of developing high energy jets directed at the channel bank.

In regime design and stream restoration cannot be undertaken with a single goal in mind (i.e., the safe passage of an extreme event). In addition to the passage of the extreme event, the design must consider one or more of the following goals:

- *The channel should be self sustaining and self maintaining.* In order to accomplish this, the design should include a bankfull channel of appropriate dimension. The active floodplain and the extreme event floodway should be designed with the appropriate shape and dimensions for the stream type being restored, and the overall floodway should be sized to pass the design extreme flood event without excessive scour or bank erosion.
- *The channel should be capable of sustaining an in stream aquatic habitat consistent with the unimpacted natural stream channel.* Uniformly graded riprap in the bed of the channel should be avoided. The channel bed should be graded (contain a variety of particle sizes) and be fluvial in nature (able to interact with the flow) so that a variety of bed features can be formed and sustained within the channel as appropriate for the stream type being restored (pools, steps, riffles/runs, bars, spawning beds, etc.).
- *Vegetation should be used to create self sustaining erosion protection appropriate for the stream type being restored and to create riparian habitat that will allow the stream corridor to function near its peak potential.*
- *Water quality should be improved by minimizing bed and bank erosion.*

Some of the advantages of using in regime design and stream restoration principles in channel design include the following:

- The multifunctional nature of the channel usually makes the proposal more acceptable to the regulatory agencies that administer such projects and can often accelerate the permitting and approval process.
- Rarely will the cost of in regime/stream restoration channel designs exceed the cost of conventional hard lined channels. Frequently the cost is actually less than the conventional hard lined channel by as much as 40%.
- Additional cost savings can be realized in reduced maintenance and repair expenditures.
- Often a temporary diversion channel designed for operations will require further modification prior to final reclamation and abandonment. The in regime/restored channel system will already be adapted to the watershed and the natural channel systems, will be revegetated, and will have natural function and habitat values restored. It will require no further modification prior to abandonment and thus will eliminate those costs at the time of final reclamation.

On a mine site closure and reclamation project in New Mexico, a traditional riprap lined trapezoidal channel system had been designed on a steep (3% to 5% typical grade) ephemeral stream channel. Concerns were expressed about the impacts of large riprap on deer migration across the channel, and on the almost total lack of small, terrestrial wildlife habitat. Using in regime design principles, steep reaches of 5% to 10% grade were designed using boulder drop structures. In other reaches with grades on the order of 3%, rock vortex weirs were used to form a step pool geometry. The rapid drops in grade in these reaches permitted the use of sinuous, meandering channel sections in between the steep reaches, at a grade of 1% where riprap could be entirely eliminated on the active floodplain and the inside of meander bends. The result was a channel with multiple large crossings for deer completely free of riprap, and active floodplain reaches with small, terrestrial wildlife habitat (significant environmental enhancements, even though the channel design did not begin to approach full restoration). In addition, just the material cost of riprap was reduced more than $400,000 in the ¾ mile length of channel.

On an active mine site in Nevada, it became necessary to divert and relocate an existing intermittent, cobble bed stream channel away from the toe of a proposed tailings dam embankment raise. The feasibility of multiple diversion channel design alternatives were evaluated and preliminary cost estimates generated. The selected alternative was a restored channel along the new alignment which would allow the channel bed armor to re-form without excessive scour, and would rely primarily on the restoration of woody riparian vegetation (primarily willows) in the active floodplain for erosion protection in lieu of riprap. Steeper reaches (typically those in excess of 2%) would use rock vortex weirs and a step pool geometry for control of velocities and erosion. In reaches where the material encountered at the level of the new channel bed was too fine to permit armor formation without excessive scour, the bed was seeded with a coarse graded rock to permit armor formation. Construction costs were more than $250,000 lower than traditional riprap lined channel alternatives. In addition, the channel would be self maintaining and require no further alteration for final reclamation and abandonment, resulting in additional cost savings.

Some of the limitations commonly associated with the application of in regime design and stream restoration on mining projects can include the following:

- Some diversion structures used on mining projects are truly temporary in nature and may be buried and relocated several times over the life of mine. The benefits of revegetation of the channel and restoration of habitat can require 5 years or more to be substantially realized. If the expected life of the diversion structure is less than 5 years, expenditures on revegetation of the channel and habitat restoration may be largely futile.
- In regime design and stream restoration typically requires more space than conventional channel design in order to accommodate the beltwidth necessary for sinuosity and floodplain requirements (particularly for the gently sloped, highly sinuous meandering stream types). Limitations imposed by property boundaries, permit boundaries, or the

location of existing structures and facilities will sometimes preclude the proper implementation of in regime design and stream restoration.

In summary, the use of in regime design and stream restoration principles in channel design for the needs of the mining industry offers many advantages and benefits at little or no increase in cost (and in fact in many cases at reduced cost). Even if circumstances preclude full implementation of in regime design and stream restoration, the use of some of the principles in design can effect some improvements and benefit. For example, elimination of riprap on the inside of meander bends and increased use of vegetation within the channel corridor can reduce riprap costs, improve habitat value, and eliminate a wildlife migration barrier created by a continuous line of large riprap placed on the channel bed and steep channel banks (even though such measures might not begin to approach something which could be considered stream restoration). Where space and circumstances permit, in regime design and stream restoration should be given serious consideration in lieu of conventional hard lined channel designs.

References

Dury, G. H., 1976, *Discharge Prediction, Present and Former, From Channel Dimensions*, A.S.C.E., Journal of Hydrology, No. 30, pg. 219 – 245.
https://doi.org/10.1016/0022-1694(76)90102-5

Gordon, N. D., Thomas, A. M., and Finlayson, B. L., 1992, *Stream Hydrology – An Introduction for Ecologists*, John Wiley & Sons Ltd.

Lane, E. W., 1955, *The Importance of Fluvial Morphology in Hydraulic Engineering*, A.S.C.E., Proceedings, Hydraulics Division, Vol. 18, Paper No. 745, pg. 745-1 – 745-17.

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

Maidment, D. R., 1993, *Handbook of Hydrology*, McGraw-Hill, Inc.

Olsen, R. M., 1966, *Engineering Fluid Mechanics*, International Textbook Company.

Richardson, E. V., Simons, D. B., and Julien, P. Y., 1990, *Highways in the River Environment*, National Highway Institute, Federal Highway Administration, Publication No. FHWA-HI-90-016.

Ritter, D. F., 1986, *Process Geomorphology*, William C. Brown Publishers.

Rosgen, D., 1994, *A Classification of Natural Rivers*, Catena, Vol. 22, No. 3, pg. 169-199.

Rosgen, D., 1996, *Applied River Morphology*, Wildland Hydrology.

Schumm, S. A., 1969, *River Metamorphosis*, A.S.C.E., Journal of the Hydraulics Division, pg. 255 – 273.

Simons, Li & Associates, 1982, *Engineering Analysis of Fluvial Systems*, Simons, Li & Associates, Inc.

Strecker, E. and Forrest, C., 1995, *Urban Watershed Management: Urban Stormwater Best Management Practices*, Seminar Notebook, American Society of Civil Engineers.

Williams, G. P., 1984, *Paleohydrological Methods and Some Examples from Swedish Fluvial Environments II – River Meanders*, Geographiska Annaler, No. 66 A, pg. 89 – 102.

Yang, C. T., 1996, *Sediment Transport – Theory and Practice*, McGraw-Hill, Inc.