Application of Fluvial Geomorphologic Techniques At Abandoned Mine Sites[1]

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ABSTRACT

Watersheds that have been severely impacted by mining can no longer transport their storm flows or sediment. Many streams on mine-scarred lands lose their base flows into the ground where reactions with the abandoned mine workings produce pollution that is discharged into the waterways. To restore the affected watersheds to a functional state we must reclaim the land, collect the storm water, eliminate the infiltration, and reconstruct the streams.

To accommodate for flows generated at a reclamation site, a stable system must be designed to transport the water while preventing erosion and flooding. Traditional stable systems that have been implemented are rectangular or trapezoidal in shape and are constructed of rock and concrete. These systems have proven to be very effective and dependable, but they can also be very expensive and unnatural.

Fluvial geomorphologic techniques may be used in place of the more traditional methods. The basic concept is to use a stable natural channel as a blueprint. This blueprint will include the pattern, dimension, and profile for the stream to transport its watershed's flows and sediment while dissipating energy by controlling the direction of flow using geometry and in-stream structures.

Fluvial geomorphologic techniques have been successfully implemented at sites in the Anthracite Region of Pennsylvania. The constructed streams appear natural and studies have shown stability, water quality improvements, and biological functionality of the constructed waterways. Abandoned mine sites appear to be excellent locations to implement and perfect these techniques. Just as the health of an entire watershed is measured by the condition of its stream in a natural system, the success of a reclamation project might be measured by the resultant stream resource that is created.

[1] Paper presented at the 2001Annual Conference of the National Association of Abandoned Mine Land Programs, August 19-22, 2001, Ohio University, Athens, OH.

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INTRODUCTION

In the Anthracite Region of Pennsylvania, the mining of coal has been conducted since the mid 1800's, first by deep mining and later by surface mining. Many streams that were in the path of these mining operations were relocated numerous times as the mining progressed. When the mining ended, these sites were abandoned, leaving the streams in an unnatural condition that caused aggregation or degradation, flooding and other environmental problems. Some streams were directed into the abandoned strip pits and deep mine workings, adding to the mine pool volume and causing acid/alkaline mine drainage pollution. Other streams have been completely obliterated and encroached upon by development. These are some of the challenges the designers face in reclaiming and restoring streams.

FLUVIAL GEOMORPHOLOGY DESIGN

Using a variety of effective and proven methods, engineers have been solving many of the problems that have been associated with abandoned mine lands. Designs for the backfilling of strip pits, grading of embankments, and the construction of wetlands have used innovative methods to restore these lands and the watershed in whole. The sealing of mine openings, rediversion of channels, construction of engineered channels, and sealing of streambeds above fractured strata have already restored a large volume of fresh water back to our waterways.

However, the design area that has not incorporated the use of many new techniques is channel and ditch design. The lack of a mathematical method to calculate the forces exerted by storm flows throughout the newly constructed channel or ditch, and the lack of science that can predict how the stream will react at a reclamation site cause many engineers to shy away from experimenting with new methods.

To begin to understand what must be accomplished to build a stable and natural channel, you will need to find one and study it. As soon as you begin examining the stream you will notice that concrete and steel were not needed to stabilize it, and the stream is in balance with its watershed. A natural channel is in sharp contrast to a stream that has been ravaged by mining or development. To restore a stream that has been altered, it will be necessary to collect data to design a channel that fits its watershed. Ideally, this data should be collected from a section of channel within the watershed that was never affected or from a stream in a very similar system – this section of channel will be the "blueprint" and is called the *reference reach*. This data will be used to determine the dimension, pattern, and profile of the stream that was preordained in nature for this watershed. Once one knows what nature has intended, one can begin developing a design that is in tune with, and will not be constantly fighting against, the forces of nature.

Thanks to the work of Dave Rosgen, Luna Leopold, and others, the secrets of the river are beginning to be revealed and stable stream restoration projects are being constructed without dependence on rock lining, concrete, or steel. A stable stream has the ability, over time, to transport sediment and flows produced by the stream's watershed in such a manner that the stream's dimension, pattern and profile are maintained without agrading or degrading. "The consistency of dimension, pattern, and profile that exists among rivers is more than chance or spurious correlation. Mathematical relations exist illustrating a stratification of river systems by unique morphological forms, that provide meaning to an otherwise random appearing, complex set of interrelated variables." (Rosgen, 1996)

Fluvial geomorphology has long been studied, but not until recently has the science been applied in such a manner that engineers could begin to use it. The Rosgen Classification System for Natural Rivers was developed for this purpose. (See Table 1.) This classification system allows a designer to determine the range in which a stream's width, depth, sinuosity, entrenchment, slope, and bed will be stable within a particular river valley. Properly applied, this data can be used to design a stable channel that does not depend on hard controls.

The design data must be collected at the reference reach, which has been identified for the restoration site. Cross sections and profiles should be surveyed to prepare for extraction of geomorphological data. At the cross section, one will be able to determine the *bankfull* discharge of the watershed. This stage or elevation is the single most important parameter used in classification, because bankfull is a function of the dimension, pattern, and profile of the stream.

Bankfull discharge is associated with a momentary maximum flow that, on the average, has a recurrence interval of 1.5 years as determined using a flood frequency analysis (Dunne and Leopold, 1978). This interval may vary from 1.4 – 1.6 years for most watersheds to a 1.2 year return for highly developed urban watersheds. A universally accepted definition of bankfull was also provided by Dunne and Leopold in 1978. "The bankfull stage corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphological characteristics of channels."

Determining bankfull can be accomplished by various methods. First, if a reference reach is available, measurements can be taken as described previously. Second, if a USGS gaging station for a similar channel in the watershed or adjoining watershed is found, data from that station can be analyzed to determine bankfull and other parameters to be utilized in the stream design. Last, if a reference reach or gaging station is not available (which more than likely happens in disturbed mining areas), a *regional curve* may be used (See Figure 1 and Figure 2). These curves have been developed for various hydro-physiographic provinces in the United States. The curves compare drainage areas to bankfull width, cross-sectional area and mean depth, as well as flows relative to that storm. Ideally, a regional curve should be developed for each local region to provide a more accurate determination of the characteristics of streams in that region. In Pennsylvania, these curves have begun to be developed. Reclamation of mine sites and the construction of natural stream channels will provide data for future regional curve development.

Once bankfull discharge is known, one can begin to determine the stream type with which one is dealing with by identifying the five (5) primary criteria used for the Rosgen Classification. The five "Rosgen" criteria are the following:

1) **Entrenchment**

   Entrenchment (ER) is generally the ratio of the width of the existing flood prone area (W_{fpa}), divided by the width of the bankfull stage (W_{bkf}),

   $$ER = W_{fpa} / W_{bkf}$$

   where the bankfull width (W_{bkf}) at the bankfull stage elevation and the flood prone area width (W_{fpa}) is the width at twice the maximum depth of the bankfull stage.

   $$W_{fpa} = 2(d_{mbkf})$$

2) **Width/Depth Ratio**

   The width/depth (W/D) ratio is the stream's width at bankfull (W_{bkf}), divided by its mean depth (d_{bkf}).

   $$W/D = W_{bkf} / d_{bkf}$$

   The width/depth ratio will determine the velocity and shear stress distributions within the channel during channel-forming bankfull flows. An improperly dimensioned channel will not be able to transport sediment, and will be susceptible to bank erosion, because the energy is not properly distributed.

3) **Sinuosity**

   Sinuosity (K) is the stream length (SL) divided by the valley length (VL).

   $$K = SL / VL$$

   Sinuosity is the result of the path a stream takes to dissipate energy. In nature, a channel will strive to reach a form where the dissipation of energy is simplest.

4) **Channel Materials**

   The composition of the channel bed and banks influences the stream's sediment transportation capability and its resistance to erosion. The analysis of bed materials is done by a "pebble count", which measures the size of the bed material.

5) **Slope**

The slope of a channel is measured as the difference in water surface elevations along a length of stream. A profile taken along the reference reach will identify the slope. The slope of the channel plays a major role in determining the stream classification.

The results of the field work and calculations will enable values for the five (5) criteria to be determined. Then a stream type can be chosen using the Rosgen Classification of Natural Rivers. (See Table 1.) This will show the range of values for which the criteria could have fallen within the same stream type. Now, knowing the range, the proper channel can be geometrically fit into the project. The criteria are interdependent. A change in sinuosity will affect the slope, which could change the bankfull dimensions, thereby changing the width/depth ratio and the entrenchment. The proper channel type will be stable at the restoration site only within the ranges of the classification criteria; therefore, site specific design decisions will be necessary to prevent any portion of the project from deviating out of range.

After the geometry of the proposed channel is laid out, structures for grade control and bank erosion protection must be designed. Pebble count data in the reference reach riffle area is used, along with bedload data from a *point bar* (a depositional feature on the inside bend of “C” type channel) in the stream, to calculate Manning’s “n”, shear stress, and probable scour depth for the proposed channel.

To calculate Manning’s “n”:

The ratio of bankfull mean water depth (d_{bkf}) (in millimeters) to the bed material size D84 (mm.) is plotted in a table found in The Reference Reach Field Book, to obtain a dimensionless *Fricton Factor* (u/u*) (See Figure 3). This number is plotted on another chart in that book to obtain Manning’s “n” (See Figure 4).

The *Critical Dimensionless Shear Stress* ($\tau_{ci}*$) is calculated by the following formula:

$$\tau_{ci}* = 0.0834(D50/D_{bed}50)^{-0.872}$$

where: D50 = pebble count data (mm.)
$D_{bed}50$ = sub surface (bar sample) data (mm.)

This number is used to calculate the maximum scour depth (d) in the pools by the following formula:

$$d = (\tau_{ci} * 1.65\ D_i) / S$$

where: D_i = size of largest particle in bar sample (ft.)
S = bankfull water surface slope (ft./ft.)

The results of these calculations can be used to size rock for the structures. If a reference reach is not found, large size rocks measuring approximately 3’ x 3’ x 3’ may be used for the structures with confidence that it will not be moved during large storm events.

Structure type, alignment and construction details can be found in Applied River Morphology.

LITERATURE CITED

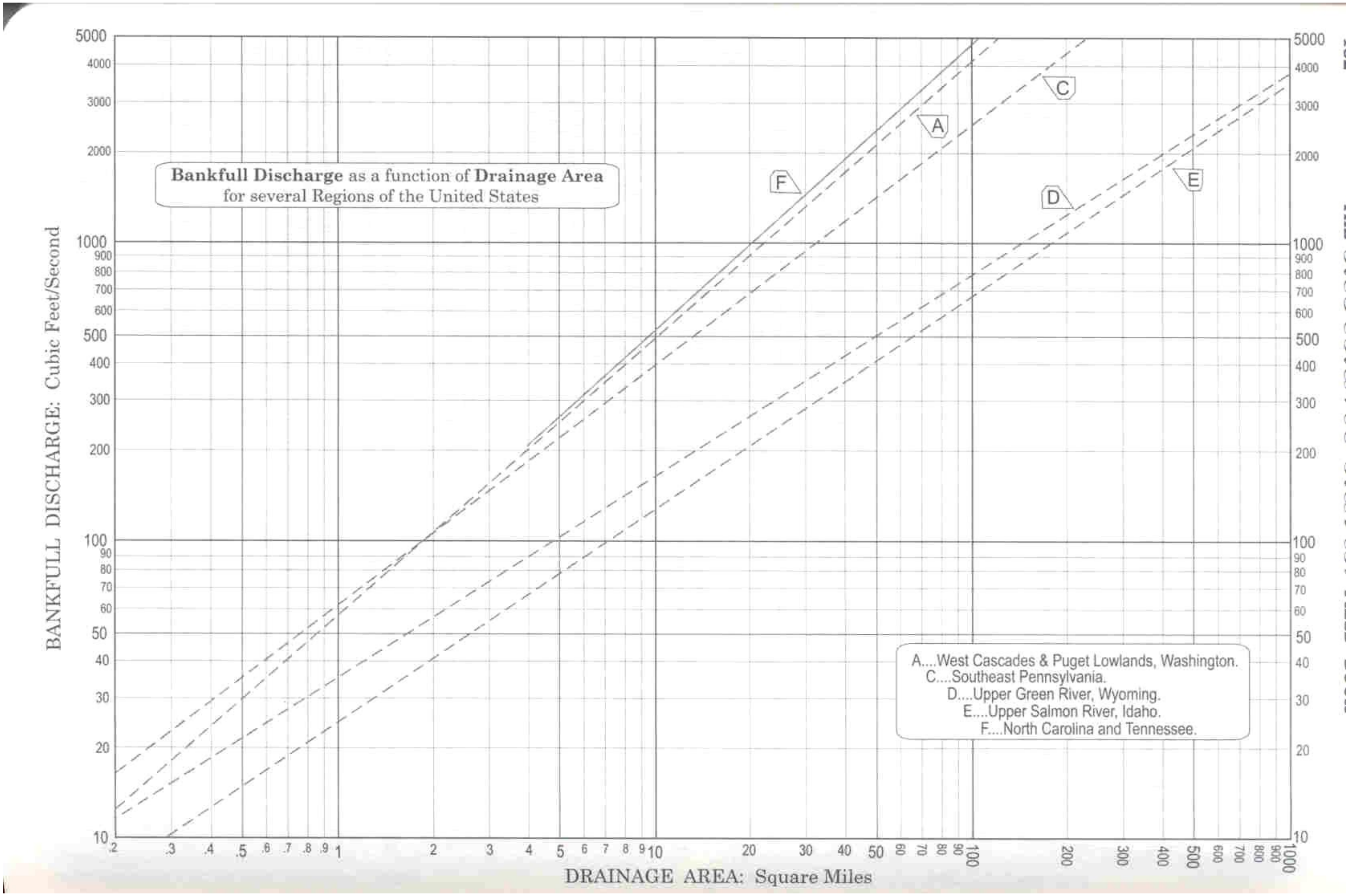
Rosgen, D. L. (1996): Applied River Morphology. Printer Media Companies, Minneapolis, Minnesota: 336 pp

Rosgen, D. L. (1998): The Reference Reach Field Book, Wildland Hydrology, Pagosa Springs, Colorado: 210 pp

	Single-Thread Channels														Multiple Channels			
Entrenchment Ratio	Entrenched (Ratio: <1.4)						Moderately Entrenched (1.4-2.2)			Slightly Entrenched (> 2.2)								
Width/Depth Ratio	LOW Width/Depth Ratio (< 12)				Moderate to HIGH W/D (> 12)		MODERATE Width/Depth Ratio (> 12)			VERY LOW Width/Depth (< 12)		Moderate to HIGH Width/Depth (> 12)			Very HIGH Width/Depth (> 40)			LOW W/D (< 40)
Sinuosity	LOW Sinuosity (< 1.2)		MODERATE Sinuosity (> 1.2)		MODERATE Sinuosity (> 1.2)		MODERATE Sinuosity (> 1.2)			VERY HIGH Sinuosity (> 1.5)		HIGH Sinuosity (> 1.2)			LOW Sinuosity (< 1.2)			Low-Hi Sinuosity (1.2-1.5)
Stream Type	**A**		**G**		**F**		**B**			**E**		**C**			**D**			**Da**
Slope	Slope Range		Slope Range		Slope Range		Slope Range			Slope Range		Slope Range			Slope Range			Slope
	> 0.10	0.04-0.099	0.02-0.039	< 0.02	0.02-0.039	< 0.02	0.04-0.099	0.02-0.039	< 0.02	0.02-0.039	< 0.02	0.02-0.039	0.001-0.020	< 0.001	0.02-0.039	0.001-0.020	< 0.001	< 0.005
CHANNEL MATERIAL																		
Bedrock	A1a+	A1	G1	G1c	F1b	F1	B1a	B1	B1c			C1b	C1	C1c-				
Boulders	A2a+	A2	G2	G2c	F2b	F2	B2a	B2	B2c			C2b	C2	C2c-				
Cobble	A3a+	A3	G3	G3c	F3b	F3	B3a	B3	B3c	E3b	E3	C3b	C3	C3c-	D3b	D3		
Gravel	A4a+	A4	G4	G4c	F4b	F4	B4a	B4	B4c	E4b	E4	C4b	C4	C4c-	D4b	D4	D4c-	DA4
Sand	A5a+	A5	G5	G5c	F5b	F5	B5a	B5	B5c	E5b	E5	C5b	C5	C5c-	D5b	D5	D5c-	DA5
Silt/Clay	A6a+	A6	G6	G6c	F6b	F6	B6a	B6	B6c	E6b	E6	C6b	C6	C6c-	D6b	D6	D6c-	DA6

Key to the ROSGEN Classification of Natural Rivers. As a function of the “continuum of physical variables” within stream reaches, values of **Entrenchment** and **Sinuosity** ratios can vary by +/- 0.2 units; while values for **Width/Depth** ratios can vary by +/- 2.0 units. [This table is from “Applied River Morphology” (Rosgen, 1996).]

Table 1


Bankfull Discharge as a function of Drainage Area
for several Regions of the United States
BANKFULL DISCHARGE: Cubic Feet/Second
DRAINAGE AREA: Square Miles
A....West Cascades & Puget Lowlands, Washington.
C....Southeast Pennsylvania.
D....Upper Green River, Wyoming.
E....Upper Salmon River, Idaho.
F....North Carolina and Tennessee.
A
C
D
E
F
5000
4000
3000
2000
1000
500
400
300
200
100
50
40
30
20
10
.2
.3
.4
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1
2
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100
200
300
400
500
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Table 1

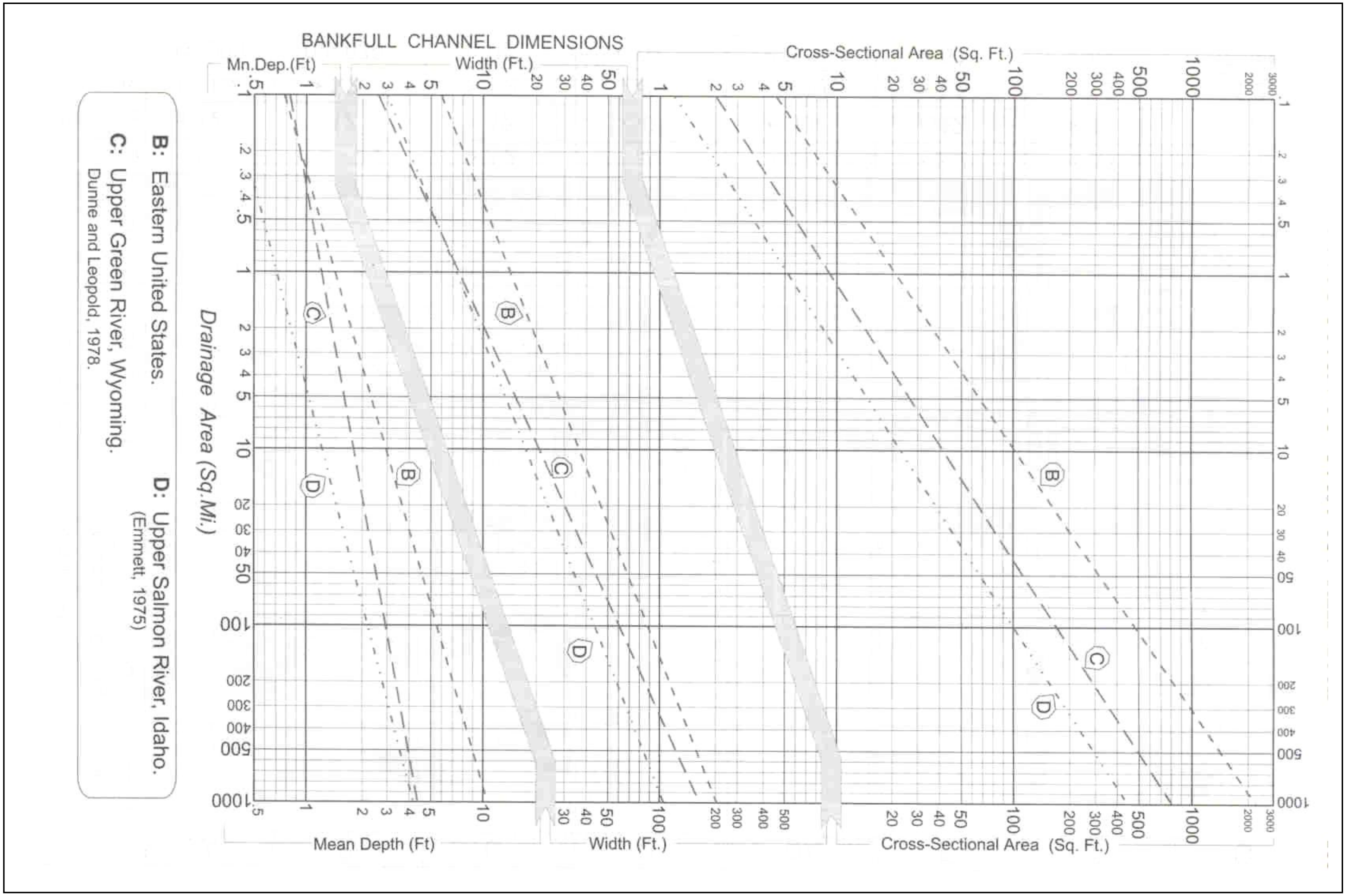
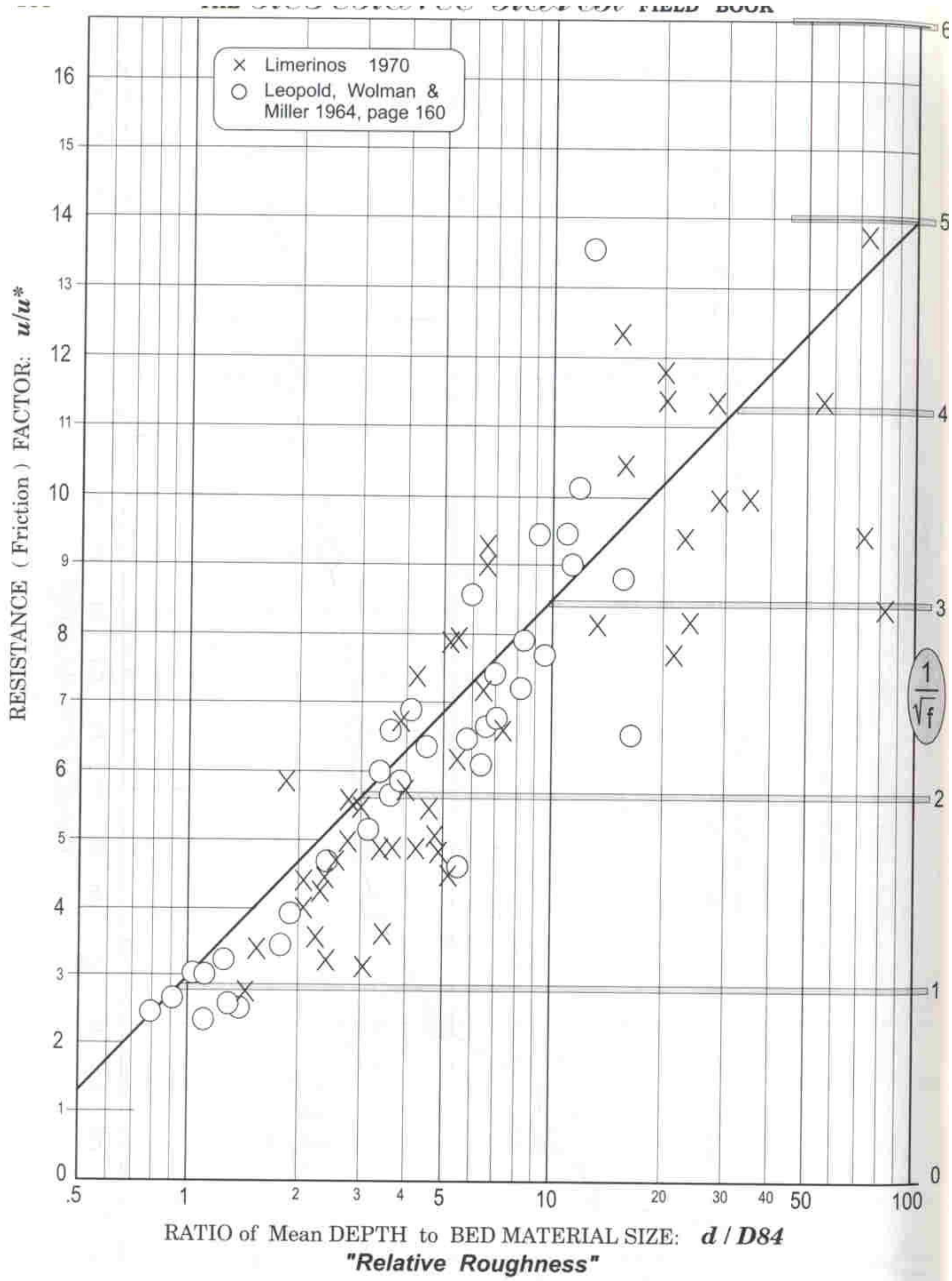

BANKFULL CHANNEL DIMENSIONS
Mn.Dep.(Ft)
Width (Ft.)
Cross-Sectional Area (Sq. Ft.)
Drainage Area (Sq.Mi.)
Mean Depth (Ft)
Width (Ft.)
Cross-Sectional Area (Sq. Ft.)
B
C
D
B: Eastern United States.
C: Upper Green River, Wyoming.
Dunne and Leopold, 1978.
D: Upper Salmon River, Idaho.
(Emmett, 1975)

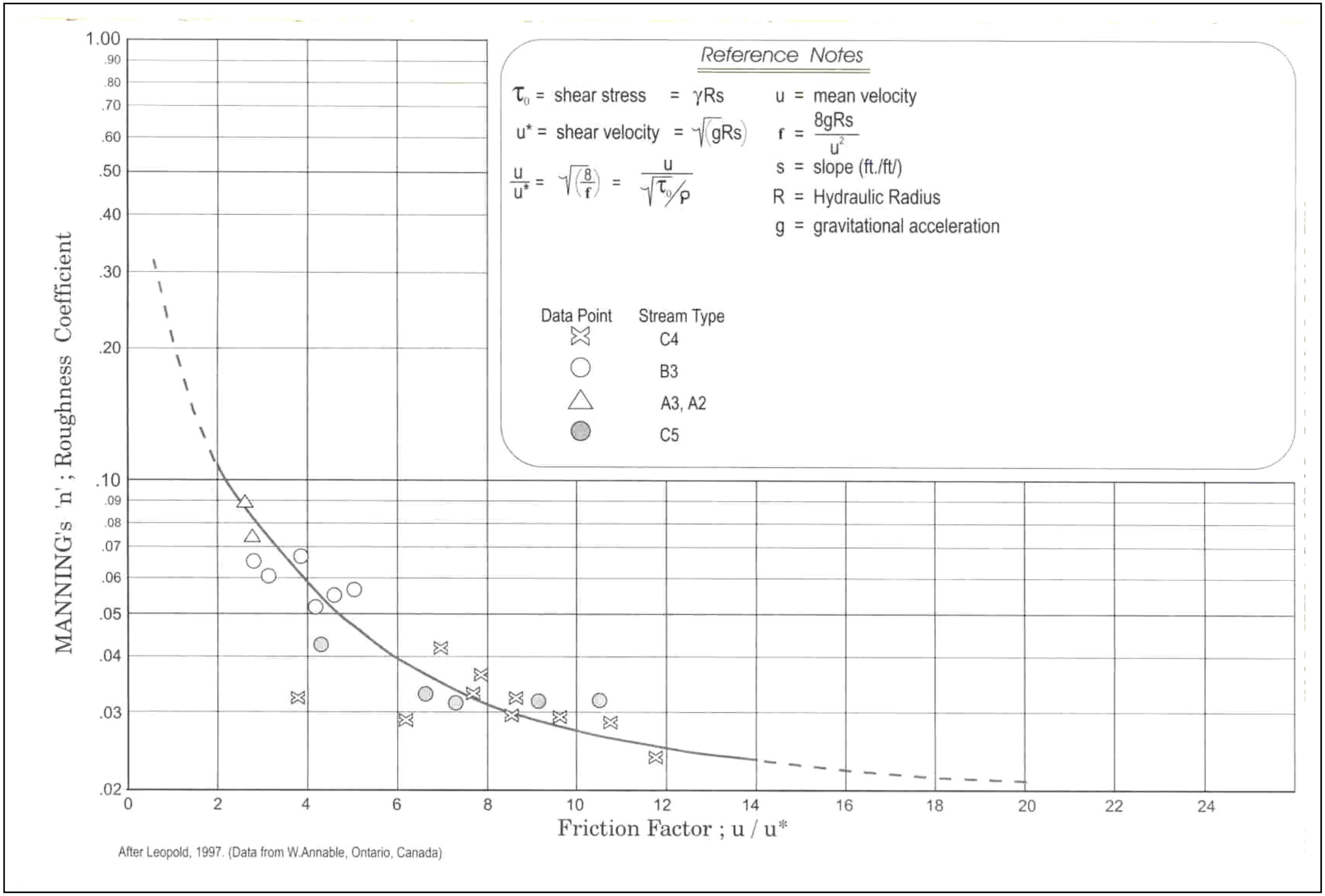
Table 1



The relation of channel bed-particle size to hydraulic resistance, with river data from a variety of eastern and western streams.

Resistance Factors, **u/u*** and **1** / $\sqrt{f}$ are shown as a function **Relative Roughness**, i.e., a Ratio of mean water depth (**d**) to a bed material size index (**D84**) taken from field measurements.

Table 1



After Leopold, 1997. (Data from W.Annable, Ontario, Canada)

Table 1