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Geomorphic Metrics Used in FluvialGeomorph

by Christopher Haring and Michael Dougherty

PURPOSE: FluvialGeomorph (FG) is a geographic information system-based geomorphic analysis toolkit that analyzes high-resolution terrain data to provide river-reach assessments for watershed studies. This report demonstrates the utility of FG to identify physical stream channel characteristics that are used to determine channel stability. The FG toolbox is a remote-sensing approach based on lidar data, designed to measure channel, floodplain, valley, and watershed metrics necessary for watershed assessments. Currently, channel slope and cross-sectional analysis and planform metrics are being evaluated with existing lidar data from different hydrophysiographic regions within the United States. Recent study areas include the Northwest, Southwest, South, Midwest, and upper Midwest of the United States.

INTRODUCTION: In 2004, Alan Gulso with the Illinois Department of Agriculture as part of the Streambank Stabilization and Restoration Program, reported that streambank erosion generated between 30% to 55% of the suspended sediment loads in Illinois streams.[*] Similar numbers were reported by Schilling et al. (2011) for the Walnut Creek Watershed in south-central Iowa with 30% to 64% of the annual sediment load contributed from eroding streambanks. The Delta Headwaters Program used the addition of grade-control structures to stabilize stream bed and banks and quantitatively reduce sediment delivery downstream by an average of 62%.[†]

FLUVIALGEOMORPH (FG) TOOLKIT BACKGROUND: The FG toolbox was developed through the Ecosystem Management and Restoration Research Program and Flood and Coastal Systems (FCS) Program to provide a rapid approach to detect riverine erosion and sedimentation and identify source locations within the of watershed. The rapid assessment approach was developed to quantify the benefits of streambank stabilization in Illinois River tributaries to protect mainstem floodplain habitats impacted by excessive sedimentation. The FG toolbox measures channel morphological features using lidar high-resolution digital elevation models (DEMs). The channel features include water-surface profile (channel bottom in ephemeral or in low-flow conditions), dimension (cross section), and pattern. The water-surface profile is used to identify nick points or areas along the profile that show extreme change in channel slopes. The cross sections are used to determine local channel geomorphology, bank erosion rates, and changes in channel location. Cross-section analysis is further expanded to include channel dimensions based on bankfull channel forming identification. The bankfull identification allows for the comparison of empirically derived relationships to be compared to actual lidar DEM-derived channel dimensions at each cross-section location. Channel stability assessments can then be compared to

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[*] A. Gulso, pers. comm.

[†] Biedenharn, D. S., and C. C. Watson. 2012 (unpublished). *Delta Headwaters Project: A Review.* Report to the Vicksburg District, US Army Corps of Engineers.

empirical data to determine channel stability. Channel stability values can then be mapped spatially based on each metric. In addition, channel pattern is derived from the channel-terrain data to assess stable planform conditions. Individual reach analysis is then combined and integrated to provide a comprehensive channel stability assessment to support watershed planning efforts. Haring et al. (2020) describes the background needs and requirements for US Army Corps of Engineers (USACE) watershed studies.

FG WORKFLOWS: Watershed studies provide a comprehensive approach to identifying and treating areas of concern. Such studies typically involve flood-risk management issues, critical habitat protection or enhancement opportunities, water-quality issues, excessive sediment delivery from erosion of streambanks, gullies and concentrated overland flow areas, land-use change, and protection for critical public infrastructure. The FG toolkit provides a five-step approach to investigate watersheds (Figure 1). The five steps include defining the purpose of the study, determining the extent of the study area, researching and collecting available data, completing a rapid geomorphic assessment, and defining further studies as required.

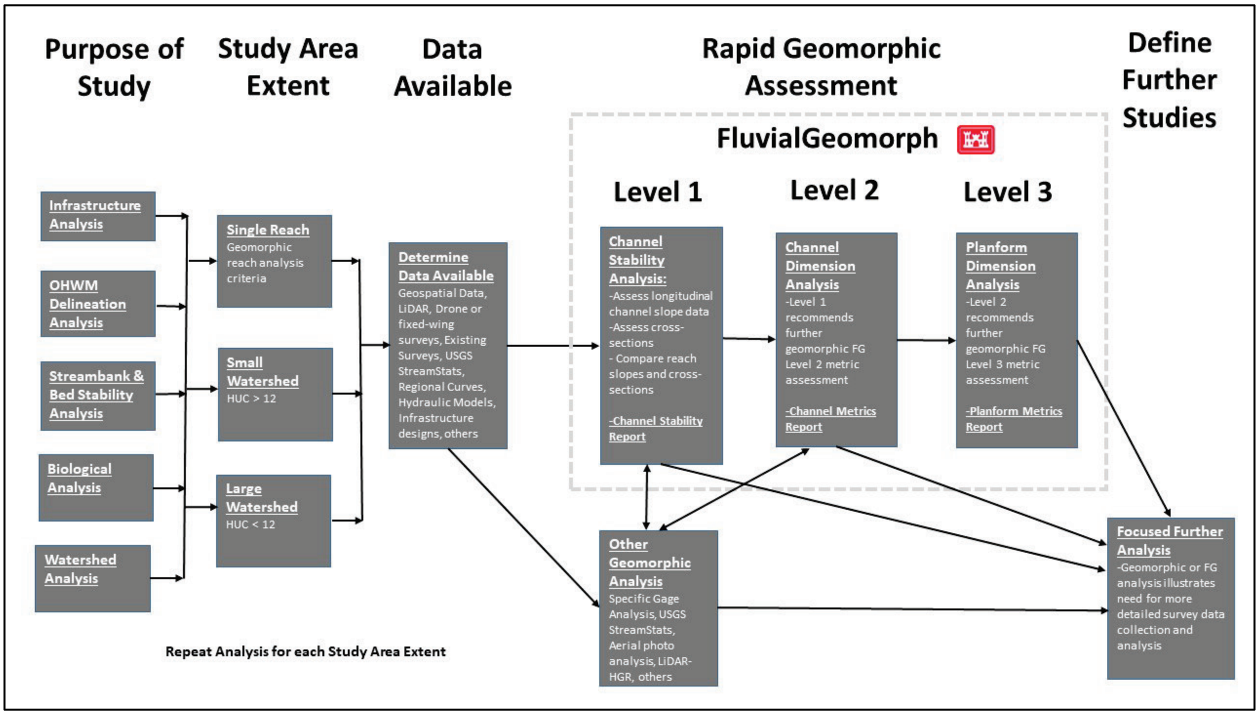

Figure 1. FluvialGeomorph (FG) rapid geomorphic assessment approach.

FG LEVEL I: Channel Stability Analysis (CSA): Channel Stability Analysis (CSA) analyzes the longitudinal water-surface slope profiles and cross sections. The CSA workflow is illustrated in Figure 2. Such an analysis provides a reconnaissance level of detail to identify potential areas of instability based on simple slope and cross-sectional area comparative analysis. The CSA provides a basis for identifying potential areas of interest where channel degradation, aggradation, or widespread channel changes are observed to determine if more detailed study is required (Haring and Biedenharn 2021). The CSA should be completed prior to field site visits to allow for the focus on areas of concern based on existing information.

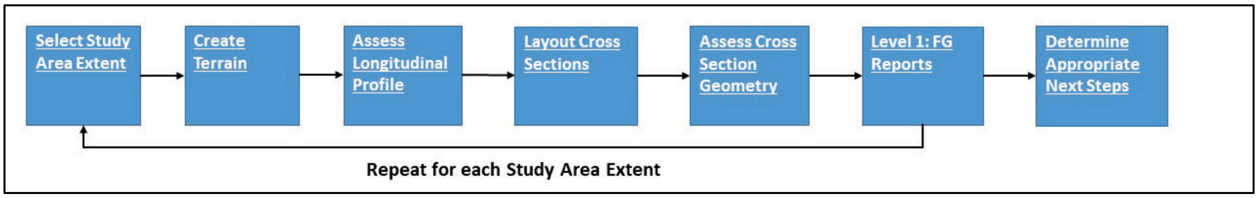

Figure 2. FG Level 1: channel stability analysis.

SLOPE RATIO (S): The slope or longitudinal profile includes water surface, floodplain, valley slope, and the vertical variability of these features. Slope is one of the most critical channel assessment components for geomorphic analysis because it defines the direct link to energy, typically called *energy slope*. Variability of the longitudinal profile provides energy dissipation, hydraulic diversity, and thus habitat diversity and maintenance. Types of variability include pools, riffles, steps, glides, runs, cascades, engineered structures. Slope can be derived from hydraulic model analysis, historic surveys, reference reaches, regional curves, and lidar (water-surface, channel-bottom bathymetric). Slope measurements should be taken through a channel reach that is a minimum of 20 channel widths in length or for a distance equal to two meander wavelengths (Harrelson et al. 1994; Rosgen 1996). When completing local channel-slope surveys, they should be measured by taking the difference in elevation from the one bed feature to the same bed feature either upstream or downstream (Harrelson et al. 1994; Rosgen 1999) In general, a longitudinal profile that shows a characteristic concave shape with slope decreasing from the upper reaches (eroding) to the lower depostional reaches is associated with an increase in discharge and a decrease in sediment size in the downvalley direction (Schumm 1977; Gordan et al. 1994). In high rainfall watersheds, concave shapes are more pronouonced whereas in watersheds that are primarily fed from only upstream inputs may not have a direct concave profile. A convex channel slope likely provides an indication of excessive sedimentation or the presence of resistive materials in the channel bend.

When available, plotting multiple lidar water-surface profiles can be diagnostic for locating oversteepened channel slope sections as possible nick points as illustrated in Figure 3 at approximate station 3700 ft.[*] In this case, there is a large grade-control structure located below a railroad crossing stabilizing the upstream section of this reach.

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[*] For a full list of the spelled-out forms of the units of measure and unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248–252 and 345–347, respectively. *https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf*.

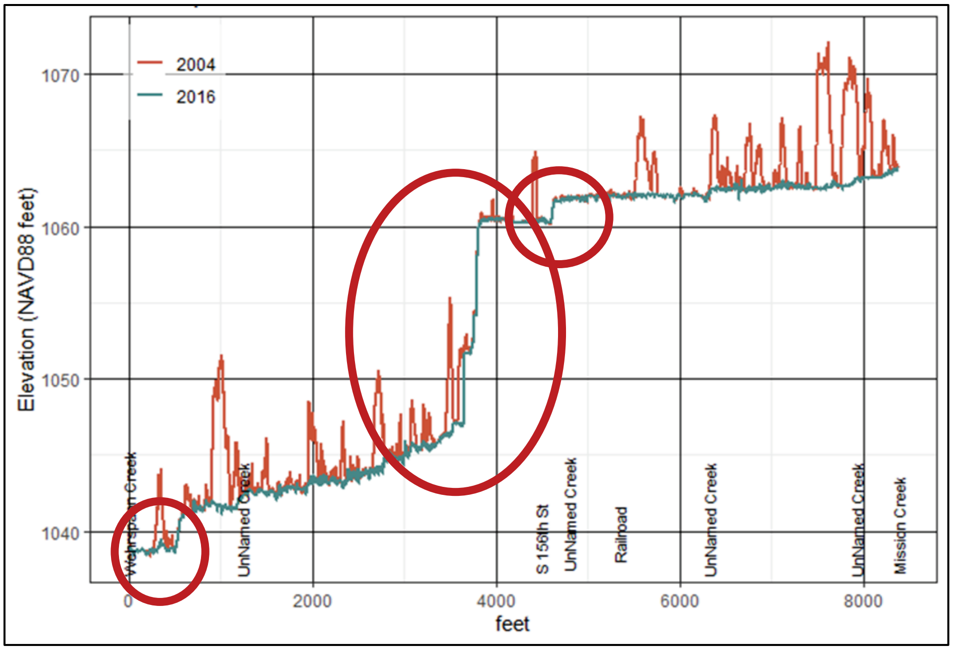


Figure 3. FG Level 1: channel stability analysis (CSA): plot of lidar water-surface profiles illustrating locations of grade-control structures (South Papillion Creek, Omaha, Nebraska).

There may be another grade-control structure downstream at approximately 500 ft and one upstream at station 4,300 ft (S. 150th Street). These would be locations that would be good to identify for field verification. In additon, comparing reach slopes can provide insight into eroding, depositional, or transport channel locations.

Cross-section relationships are also analyzed during the CSA. Cross sections can show areas of channel degradation, agradation, migration (Figure 4), and areas of erosion (Figure 5). Locating the potential physical channel processes provides a well-rounded approach to identifing areas for field validation and also focused stabilization and restoration projects.

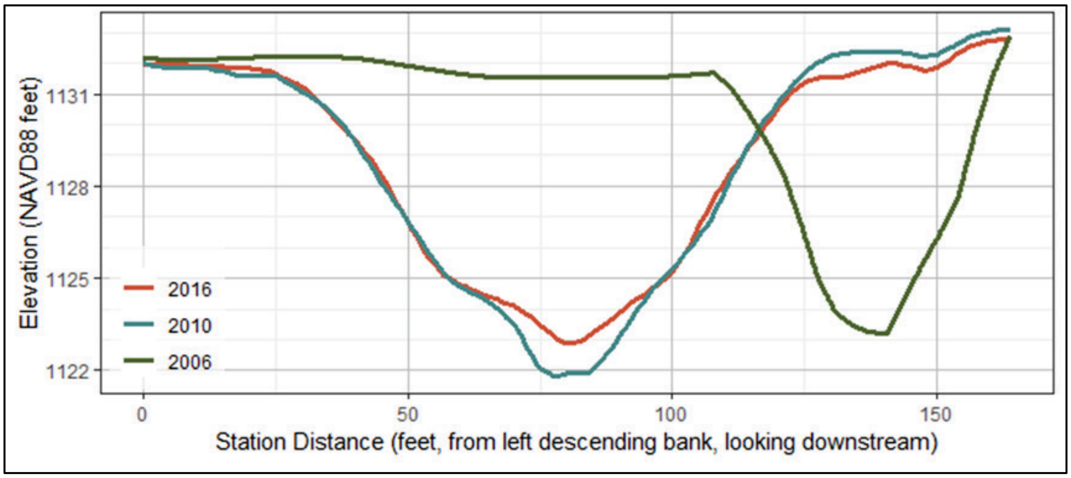


Figure 4. FG Level 1: CSA: plot of lidar cross sections illustrating a location where the channel was moved during a restoration project (Cole Creek, Omaha, Nebraska).

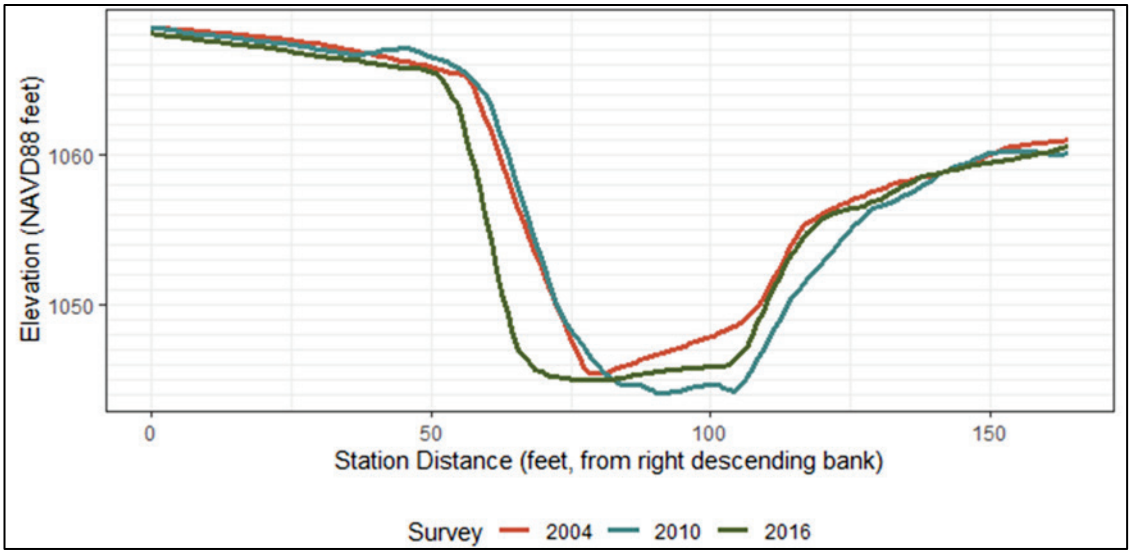


Figure 5. FG Level 1–CSA: plot of lidar cross sections illustrating left-bank erosion (Cole Creek, Omaha, Nebraska).

FG LEVEL II: CHANNEL DIMENSION ANALYSIS (CDA): Channel dimension analysis (CDA) analyzes bankfull channel conditions based on lidar-derived DEMs to compare against empirically based data to assess channel stability (Figure 6). The final products of the CDA are reach-level reports that plot and map the metrics at a stream channel reach scale. The metrics are compared based on standard existing or user-defined thresholds. The metrics are mapped by color-coded signals.

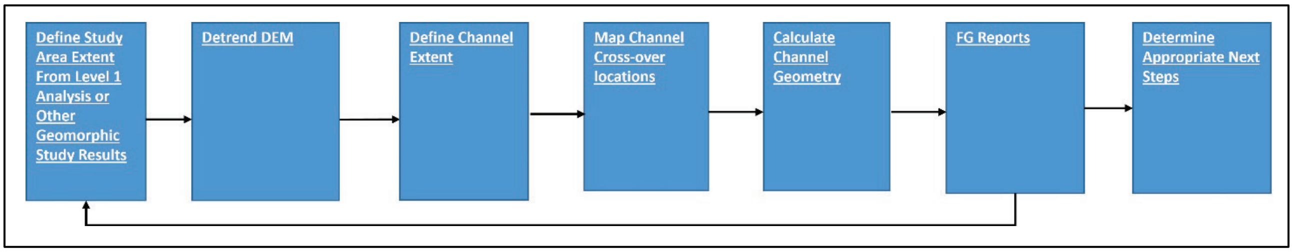


Figure 6. FG Level 2: channel dimension analysis.

In fluvial settings, common measurement is required to *capture* channel morphological characteristics. Key channel morphology includes channel width, depth, cross-sectional area, slope, sediment type/size, and planform relationships. To assess the channel morphology, empirical relationships have been developed through years of research and data gathering (Leopold et al. 1964 Dunne and Leopold 1978; Rosgen 1996; Knighton 1998). Standard fluvial geomorphic procedures for collecting channel morphology include analysis based on assessing two basic geomorphic units of measurement: the channel forming discharge (bankfull stage) and the channel reach length (Harrelson et al. 1994). Harrelson et al. (1994) recommends measuring bankfull conditions at cross sections located in stable reaches between channel bends where the riffle cross-over locations are located (Figure 7). Riffle cross-over locations are areas where the channel typically has the best geomorphic signature for capturing the bankfull stage (Rosgen 1996). The bankfull stage may vary widely depending on what literature source used. For example, Williams (1984) found that the bankfull discharge for the rivers studied had a range of 1 to 30 yr recurrence interval. Rosgen (1996) found that the typical bankfull discharge ranged from 1 to 2 yr for the rivers in his studies. The main point of this discussion is to acknowledge there is much variability in determining the bankfull discharge based on which research base is referenced. There are likely differences in the local and regional conditions in which the data analyzed from study comparisons that need to be considered when determining bankfull discharge.

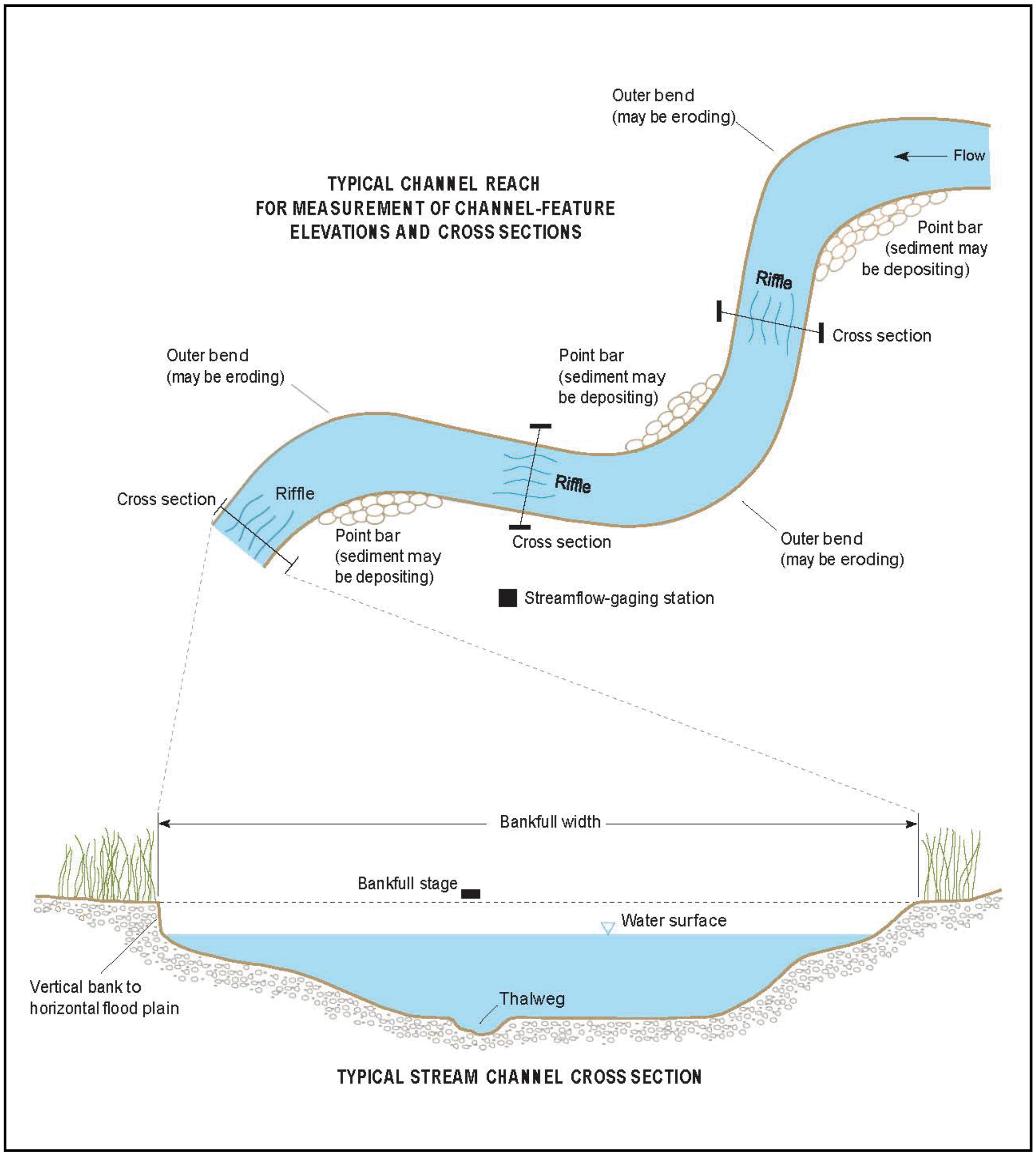


Figure 7. Typical stream reach and cross-section locations for channel features with bankfull stage identified. (Image reproduced from Lawlor 2004. Public domain.)

The minimum recommended unit of geomorphic channel-reach analysis consists of two meander bends as defined in Figure 7. The geomorphic channel reach has been defined by Leopold (1994), Harrelson et al. (1994), Rosgen (1994), and the Federal Interagency Stream Restoration Working Group (FISRWG 1998) as the stream length equal to at least 20 to 30 times the bankfull width. The definition makes it very important to understand the bankfull channel conditions or further define the study conditions if bankfull cannot be identified. Additional descriptions for determining bankfull channel conditions and options for channel reach analysis are described in the channel assessment tools for rapid watershed assessments (Haring and Biedenharn 2021).

Channel-dimension metrics are based on the ability to determine a bankfull elevation for FG to use to plot at chosen cross sections within the reach. Bankfull elevations can be used in FG in a variety of ways. For example, the bankfull elevation can be picked by assessing the Level 1 cross sections for the presence of bankfull berms or floodplain connections along the reach (Figure 8). They can also be calibrated from a local gage and extrapolated for the reach through the development of regional curves (Haring et al. 2019). Depth grids from hydraulic models are also an appropriate method for using in FG for assessing bankfull conditions (Haring et al. 2020. A final option is to use local geomorphic surveys or field site visits to establish bankfull conditions.

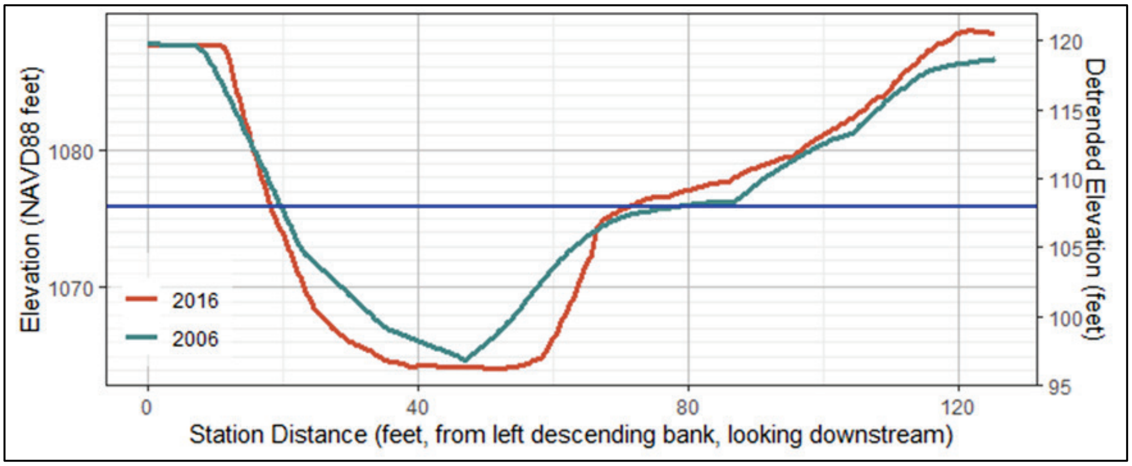
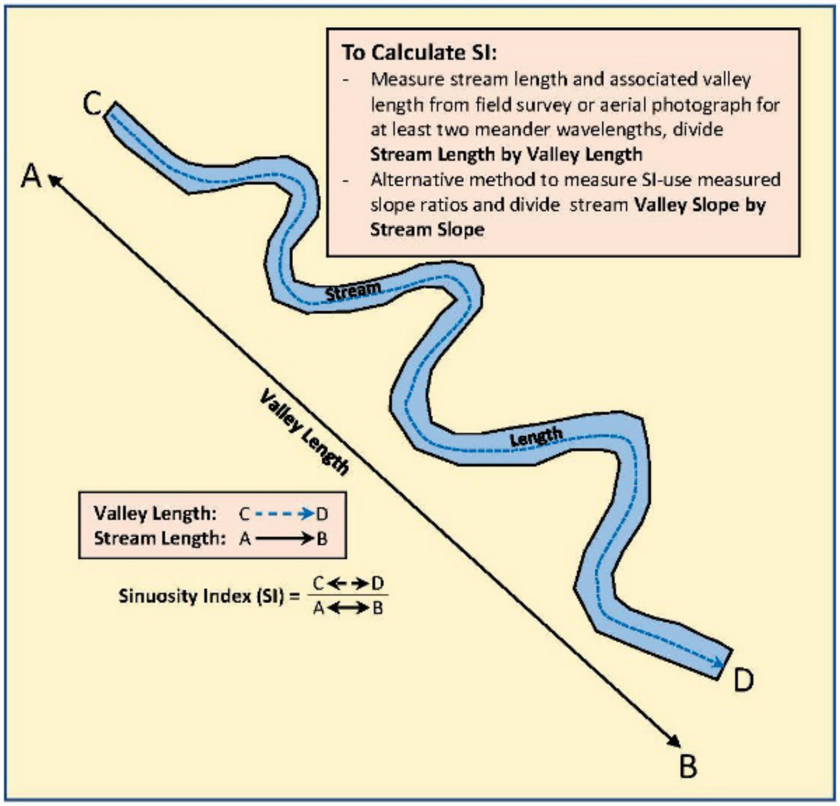


Figure 8. FG Level 2 plot of bankfull elevation illustrating floodplain berm connection on South Papillion Creek, Omaha, Nebraska.

Once bankfull conditions are estimated, channel dimensions are derived from the lidar DEM based on measuring width, depth, and slope. The channel dimension metrics are then developed for width-to-depth, entrenchment ratios, slope, sinuosity, shear stress, and stream power. In general, for CDA, width is the most consistent parameter in streams from hydraulic geometry relationships, and depth is critical for sediment transport. Depth should be analyzed for pools and riffles to ensure that sediment transport through the pools and deposition of the larger bed-load materials occur at the riffle locations. When using lidar DEM data, lack of water depth can be an issue for calculating some depth-dependent metrics. However, this can be relatively minimal in streams that have riffle crossover locations with little or no water depth. The riffle cross-over location is where Harrelson et al. (1994) and Rosgen (1996) recommend collecting bankfull channel conditions. Also note that for ephemeral streams and smaller stream systems in which lidar was flown during low-water conditions, determination of water depth is not an issue as there is little to no water in the channel. When possible, field validation is highly recommended for all data input for FG analysis.

SINUOSITY INDEX (SI): SI is a measure of the winding and curving nature of a stream channel and is defined as the channel (thalweg) length divided by the valley length for that stream length (Figure 9). Sinuosity is highly dependent on channel boundary conditions with influences from bedrock control, channel confinement, cohesive materials, non-cohesive materials, infrastructure, vegetation, and others. The SI tends to increase in a downstream direction as lower channel gradients and decreasing sediment sizes are typically encountered. The SI is measured for a channel distance of at least 20 to 30 bankfull widths (Harrelson et al. 1994). An SI of 1.0 is a straight channel. An SI of less than 1.2 is considered low sinuosity; 1.2–1.5, moderate; and greater than 1.5, high (Rosgen 1996). There are differing sinuosity indexes that can be used to classify a stream reach developed by Schumm (1977), Brice (1982), Selby (1985), and others. Sinuosity along with other metrics such as width-to-depth ratio (W/D) and entrenchment ratio (ER) are diagnostic for identifying areas of potential channel instability.



To Calculate SI:

- Measure stream length and associated valley length from field survey or aerial photograph for at least two meander wavelengths, divide **Stream Length by Valley Length**
- Alternative method to measure SI-use measured slope ratios and divide stream **Valley Slope by Stream Slope**

Figure 9. Calculation of sinuosity (adapted from Rosgen 1996).

ENTRENCHMENT RATIO (ER): The term *entrenchment ratio,* which is the vertical containment of the river, has been quantitatively defined (Rosgen 1996 to provide a consistent method for field determination. Rosgen (1996) further describe the ER as “the ratio of the width of the flood-prone area to the surface width of the bankfull channel. The flood-prone area width is measured at the elevation that corresponds to twice the maximum depth of the bankfull channel as taken from the established bankfull stage (Rosgen 1996). In general terms, ratios of 1–1.4 represent entrenched streams; 1.41–2.2 represent moderately entrenched streams; and ratios greater than 2.2 indicate rivers only slightly entrenched in a well-developed floodplain (Rosgen 1996).

Incised alluvial channels tend to erode laterally until they rebuild a floodplain and the ER reaches 2.5 to 3 times bankfull width (Rosgen 1994). Therefore, at 2 times the maximum bankfull depth, the water surface width should be at least 2.5 to 3 times the water-surface width at bankfull stage, for general stability. These value ranges are not applicable to threshold channel systems.

WIDTH-TO-DEPTH RATIO (W/D): W/D is a ratio that refers to the geometric shape of the channel cross section based on bankfull width (feet) and mean depth (feet). The W/D ratio is the most-used index in channel shape. However, some consider W/D not appropriate for measuring channel shape because it does not provide indications of cross-sectional asymmetry linked to meander planform (Knighton 1998). General W/D ratio applications are bulleted below:

- Typically applied and discussed in relation to bankfull discharge but has been equated to other discharge ranges as well
- Generally, increase the downstream direction but are highly dependent on the composition of the streambanks
- Can respond rapidly to changes in sediment load and discharge, affected by bed and bank shear stress
- Bank vegetation increases resistance to erosion effects, generally increasing W/D with erosion decreasing as the percent of roots in the soil increases (Fischenich 2003).
- Newbury and Gaboury (1988) from work on Mink Creek (cobble/gravel bed stream) suggest that natural channel cross sections tended to be wider and shallower with a W/D ratio of 15:1.
- Schumm (1960) related W/D ratios to the weighted mean percentage of silt-clay in the channel boundary (Figure 10). Relationship based on data from Great Plains (USA) and the Riverine Plains in New South Wales, Australia.
- Rosgen (1994) incorporated the W/D ratio into the stream classification system as one of the five stream characteristics for determining channel type.

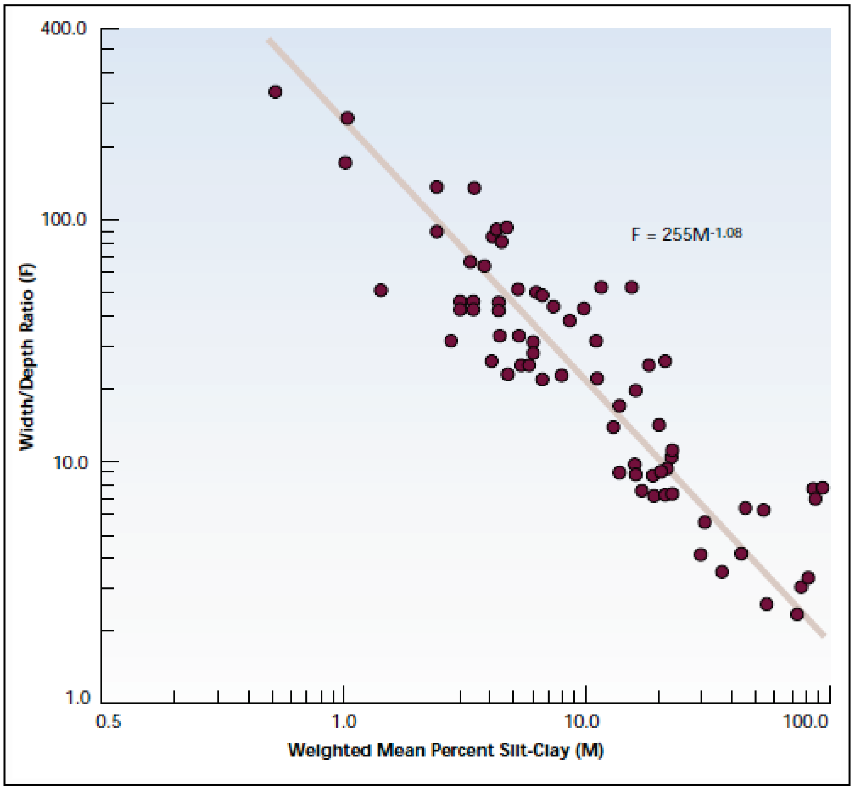


Figure 10. Schumm's (1960) width/depth ratio (W/D) (*F*) versus weighted mean percent silt-clay (*M*). (Image reproduced from FISRWG 1998. Public domain.)

Additional W/D rules were developed to provide general threshold rules for alluvial streams (Dunne and Leopold 1978; FISRWG 1998):

- If W/D ratio is less than 10, suspect *downcutting* degradation channel regime in combination with a sinuosity less than 1.8 and the ER is less than 1.4.
- If W/D ratio is over 20, then suspect an *overwidening* aggradational channel reach and possible sediment transport issues in combination with high sinuosity and ER with low stream-power values.
- For FG analysis in Figure 10, *F* is based on <10 incised, 10–20 stable, and >20 over widened. This specified range for *F* is based on alluvial systems but can be adjusted dependent on hydrophysiographic region being studied (Figure 11).

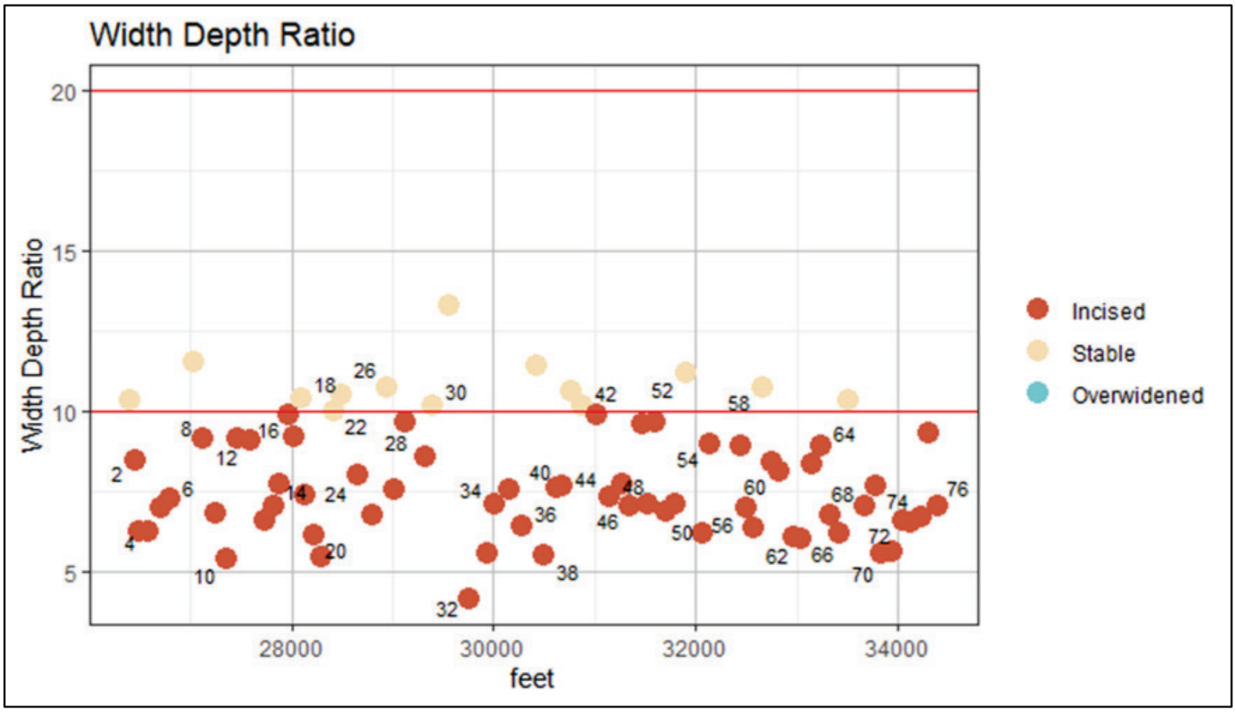


Figure 11. FG Level 2 plot of W/D reach four metrics on South Papillion Creek, Omaha, Nebraska.

STREAM POWER (SP): Stream power (SP) is the rate of energy dissipation against the bed and banks of a stream channel. SP is a useful index in describing erosion capacity of streams, development of channel profile and pattern, and sediment transport. The SP used for this analysis is based on the amount of work done per unit of time. The density of water and acceleration due to gravity are assumed constant while discharge and slope are adjusted per cross section.

UNIT STREAM POWER (USP): The unit stream power (USP) is the rate of energy dissipation per unit width of stream (kilogram per meter per second). The USP is a useful index in describing erosion capacity of streams, development of channel profiles and patterns, and sediment transport. There is a wide range of usage and definitions for USP for geomorphic analysis (Rhoads 1987) with relative values less important than the actual influence the method has on shaping the channel and sediments. The USP used for this analysis is based on the amount of work done per unit of time per length of stream. The density of water and acceleration due to gravity are assumed constant while discharge, slope, and stream width are adjusted per cross section.

SHEAR STRESS (*t*): Shear stress is a measure of force per unit area (pounds per square foot). Shear stress is the shearing force divided by the area over which it interacts. For wide rectangular channels, the mean depth can be substituted for the hydraulic radius. Shields (1936) developed a relation between the shear stress required to initiate particle movement, which was expanded upon by Lane (1955), Leopold et al. (1964), and Rosgen and Silvey (2005). By plotting values, critical shear stress comparisons can be made on the size of materials mobilized during the bankfull discharge event. This analysis provides a basic understanding of potential sediment sizes in transport through reaches and the system (Rosgen 2006).

FG Level III-Planform Dimension Analysis (PDA). PDA analyzes planform dimensions measured from the lidar-derived DEM to compare against empirically based data to further assess channel stability (Figure 12). The final products of the PDA are reach-level reports that plot and map the metrics at a stream channel reach scale. The metrics are compared based on standard existing or user-defined thresholds. The metrics are mapped by color-coded signals.

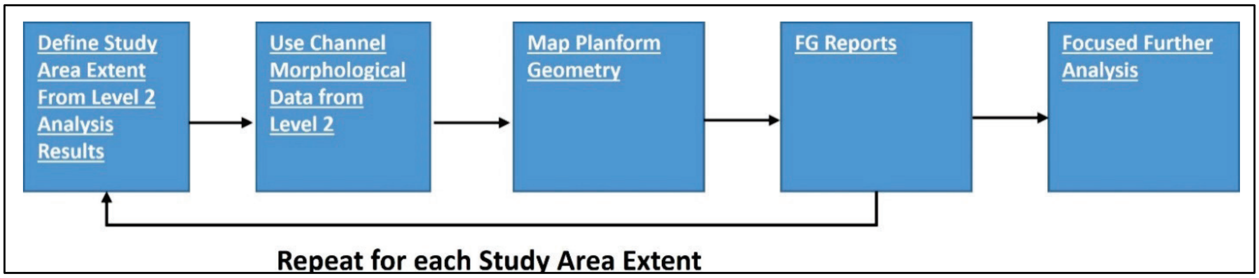


Figure 12. FG Level 3: planform dimension analysis.

Channel Pattern Geometry. Channel planform metrics measure the variability in the stream channel pattern that provide insight into morphologic interpretation. The pattern is evident in the way the stream channel moves back and forth across a floodplain and develops physical attributes associated with the patterns. The patterns are measured and combined with channel metrics to derive diagnostic geomorphic assessments of reaches and site-specific areas of concern. Figure 13 illustrates the common planform characteristics that are derived from this analysis.

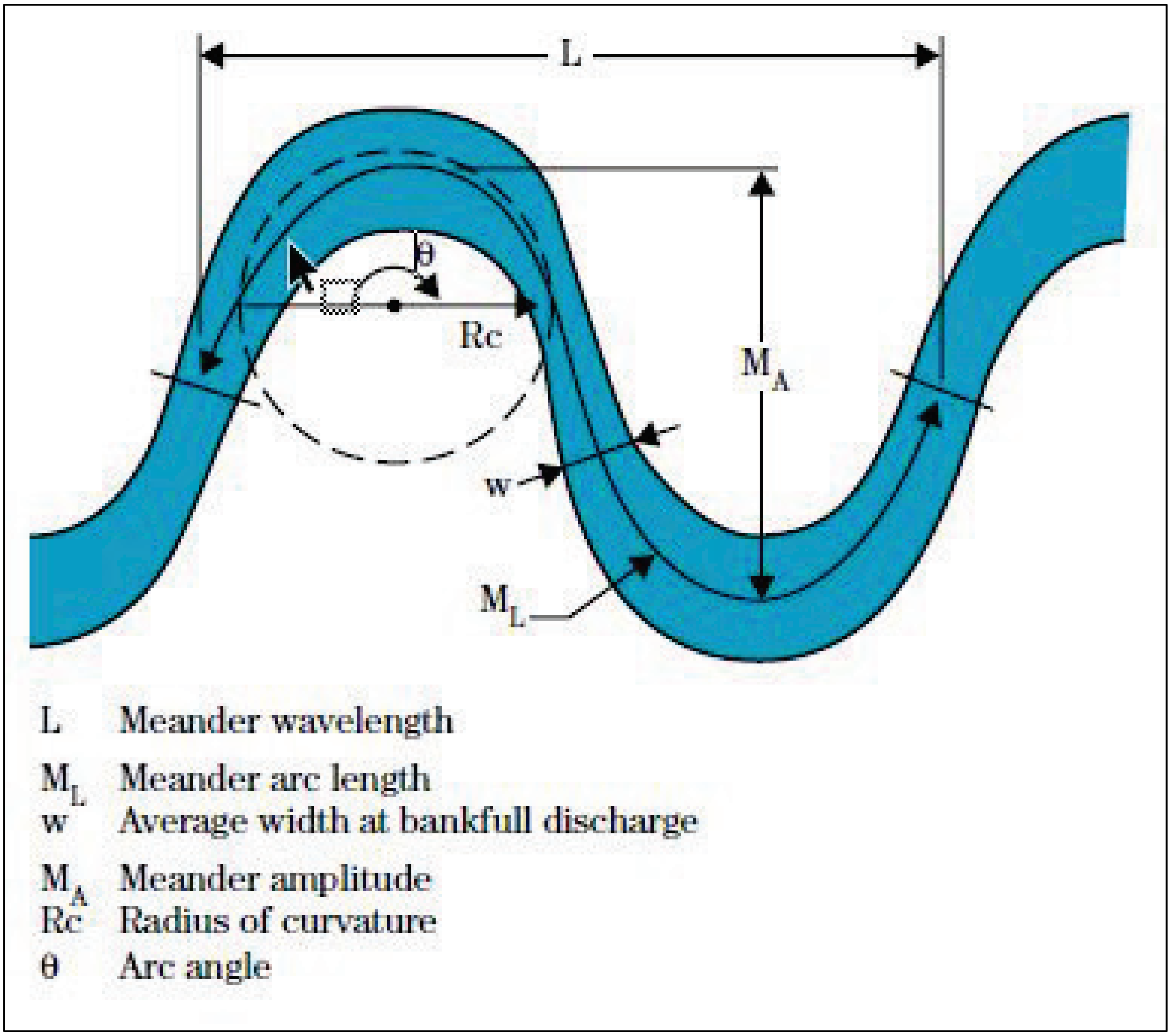


Figure 13. FG Level III: common channel geometry relationships. (Image reproduced from USDA NRCS 2007. Public domain.)

MEANDER WAVELENGTH (*Lm*): Meander wavelength (*Lm*) is a planform metric that measures the longitudinal distance between two sequential meander bends (Figure 14). The *Lm* is made parallel to the fall line of the valley connecting the meanders. Based on the empirical relationships developed measuring *Lm*, *Lm* can be used to predict a value for stable channel bankfull width (*Bw*). *Bw* in turn could be used to assess a potential stable *Lm.*

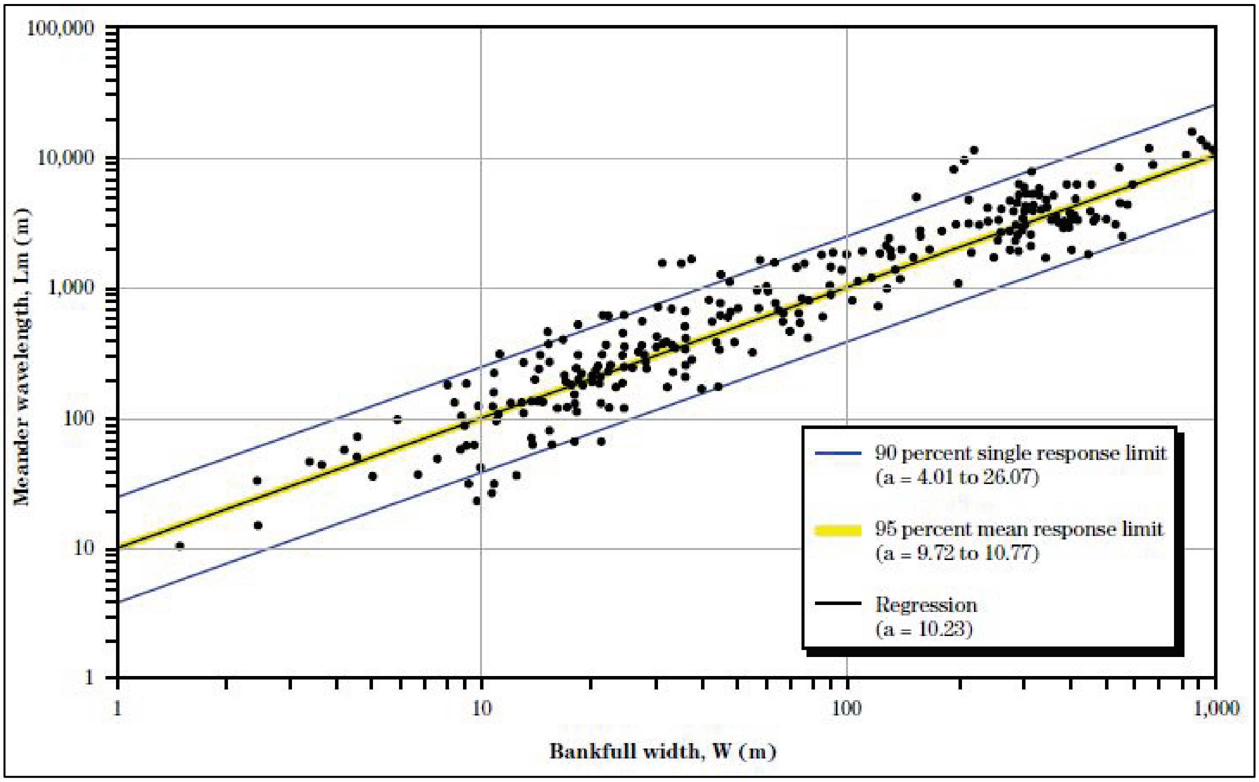
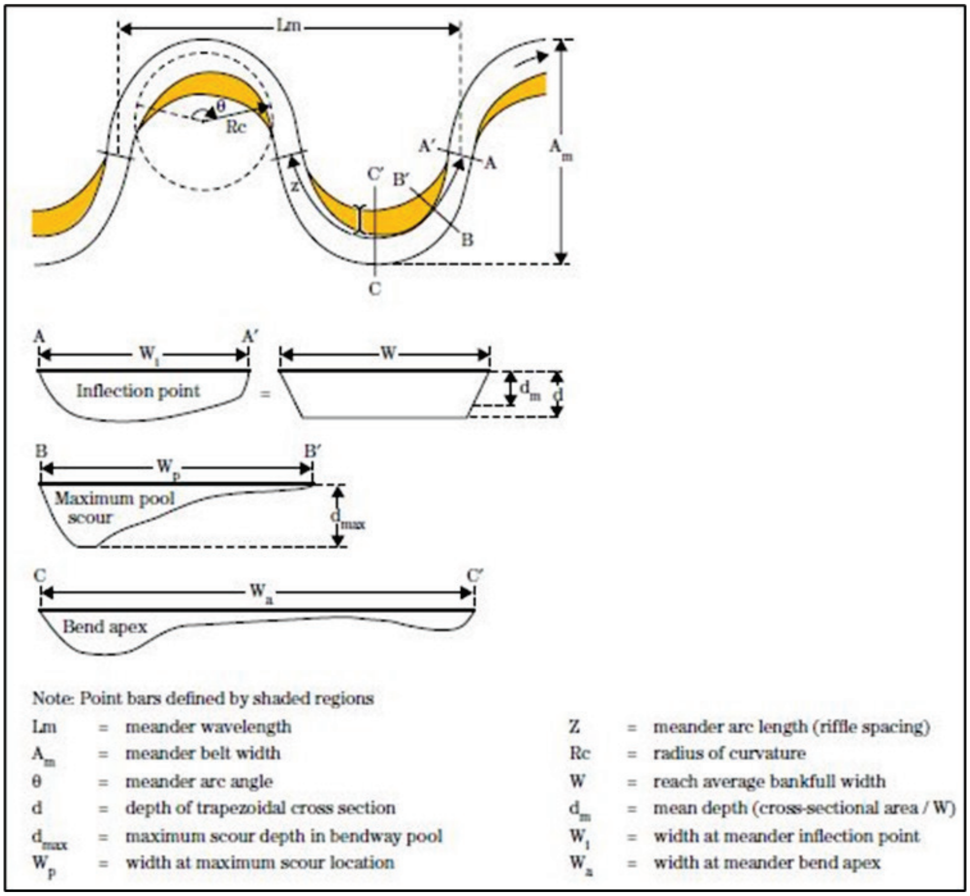


Figure 14. Channel geometry: meander wavelength (*Lm*) analysis to bankfull width (*Bw*). (Image reproduced from NRCS 2007. Public domain.)

BELT WIDTH (W_{blt}): The W_{blt} measures the lateral distance between outer edges of two meanders bends defined in Figure 15 as A_m. The measurements must be made at opposite sides of the two meanders and perpendicular to the valley profile. The W_{blt} is an index of lateral containment or confinement of the stream when compared to the bankfull width of the channel (W_{blt}/Bw). The meander width ratio (MWR) is measured by dividing the W_{blt} by the bankfull width. Rogen (1996) uses MWR as a diagnostic tool to classify stream type categories.



Note: Point bars defined by shaded regions

Lm = meander wavelength
A_m = meander belt width
θ = meander arc angle
d = depth of trapezoidal cross section
d_{max} = maximum scour depth in bendway pool
W_p = width at maximum scour location
Z = meander arc length (riffle spacing)
Rc = radius of curvature
W = reach average bankfull width
d_m = mean depth (cross-sectional area / W)
W_i = width at meander inflection point
W_a = width at meander bend apex

Figure 15. Meander geometry and variability. (Image reproduced from USDA NRCS 2007. Public domain.)

RADIUS OF CURVATURE TO BANKFULL WIDTH (*Rc/BW*): The *Rc/BW* is a measurement of the *tightness* of an individual meander bend. Radius of curvature is measured from the edge of the bankfull channel on the outside of the meander bend to the intersection of two lines that perpendicularly bisect the tangent lines of each curve's departure point (Rosgen 2004). The curve departure points are defined as the upstream point-of-curvature and the downstream point-of-tangent (Figure 15).

The ratio values of *Rc/Bw* are used as a diagnostic test for channel planform stability in riffle-pool systems (Haring et al. 2018). The ranges of the ratio that can occur in nature are highly variable, but in general if the *Rc/Bw* ratio is less than 2.0, then the outside bend channel banks will likely be eroding very agressively as the channel bend erosion progresses in a downvalley direction (Haring et al. 2018). An *Rc/Bw* ranging from 2.0 to 5.0 is considered a range of active erosion, and *Rc/Bw* greater than 5 have less of a tendancy to erode. For more detailed *Rc/Bw* relationships compared to channel migration rates, see Nanson and Hickin (1983) and Biedenharn at el. (1989) (Figure 16). Those two studies investigated and developed more detailed information on *Rc/Bw* values for North America rivers. Resistant bank materials such as clay plugs, geologic materials, or thick, dense vegetation may alter the rate at which the downvalley meander bend migration occurs. The metric is used for a diagnostic evaluation of the state of meander bends and their relative stability. Low *Rc/Bw* are indicative of unstable meander bends. High *Rc/Bw* are indicators of straighter channel sections.

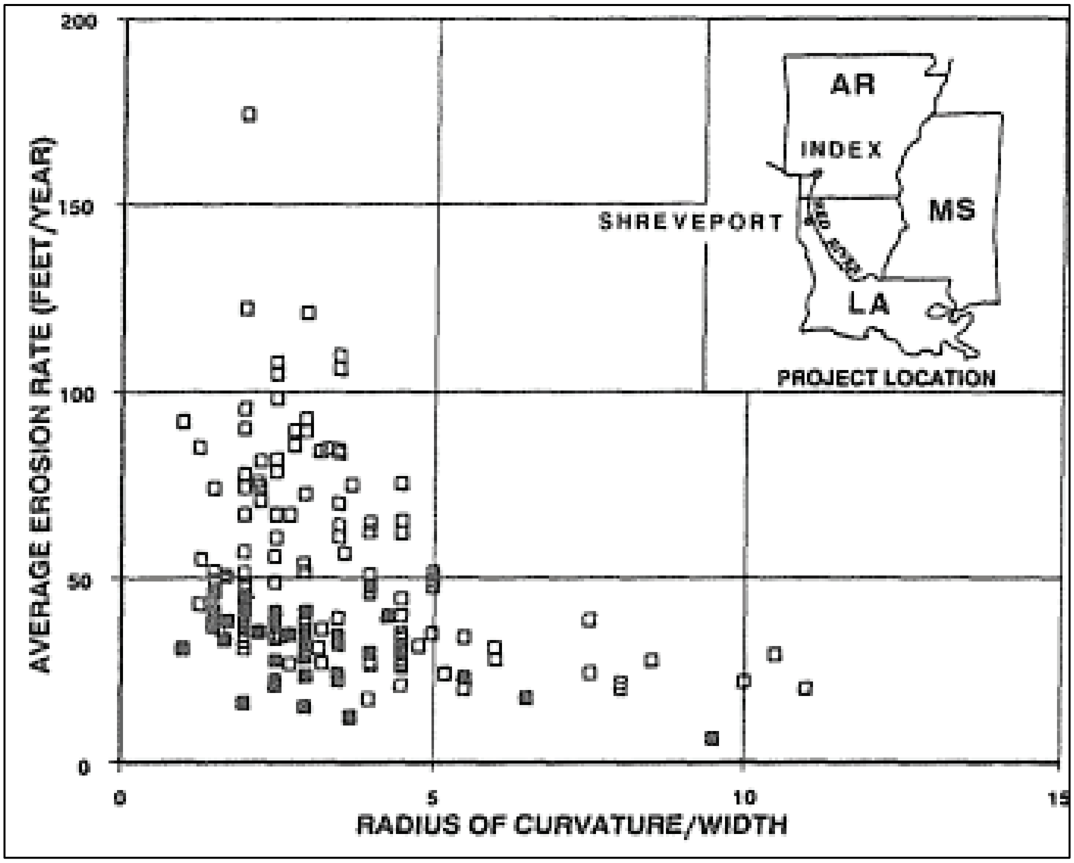


Figure 16. Relation of migration rate (ft/yr) to *Rc/Bw* Red River. (Biedenharn et al. 1989).

SUMMARY: The USACE and other organizations require a rapid watershed assessment approach that is based on geomorphic principles. FG provides a geomorphic-based analysis approach for rapid watershed assessments that can be applied for USACE planning studies. The toolbox has been used on watershed studies nationwide to analyze existing stream channel reaches and watersheds using existing surveys, topographic models, hydraulic model data and lidar high-resolution terrain data. The approach uses existing empirically derived geomorphic or user-defined metrics to provide a diagnostic approach in identifying potential channel stability issues. The toolkit continues to be tested in a wide range of hydro-physiographic regions within the United States to determine the range of uses and user further define regional geomorphic variability.

ADDITIONAL INFORMATION: This Coastal and Hydraulics engineering technical note (CHETN) was prepared as part of the FCS program and was written by Dr. Christopher P. Haring (*Christopher.P.Haring@usace.army.mil*) of the US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, and Mr. Michael P. Dougherty (*Michael.P.Dougherty@usace.army.mil*) of the USACE, Rock Island District. Questions about this CHETN can be addressed to Dr. Christopher P. Haring (*Christopher.P.Haring@usace.army.mil*).

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REFERENCES

Biedenharn, D. S., P. G. Combs, G. J. Hill, C. F. Pinkard, and C. B. Pinkston. 1989. "Relationship between Channel Migration and Radius of Curvature on the Red River." In *Sediment Transport Modeling: Proceedings of the International Symposium: Hydraulics Division, American Society of Civil Engineers*, edited by S. Y. Wang, 536–541.

Brice, J. C. 1982. *Stream Channel Stability Assessment*. Federal Highway Administration Report FHWA/RD-82/021. Washington, DC: Federal Highway Administration.

Dunne, T., and L. B. Leopold. 1978. *Water in Environmental Planning*. San Francisco, CA: W. H. Freeman and Co.

Fischenich, J. C. 2003. *Effects of Riprap on Riverine and Riparian Ecosystems*. ERDC/EL TR-03-4. Vicksburg, MS: US Army Engineer Research and Development Center, Environmental Laboratory.

FISRWG (Federal Interagency Stream Restoration Working Group). 1998. *Stream Corridor Restoration: Principles, Processes and Practices*. National Technical Information Service. Springfield, VA: US Department of Commerce.

Gordan, N. D., T. A. McMahon, B. L. Finlayson, C. J. Gippel, and J. N. Rory. 2004. *Stream Hydrology: An Introduction for Ecologists*. 2nd Edition. Hoboken, NJ: John Wiley & Sons, Ltd.

Haring, C. H. 2019. *An Assessment of a LiDAR-based Approach for Estimating Hydraulic Geometry Regional and Regime Relationship Curves for the Southern Driftless Area of the Midwest*. Contributors: F. H. Weirich, B. D. Cramer, J. A. Dorale, T. C. Foster, and L. J. Weber. PhD dissertation. University of Iowa.

Haring, C. H., and D. W. Biedenharn. 2021. *Channel Assessment Tools for Rapid Watershed Assessment*. ERDC/CHL CHETN-VII-24. Vicksburg, MS: US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. *http://dx.doi.org/10.21079/11681/40379*.

Haring, C. H., C. H. Theiling, and M. P. Dougherty 2018. *Rapid Watershed Assessment Planning Tools Based on High-Resolution Terrain Analysis*. ERDC/CHL CHETN-VII-22. Vicksburg, MS: US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. *http://dx.doi.org/10.21079/11681/36714*.

Haring, C. H., C. H. Theiling, and M. P. Dougherty. 2020. *Rapid Watershed Assessment Planning Tools Based on High-Resolution Terrain Analysis*. ERDC/CHL CHETN-VII-22. Vicksburg, MS: U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. *http://dx.doi.org/10.21079/11681/36714*.

Harrelson, C. C., C. L. Rawlins, and J. P. Potyondy. 1994. *Stream Channel Reference Sites: An Illustrated Guide to Field Technique.* General Technical Report RM-245. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Knighton, D. 1998. *Fluvial Forms and Processes: A New Prospective*. Oxfordshire, England, UK: Routledge.

Lane, E. W. 1955. "The Importance of Fluvial Geomorphology in Hydraulic Engineering." *Proceedings of the American Society of Civil Engineers* 81 (7) Paper 745: 1–17.

Lawlor, S. M. 2004. *Determination of Channel-Morphology Characteristics, Bankfull Discharge, and Various Design-Peak Discharges in Western Montana.* Scientific Investigations Report 2004–5263. Washington, DC: Department of the Interior, US Geological Survey.

Leopold, L. B. 1994. *A View of the River*. Cambridge, MA: Harvard University Press.

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

Nanson, G. C., and E. J. Hickin. 1983. "Channel Migration and Incision on the Beatton River." *Journal of Hydraulic Engineering* 109 (3): 327–337

Newbury, R. W., and M. N. Gaboury. 1988. "The Use of Natural Stream Characteristics for Stream Rehabilitation." *Canadian Water Resources Journal* 13 (4): 35–51.

Rhoads, B. L. 1987. "Stream Power Terminology." *The Professional Geographer* 39 (2): 189–195.

Rosgen, D. L. 1994. "A Classification of Natural Rivers." *Catena* 22 (3): 169–199.

Rosgen, D. L. 1996. *Applied River Morphology*. Pagosa Springs, CO: Wildland Hydrology.

Rosgen, D. L. 2006. *WARSSS (A Watershed Assessment for River Stability and Sediment Supply)*. Fort Collins, CO: Wildland Hydrology Books.

Rosgen, D. L., and H. L. Silvey. 2005. *The Reference Reach Field Book*. Fort Collins, CO: Wildland Hydrology Books.

Schilling, K. E., T. M. Isenhart, J. A. Palmer, C. F. Wolter, and J. Spooner. 2011. "Impacts of Land-Cover Change on Suspended Sediment Transport in Two Agricultural Watersheds." *Journal of American Water Resources Association* 47 (4): 672–686.

Schumm, S. A. 1960. *The Shape of Alluvial Channels in Relation to Sediment Type.* US Geological Survey Professional Paper 352B. Reston, VA: US Geological Survey. https://doi.org/10.3133/pp352B.

Schumm, S. A. 1977. *The Fluvial System*. Caldwell, NJ: The Blackburn Press.

Selby, M. J. 1985. *Earth's Changing Surface: An Introduction to Geomorphology*. Oxford, Oxfordshire, England: Oxford University Press.

Shields, A. 1936. *Sediments and Sediment Transport*. Translated by W. P. Ott and J. C. van Uchelen. Pasadena, CA: California Institute of Technology.

USDA NRCS (US Department of Agriculture, Natural Resources Conservation Service). 2007. *Developing Regional Relationships for Bankfull Discharge Using Bankfull Indices*. National Engineering Handbook Technical Supplement 5, Part 654. Washington, DC: US Department of Agriculture, Natural Resources Conservation Service. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17834.wba.

Williams, G. P. 1978. "Bankfull Discharge of Rivers." *Water Resources Research* 14 (6): 1141–1154.