THESIS

FULL SPECTRUM ANALYTICAL CHANNEL DESIGN WITH THE CAPACITY/SUPPLY RATIO (CSR)

Submitted by

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ABSTRACT

FULL SPECTRUM ANALYTICAL CHANNEL DESIGN WITH THE CAPACITY/SUPPLY RATIO (CSR)

Analytical channel design tools have not advanced appreciably in the last decades, and continue to produce designs based upon a single representative discharge that may not lead to sediment continuity. It is beneficial for designers to know when a simplified design may be problematic and to efficiently produce alternative designs that approximate sediment balance over the entire flow regime. The Capacity/Supply Ratio (CSR) approach, an extension of the Copeland method of analytical channel design for sand channels, balances the sediment transport capacity of a design reach with the sediment supply of a stable upstream reach over the entire flow duration curve (FDC) rather than just a single discharge. Although CSR has a stronger physical basis than previous analytical channel design approaches, it has not been adopted in practice because it can be a cumbersome and time-consuming iterative analysis without the use of software. I present a novel design tool that was developed using the Visual Basic for Applications (VBA) programming language in Excel® and produces stable channel slope/width combinations based on the CSR methodology for both sand- and gravel-bed streams. The CSR Stable Channel Design Tool's (CSR Tool) code structure was based on Copeland's method in SAM and HEC-RAS (Hydrologic Engineering Center – River Analysis System) and was tested with a single discharge to verify outputs. Eighteen sand-bed rivers were investigated with the tool in a comparison of designs based on the CSR approach and five single-discharge metrics: the effective discharge (Q_{eff}) or discharge that transports the most sediment over time, the 1.5-year recurrence interval discharge ($Q_{1.5}$), bankfull discharge (Q_{bf}), and the discharges associated with 50th (Q_{s50}) and 75th (Q_{s75}) percentiles of the cumulative sediment yield curve. The Q_{s50} and Q_{s75} single-discharge designs match the CSR output most closely followed by the Q_{bf} and Q_{eff}. The Q_{eff} proved to be the most inconsistent design metric because it can be highly dependent on the binning procedure used in the effectiveness analysis. Furthermore, I found that the more rigorous physical basis of the CSR analysis is potentially most important in designing ‘labile’ channels with highly erodible substrate, high perennial flow ‘flashiness’, low width-to-depth ratio, and high incoming sediment load. The CSR Tool provides a resource for river-restoration practitioners to utilize process-based design techniques that can promote more reliable and sustainable designs for dynamic fluvial systems.

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DEDICATION

In loving memory of my dad Gary "Daddio" Stroth,

for giving me the relentless resilience that I will keep for the rest of my life.

I will forever continue to try to make you proud!

R.I.P.

(July 30, 1944 – January 3, 2017)

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Symbols

A = cross-sectional area

A_{OB} = area of floodplain partition

D_{50} = median grain size of the bed material

i = day

K = conveyance

K_{OB} = conveyance of bed partition

n = Manning’s roughness coefficient

$n_{floodplain}$ = Manning’s roughness of floodplain partition

P_{bank} = wetted perimeter of bank partition

P_{bed} = bottom width = wetted perimeter of bed partition

q = daily-averaged discharge;

Q = discharge

$Q_{1.5}$, Q_{2} = 1.5-yr and 2-yr return interval discharges, respectively

Q_{bf} = bankfull discharge

Q_{eff} = effective discharge

Q_{m} = mean annual discharge

Q_{s50} = half-load discharge

Q_{s50}, Q_{s75} = discharge associated with 50% and 75% of cumulative sediment transport over the sorted flow record, respectively

R = radius

R_{bed} = hydraulic radius of bed partition

R_{OB} = hydraulic radius of floodplain partition

S_o = bed slope

S_v = valley slope

V = binary variable that is unity if tree cover over the banks is less than 50% or zero if tree cover is more than 50%

V = cross-section averaged velocity

w = width, channel top width

<u>Statistical Terms</u>

CDF	cumulative distribution function
CSR	Capacity/Supply Ratio
p	probability
PDF	probability density function
R^2	coefficient of determination

UNITS OF MEASURE

cfs	cubic feet per second
cms	cubic meter(s) per second
ft	foot or feet
H:V	horizontal:vertical
km	kilometer(s)
m	meter(s)
m/yr	meter(s) per year
mm	millimeter(s)
%	percent
ppm	parts per million
yr(s)	year(s)

CHAPTER 1: THESIS INTRODUCTION

1.1 Introduction

Efforts to manage watersheds for freshwater sustainability have become increasingly important as pressures from population growth and development increasingly strain water resources in an atmosphere of burgeoning climate uncertainty. Almost half (44%) of the rivers in the United States are listed as polluted or impaired, and extinction rates of fresh-water fauna are five times that for terrestrial biota (U. S. Environmental Protection Agency (EPA) 2009; Ricciardi and Rasmussen 1999; Strayer and Dudgeon 2010). Human influences such as urban development can trigger rapid geomorphic change in streams with excessive erosion or sedimentation that can compromise surrounding infrastructure and impede municipal or recreational usages (Hawley et al. 2012; Trimble 1997; Piégay et al. 1997). These issues often have a common root cause: river channel instability resulting from altered flows of water and sediment. Fortunately, these issues can be addressed in many instances through stream restoration and the application of stable channel design principles. Stable channel design aims to bring a river channel to a state of dynamic equilibrium between flows of water and sediment, which can reduce excess lateral and vertical instability, as well as improve water quality and habitat for biota (Wohl et al. 2015). The need for river channel design has been recognized and is practiced all over the world with billions of dollars being spent on stream restoration each year, yet riverine systems continue to deteriorate and many channel designs have failed (Bernhardt et al. 2005). Consequently, the science of river channel design needs to advance to support the practice and develop techniques and tools that increase the performance and sustainability of stream channel designs.

There is a diverse and eclectic array of methods used in the current practice of river-channel design, but the three most common methods are the analog, empirical, and analytical approaches

(Skidmore et al. 2001). The analog and empirical approaches are the most commonly used methods, but have many limitations and assumptions that can lead to faulty designs. Empirical relationships are often limited by the data sets from which they are derived, and significant assumptions must be made about regional conditions being representative of reach-scale processes that can be tremendously variable within a watershed (Skidmore et al. 2001). The analog approach places a particular reliance on the emulation of reference reaches to formulate a river reach design. This method has the underlying assumption that if the form of a reference reach that is presumably stable and of comparable channel type is matched to the design reach then the stability conditions will also be matched in the design reach. In addition, these approaches typically rely on designing the channel to a single ‘dominant’ discharge. This single discharge is often assumed to be the discharge that most influences channel form and an adequate proxy of all flows that influence channel form in the flow regime (Doyle et al. 2007). A ‘channel-forming’ discharge is usually identified through bankfull field indicators, recurrence interval analysis of peak flows, regional flood regression relationships, an effective discharge analysis, or a combination of these methods. Many problems can arise if care and astuteness are not employed while choosing the proper discharge, recognizing the limitations of comparing to a reference system, and using

River Channel Design Methods
(summarized from Skidmore et al. (2001))

Analog Approach – Adopts templates from historic or adjacent channel characteristics and assumes equilibrium between channel form and sediment and hydrologic inputs.

Empirical Approach – Uses equations that relate various channel characteristics derived from regionalized or “universal” data sets, and also assumes equilibrium conditions.

Analytical Approach – Makes use of hydraulic models and sediment transport functions to derive equilibrium conditions, and thus is applicable to situations where historic or current channel conditions are not in equilibrium with existing or predicted sediment and hydrologic inputs.

regionalized relationships. These techniques can be highly uncertain and often oversimplify the site-specific processes that govern channel morphodynamics. Furthermore, even if great effort is put into finding a single representative discharge, resulting designs may still lead to an unstable channel design because other influential flows were not accounted for in the analysis (Bledsoe et al. 2016).

An alternative approach to help alleviate some of these uncertainties is analytical channel design. This approach is often described as process-based because it relies on finding a site-specific equilibrium state of the processes governing the overall stability of the channel such as the sediment transport continuity which is estimated using empirical models (Beechie et al. 2010; Palmer et al. 2005). This concept is essential to effective river management because, "*water and sediment supplied to and transported by rivers are the fundamental drivers of river condition, affecting water quality, thermal regime, habitat and aquatic communities, river stability, and natural hazards*" (Wohl et al. 2015).

A well-known application of the analytical design methodology is the Copeland method (Copeland 1994) in the stable channel design feature of Hydrologic Engineering Center – River Analysis System (HEC-RAS; Brunner 2010; U. S. Army Corps of Engineers (USACE)). This method involves a sediment balance analysis for channel design which can potentially reduce the uncertainty associated with the aforementioned methods; however, this method still relies on calculating the sediment balance using a single dominant discharge and does not account for the sediment transported by any other flows. The assumptions stated above associated with using a single-discharge methodology can increase the risk of highly unstable channel designs since other influential flows substantially affect sediment transport.

A more recent approach that aims to improve the physical basis of the Copeland method is the Capacity/Supply Ratio (CSR) method first introduced by Soar and Thorne (2001). This approach is analogous to the Copeland method; however, it balances the total sediment delivered from an upstream supply reach through a design reach across the entire flow duration curve (FDC) rather than just a single representative discharge. The CSR approach can provide a more rigorous analysis of stable channel designs compared to single-discharge methods because it accounts for the influence of flows across the entire FDC, helping alleviate the uncertainty of selecting and assuming the encompassing influence of a single discharge (Soar and Thorne 2013). There are many uncertainties that can arise in the CSR methodology as well, specifically in deriving a representative FDC; however, this approach still has the potential to provide a more comprehensive and robust channel design analysis over the single-discharge technique. This begs the question: are there situations (channel types, etc.) that can be identified where the CSR is more important to use over the simplified single-discharge design? Soar and Thorne (2001) developed the CSR to explore the design flaws that led to a failed river-restoration project at White Marsh Run in Maryland. They proved the CSR could be a useful tool to explain the sediment continuity issues involved with the original design; although, there was no specific evidence to what approach was used in the original project which led to the faulty design. Unfortunately, since the publication of Soar and Thorne (2001), the CSR approach has not been widely applied in practical design scenarios or researched and thus lacks support to when it is useful and most needed in channel design. A limiting factor to the research and development of the CSR method has been the lack of a tool that allows users to easily perform the analysis, because it can be a cumbersome and time-consuming iterative analysis without the use of software. This has limited the use of the method to produce abundant results for research or to be applied to practical design situations that have many socioeconomic and time constraints that restrict designers from performing rigorous analyses. *Thus, (1) there is a pressing need for a tool that can perform this analysis and give the user a means to produce the full spectrum of information that can be used to aid in the stable channel design process, and (2) there is a need to have research that applies the use of this tool to explore when the tool is most needed and is recommended to produce the most sustainable and robust channel designs.*

This thesis presents the development of the CSR Stable Channel Design Tool (CSR Tool) which can perform this analysis for a given reach of interest to produce a range of possible stable channel design solutions with CSRs equal to 1 (Chapter 2). Then, I also present associated research performed to apply the tool and give guidance to the question of when to use the CSR Tool (Chapter 3).

Many gaps in knowledge still remain about the validity of the CSR methodology and how it compares to the more common single-discharge design approach. The CSR analysis has a more rigorous physical basis over the single discharges, which could lead to a more robust channel design that fosters the continuity of water and sediment. I first determine the biggest influences on the deviation of single-discharge designs from the CSR output are, and from this assess if the CSR analysis is really needed, and if so when is it most important to use over the single-discharge approach? I hypothesize that there will be situations where the CSR analysis is recommended to use over the single discharge, especially in fine-grained rivers with highly erodible substrate and streams with ‘flashy’ hydrographs. Lastly, in the absence of a CSR analysis, which single-discharge designs will be most likely to match the CSR output? I hypothesize designs based on the half-load discharge (Q_{s50}), the discharge associated with 50% of the cumulative sediment yield (Sholtes and Bledsoe 2016; Vogel et al. 2003), will match CSR designs closer than conventional proxies for the full range of geomorphically effective flows, i.e., the bankfull and effective discharges (Andrews 1980, Emmett and Wolman 2001, Shields et al. 2003).

1.2 Objectives

My research focused on developing a stable channel design tool that performs the CSR analysis to provide a full spectrum of information to aid in the stable channel design process. The platform chosen to develop the tool was the programming language of Excel®, Visual Basic for Applications (VBA). This platform was selected to extend the applicability of the tool to both practitioners and researchers by using the user-friendly and familiar environment of Excel®. More specifically, the following presents the detailed objectives for developing the CSR Tool:

- Develop an Excel-based stable channel design tool using the CSR analysis to produce a family of stable channel slope and width configurations with a CSR of unity, and provide ability to perform the analysis on both sand-bed and gravel- / cobble-bed streams.
    - Expand applicability of the tool by providing the function to enter a user-defined FDC or a flow record for the hydrologic analysis, and provide additional outputs to guide in the planform design process.
    - Design and code tool to optimize the efficiency and rigor of the analysis while providing understandability and user friendliness that allows the tool to be assessable for scientific researchers or channel design practitioners.
- Develop a CSR Tool Reference Manual with detailed explanations of the theory behind its development and the equations used in each analysis.

- Create a CSR Tool Guidance Document with screenshots on how to run each tab in the workbook, guidance on the selection and input of each tab, and two examples (one sand-bed and one gravel-bed) showing the functionality of running the tool.
- Perform research to identify the contexts in which CSR and single event designs diverge as a result of differences in channel type, flow regime, and other factors. Provide sequent guidance on the application of these methods based on the findings.
- Compare the sensitivity of stable channel solutions between gravel- / cobble-bed (bed load) and sand-bed (total load) dominated streams with changes to incoming sediment load.

1.3 Thesis Layout

Subsequent chapters (Chapters 2 and 3) of this thesis are written as standalone documents. Chapter 2 presents the details of the development of the CSR Tool. It explains the methodology and methods used to create the models and the validation models outputs. Chapter 3 summarizes the development of the tool and then explores research performed to address the questions presented above, and to support or refute the aforementioned hypotheses. The third chapter is organized as a standalone document with the intent of publishing in a peer-reviewed journal and thus has intentional overlap with the first two chapters in order to present the complete story. The three chapters (Chapters 1 through 3) and the associated CSR Tool collectively provide a useful contribution to the science and practice of watershed restoration and promote more sustainable and resilient river channel designs. Chapter 4 presents the thesis conclusion.

Appendix A and Appendix B are also created as standalone documents. Appendix A is a Reference Manual that summarizes the theoretical background and methodology used to develop the CSR Tool. Appendix B is a Guidance Document that was developed as a quick reference that provides step-by-step workbook guidance for the CSR Tool.

REFERENCES

Andrews, E.D. 1980. "Effective and Bankfull Discharges of Streams in the Yampa River Basin, Colorado and Wyoming." *Journal of Hydrology*, Vol. 46, No. 3, pp. 311–330, DOI: 10.1016/0022-1694(80)90084-0.

Beechie, T.J., D.A. Sear, J.D. Olden, G.R. Pess, J.M. Buffington, H. Moir, P. Roni, and M.M. Pollock. 2010. "Process-based Principles for Restoring River Ecosystems." *BioScience*, Vol. 60, No. 3, pp. 209–222, DOI: 10.1525/bio.2010.60.3.7.

Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. 2005. "Synthesizing U.S. River Restoration Efforts." *Science*, Vol. 308, No. 5722, pp. 636–637, DOI: 10.1126/science.1109769.

Bledsoe, B.P., D. Baker, P.A. Nelson, T. Rosburg, J. Sholtes, and T.R. Stroth. Submitted 2016. "Design Hydrology for Stream Restoration and Channel Stability at Stream Crossings." Prepared for National Cooperative Highway Research Program (NCHRP) Project 24-40.

Brunner, G.W. 2010. "HEC-RAS River Analysis System, User's Manual." *Report No. CPD-68*, Version 4.1, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, 790 p., URL: http://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS_4.1_Users_Manual.pdf.

Copeland, R.R. 1994. "Application of Channel Stability Methods – Case Studies." *Technical Report HL-94-11*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, September, 60 p., URL: http://www.dtic.mil/dtic/tr/fulltext/u2/a285625.pdf.

Doyle, M.W., D. Shields, K.F. Boyd, P.B. Skidmore, and D. Dominick. 2007. "Channel-forming Discharge Selection in River Restoration Design." *Journal of Hydraulic Engineering*, Vol. 133, No. 7, pp. 831–837, DOI: 10.1061/(ASCE)0733-9429(2007)133:7(831).

Emmett, W.W., and M.G. Wolman. 2001. "Effective Discharge and Gravel-bed Rivers." *Earth Surface Processes and Landforms,* Vol. 26, No. 13, pp. 1369–1380, DOI: 10.1002/esp.303.

Hawley, R.J., B.P. Bledsoe, E.D. Stein, and B.E. Haines. 2012. "Channel Evolution Model of Semiarid Stream Response to Urban-induced Hydromodification." *Journal of the American Water Resources Association*, Vol. 48, No. 4, pp. 722–744, DOI: 10.1111/j.1752-1688.2012.00645.x.

Palmer, M.A., E.S. Bernhardt, J.D. Allan, P.S. Lake, G. Alexander, S. Brooks, J. Carr, S. Clayton, C.N. Dahm, J.F. Shah, D.L. Galat, S.G. Loss, P. Goodwin, D.D. Hart, B. Hassett, R. Jenkinson, G.M. Kondolf, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, and E. Sudduth. 2005. "Standards for Ecologically Successful River Restoration." *Journal of Applied Ecology*, Vol. 42, No. 2, pp. 208–217, DOI: 10.1111/j.1365-2664.2005.01004.x.

Piégay, H., M. Cuaz, E. Javelle, and P. Mandier. 1997. "Bank Erosion Management Based on Geomorphological, Ecological and Economic Criteria on the Galaure River, France." *Regulated Rivers: Research & Management*, Vol. 13, No. 5, pp. 433–448, DOI: 10.1002/(SICI)1099-1646(199709/10)13:5<433::AID-RRR467>3.0.CO;2-L.

Ricciardi, A., and J.B. Rasmussen. 1999. "Extinction Rates of North American Freshwater Fauna." *Conservation Biology*, Vol. 13, No. 5, pp. 1220–1222, DOI: 10.1046/j.1523-1739.1999.98380.x.

Shields Jr., F.D., R.R. Copeland, P.C. Klingeman, M.W. Doyle, and A. Simon. 2003. "Design for Stream Restoration." *Journal of Hydraulic Engineering*, Vol. 129, No. 8, pp. 575–584, DOI: 10.1061/(ASCE)0733-9429(2003)129:8(575).

Sholtes, J.S., and B.P. Bledsoe. 2016. "Half-yield Discharge: Process-based Predictor of Bankfull Discharge." *Journal of Hydraulic Engineering*, Vol. 142, No. 8, DOI: 10.1061/(ASCE)HY.1943-7900.0001137, 04016017.

Skidmore, P.B., F.D. Shields, M.W. Doyle, and D.E. Miller. 2001. "A Categorization of Approaches to Natural Channel Design." Pages 1–12 in D.F. Hays (Ed.): *Proceedings of the 2001 Wetlands Engineering and River Restoration Conference*, Reno, NV, August 27-31, DOI: 10.1061/40581(2001)38.

Soar, P.J., and C.R. Thorne. 2001. "Channel Restoration Design for Meandering Rivers." *Technical Report No. ERDC/CHL CR-01-1*, Coastal and Hydraulics Laboratory, U.S. Army, Engineer Research and Development Center, Vicksburg, MS, URL: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043218.pdf.

Soar, P.J., and C.R. Thorne. 2013. "Design Discharge for River Restoration." Pages 123–150 in A. Simon, S.J. Bennett, and J.M. Castro (Eds.): *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*, Geophysical Monograph Series, Volume 194, American Geophysical Union, Geopress, Washington, DC.

Strayer, D.L., and D. Dudgeon. 2010. "Freshwater Biodiversity Conservation: Recent Progress and Future Challenges." *Journal of the North American Benthological Society*, Vol. 29, No. 1, pp. 344–358, DOI: 10.1899/08-171.1.

Trimble, S.W. 1997. "Contribution of Stream Channel Erosion to Sediment Yield from an Urbanizing Watershed." *Science*, Vol. 278, No. 5342, pp. 1442–1444, DOI: 10.1126/science.278.5342.1442.

U.S. Environmental Protection Agency (EPA). 2009. "National Water Quality Inventory: Report to Congress: 2004 Reporting Cycle." *EPA Publication 841-R-08-001*, EPA, Washington, DC, 37 p., URL: https://www.epa.gov/sites/production/files/2015-09/documents/2009_01_22_305b_2004report_2004_305breport.pdf.

Vogel, R.M., J.R. Stedinger, and R.P. Hooper. 2003. "Discharge Indices for Water Quality Loads." *Water Resources Research*, Vol. 39, No. 10, DOI: 10.1029/2002WR001872.

Wohl, E., B.P. Bledsoe, R.B. Jacobson, N.L. Poff, S.L. Rathburn, D.M. Walters, and A.C. Wilcox. 2015. "The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management." *Bioscience*, Vol. 65, No. 4, pp. 358–371, DOI: 10.1093/biosci/biv002.

CHAPTER 2: CSR TOOL DEVELOPMENT

2.1 Introduction

There is a diverse and eclectic array of methods used in the current practice of river-channel design, but the three most common methods as identified by Skidmore et al. (2001) are the analog, empirical, and analytical approaches. The analog and empirical approaches are often the most commonly used methods, but have many limitations and assumptions that can lead to faulty designs. In addition, these approaches typically rely on designing the channel to a single ‘dominant’ discharge. This single discharge is often assumed to be the discharge that most influences channel form and an adequate proxy of all flows that influence channel form in the flow regime (Doyle et al. 2007). A ‘channel-forming’ discharge is usually identified through bankfull field indicators, recurrence interval analysis of peak flows, regional flood regression relationships, an effective discharge analysis, or a combination of these methods. Many problems can arise if care and astuteness are not employed while choosing the proper discharge, recognizing the limitations of comparing to a reference system, and using regionalized relationships. These techniques can be highly uncertain and often oversimplify the site-specific processes that govern channel morphodynamics. Furthermore, even if great effort is put into finding a single representative discharge, resulting designs may still lead to an unstable channel design because other influential flows were not accounted for in the analysis (Bledsoe et al. 2016).

An alternative approach to help alleviate some of these uncertainties is analytical channel design. This approach is often referred to as a process-based approach, because it relies on finding a site-specific equilibrium state of the processes governing the overall stability of the channel such as the sediment transport continuity (Skidmore et al. 2001). A well-known application of this method is the Copeland method in the stable channel design feature of Hydrologic Engineering

Center – River Analysis System (HEC-RAS; Brunner 2010; Copeland 1994). This method can perform a sediment balance analysis for channel design and thereby lowers the uncertainty of relying on the aforementioned methods. However, this method still relies on calculating the sediment balance using a single representative discharge that does not account for the sediment transported by any other flows. The assumptions associated with using a single discharge in this methodology can increase the risk of an unstable channel design, since systems often have other influential flows that affect sediment transport.

A more recent approach that aims to improve the physical basis of the Copeland method is the CSR method first introduced by Soar and Thorne (2001). This approach is analogous to the Copeland method; however, it balances the total sediment delivered from an upstream supply reach through a design reach across the entire flow duration curve (FDC) rather than just a single representative discharge. The Capacity/Supply Ratio (CSR) approach can provide a more rigorous analysis of stable channel designs compared to single-discharge methods because it accounts for the influence of flows across the entire FDC, helping alleviate the uncertainty of selecting and assuming the encompassing influence of a single discharge (Soar and Thorne 2013). There are many uncertainties that can arise in the CSR methodology as well, specifically in deriving a representative FDC; however, this approach still has the potential to provide a more comprehensive and robust channel design analysis over the single-discharge technique. Unfortunately, since the CSR was first introduced, the approach has not been widely applied in practical design scenarios or researched and thus lacks support to when it is useful and most needed in channel design. A limiting factor to the research and development of the CSR method has been the lack of a tool that allows users to easily perform the analysis, because it can be a cumbersome and time-consuming iterative analysis without the use of software. This has limited the use of the method to mass produce results for research or to be applied to practical design situations that have many socioeconomic and time constraints that restrict designers from performing rigorous analyses. Thus, there is a pressing need for a tool that can perform this analysis and give the user a means to produce the full spectrum of information that can be used to aid in the stable channel design process.

The CSR Stable Channel Design Tool (CSR Tool) was developed to perform this analysis for a given reach of interest and to produce a range of possible stable channel design solutions with CSRs equal to 1.

2.2 Background

The following gives a background of the theoretical basis used to develop the CSR Tool. This section explains the Copeland method and CSR method, how they are related, and how they were used in the context of developing the CSR Tool.

2.2.1 Copeland Method

The Copeland method was developed by Dr. Ronald Copeland at the U.S. Army Corps of Engineers (USACE) for use in the SAM software package (Copeland 1994). It is an analytical channel design approach that was developed solely to design sand-bed channels by estimating sediment continuity in a design reach using the Brownlie (1981) total load sediment transport and depth predictor equations (Brownlie 1983). For a given design discharge, the model solves for stable depth and slope for a range of bottom widths for trapezoidal cross sections.

The Copeland method requires several inputs including an inflowing sediment load which can be entered by the user, or the program can estimate the concentration based on a user-defined trapezoidal cross section that represents an upstream supply reach with a sediment transport capacity that yields the inflowing sediment load.

The user must then define the bank angles and other characteristics of the design reach and enter a single design discharge that will be used in the analysis. This discharge is assumed to be the channel-forming flow. The HEC-RAS reference manual (Brunner 2010) suggests the use of a 2-yr frequency flood (perennial streams), 10-yr frequency flood (ephemeral streams), bankfull discharge, or effective discharge for the design discharge. The program then solves for depth, slope, and width combinations that pass the incoming sediment load through the design channel without aggradation or degradation based on its estimated sediment transport capacity per Brownlie (1981). The results from the model produce a family of channel slope/width combinations that provide continuity of water and sediment (Figure 2-1, presented and discussed later).

2.2.2 CSR Method

The CSR concept was first introduced by Soar and Thorne (2001). They used this concept to analyze the faults in a design that led to a failed river-restoration project at White Marsh Run in Maryland. The CSR is a simple balance between the ability of a given river reach to transport sediment (Capacity) to the sediment that is being transported into the reach of interest (Supply). This is the same sediment balance concept as used in the Copeland method; however, the difference lies in the range of discharge(s) for which the sediment transport capacity is calculated. More specifically, the CSR can be described as:

$$\text{CSR} = \frac{\int_{\text{time}} \text{transport capacity of Design Reach}}{\int_{\text{time}} \text{transport capacity of Supply Reach}} \qquad \textbf{(2-1)}$$

Equation (2-1) describes the CSR as the time-integrated ratio of sediment transport capacity of a design reach to the incoming sediment supply. In other words, "*The CSR is defined as the bed-material load transported through the river reach by a sequence of flows over an extended time period divided by the bed-material load transported into the reach by the same sequence of flows over the same time period*" (Wohl et al. 2015). Ultimately, the CSR method balances the total average sediment yield over an entire distribution of flows for a particular time period rather than just for a single representative discharge as in the Copeland method.

If the capacity of the reach to transport sediment exceeds the sediment entering the reach from upstream, then degradation or erosion can be expected in the reach with a CSR > 1. Alternatively, if the sediment entering the reach exceeds the capacity of the reach to transport it, then aggradation or sediment accumulation is expected with a CSR < 1. A CSR within 10% of unity will be the most likely to have sediment balance with minimal aggradation or degradation in the channel (Soar and Thorne 2001).

2.2.3 Effectiveness Analysis

In order to find the time-integrated sediment transport, a magnitude-frequency analysis (MFA) needs to be performed to find the total 'effectiveness' for each reach. In the context of this tool, the sequence of flows over an extended time period is derived from a user-defined gage flow record, or a FDC from another source for the river reach of interest. First, these flows are used to calculate the probability that a given flow will occur on average in the associated reach in a given day. Second, the potential that the given flow has to move sediment is estimated with an appropriate sediment transport equation. Then, the effectiveness or the sediment transported on average over a period of time is calculated by multiplying the probability of the given flow by the potential sediment that can be transported by that flow. The effectiveness for each flow in the record is summed to estimate the total effectiveness or time-integrated sediment transport capacity of the reach. The total effectiveness represents the area under the effectiveness curve as shown in Figure 2-2 (presented and discussed later) for the associated supply or design reaches and is ultimately used in Equation (2-1) to predict the sediment balance (CSR) of the designs.

2.2.4 Using the CSR / Effectiveness in the Context of the CSR Tool

A MFA is performed for the supply reach to estimate the total effectiveness or sediment supply entering the design reach of interest downstream. The program then searches for slope/width combinations for the design reach that will produce an effectiveness that balances with the calculated incoming sediment load giving a CSR = 1. The results produce a curve as in Figure 2-1 which represent channel slope/width combinations which provide continuity of water and sediment (i.e., CSR = 1). This curve is analogous to the output produced by the Copeland method of HEC-RAS. Any slope/width combinations above this line are expected to result in net degradation or erosion over time, while any below are expected to produce aggradation or sediment accumulation. Every design along the curve would, according to the model, successfully pass the incoming sediment load and through time establish sediment continuity. However, in reality, not all the designs on the curve usually fall within the realm of most downstream hydraulic geometry equations and field observations of how width scales with bankfull discharge. In general, the lowest width designs on the curve that are below minimum specific stream power and the highest width designs are the least feasible for practical applications.

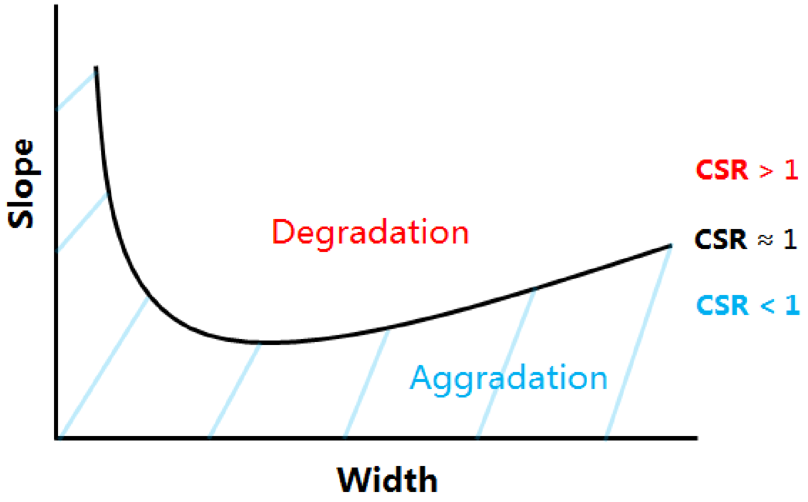


Figure 2-1. Family of slope/width combinations that provide continuity of water and sediment between supply and design reaches.

Figure 2-1 shows a visual representation of the methodology behind the CSR analysis tool. A delineated upstream supply reach and downstream design reach each show an idealized flow frequency / probability distribution (section A), an idealized sediment discharge curve (section B), and the resulting product of (section A) and (section B) which gives the effectiveness curve (section C). The area under the effectiveness curve represents the total sediment moved by each reach and is used to quantify the sediment balance of the design reach using the CSR. The curves are colored-coded to correspond with the CSR equation shown at the top of Figure 2-2. Lastly, the tool uses a simplified trapezoidal channel to represent the supply reach and design reach as shown at the bottom of Figure 2-2. All of the trapezoidal dimensions (bank height, bottom width, bank/floodplain angle) and roughness characteristics (bank/floodplain Manning's *n*) are required inputs for the tool.

$$\text{Capacity/Supply Ratio(CSR)} = \frac{\int_{\text{time}} \text{Sediment transport capacity of Design Reach}}{\int_{\text{time}} \text{Sediment transport capacity of Supply Reach}}$$

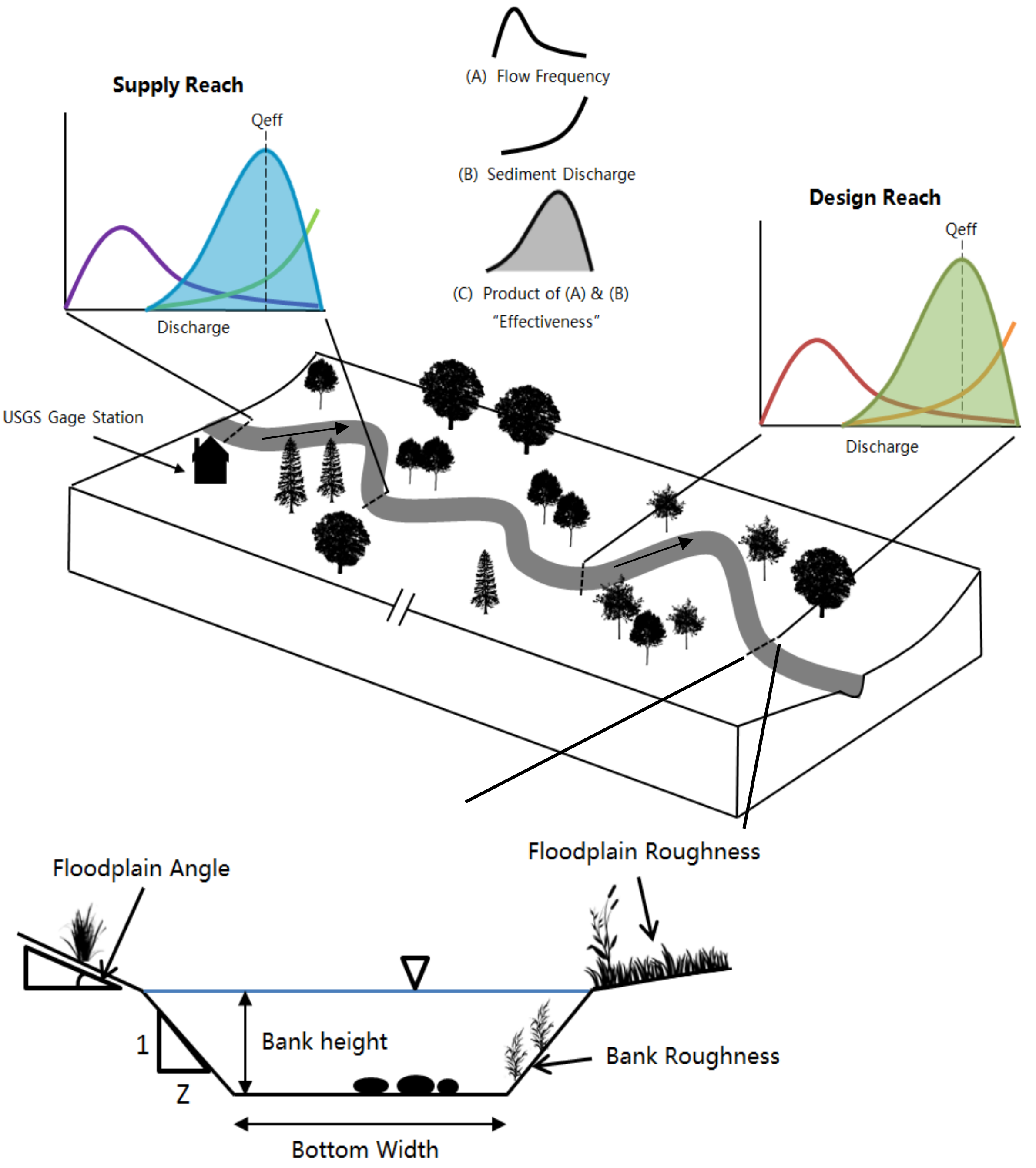


Figure 2-2. Visual representation of CSR analysis and simplified trapezoidal channel geometry assumed in tool.

2.3 Methods

The platform chosen to develop the tool was the programming language of Excel®, Visual Basic for Applications (VBA). This platform was selected to extend the applicability of the tool to both practitioners and researchers by using the user-friendly and familiar environment of Excel®.

2.3.1 Code Methodology and Assumptions Summary

The basic methodology of the code behind the CSR Tool was closely modeled after the Copeland method in HEC-RAS (Brunner 2010; Copeland 1994). This provides a means of comparison between the two methods and a means to verify the accuracy of the tool output to a well-reviewed and respected method. Some of the main assumptions used in this approach to model flow are listed below:

- 1-D steady, uniform flow;
- a simplified trapezoid is used to represent the actual channel cross section;
- the channel is split into bank and bed components;
- sediment transport is only on the bed of the channel;
- the bed and bank components have the same velocity which is the cross-section averaged velocity of the entire channel;
- the provided hydrology information is assumed to be valid for both the supply reach and design reach in the tool; and
- the sediment transport capacity estimated for the supply reach is assumed to be the incoming sediment load to the design reach.

For a detailed review of all the equations used in the calculations of the CSR Tool and explanations of their application within the tool, refer to the CSR Tool Reference Manual

(Appendix A). Features of the CSR Tool that are not present in the Copeland method of HEC-RAS include:

- Sediment transport is calculated using the entire FDC associated with the design reach rather than just a single representative discharge and, therefore, accounts for the morphological influence of the other flows.
- Overbank flow is modeled and considered in transport calculations unlike the Copeland method that uses a single trapezoid model. This can help avoid overestimating the effectiveness of higher flows since the model can account for a floodplain angle that is lower relief than the bank angle.
- The tool is capable of performing the CSR analysis for not only sand-bed streams but also gravel- / cobble-bed streams.
- Additional planform outputs and sediment yield percentiles are listed for each solution.

2.3.2 Channel Partitioning

The program models the flow through the specified cross sections by partitioning the channel into bed, bank, and overbank components (Figure 2-3). The in-channel partitioning approach follows the method used by Copeland in HEC-RAS. This approach breaks the channel into bed and bank components with separate roughness characteristics (Figure 2-3(a)). The bank roughness is specified by the user and the bed roughness is calculated in conjunction with the sediment transport analysis.

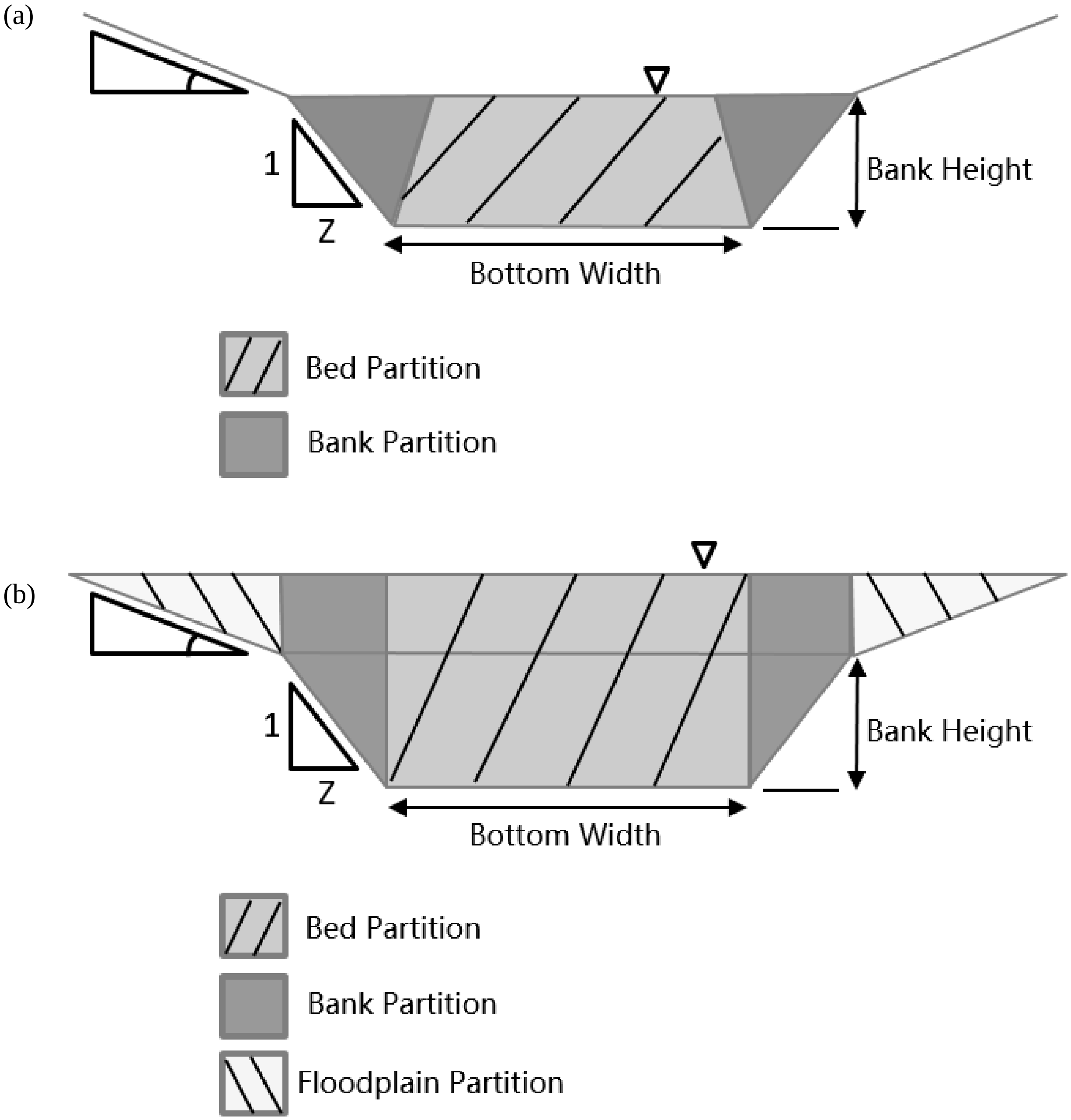


Figure 2-3. Visual representation of channel partitioning methodology for the (a) in-channel flow partitioning approach and (b) overbank flow partitioning approach.

The Einstein (1950) equation is utilized to partition the components:

$$A = R_{bed}P_{bed} + R_{bank}P_{bank} \tag{2-2}$$

where:

A = cross-sectional area;

R_{bed} = hydraulic radius of bed partition;

P_{bed} = bottom width = wetted perimeter of bed partition;

R_{bank} = hydraulic radius of bank partition; and

P_{bank} = wetted perimeter of bank partition.

This equation allows the program to solve for R_{bed} which is a key variable used to help solve for the depth in the channel. This method varies the bank component areas until the velocity through the bed and bank components are equal to the cross-section averaged velocity for the whole channel (Figure 2-3(a)).

Unlike the Copeland method, the CSR Tool also models overbank flow. Once the flow in the channel breaks into overbank flow, the partition approach is altered because the Einstein (1950) method is no longer valid. In contrast to the in-channel method, the partitions are simply delineated by vertical lines as shown in Figure 2-3(b). The bed partition is centered over the bed, the bank components over both banks, and the floodplain components over each floodplain. Instead, a conveyance method that is used by HEC-RAS (Brunner 2010) is utilized to help converge on a depth solution. The conveyance (K) of the floodplain partition is calculated with the following:

$$K_{OB} = \frac{1}{n_{floodplain}} A_{OB} R_{OB}^{2/3} \tag{2-3}$$

where:

K_{OB} = conveyance of bed partition;

$n_{floodplain}$ = Manning's roughness of floodplain partition;

A_{OB} = area of floodplain partition; and

R_{OB} = hydraulic radius of floodplain partition.

This variable is used in solving the system of equations to converge on a depth solution.

2.3.3 Hydrology Calculations

A more extensive hydrologic analysis is required by the CSR Tool in order to estimate the time-integrated sediment transport capacity of the reaches over the entire FDC rather than a single discharge. The CSR Tool can use a flow gage record or a pre-derived FDC. These flow characteristics are assumed to be the same and representative of the flows seen by the supply and design reaches.

More detail on the equations used for the hydrology calculations can be found in the CSR Tool Reference Manual (Appendix A).

If a gage record is chosen for the hydrology data, then the program will sort the discharges using an arithmetic binning procedure. This method splits the flows into a specified number of equal interval bins. A total number of bins must be defined by the user or the program defaults to 25 bins as recommended by Biedenharn et al. (2000). The process starts at 25 arithmetic discharge bins and reduces the amount of bins until there are no bins with zero frequency. In cases where there is still zero frequency at 10 bins, then the process starts again at 25 bins and combines the discharges above the zero frequency bin into one. Each bin represents a range of discharges that the flows of the record could fall into. The probability of occurrence for the flows in each range are calculated and ultimately used to find the total effectiveness or sediment yield for the supply and design reaches.

The most common method to perform a MFA is using a flow record when possible; however, it is rare in practice to have a sufficiently long flow record for a stable reach upstream of the design reach. In these instances, the CSR Tool can take a user-defined FDC, such as the output from SWAT-DEG (channel DEGradation portion of SWAT (Soil and Water Assessment Tool)) in eRAMS (environmental Risk Assessment & Management System) or any other continuous hydrologic simulation model. For example, SWAT-DEG creates a very detailed FDC and outputs a table of exceedance probabilities versus discharges that can be directly pasted into the CSR Tool. The FDC in this program is very detailed and often thousands of cells long so the user is required to define a lower number of bins to consolidate the FDC for use in sediment calculations. The default is set to 25 bins in the CSR Tool, but the user can choose up to 50 bins. The user can then run the associated tab to consolidate the original FDC. The larger FDC is sampled logarithmically for the user-defined number of bins. This is converted to a cumulative distribution function (CDF), then to a probability density function (PDF) by differentiating each point on the CDF with the central difference method. The PDF can then be used in the sediment transport calculations for the tool.

2.3.4 Sediment Transport Calculations

The CSR Tool can run the CSR analysis to find stable channel design solutions for both sand-bed and gravel- /cobble-bed streams. The sand-bed portion of the tool uses the Brownlie (1981) total load sediment transport equation to estimate transport rate just like the Copeland method in HEC-RAS. Two bedload sediment transport equations, the Parker (1990a) and Wilcock-Crowe (2003) equations, are available to estimate sediment transport rates in gravel- and cobble-bed streams. The Parker (1990a) bedload equation is appropriate for use with rivers of gravel size (> 2 mm diameter) and larger substrate. The Wilcock-Crowe (2003) bedload equation can be used with gravel- and cobble-bed streams that include a sand fraction (< 2 mm diameter).

The code methodology for the gravel- /cobble-bed portion was matched as closely as possible to the sand-bed structure. The biggest difference between the methodologies for the calculation of hydraulic parameters is the quantification of flow resistance. The sand-bed portion of the tool uses the Manning's equation and the depth predictor equations from Brownlie (1981) that account for bedforms. Manning's equation and the Limerinos (1970) equation were chosen to calculate bed roughness in the channel for the gravel-bed portion of the tool. The Limerinos (1970) equation was calibrated to account for mostly grain roughness of larger particles from gravels to boulders.

2.3.5 CSR Analysis Code Structure

The main routine of the tool performs the CSR analysis and searches for stable channel designs after the incoming sediment load is calculated for the supply reach using the given hydrologic information. The CSR Tool code structure resulted from many iterations to find the most reliable and efficient configuration. The average runtime for the tool is typically 2 to 8 seconds depending on the example and computer speed. The code methodology for calculating stable channel design solutions is outlined in Figure 2-4.

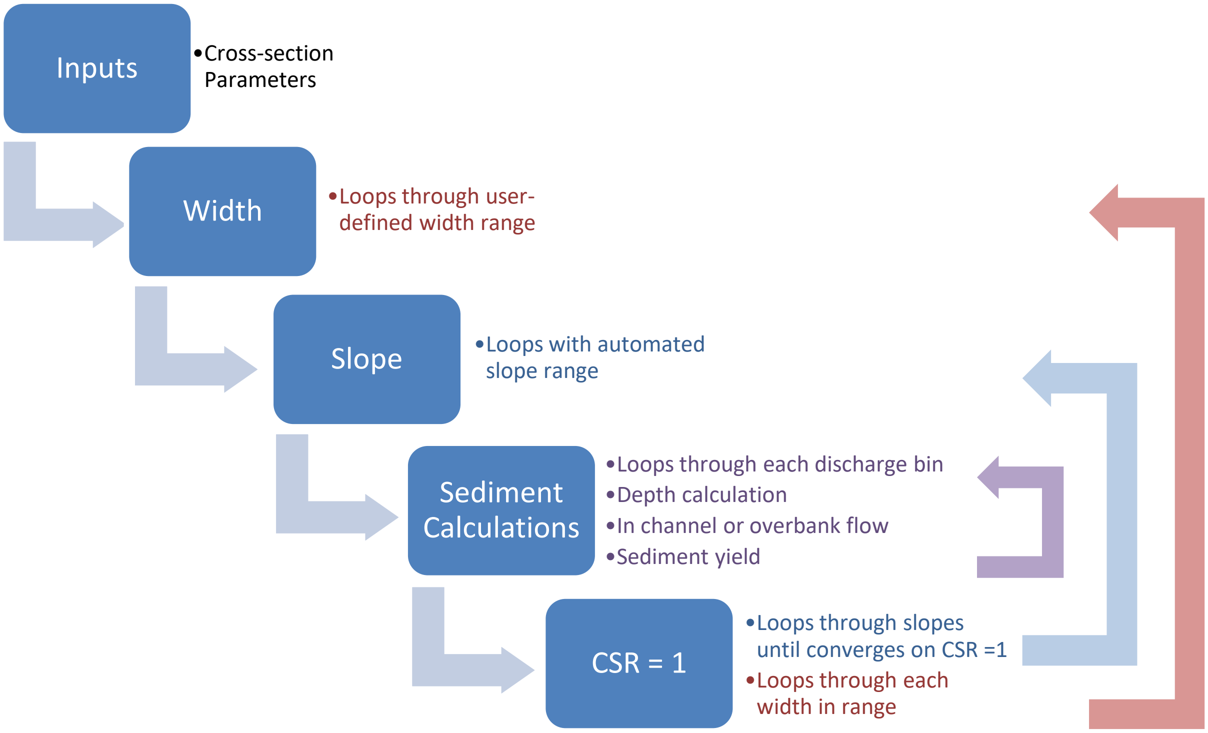
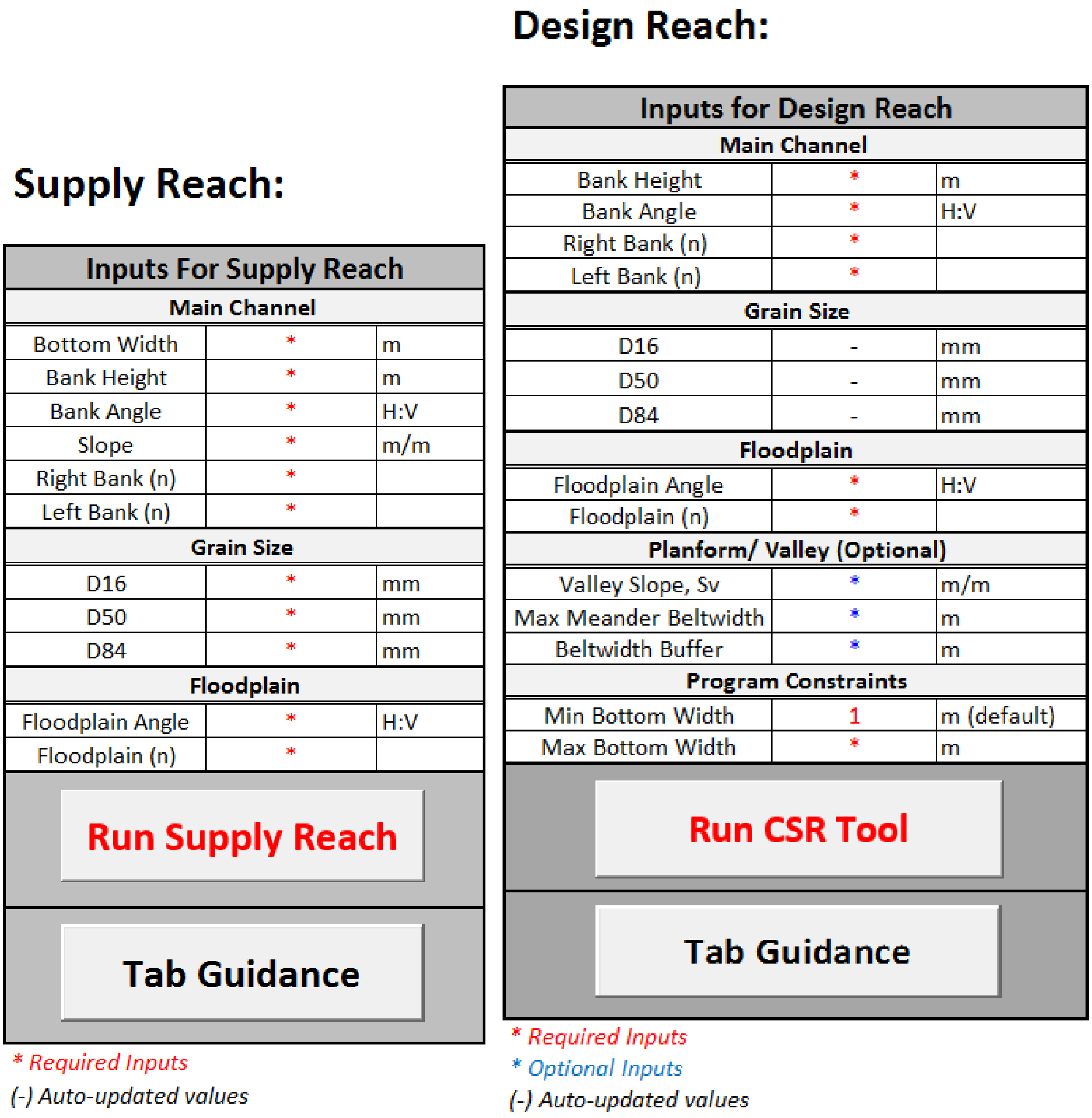


Figure 2-4. Schematic of design reach code methodology.

Firstly, the program reads the cross-sectional information entered by the user. Screenshots of the required inputs for the supply and design reaches are shown in Figure 2-5. The user provides a range of channel widths, and the program loops through this range in 2-m increments. For each width in the range, the slope corresponding to CSR = 1 is iteratively determined. The program generates an initial slope and calculates the depth, in channel or overbank flow, and upper or lower regime to calculate sediment yield for each average discharge in the binned FDC. The sediment yield summed over all discharges is compared with the supply reach total sediment yield to calculate the CSR for that slope estimate. The slope is then updated using a bisection method until it converges on the slope that will give a CSR = 1 within a tolerance of 2.5% for each width in the defined range.



Supply Reach:

Inputs For Supply Reach		
Main Channel		
Bottom Width	*	m
Bank Height	*	m
Bank Angle	*	H:V
Slope	*	m/m
Right Bank (n)	*	
Left Bank (n)	*	
Grain Size		
D16	*	mm
D50	*	mm
D84	*	mm
Floodplain		
Floodplain Angle	*	H:V
Floodplain (n)	*	

* *Required Inputs*

(-) Auto-updated values

Design Reach:

Inputs for Design Reach		
Main Channel		
Bank Height	*	m
Bank Angle	*	H:V
Right Bank (n)	*	
Left Bank (n)	*	
Grain Size		
D16	-	mm
D50	-	mm
D84	-	mm
Floodplain		
Floodplain Angle	*	H:V
Floodplain (n)	*	
Planform/ Valley (Optional)		
Valley Slope, Sv	*	m/m
Max Meander Beltwidth	*	m
Beltwidth Buffer	*	m
Program Constraints		
Min Bottom Width	1	m (default)
Max Bottom Width	*	m

* *Required Inputs*

* *Optional Inputs*

(-) Auto-updated values

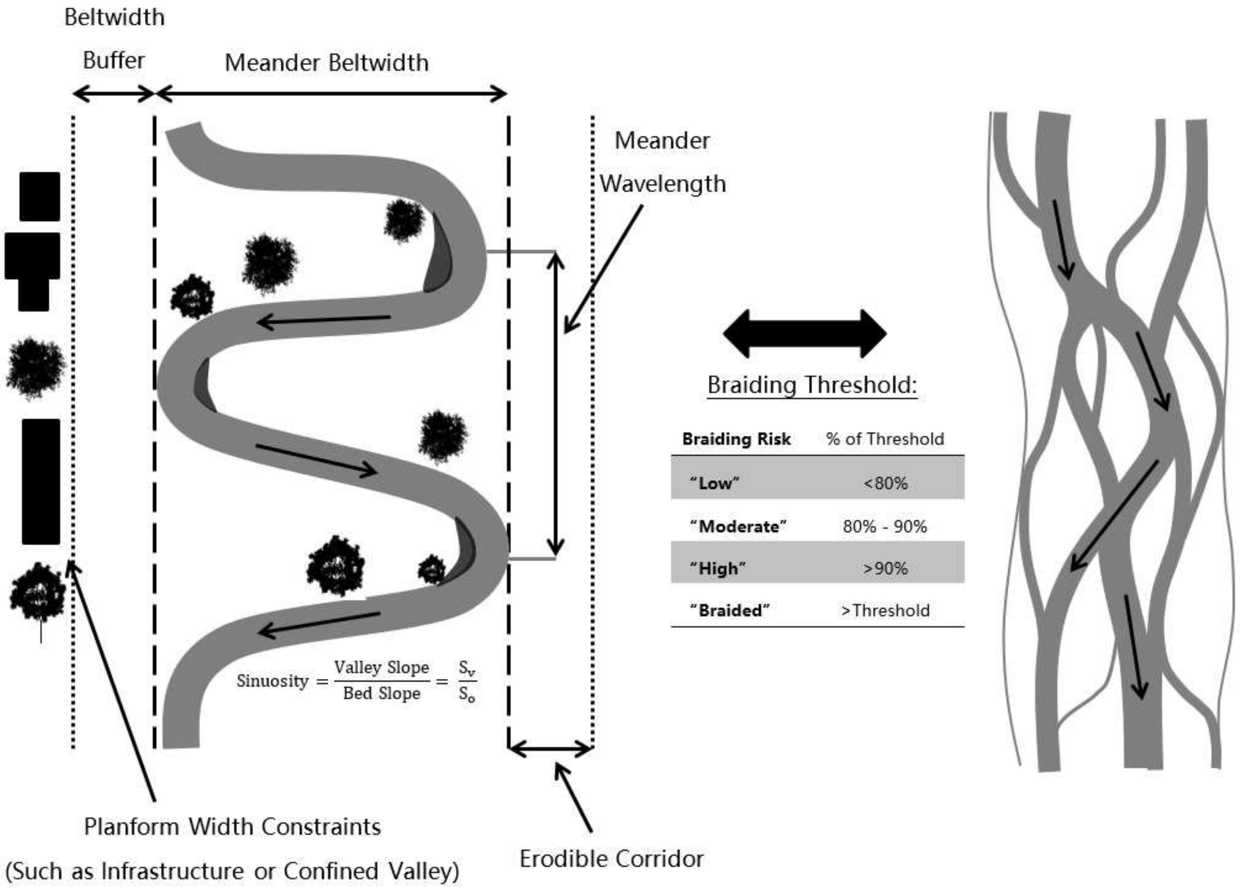
Figure 2-5. Screenshot of required inputs for the supply reach and the design reach of the CSR Tool.

2.3.6 Planform Characteristics

Several additional outputs were added to the results page of the tool including a width-to-depth ratio for each stable channel solution. If a valley slope of the design reach is entered, then each stable channel solution found will have an associated output of

Refer to the CSR Tool Reference Manual (Appendix A) for further explanation of these concepts and the associated equations used.

sinuosity, meander belt width, and a channel braiding risk. The meander belt width is an estimation of the total planform width the river will span to support the projected dimensions and sinuosity of the design (Hagerman and Williams 2000). This can be useful for visualizing the size of the design and determining whether planform width constraints exist in the design area. The user can define a maximum allowable meander belt width between the edge of the river and any planform constraint such as infrastructure. If any solution is over this amount then it will be highlighted in red in the outputs, so the user can know which solutions might conflict with this lateral restriction. Braiding risk is calculated for each slope/width combination using equations developed by van den Berg (1995). The level of risk for each design is calculated based on how close the design is to a braiding threshold. Figure 2-6 shows a visual representation of these planform concepts.



Braiding Risk	% of Threshold
"Low"	<80%
"Moderate"	80% - 90%
"High"	>90%
"Braided"	>Threshold

Figure 2-6. Screenshot of visual representation of the planform descriptors included in the tool.

2.4 Results

The following sections present performance and accuracy testing of the CSR Tool, example outputs and stable channel design solutions for both a sand-bed and a gravel-bed stream, and additional results from various tests of the tool.

2.4.1 CSR Tool Validation

When the CSR Tool is given a single discharge rather than a full FDC, the results can be directly compared to the implementation of the Copeland method in the HEC-RAS stable channel design tool. I found very similar results between HEC-RAS output and single-discharge calculations from the CSR Tool, which fosters confidence in the validity of tool outputs. The data for the following examples were retrieved from Soar and Thorne (2001).

Figure 2-7(a) is an example of the tool output with a single discharge for Big Raccoon Creek in Indiana compared to HEC-RAS's stable channel design using the Copeland method. The CSR Tool and HEC-RAS estimated a total sediment concentration of 342 ppm and 343 ppm, respectively, at 50 cms (1,765 cfs). Figure 2-7(b) shows the supply reach geometry of this example as depicted in the CSR Tool. The bank and floodplain angles were matched to closely approximate the output of the Copeland method which uses a single trapezoid model. This diagram is dynamic to the inputs of the user and displayed on the supply reach tab of the tool for user reference.

Figure 2-8(a) shows another example of the comparison of the single-discharge design outputs for the CSR Tool versus HEC-RAS's stable channel design using the Copeland method. This example is for the South River in North Carolina. The CSR Tool and HEC-RAS estimated a total sediment concentration of 86.7 ppm and 87.4 ppm, respectively, at 25 cms (883 cfs). Figure 2-8(b) shows the supply reach geometry of this example in the CSR Tool. As the last example, the bank and floodplain angles were matched to closely approximate the output of the Copeland method which uses a single trapezoid model.

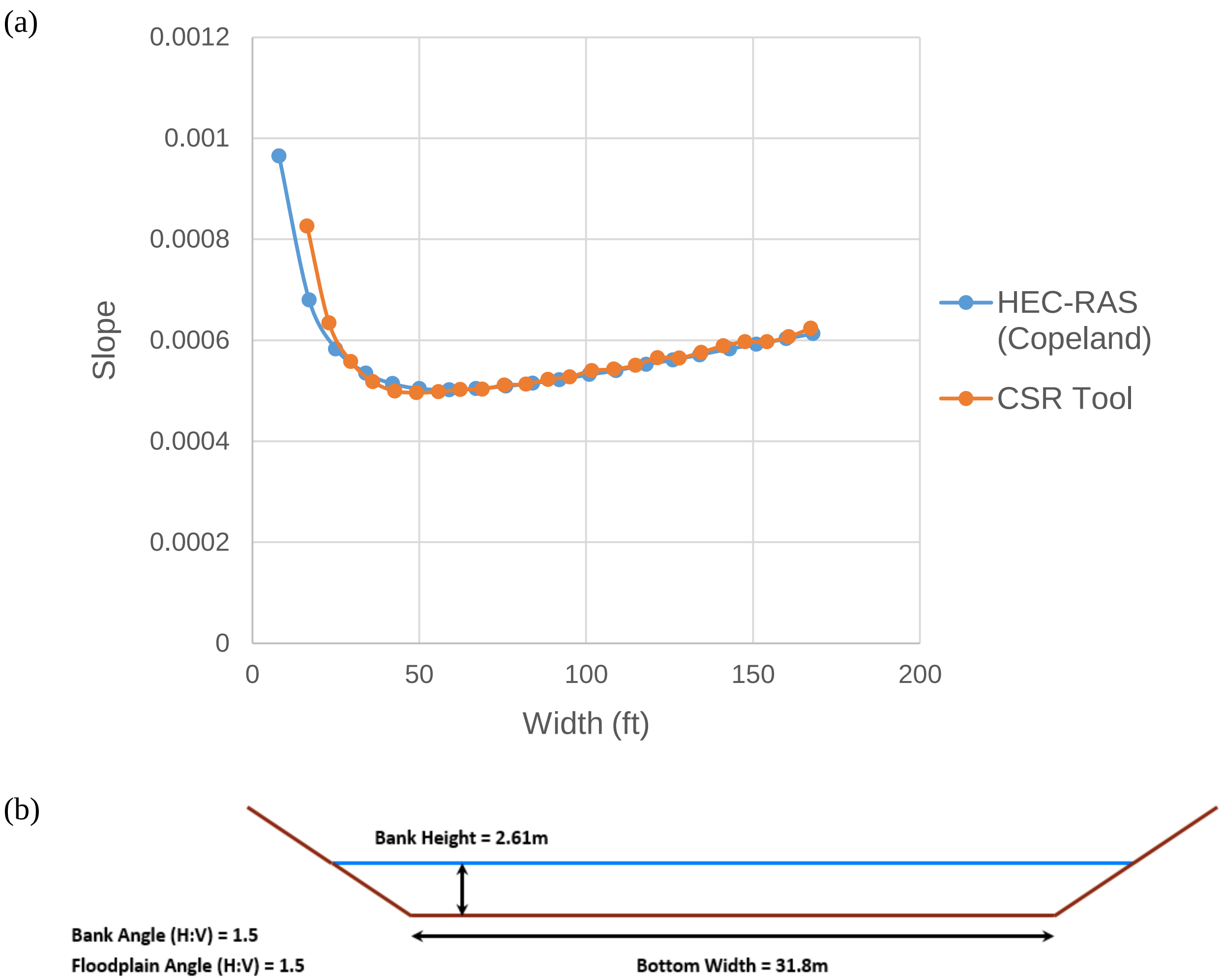


Figure 2-7. (a) Comparison of CSR Tool with HEC-RAS stable channel design using the Copeland method with the same channel dimensions, grain size distribution, and single discharge; and (b) diagram of the supply reach geometry. Example: Big Raccoon Creek, Indiana.

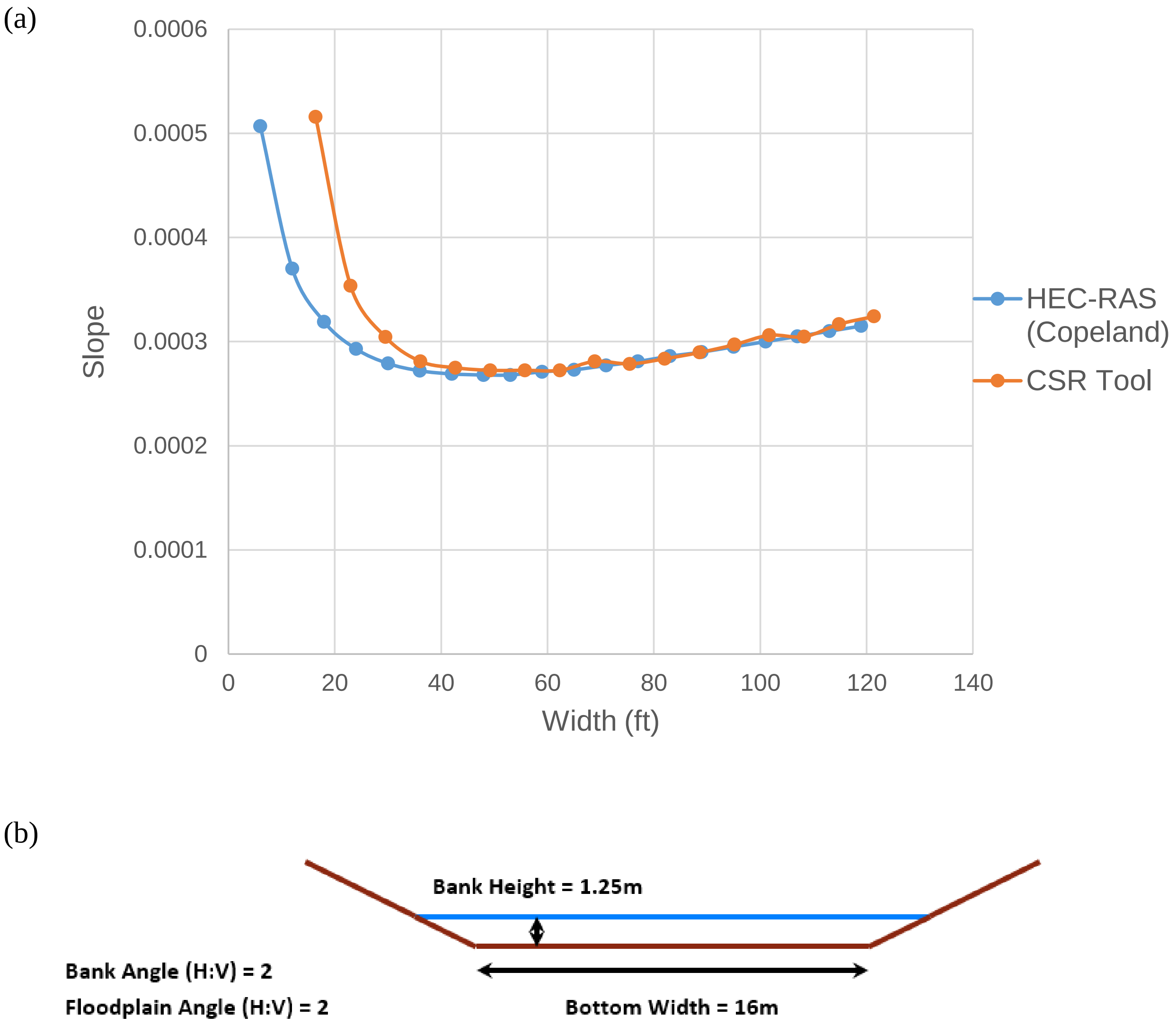


Figure 2-8. (a) Comparison of CSR Tool with HEC-RAS stable channel design using the Copeland method with the same channel dimensions, grain size distribution, and single discharge; and (b) diagram of the supply reach geometry. Example: South River, North Carolina.

The gravel-bed portion of the tool could not be validated for single-discharge design through comparison with output from Copeland's method in HEC-RAS or SAM (Thomas et al. 2002), because the Parker (1990a) and Wilcock-Crowe (2003) equations are not currently available in those software packages. The code used in the CSR Tool for the Parker (1990a) and Wilcock-Crowe (2003) bedload relations was obtained directly from a VBA-based tool created by Gary Parker called the 'acronym' series (Parker 1990b). Gary Parker also added the use of the Wilcock-

Crowe (2003) relationship in his tool in a later version (Parker 2004). These codes were directly implemented in the CSR Tool and adapted to fit the methodology of the CSR analysis. Outputs from the CSR Tool were then compared to results from both Gary Parker's original tools and manual calculations to confirm the output of estimated sediment yield.

2.4.2 CSR Tool Outputs

2.4.2.1 Stable channel design solutions

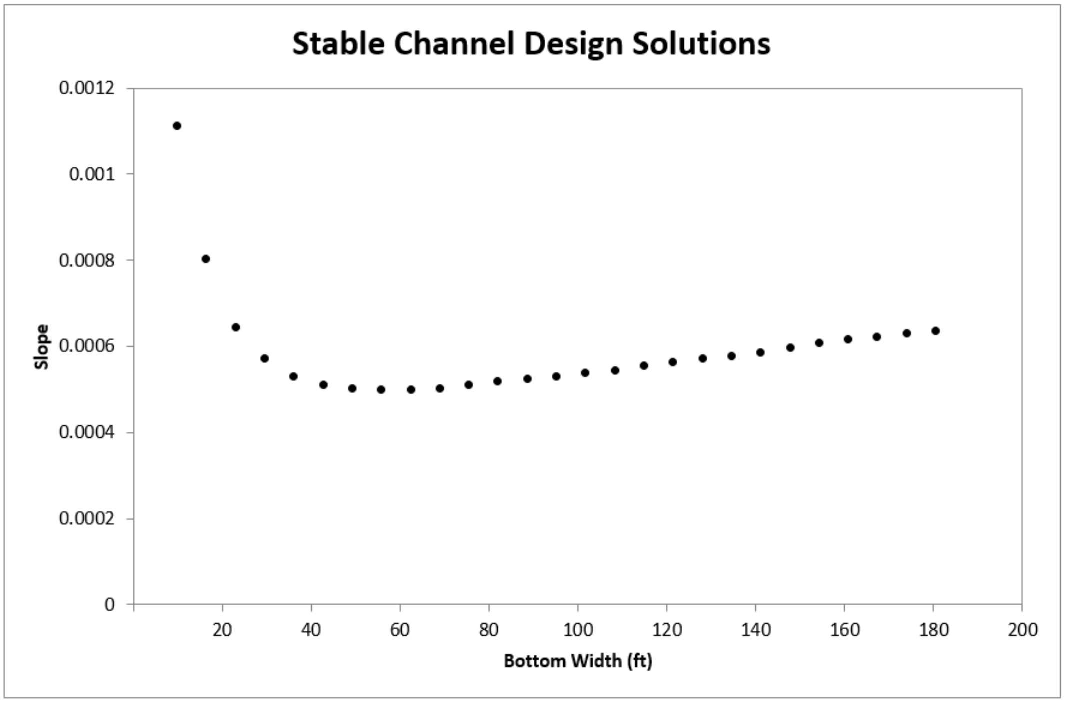
Figures 2-9 through 2-11 (presented and discussed later) show screenshots from the CSR Tool of the output solutions produced for both a sand-bed and a gravel-bed stream. The plot of channel slope/width combinations which provide continuity of water and sediment (i.e., CSR = 1) for the associated sand-bed example is shown in Figure 2-9(a). The associated table of solutions with the planform characteristics listed for each design from the 'Results' tab of the CSR Tool is shown in Figure 2-9(b). An example output from the 'Detailed Results' tab of the CSR Tool for the sand-bed example is shown in Figure 2-10. This is a summary of the 'effectiveness' in tons/day for each average bin discharge for the supply reach. The 'effectiveness' table (Figure 2-10) shows the associated sediment yield percentiles summary. The sediment percentile output shows the discharge that corresponds to the associated percent on the cumulative sediment yield curve (see the CSR Tool Reference Manual (Appendix A) for more information). This output is generated for each stable channel design solution as well and is displayed on the "Detailed Results" tab of the CSR Tool. Furthermore, the plot of channel slope/width combinations that provide continuity of water and sediment (i.e., CSR = 1) for the associated gravel-bed design is shown in Figure 2-11(a), along with the associated table of solutions with the planform characteristics listed for each design (Figure 2-11(b)).

2.4.2.2 Comparing sand-bed versus gravel-bed

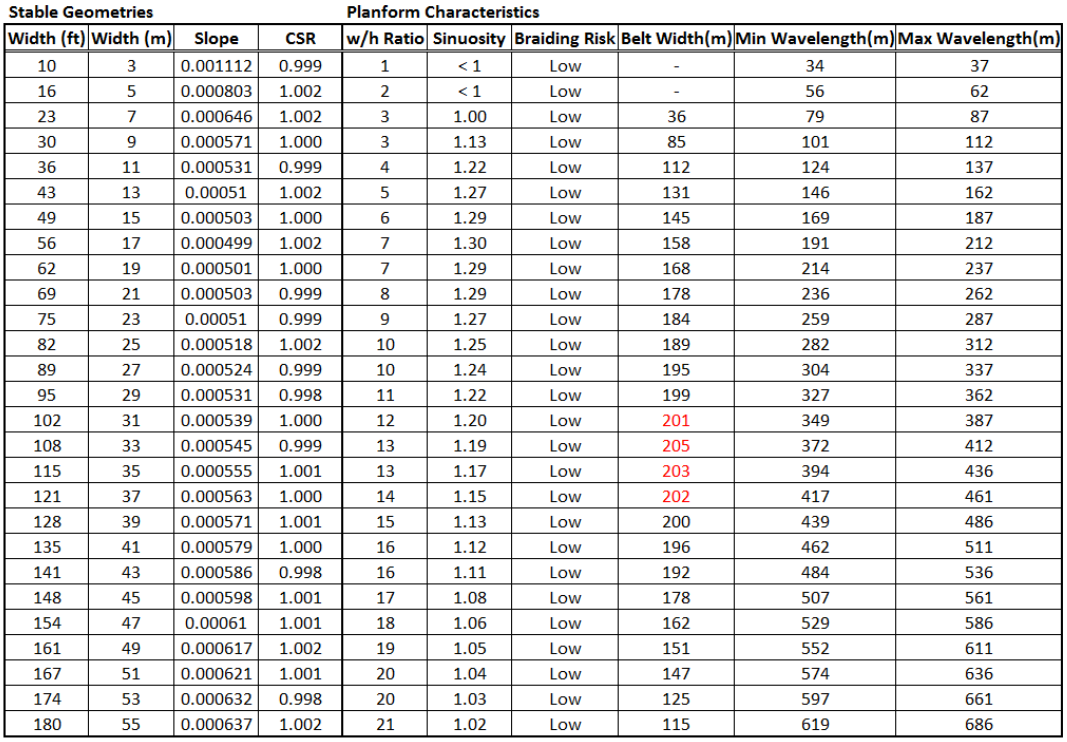
The analytical channel design approach used by the CSR Tool and Copeland method has not been performed on gravel-bed streams, so the CSR Tool can reveal interesting comparisons between the two. The differences between the two stable channel design curves for examples of each channel morphology (sand and gravel) are apparent. Firstly, the slope sensitivity at the lower widths of the stable channel design curve is less for gravel-bed examples versus sand-bed examples. Secondly, the slope of the sand-bed examples change much less sensitive per changes in width than the gravel-bed example.

As stated above, the solutions that are often most viable for design on the stable channel design curve are from the lowest slope (minimum specific stream power) to the outer right of the curve. Comparing this part of the curves in Figures 2-9 and 2-11 indicates that the percent difference in slope for the two channel morphologies is very similar. The sand-bed example, Big Raccoon Creek, has a 23.3% difference and the gravel-bed example, Red River, has a 21.1% difference between the minimum slope and the highest slope on the right-side of the curve. However, this same range spans a much larger spectrum of slopes for the gravel-bed example. More specifically, the average change in slope per change in width is much lower for the sand-bed example than the gravel-bed. The average change in slope per two meters change in width is 0.00011 for the gravel-bed example (Figure 2-11(a)), while only 0.0000074 for the sand-bed example (Figures 2-9(a)).

(a)

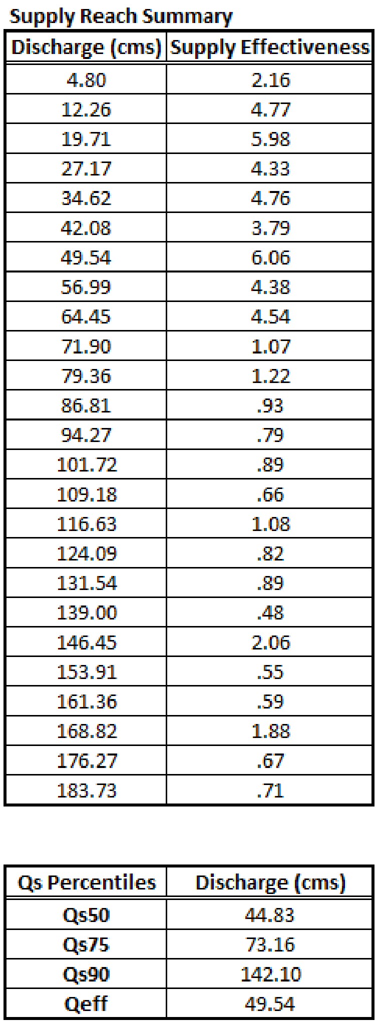


(b)



Stable Geometries				Planform Characteristics					
Width (ft)	Width (m)	Slope	CSR	w/h Ratio	Sinuosity	Braiding Risk	Belt Width(m)	Min Wavelength(m)	Max Wavelength(m)
10	3	0.001112	0.999	1	< 1	Low	-	34	37
16	5	0.000803	1.002	2	< 1	Low	-	56	62
23	7	0.000646	1.002	3	1.00	Low	36	79	87
30	9	0.000571	1.000	3	1.13	Low	85	101	112
36	11	0.000531	0.999	4	1.22	Low	112	124	137
43	13	0.00051	1.002	5	1.27	Low	131	146	162
49	15	0.000503	1.000	6	1.29	Low	145	169	187
56	17	0.000499	1.002	7	1.30	Low	158	191	212
62	19	0.000501	1.000	7	1.29	Low	168	214	237
69	21	0.000503	0.999	8	1.29	Low	178	236	262
75	23	0.00051	0.999	9	1.27	Low	184	259	287
82	25	0.000518	1.002	10	1.25	Low	189	282	312
89	27	0.000524	0.999	10	1.24	Low	195	304	337
95	29	0.000531	0.998	11	1.22	Low	199	327	362
102	31	0.000539	1.000	12	1.20	Low	201	349	387
108	33	0.000545	0.999	13	1.19	Low	205	372	412
115	35	0.000555	1.001	13	1.17	Low	203	394	436
121	37	0.000563	1.000	14	1.15	Low	202	417	461
128	39	0.000571	1.001	15	1.13	Low	200	439	486
135	41	0.000579	1.000	16	1.12	Low	196	462	511
141	43	0.000586	0.998	16	1.11	Low	192	484	536
148	45	0.000598	1.001	17	1.08	Low	178	507	561
154	47	0.00061	1.001	18	1.06	Low	162	529	586
161	49	0.000617	1.002	19	1.05	Low	151	552	611
167	51	0.000621	1.001	20	1.04	Low	147	574	636
174	53	0.000632	0.998	20	1.03	Low	125	597	661
180	55	0.000637	1.002	21	1.02	Low	115	619	686

Figure 2-9. Screenshots from CSR Tool of (a) plot of family of slope/width combinations which provide continuity of water and sediment, and (b) output table of stable geometries and planform characteristics for each solution. Example: Big Raccoon Creek, Indiana (Soar and Thorne 2001).



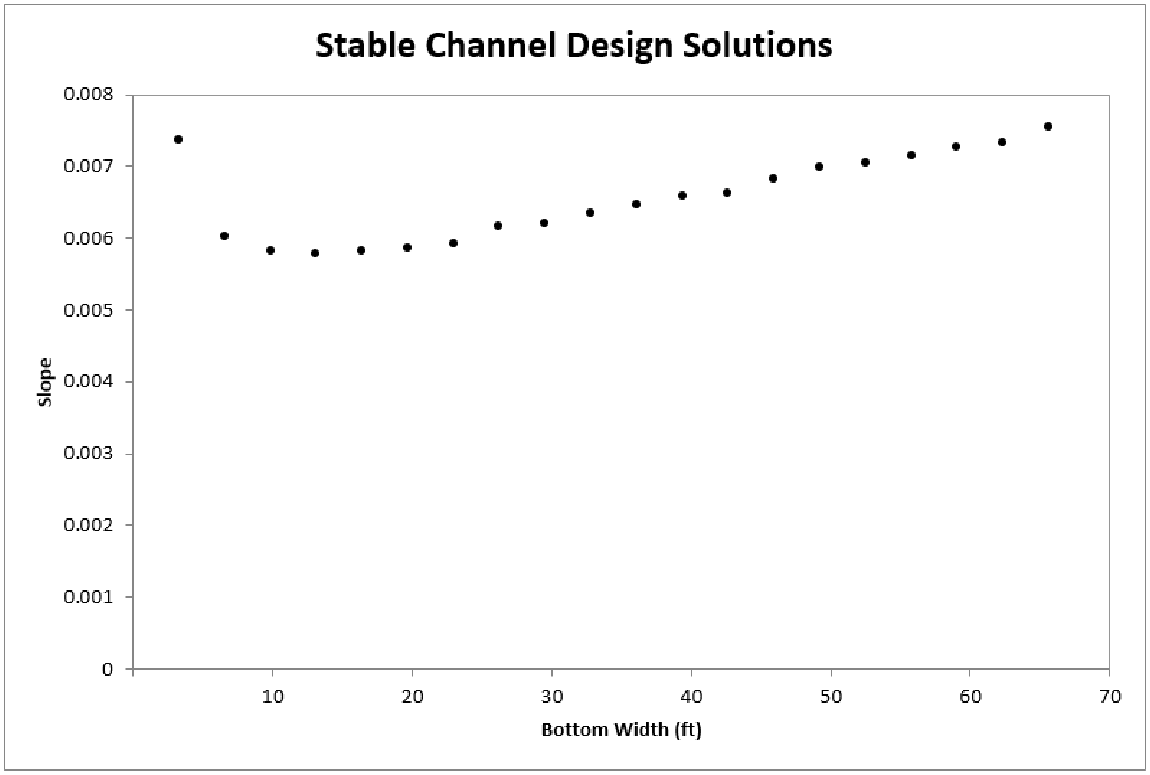
Supply Reach Summary

Discharge (cms)	Supply Effectiveness
4.80	2.16
12.26	4.77
19.71	5.98
27.17	4.33
34.62	4.76
42.08	3.79
49.54	6.06
56.99	4.38
64.45	4.54
71.90	1.07
79.36	1.22
86.81	.93
94.27	.79
101.72	.89
109.18	.66
116.63	1.08
124.09	.82
131.54	.89
139.00	.48
146.45	2.06
153.91	.55
161.36	.59
168.82	1.88
176.27	.67
183.73	.71

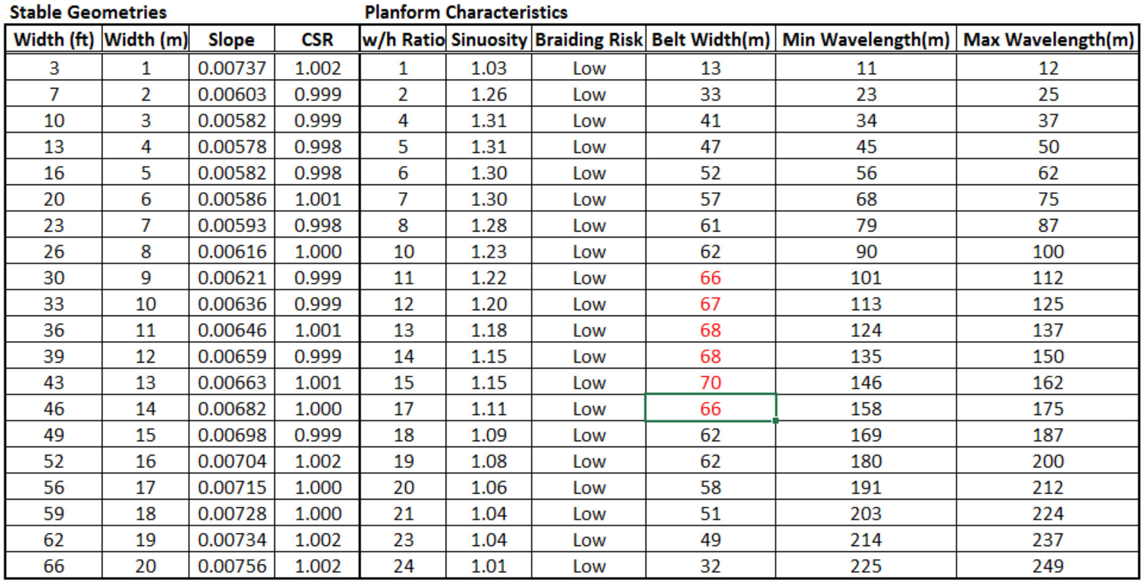
Qs Percentiles	Discharge (cms)
Qs50	44.83
Qs75	73.16
Qs90	142.10
Qeff	49.54

Figure 2-10. Screenshot from CSR Tool of example output on "Detailed Results" tab. Example: Big Raccoon Creek, Indiana (Soar and Thorne 2001).

(a)



(b)



Stable Geometries				Planform Characteristics					
Width (ft)	Width (m)	Slope	CSR	w/h Ratio	Sinuosity	Braiding Risk	Belt Width(m)	Min Wavelength(m)	Max Wavelength(m)
3	1	0.00737	1.002	1	1.03	Low	13	11	12
7	2	0.00603	0.999	2	1.26	Low	33	23	25
10	3	0.00582	0.999	4	1.31	Low	41	34	37
13	4	0.00578	0.998	5	1.31	Low	47	45	50
16	5	0.00582	0.998	6	1.30	Low	52	56	62
20	6	0.00586	1.001	7	1.30	Low	57	68	75
23	7	0.00593	0.998	8	1.28	Low	61	79	87
26	8	0.00616	1.000	10	1.23	Low	62	90	100
30	9	0.00621	0.999	11	1.22	Low	66	101	112
33	10	0.00636	0.999	12	1.20	Low	67	113	125
36	11	0.00646	1.001	13	1.18	Low	68	124	137
39	12	0.00659	0.999	14	1.15	Low	68	135	150
43	13	0.00663	1.001	15	1.15	Low	70	146	162
46	14	0.00682	1.000	17	1.11	Low	66	158	175
49	15	0.00698	0.999	18	1.09	Low	62	169	187
52	16	0.00704	1.002	19	1.08	Low	62	180	200
56	17	0.00715	1.000	20	1.06	Low	58	191	212
59	18	0.00728	1.000	21	1.04	Low	51	203	224
62	19	0.00734	1.002	23	1.04	Low	49	214	237
66	20	0.00756	1.002	24	1.01	Low	32	225	249

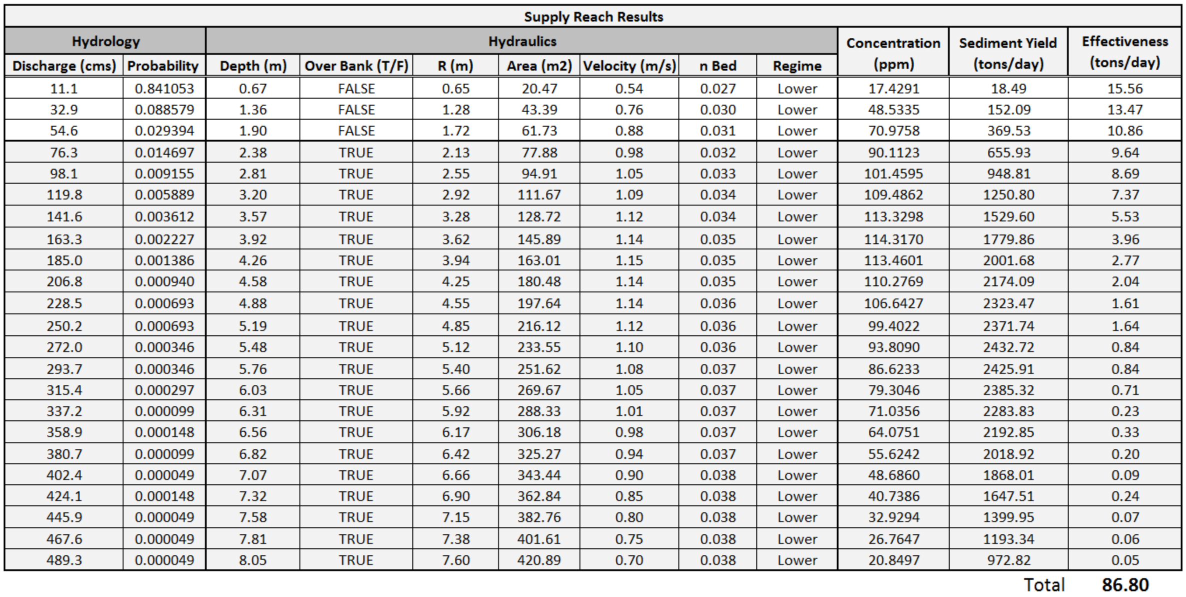
Figure 2-11. Screenshots from CSR Tool of (a) plot of family of slope/width combinations which provide continuity of water and sediment, and (b) output table of stable geometries and planform characteristics for each solution. Example: Red River, Idaho (King et al. 2004)

2.4.2.3 Effects of modeling the floodplain

The inclusion of channel floodplain modeling is a primary difference between the approaches of the CSR Tool and the Copeland method. Intuitive differences in flow characteristics caused by changing the floodplain geometry were confirmed in the model. For example, if the specified floodplain angle is much flatter than the channel banks then physical understanding suggests that the overbank depth and velocity should increase less drastically. The opposite and less common case is also observed for very steep, confined floodplain walls in comparison to the bank angles, which show faster increases in depth and velocity for overbank flows.

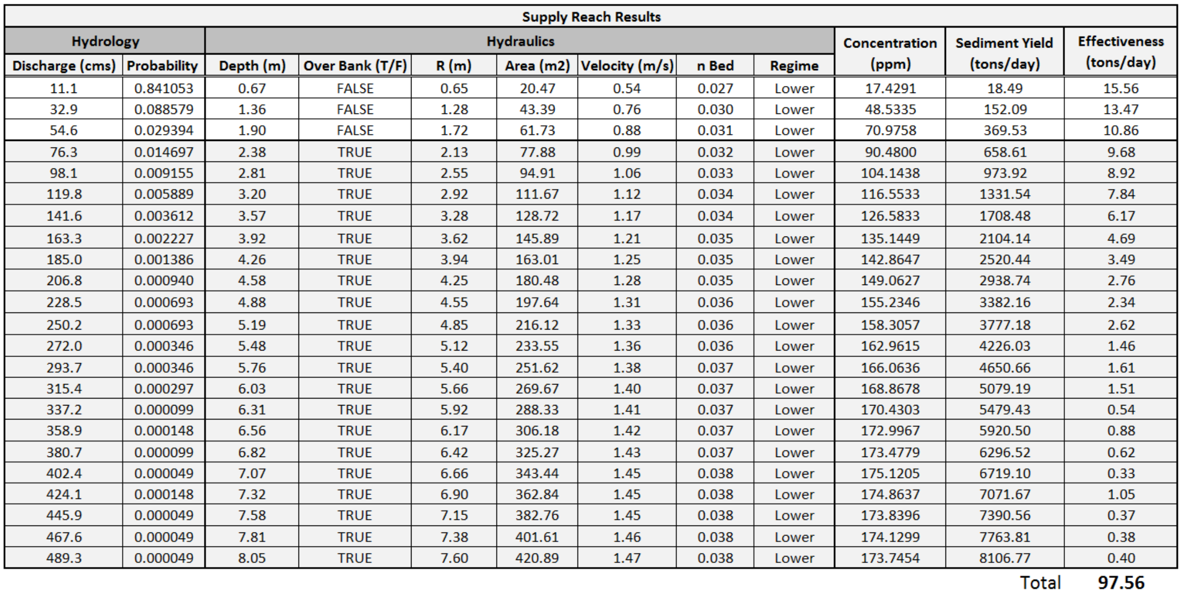
In addition to the influence of floodplain geometry, perhaps less intuitive results are observed by altering floodplain roughness. Figure 2-12 shows the supply reach results for an example of a reach on Sugar Creek in Indiana. These tables show the effects of changing only the Manning’s *n* value of the floodplain. Note that the fourth column from the left of each table shows when the flow is overbank (true) or in-channel (false). This example was chosen because a large portion of the flow record is overbank, which accentuates the effects of changing the floodplain characteristics. The bottom right of Figure 2-12(a) shows that the total estimated sediment yield on average per year, or the effectiveness, is 86.80 tons/day with a floodplain Manning’s *n* of 0.02. The bottom right of Figure 2-12(b) shows the effectiveness increases to 97.56 tons/day with a floodplain Manning’s *n* of 0.07 as would be expected with more flow energy and depth concentrated in the main channel.

(a)



Supply Reach Results											
Hydrology		Hydraulics							Concentration (ppm)	Sediment Yield (tons/day)	Effectiveness (tons/day)
Discharge (cms)	Probability	Depth (m)	Over Bank (T/F)	R (m)	Area (m2)	Velocity (m/s)	n Bed	Regime			
11.1	0.841053	0.67	FALSE	0.65	20.47	0.54	0.027	Lower	17.4291	18.49	15.56
32.9	0.088579	1.36	FALSE	1.28	43.39	0.76	0.030	Lower	48.5335	152.09	13.47
54.6	0.029394	1.90	FALSE	1.72	61.73	0.88	0.031	Lower	70.9758	369.53	10.86
76.3	0.014697	2.38	TRUE	2.13	77.88	0.98	0.032	Lower	90.1123	655.93	9.64
98.1	0.009155	2.81	TRUE	2.55	94.91	1.05	0.033	Lower	101.4595	948.81	8.69
119.8	0.005889	3.20	TRUE	2.92	111.67	1.09	0.034	Lower	109.4862	1250.80	7.37
141.6	0.003612	3.57	TRUE	3.28	128.72	1.12	0.034	Lower	113.3298	1529.60	5.53
163.3	0.002227	3.92	TRUE	3.62	145.89	1.14	0.035	Lower	114.3170	1779.86	3.96
185.0	0.001386	4.26	TRUE	3.94	163.01	1.15	0.035	Lower	113.4601	2001.68	2.77
206.8	0.000940	4.58	TRUE	4.25	180.48	1.14	0.035	Lower	110.2769	2174.09	2.04
228.5	0.000693	4.88	TRUE	4.55	197.64	1.14	0.036	Lower	106.6427	2323.47	1.61
250.2	0.000693	5.19	TRUE	4.85	216.12	1.12	0.036	Lower	99.4022	2371.74	1.64
272.0	0.000346	5.48	TRUE	5.12	233.55	1.10	0.036	Lower	93.8090	2432.72	0.84
293.7	0.000346	5.76	TRUE	5.40	251.62	1.08	0.037	Lower	86.6233	2425.91	0.84
315.4	0.000297	6.03	TRUE	5.66	269.67	1.05	0.037	Lower	79.3046	2385.32	0.71
337.2	0.000099	6.31	TRUE	5.92	288.33	1.01	0.037	Lower	71.0356	2283.83	0.23
358.9	0.000148	6.56	TRUE	6.17	306.18	0.98	0.037	Lower	64.0751	2192.85	0.33
380.7	0.000099	6.82	TRUE	6.42	325.27	0.94	0.037	Lower	55.6242	2018.92	0.20
402.4	0.000049	7.07	TRUE	6.66	343.44	0.90	0.038	Lower	48.6860	1868.01	0.09
424.1	0.000148	7.32	TRUE	6.90	362.84	0.85	0.038	Lower	40.7386	1647.51	0.24
445.9	0.000049	7.58	TRUE	7.15	382.76	0.80	0.038	Lower	32.9294	1399.95	0.07
467.6	0.000049	7.81	TRUE	7.38	401.61	0.75	0.038	Lower	26.7647	1193.34	0.06
489.3	0.000049	8.05	TRUE	7.60	420.89	0.70	0.038	Lower	20.8497	972.82	0.05
										Total	**86.80**

(b)



Supply Reach Results											
Hydrology		Hydraulics							Concentration (ppm)	Sediment Yield (tons/day)	Effectiveness (tons/day)
Discharge (cms)	Probability	Depth (m)	Over Bank (T/F)	R (m)	Area (m2)	Velocity (m/s)	n Bed	Regime			
11.1	0.841053	0.67	FALSE	0.65	20.47	0.54	0.027	Lower	17.4291	18.49	15.56
32.9	0.088579	1.36	FALSE	1.28	43.39	0.76	0.030	Lower	48.5335	152.09	13.47
54.6	0.029394	1.90	FALSE	1.72	61.73	0.88	0.031	Lower	70.9758	369.53	10.86
76.3	0.014697	2.38	TRUE	2.13	77.88	0.99	0.032	Lower	90.4800	658.61	9.68
98.1	0.009155	2.81	TRUE	2.55	94.91	1.06	0.033	Lower	104.1438	973.92	8.92
119.8	0.005889	3.20	TRUE	2.92	111.67	1.12	0.034	Lower	116.5533	1331.54	7.84
141.6	0.003612	3.57	TRUE	3.28	128.72	1.17	0.034	Lower	126.5833	1708.48	6.17
163.3	0.002227	3.92	TRUE	3.62	145.89	1.21	0.035	Lower	135.1449	2104.14	4.69
185.0	0.001386	4.26	TRUE	3.94	163.01	1.25	0.035	Lower	142.8647	2520.44	3.49
206.8	0.000940	4.58	TRUE	4.25	180.48	1.28	0.035	Lower	149.0627	2938.74	2.76
228.5	0.000693	4.88	TRUE	4.55	197.64	1.31	0.036	Lower	155.2346	3382.16	2.34
250.2	0.000693	5.19	TRUE	4.85	216.12	1.33	0.036	Lower	158.3057	3777.18	2.62
272.0	0.000346	5.48	TRUE	5.12	233.55	1.36	0.036	Lower	162.9615	4226.03	1.46
293.7	0.000346	5.76	TRUE	5.40	251.62	1.38	0.037	Lower	166.0636	4650.66	1.61
315.4	0.000297	6.03	TRUE	5.66	269.67	1.40	0.037	Lower	168.8678	5079.19	1.51
337.2	0.000099	6.31	TRUE	5.92	288.33	1.41	0.037	Lower	170.4303	5479.43	0.54
358.9	0.000148	6.56	TRUE	6.17	306.18	1.42	0.037	Lower	172.9967	5920.50	0.88
380.7	0.000099	6.82	TRUE	6.42	325.27	1.43	0.037	Lower	173.4779	6296.52	0.62
402.4	0.000049	7.07	TRUE	6.66	343.44	1.45	0.038	Lower	175.1205	6719.10	0.33
424.1	0.000148	7.32	TRUE	6.90	362.84	1.45	0.038	Lower	174.8637	7071.67	1.05
445.9	0.000049	7.58	TRUE	7.15	382.76	1.45	0.038	Lower	173.8396	7390.56	0.37
467.6	0.000049	7.81	TRUE	7.38	401.61	1.46	0.038	Lower	174.1299	7763.81	0.38
489.3	0.000049	8.05	TRUE	7.60	420.89	1.47	0.038	Lower	173.7454	8106.77	0.40
										Total	**97.56**

Figure 2-12. Screenshots from CSR Tool of the supply reach results table for both (a) floodplain Manning's *n* of 0.02, and (b) floodplain Manning's *n* of 0.07. Example: Sugar Creek, Indiana.

2.5 Discussion

2.5.1 Deviations between the CSR Tool Output and HEC-RAS Copeland Output

Figures 2-9 and 2-11 (above) show close correspondence between the CSR Tool output using a single discharge and the HEC-RAS stable channel design tool based on the Copeland method. The main deviation between the two curves is in the narrowest widths where the curve steepens drastically. These deviations can be explained by the difference in channel partitioning between the two tools as explained above and shown in Figure 2-3. As the width decreases toward the left-side of the plots in Figures 2-7 and 2-8, the depth increases drastically with constant discharge. As this depth increases, the channel partitioning method used in the CSR Tool changes to what is seen in Figure 2-3(b) and the Copeland method remains the same. Thus, even though the bank and floodplain angles were matched in the examples to model a single trapezoidal channel, the change in partitioning method alters the lower width solutions slightly between the tool outputs. The effect is seen more in Figure 2-8 than in Figure 2-7 presumably because the bank height is lower for the South River, so more of these lower widths have overbank flow and use the alternative overbank partitioning method.

2.5.2 More Effects of Modeling the Floodplain

As expected, floodplain flows alter model outputs as a result of differences in cross-sectional area between the in-channel geometry and the compound in-channel and overbank channel combination. However, more complex behavior arises in a sensitivity analysis of floodplain roughness values in the CSR Tool. Sediment transport capacity increases with floodplain roughness as would be expected with more flow energy and depth concentrated in the main channel. This concentration can increase the velocity over the bed, causing more sediment transport capacity than lower roughness floodplains. This affect can be especially conspicuous in this model since sediment transport is assumed to occur only on the bed of the channel. The effect of the floodplain roughness and changes to the floodplain geometry are the most apparent in examples that have a great amount of overbank flows in the flow record such as in Figure 2-12.

Many other examples that have less frequent overbank flows show a relatively small effect of changing floodplain characteristics on cumulative sediment transport.

2.5.3 Differences between Sand-bed and Gravel-bed Solutions

Unlike previous tools, the CSR Tool facilitates comparison of sand- versus gravel-bed designs. In reality, there is not a discrete threshold between sand- and gravel-bed streams but rather a continuous spectrum of morphological types with different grain size mixtures (Montgomery and Buffington 1997; Schumm 1977). However, there are distinct characteristics exhibited by streams that are dominated by one or the other (Church 2002; Howard 1987), and accordingly, there are clear differences between the solutions for sand-bed and gravel-bed streams (Figures 2-9 and 2-11, respectively) using the CSR analysis. The two most distinct differences between the stability curves for sand-bed and gravel-bed examples are the slope sensitivity at lower widths and the sensitivity of slope to changes in width.

In general, the gravel-bed solution curves rise less steeply at lower widths than the sand-bed curves relative to the increase in slope on the right-side of the curves. Many gravel-bed examples only have small increases relative to the change in slopes on the right-side of the curve or no increase at all. The differences between sand and gravel examples on this part of the curve is attributed to the mechanisms that drive up the slopes for each channel morphology which are attributed to changes in shear stress for gravel and changes in velocity and bedforms for sand. The sand-bed mechanisms are evidently more influential than the gravel, because the slope is consistently more sensitive at lower widths on the stable curve. Although, as previously stated, the solutions on this part of the curve are often less realistic than the solutions on the right-side of the curve, since they usually do not fall within the realm of most downstream hydraulic geometry equations and field observations of how width scales with bankfull discharge.

The comparisons between the percent differences in slope for Big Raccoon Creek and Red River showed similar results suggesting that the sediment balance methodology used by the tool behaves similar for sand and gravel and may be applied in a similar way. However, further analysis showed great discrepancies between the absolute differences in slope per changes in width for these examples. This is expected because of the differences in sediment transport characteristics of each channel morphology. More change in slope is required for gravel-dominated streams to produce the difference in sediment yield required to match the inflowing sediment load, because it demands more energy to mobilize the larger grains. This is the main contribution to why the Red River gravel example needs more change in slope per change in width to maintain a CSR of unity. On the other hand, sand particles are characteristically more easily mobilized than gravel and larger particles thus respond much more drastically to changes in flow characteristics. This morphologic trait enables sand-bed streams to require less change in slope to produce a larger change in sediment yield in comparison to more resistant gravel- / cobble-bed streams. In a practical design situation, this suggests there is a much tighter band or tolerance of solutions that will provide the continuity of water and sediment for sand-dominated streams. Thus, a designer might need to take more caution when selecting a design slope for sand-bed streams to avoid excessive erosion or sedimentation. Additionally, large sand fractions in gravel streams can greatly increase gravel transport rates and thus could display similar transport characteristics to sand-bed streams and need just as much caution in the design process (Wilcock et al. 2001).

2.5.4 Strengths and Weaknesses of the CSR Tool

The CSR Tool has many features that improve the physical basis of stable channel design, but still has many caveats that can limit its applicability. In general, the approach requires specification of an incoming sediment load to the design reach to calculate the sediment balance.

In the context of this tool, this requires the user to have a stable upstream supply reach that will be representative of the incoming sediment load into the design reach. This can introduce many uncertainties / or may not be possible at all in some situations. Secondly, the sediment balance is based on estimates from sediment transport equations, which inherently have great uncertainties. Although, some uncertainties are alleviated using this approach because the solutions are based off a relative balance from the same equation rather than relying on any absolute magnitude.

The CSR approach adds the complexity of modeling sediment transport across the entire FDC rather than relying on a single representative discharge. This approach is much more representative of which flows the actual channel conveys through time, but still requires many assumptions in the design process. First, the flow record used must be available for a stable upstream supply reach and be representative of inflows to the design reach of interest, or the user must use a derived FDC that is often based on regionalized curves and extrapolation to ungaged sites that can add additional uncertainty. Secondly, in order to calculate the ‘effectiveness’ or the estimated total sediment transported for the channel, a binning procedure must be used with average discharges which can substantively change the output depending on the method used.

Lastly, the CSR Tool has many fundamental assumptions as do all hydraulic models. The underlying hydraulic relationships are based on 1-D cross-section averaged, steady flow, sediment transport is assumed to only happen on the bed even when flow is overbank, and the cross section is trapezoidal. Overall, the CSR Tool can better account for the full range of geomorphically effective flows over the single-discharge methods, but remains a highly simplified representation of a complex system that provides one line of evidence in the overall design process.

2.6 Conclusion

The practice of stream channel design is very broad-based and encompasses a diverse set of tools and applications. Channel design is a very complex task and involves numerous factors that can influence the design outcome. Riverine ecosystems are in many ways too complex to consider all the influencing factors on the design, but it can be argued that establishing an approximate balance of water and sediment can provide a platform upon which to foster other essential ecosystem functions (Wohl et al. 2015). The CSR Tool enhances the channel designer's toolbox and bolsters the design of channels formed in response to a wide range of influential flows with its greater emphasis on physical processes compared to analog or single-discharge approaches.

The CSR Tool developed in this study performs a full spectrum analytical channel design calculation using the CSR sediment balance concept. Outputs include a family of stable channel design solutions that provide the continuity of water and sediment over the entire FDC, which can provide a more complete physical basis than analyses that rely on a single representative discharge design methodology (Soar and Thorne 2001). The tool has been verified for accuracy with comparisons to the Copeland method in HEC-RAS with slight deviations that can most likely be explained from the difference in modeling approach for overbank flow. The CSR Tool has the additional feature of floodplain modeling which can increase the fidelity of the model to actual physical processes. I found that higher floodplain roughness concentrates flow in the channel and increases velocity and, therefore, sediment transport capacity. Lastly, the CSR Tool provides the ability to perform the CSR analysis on both sand- and gravel-bed streams. Comparisons between the resulting stability curves for the sand- and gravel-bed examples (Figures 2-9 and 2-11, respectively) show that stable slopes for sand often change much less per unit width and thus have a tighter tolerance for stable slope configurations. This finding supports my hypothesis that the CSR analysis will be more important for finer grain channels.

2.6.1 New Questions and Future Directions

Upon developing and exploring the outputs of the CSR Tool, many new questions and possible new directions for research arise. The simplifying assumptions mentioned above point to potential improvements that could enhance the physical rigor of the tool. However, such improvements can increase data requirements and complexity. Here I focus on variables and methods to which the tool is particularly sensitive.

The assumption that the cross-section averaged flow is the same for the bank and bed components (Einstein 1950) is questionable in naturalized channels and alternative methods could produce better results. In the context of the CSR Tool, the Einstein (1950) equation could not be used for overbank flow which results in some inconsistency between models. Future versions could apply the same methodology for both in-channel and overbank flow.

Another main assumption in the model is that sediment transport only occurs over the bed partition. This can be a reasonable assumption in many instances, certainly with in-channel flow over a large bottom width with steep banks; however, with the addition of floodplain modeling, the assumption is stretched even further. One hypothesis of this research is that the CSR method can provide a more encompassing physical basis over single-discharge designs when there are multiple influential flows for sediment transport, and that the most influential flows on sediment transport are often overbank. The current model only accounts for the change in area and roughness for overbank flows and does not consider sediment transported on floodplains. If this process was considered, it could lend support to the aforementioned assumption in some scenarios, although modeling floodplain sediment transport can become very complicated especially when there is heavy vegetation or grain size mixtures that are different than the bed.

As with any tool or model, the best way to verify and strengthen its utility is through application and experience in practice. There could be much gained from applying the CSR Tool to case studies in channel design such as the evaluation of the failed restoration design at White Marsh Run in Maryland by Soar and Thorne (2001). Also, using the tool to compare to designs implemented in projects, or using flume studies to test a specific aspect of the CSR analysis.

REFERENCES

Biedenharn, D.S., R.R. Copeland, C.R. Thorne, P.J. Soar, R.D. Hey, and C.C. Watson. 2000. "Effective Discharge Calculation: A Practical Guide." *Technical Report No. ERDC/CHL TR-00-15*, U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Bledsoe, B.P., D. Baker, P.A. Nelson, T. Rosburg, J. Sholtes, and T.R. Stroth. Submitted 2016. "Design Hydrology for Stream Restoration and Channel Stability at Stream Crossings." Prepared for National Cooperative Highway Research Program (NCHRP) Project 24-40.

Brownlie, W.R. 1981. "Prediction of Flow Depth and Sediment Discharge in Open-channels." *Report No. KH-R-43A*, California Institute of Technology, W.M. Keck Laboratory, Pasadena, CA.

Brownlie, W.R. 1983. "Flow Depth in Sand-bed Channels." *Journal of Hydraulic Engineering*, Vol. 109, No. 7, pp. 959–990, DOI: 10.1061/(ASCE)0733-9429(1983)109:7(959).

Brunner, G.W. 2010. "HEC-RAS River Analysis System, User's Manual." *Report No. CPD-68*, Version 4.1, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, 790 p., URL: http://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS_4.1_Users_Manual.pdf.

Church, M. (2002). "Geomorphic Thresholds in Riverine Landscapes." *Freshwater Biology*, Vol. 47, No. 4, pp. 541–557, URL: 10.1046/j.1365-2427.2002.00919.x.

Copeland, R.R. 1994. "Application of Channel Stability Methods – Case Studies." *Technical Report HL-94-11*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, September, 60 p., URL: http://www.dtic.mil/dtic/tr/fulltext/u2/a285625.pdf.

Doyle, M.W., D. Shields, K.F. Boyd, P.B. Skidmore, and D. Dominick. 2007. "Channel-forming Discharge Selection in River Restoration Design." *Journal of Hydraulic Engineering*, Vol. 133, No. 7, pp. 831–837, DOI: 10.1061/(ASCE)0733-9429(2007)133:7(831).

Einstein, H.A. 1950. "The Bed Load Function for Sediment Transport in Open Channel Flows." *Technical Bulletin No. 1026*, U.S. Department of Agriculture, Soil Conservation Service, Washington, DC.

Hagerman, J.R., and J.D. Williams. 2000. "Meander Shape and the Design of Stable Meanders." Pages 563–568 in: *Riparian Ecology and Management in Multi-land Use Watersheds*, Proceedings of the American Water Resources Association, Spring Specialty Conference, Anchorage, AK, April 30 - May 4.

Howard, A.D. 1987. "Modelling Fluvial Systems: Rock-, Gravel-, and Sand-bed Channels." Pages 69–94 in K. Richards (Ed.): *River Channels: Environment and Process*, Blackwell, New York, NY.

King, J.G., W.W. Emmett, P.J. Whiting, R.P. Kenworthy, and J.J. Barry. 2004. "Sediment Transport Data and Related Information for Selected Coarse-Bed Streams and Rivers in Idaho." *General Technical Report RMRS-GTR-131*, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 26 p., URL: http://www.fs.fed.us/rm/pubs/rmrs_gtr131.pdf\.

Limerinos, J.T. 1970. "Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels." *U.S. Geological Survey Water-Supply Paper 1898-B*, 47 p., U.S.

Government Printing Office, Washington, DC, URL: http://pubs.usgs.gov/wsp/1898b/report.pdf.

Montgomery, D.R., and J.M. Buffington. 1997. "Channel-reach Morphology in Mountain Drainage Basins." *Geological Society of America Bulletin*, Vol. 109, No. 5, pp. 596–611, DOI: 10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2.

Parker, G. 1990a. "Surface-based Bedload Transport Relation for Gravel Rivers." *Journal of Hydraulic Research*, Vol. 28, No. 4, pp. 417–436, DOI: 10.1080/00221689009499058.

Parker, G. 1990b. "The "acronym" Series of Pascal Programs for Computing Bedload Transport in Gravel Rivers." *External Memorandum M-220*, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MN, 24 p.

Parker, G. 2004. "The "acronym" Series of Pascal Programs for Computing Bedload Transport in Gravel Rivers." *External Memorandum M-220*, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MN, 24 p.

Schumm, S.A. 1977. *The Fluvial System*. Vol. 338, Wiley, New York, NY.

Skidmore, P.B., F.D. Shields, M.W. Doyle, and D.E. Miller. 2001. "A Categorization of Approaches to Natural Channel Design." Pages 1–12 in D.F. Hays (Ed.): *Proceedings of the 2001 Wetlands Engineering and River Restoration Conference*, Reno, NV, August 27-31, DOI: 10.1061/40581(2001)38.

Soar, P.J., and C.R. Thorne. 2001. "Channel Restoration Design for Meandering Rivers." *Technical Report No. ERDC/CHL CR-01-1*, Coastal and Hydraulics Laboratory, U.S. Army, Engineer Research and Development Center, Vicksburg, MS, URL: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043218.pdf.

Soar, P.J., and C.R. Thorne. 2013. "Design Discharge for River Restoration." Pages 123–150 in A. Simon, S.J. Bennett, and J.M. Castro (Eds.): *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*, Geophysical Monograph Series, Volume 194, American Geophysical Union, Geopress, Washington, DC.

Thomas, W.A., R.R. Copeland, and D.N. McComas. 2002. "SAM Hydraulic Design Package for Channels." Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Vicksburg, MS, URL: http://www.stream.fs.fed.us/fishxing/fplibrary/ACOE_2002_SAM_Hydraulic_Design_Package_for_Channels.pdf.

van den Berg, J.H. 1995. "Prediction of Alluvial Channel Pattern of Perennial Rivers." *Geomorphology*, Vol. 12, No. 4, pp. 259–279, DOI: 10.1016/0169-555X(95)00014-V.

Wilcock, P.R., S.T. Kenworthy, and J.C. Crowe. 2001. "Experimental Study of the Transport of Mixed Sand and Gravel." *Water Resources Research*, Vol. 37, No. 12, pp. 3349–3358, DOI: 10.1029/2001WR000683.

Wilcock, P.R., and J.C. Crowe. 2003. "Surface-based Transport Model for Mixed-size Sediment." *Journal of Hydraulic Engineering*, Vol. 129, No. 2, pp. 120–128, DOI: 10.1061/(ASCE)0733-9429(2003)129:2(120).

Wohl, E., B.P. Bledsoe, R.B. Jacobson, N.L. Poff, S.L. Rathburn, D.M. Walters, and A.C. Wilcox. 2015. "The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management." *Bioscience*, Vol. 65, No. 4, pp. 358–371, DOI: 10.1093/biosci/biv002.

CHAPTER 3: CSR TOOL APPLICATIONS

3.1 Introduction

Efforts to manage watersheds for freshwater sustainability have become increasingly important as pressures from population growth and development increasingly strain water resources in an atmosphere of burgeoning climate uncertainty. Almost half (44%) of the rivers in the United States are listed as polluted or impaired, and extinction rates of fresh-water fauna are five times that for terrestrial biota (U.S. Environmental Protection Agency (EPA) 2009; Ricciardi and Rasmussen 1999; Strayer and Dudgeon 2010). Human influences such as urban development can trigger rapid geomorphic change in streams with excessive erosion or sedimentation that can compromise surrounding infrastructure and impede municipal or recreational usages (Hawley et al. 2012; Trimble 1997; Piégay et al. 1997). These issues often have a common root cause: river channel instability resulting from altered flows of water and sediment. Fortunately, these issues can be addressed in many instances through stream restoration and the application of stable channel design principles. Stable channel design aims to bring a river channel to a state of dynamic equilibrium between flows of water and sediment, which can reduce excess lateral and vertical instability, as well as improve water quality and habitat for biota (Wohl et al. 2015).

There is a diverse and eclectic array of methods used in the current practice of river-channel design; however, the most common methods usually involve a particular reliance on the use of reference reaches and designing the channel to a single ‘dominant’ discharge. This single discharge is often assumed to be the discharge that most influences channel form and an adequate proxy of all flows that influence channel form in the flow regime (Doyle et al. 2007). Many problems such as excessive erosion or sedimentation that leads to an unstable channel can arise if care and sound judgment are not employed in choosing the proper discharge, recognizing the limitations of comparing to a reference system, and using regionalized relationships. These techniques can be highly uncertain and often oversimplify the site-specific processes that govern channel morphodynamics. Furthermore, even if great effort is put into finding a single representative discharge, resulting designs may still lead to an unstable channel design because other influential flows were not accounted for in the analysis (Bledsoe et al. 2016).

Analytical channel design is an alternative approach with the potential to alleviate some of these uncertainties by utilizing hydraulic models and sediment transport functions to derive equilibrium conditions, which makes it applicable to scenarios where historic or current conditions are not in a state of equilibrium between water and sediment (Skidmore et al. 2001). This approach is often described as process-based because it relies on finding a site-specific equilibrium state of the fluxes governing overall channel stability, i.e., water and sediment continuity (Beechie et al. 2010). This concept is essential to effective river management because the balance of water and sediment is a fundamental driver of river condition, affecting water quality, thermal regime, habitat and aquatic communities, river stability, and natural hazards (Wohl et al. 2015).

A well-known application of the analytical design concept is the Copeland method (Brunner 2010; Copeland 1994) in the stable channel design feature of HEC-RAS made by the U.S. Army Corp of Engineers (USACE; Brunner 2010). This method involves a sediment balance analysis for channel design which can potentially reduce the uncertainty associated with the aforementioned methods; however, this method still relies on calculating the sediment balance using a single dominant discharge and does not account for the sediment transported by any other flows. The assumptions stated above associated with using a single-discharge methodology can increase the risk of highly unstable channel designs since other influential flows substantially affect sediment transport.

A more recent approach that aims to improve the physical basis of the Copeland method is the CSR method introduced by Soar and Thorne (2001). This approach is analogous to the Copeland method; however, it balances the total sediment delivered from an upstream supply reach through a design reach across the entire FDC. The CSR approach can provide a more rigorous analysis of stable channel designs compared to single-discharge methods because it accounts for the influence of geomorphically effective discharges across the entire FDC and thereby alleviating the uncertainty of selecting and assuming the dominant influence of a single discharge (Soar and Thorne 2013). There are many uncertainties that can arise in the CSR methodology as well, specifically in deriving a representative FDC; however, this approach nevertheless has the potential to provide a more comprehensive and robust channel design analysis over the single-discharge technique. This begs the question: are there design scenarios (channel types, etc.) in which it is more important to use the CSR approach over the simplified single-discharge design? Soar and Thorne (2001) developed the CSR to explore the design flaws that led to a failed river-restoration project at White Marsh Run in Maryland. They demonstrated how analysis based on CSR is useful for explaining the sediment imbalance involved with the original analog-based design. Unfortunately, since this publication, the CSR approach has not been widely investigated nor applied in practical design scenarios. A limiting factor in research on and development of the CSR method has been the lack of a tool that allows users to readily assess sediment continuity across the FDC of supply and design reaches, because it can be a cumbersome and time-consuming iterative analysis without the use of software. This has limited the use of the method to produce batch results for research or practical tests of design efficacy. Thus there is a pressing need for: (1) a tool that can facilitate the CSR analysis and provide users with the full spectrum of information needed in the stable channel design process, and (2) research to define the design situations in which the CSR approach is most needed for sustainable and robust channel designs.

In this study, I describe the development of a software tool, hereafter referred to as the "CSR Tool," created to facilitate analytical channel design using the CSR method to produce a range of possible design solutions that provide sediment continuity across the entire FDC. I test the CSR Tool through application to eighteen sand-bed rivers to understand deviations between single-discharges versus CSR designs and identify the situations in which it is most important to use the CSR method over a conventional single-discharge approach. I hypothesize that there will be situations where the CSR analysis is recommended over a single-discharge approach, especially in 'labile' channels with highly erodible substrate, and 'flashy' hydrologic regimes that produce a relatively wide range of influential flow events. Here 'labile' is defined as an alluvial channel type that has bed sediments that are easily and frequently entrained by flow, have fine grains (typically sand bed), and can characteristically undergo rapid morphological change (Church 2006). For the sake of this research, 'flashiness' is defined as a perennial flashiness, or the amount of change in discharge from day-to-day as per Baker et al. (2004) rather than describing dynamic, ephemeral streams. Lastly, I seek to identify the single-discharge designs that are most likely to match the CSR output. Finally, I hypothesize designs based on the half-load discharge (Q_{s50}), the discharge associated with 50% of the cumulative sediment yield (Sholtes and Bledsoe 2016; Vogel et al. 2003), will match CSR designs closer than conventional proxies for the full range of geomorphically effective flows, i.e., the bankfull and effective discharges (Andrews 1980; Emmett and Wolman 2001; Shields et al 2003).

3.2 Background

3.2.1 CSR Method

The CSR concept was introduced by Soar and Thorne (2001). They used this concept to analyze the faults in a channel design that led to a failed river-restoration project at White Marsh Run in Maryland. It is an extension of the Copeland method developed by Dr. Ronald Copeland for the USACE SAM software package (Copeland 1994), and subsequently included in the stable channel design section of HEC-RAS. The CSR is an analytical channel design methodology that uses a simple balance between the *capacity* of a design reach to transport sediment, and the *supply* of sediment transported into the design reach. This is the same sediment balance concept as used in the Copeland method; however, the difference lies in the range of discharge(s) for which the sediment transport capacity is calculated over a period of years:

$$\mathrm{CSR} = \frac{\int_{\mathrm{time}} \text{transport capacity of Design Reach}}{\int_{\mathrm{time}} \text{transport capacity of Supply Reach}} \qquad \textbf{(3-1)}$$

Equation (3-1) defines the CSR as the bed-material load transported through the river reach by a sequence of flows over an extended time period divided by the bed-material load transported into the reach by the same sequence of flows over the same time period (Soar and Thorne 2001). Ultimately, the CSR method balances the total average sediment yield over an entire distribution of flows for a particular time period rather than just for a single representative discharge as in the Copeland method. The sequence of flows over an extended time period is derived from a user-defined gage flow record, or a FDC from another source such as a hydrologic model for the river reach of interest. A magnitude/frequency analysis (MFA) is performed to find the ‘effectiveness,’ or sediment transported on average over a period of time, by multiplying the probability of flows by their estimated sediment transport capacity (Andrews 1980; Emmett and Wolman 2001;

Biedenharn et al. 2000). A MFA is performed on a user-defined supply reach to find the incoming sediment load to the design reach of interest downstream as depicted in Figure 3-1. Various slope/width combinations for the associated design reach are iteratively evaluated to identify a set of solutions that produce a CSR approximating unity within a 2.5% tolerance (Figure 3-2). The resulting curve or “family” of stable channel solutions is analogous to the output produced by the Copeland method of HEC-RAS. Slope/width combinations above this line are expected to result in net degradation or erosion over time, while those below are expected to produce aggradation or sediment accumulation. A CSR within 10% of unity will be the most likely to have sediment balance with minimal aggradation or degradation in the channel (Soar and Thorne 2001). Every design along the curve would theoretically pass the incoming sediment load and through time establish sediment continuity. However, in reality, not all the designs on the curve usually fall within the realm of most downstream hydraulic geometry equations and field observations of how channel top width scales with bankfull discharge. In general, the lowest width designs on the curve that are below minimum slope (minimum total stream power for a given discharge) and the highest width designs are not for the focus of most practical applications as a result of habitat considerations and a tendency toward braiding.

$$\text{Capacity/Supply Ratio(CSR)} = \frac{\int_{\text{time}} \text{Sediment transport capacity of Design Reach}}{\int_{\text{time}} \text{Sediment transport capacity of Supply Reach}}$$

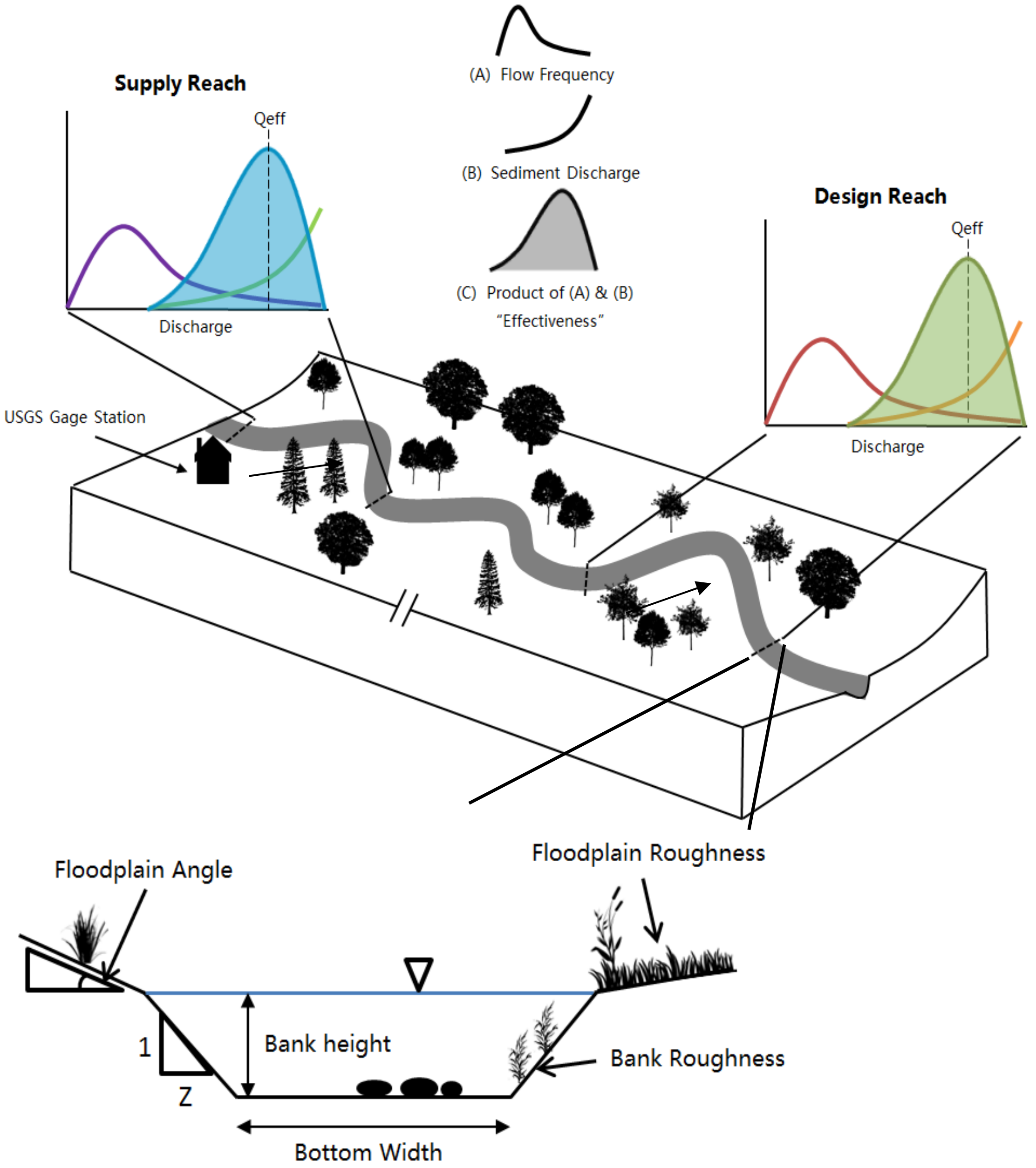


Figure 3-1. Visual representation of CSR analysis for simplified trapezoidal channel geometry.

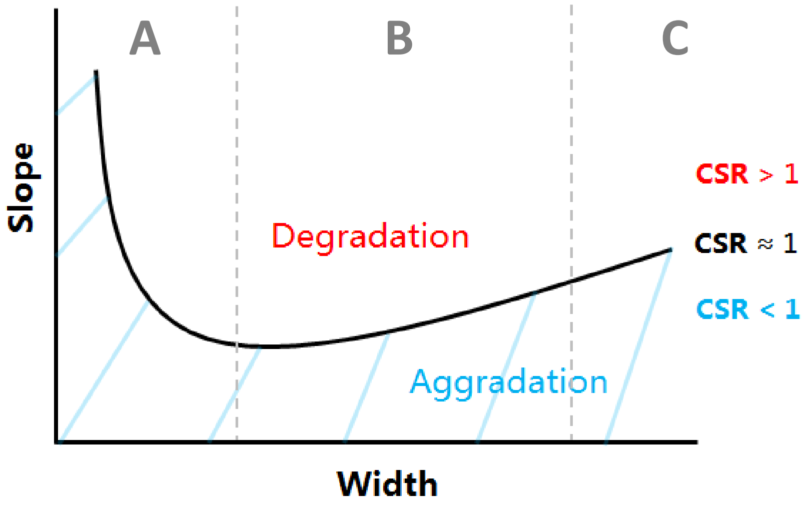


Figure 3-2. Family of slope/width combinations which provide continuity of water and sediment with solutions in section A: low width, high slope (generally too high velocity and stream power); section B: realistic range for single thread; and section C: high width (tendency toward braiding/ habitat considerations).

3.3 Methods

This section will first give an overview of the development of the CSR Tool, and then explore the methods used to apply the tool on eighteen sand-bed rivers to provide insight on the practical use of the CSR methodology, as well as fundamental insight on differences between single-discharge versus CSR-based designs.

3.3.1 CSR Tool Development

The platform chosen to develop the CSR Tool was the programming language of Excel®, VBA. This platform was selected to extend the applicability of the tool to both practitioners and researchers by using the user-friendly and familiar environment of Excel®. The basic methodology of the code behind the CSR Tool was closely modeled after the Copeland method in HEC-RAS (Brunner 2010; Copeland 1994). This provides a means of comparison between the two methods and a means to verify the accuracy of the tool output to a well-vetted and respected method. Some of the main assumptions used in this approach to model flow are listed below:

- 1-D steady, uniform flow;
- a simplified trapezoid is used to represent the actual channel cross section;
- the channel is split into bank and bed components;
- sediment transport only occurs on the bed of the channel;
- the bed and bank components have the same velocity which is the cross-section averaged velocity of the entire channel;
- the provided hydrology information (FDC) is assumed to be valid for both the supply and design reach in the tool; and
- the sediment transport capacity estimated for the supply reach is assumed to be the incoming sediment load to the design reach.

For a detailed review of all the equations used in the calculations of the CSR Tool and explanations of their application within the tool, refer to the CSR Tool Reference Manual (Appendix A). Features of the CSR Tool that are not present in the Copeland method of HEC-RAS include:

- Sediment transport is calculated using the entire FDC associated with the design reach rather than just a single representative discharge and, therefore, accounts for the morphological influence of the other flows.
- Overbank flow is modeled and considered in transport calculations unlike the Copeland method that uses a single trapezoid model. This can help avoid overestimating the effectiveness of higher flows since the model can account for a floodplain angle that is lower relief than the bank angle.

- The tool is capable of performing the CSR analysis for both sand-bed streams and gravel- / cobble-bed streams.
- Additional planform outputs and sediment yield percentiles are listed for each solution.

3.3.1.1 **Channel partitioning**

The program models discharges through the specified cross sections by partitioning the channel into bed, bank, and overbank components. The in-channel partitioning approach follows the method used by Copeland in HEC-RAS. This approach breaks the channel into bed and bank components with separate roughness characteristics. The bank roughness is specified by the user and the bed roughness is calculated in conjunction with the sediment transport analysis. The Einstein (1950) equation is utilized to partition the components. This method varies the bank component areas until the velocity through the bed and bank components are equal to the cross-section averaged velocity for the whole channel.

Unlike the Copeland method in SAM and HEC-RAS, the CSR Tool also models overbank flow. Once the flow in the channel breaks into overbank flow, the partition approach is altered because the Einstein (1950) method is no longer valid. In contrast to the in-channel method, the partitions are simply delineated by vertical lines. The bed partition is centered over the bed, the bank components over both banks, and the floodplain components over each floodplain. Instead, the default conveyance method used by HEC-RAS (Brunner 2010) is utilized to converge on a depth solution.

3.3.1.2 **Hydrology calculations**

More extensive hydrologic input is required by the CSR Tool to estimate the time-integrated sediment transport capacity of the reaches over the entire FDC rather than a single discharge. The CSR Tool can use a flow gage record, or a pre-derived FDC. These flow characteristics are assumed to be the same and representative of the flows through both the supply and design reaches.

If a gage record is chosen for the hydrology data, the program will sort the discharges using an arithmetic binning procedure. This method splits the flows into a specified number of equal interval bins. A total number of bins must be defined by the user or the program defaults to 25 bins as recommended by Biedenharn et al. (2000). The process starts at 25 arithmetic discharge bins and reduces the amount of bins until there are no bins with zero frequency. In cases where there is still zero frequency at 10 bins then the process starts again at 25 bins and combines the discharges above the zero frequency bin into one. Each bin represents a range of discharges that the flows of the record could fall into. The probability of occurrence for the flows in each range is calculated and ultimately used to find the total effectiveness or sediment yield for the supply and design reaches.

The most common method to perform a MFA is using a flow record when possible; however, it is rare in practice to have a sufficiently long flow record for a stable reach upstream of the design reach. In these instances, the CSR Tool can take a user-defined FDC. A table of exceedance probabilities versus discharges can be directly pasted into the CSR Tool. If the FDC is larger than 50 bins, then it is consolidated to a default of 25 bins, but the user can choose up to 50 bins.

3.3.1.3 <u>Sediment transport calculations</u>

The CSR Tool can perform the CSR analysis to find stable channel design solutions for both sand-bed and gravel- / cobble-bed streams. The sand-bed portion of the tool uses the Brownlie (1981) total load sediment transport equation to estimate transport rate just like the Copeland method in HEC-RAS. The tool uses both versions of this equation that handle upper and lower regime, and the transitional regime is assumed to be lower. Two bedload sediment transport equations, the Parker (1990a) and Wilcock-Crowe (2003) equations, are available to estimate sediment transport rates in gravel- and cobble-bed streams. The Parker (1990a) bedload equation is appropriate for use with rivers of gravel size (> 2 mm diameter) and larger substrate. The Wilcock-Crowe (2003) bedload equation can be used with gravel- and cobble-bed streams that include a sand fraction (< 2 mm diameter).

The code methodology for the gravel- / cobble-bed portion was matched as closely as possible to the sand-bed structure. The primary difference between the methodologies for the calculation of hydraulic parameters is the quantification of flow resistance. The sand-bed portion of the tool uses the Manning equation and the Brownlie depth predictor equations (Brownlie 1981) that account for bedforms. The Manning equation and Limerinos (1970) equations were chosen to calculate bed roughness in the channel for the gravel-bed portion of the tool. The Limerinos (1970) equation was calibrated to account for mostly grain roughness of larger particles from gravels to boulders.

3.3.1.4 <u>CSR Tool validation</u>

To validate the output of the sand-bed calculations, the CSR Tool was set-up to use a single discharge for direct comparison with the output of the Copeland method in HEC-RAS. All channel dimensions and roughness characteristics were matched in each scenario, and the bank and floodplain angles were matched in the CSR Tool to approximate the single trapezoid model used by the Copeland method.

The gravel-bed portion of the tool could not be validated for single-discharge design through comparison to Copeland's method in HEC-RAS or SAM (Thomas et al. 2002), because the Parker (1990a) and Wilcock-Crowe (2003) equations are not currently available in those software packages. The code used in the CSR Tool for the Parker (1990a) and Wilcock-Crowe (2003) bedload relations was obtained directly from a VBA-based tool created by Gary Parker called the ‘acronym’ series (Parker 1990b, 2006). Gary Parker also added the Wilcock-Crowe (2003) relationship in a later version of the ‘acronym’ software. These codes were directly implemented in the CSR Tool. Outputs from the CSR Tool were then compared to results from both Gary Parker’s original tools and manual calculations to confirm the output of estimated sediment yield.

3.3.2 CSR Tool Applications

3.3.2.1 **Sand-bed examples**

The CSR Tool was applied in fulfilling the objectives of this study following its development and validation for accuracy. Eighteen sand-bed river examples were extracted from a data set that was originally collected by J.C. Brice of the U.S. Geological Survey (USGS) and was revisited for use by Soar and Thorne (2001). These data were analyzed to compare the outputs of single-discharge designs versus the CSR. Very few sites had the required data needed for the CSR analysis, so the sites selected had the optimal combination of required data, sufficiently long flow records (all sites > 18 yrs), and a diverse set of characteristics from varying physiographical regions in the U.S. The top widths for the examples ranged from 16 to 61 m as shown in Table 3-1.

Table 3-1. Summary of data for eighteen sand-bed river sites used in analytical channel design analysis.

Stream Name	Site Location	USGS Gage	Flow Days	Top Width [m]	Depth [m]	D_{50} [mm]	Bed Slope	Sinuosity
Big Raccoon Creek	Coxville, IN	03341300	14256	39.4	2.61	0.50	0.00054	1.2
St. Joseph River	near Newville, IN	04178000	18882	58.4	2.04	0.61	0.00019	2.0
Tallahala Creek	near Runnelstown, MS	02474500	15706	42.6	2.69	0.33	0.00058	1.4
Fishing Creek	near Enfield, NC	02083000	24472	43.3	3.09	1.07	0.00017	2.0
Licking River	Farmers, KY	03249500	6848	43.2	4.19	1.38	0.00025	2.9
Rough River	near Dundee, KY	03319000	8309	37.5	4.60	0.15	0.00011	2.1
South River	near Parkersburg, NC	02107000	12789	19.8	1.25	0.53	0.00027	1.5
Mud Creek	near Lewsburg, KY	03316000	12054	16.3	2.69	0.14	0.00028	2.1
Cahaba River	near Sprott, AL	02424500	11323	61.0	6.58	0.30	0.00041	1.4
East Nishnabotna River	Red Oak, IA	06809500	22805	58.6	3.17	0.43	0.00060	1.4
Buttahatchee River	near Sulligent, AL	02439000	7519	21.7	3.49	0.28	0.00044	1.7
Wolf River	Rossville, TN	07030500	15524	29.3	2.02	0.35	0.00045	1.6
Big Sioux River	Akron, IA	06485500	25600	58.3	3.55	0.59	0.00025	1.7
Cossatot River	near Dequeen, AR	07340500	15524	49.5	3.55	0.12	0.00079	1.7
Rock River	near Rock Valley, IA	06483500	18407	54.3	2.51	0.50	0.00051	1.8
Red River	Clay City, KY	03283500	21128	35.2	3.83	1.60	0.00040	1.7
Sugar Creek	near Edinburgh, IN	03362500	20208	35.1	2.03	1.34	0.00040	1.2
Washita River	Anadarko, OK	07326500	25639	55.1	2.09	0.29	0.00043	1.4

All parameters needed to run the CSR analysis were present for each example except the bank and floodplain Manning's *n* values and angles. Typical values of 0.03 to 0.035 for bank Manning's *n*, 1 to 1.5 (horizontal:vertical (H:V)) for the bank angle, and 4 (H:V) for the floodplain angle were selected in the absence of field data. All other channel dimensions and characteristics were derived from field-measured data for each site. Cross-sectional dimensions and grain size distributions were used for the supply reach and then matched for the design reach for sake of consistency to compare the examples. Each example had a sufficiently long USGS gage record of daily flows of at least 18 yrs of flow days and was assumed to be representative of the hydrology for the supply and design reaches.

The CSR Tool was run for all eighteen sites to produce a family of stable channel slope/width combinations with a CSR equal to one. In addition, the Richards-Baker flashiness index (R-B Index; Baker et al. 2004) was calculated for each example to make inferences about the deviations of the single-discharge designs and the CSR with flashy hydrographs. The R-B Index is calculated by first taking the sum of the absolute values of day-to-day changes in discharge for the entire daily flow record. This value is then divided by the sum of mean daily flows. The R-B Index is high for flashy hydrographs and low when hydrographs rise and fall gradually (Equation (3-2)):

$$\text{R - B Index} = \frac{\sum_{i=1}^{n} \left| q_i - q_{i-1} \right|}{\sum_{i=1}^{n} q_i} \qquad \textbf{(3-2)}$$

where:

q = daily-averaged discharge; and

i = day.

Furthermore, the CSR Tool was developed with a feature that also facilitates performing analyses with single discharges to compare CSR and single-discharge outputs for each of the eighteen sites. This approach was chosen over using the Copeland method in HEC-RAS to provide the most direct and consistent comparisons. Five of the most common single discharges used for design were selected to compare with the CSR output. The effective discharge (Q_{eff}), field-determined bankfull discharge (Q_{bf}), the 1.5-year recurrence interval discharge ($Q_{1.5}$), and the discharges associated with 50% and 75% of the cumulative sediment yield Q_{s50} and Q_{s75}, respectively. The Q_{eff}, Q_{s50}, and Q_{s75} discharges were derived from the MFA output for the supply reach of each example. The Q_{bf} is a field-determined metric that was available for each sand-bed site from the original data set, and the $Q_{1.5}$ was derived using the Weibull plotting position method with the USGS gage annual peak flow series for each site. Then, these design discharges were input into the CSR Tool using the same channel characteristics as the CSR analysis of the full FDC.

The entire family of stable channel design solutions is calculated to have a CSR of unity; however, not all of the solutions are viable or realistic for practical design purposes. Soar and Thorne (2001) derived a practical channel design width equation from the same sand-bed data set used in this research. This equation is a function of bankfull discharge (Q) and a binary variable that is unity if tree cover over the banks is less than 50% or zero if tree cover is more than 50% (V) (Equation (3-3)):

$$w = (3.38 + 1.94V)Q^{0.5}e^{\pm 0.083} \qquad \textbf{(3-3)}$$

where:

w = bankfull top width within a 95% confidence interval of the mean response;

The range of widths calculated by this equation was used to select relevant widths to compare between the CSR and each single-discharge design output.

The stable design slopes that fell within the derived width range were extracted to compare single-discharge designs to the CSR for each of eighteen sand-bed river sites. These slope/width combinations for each single-discharge design were input back through the CSR Tool to obtain a potential sediment yield output for that design. These solutions were then compared to the associated CSR design sediment yield for that same width as a percent difference from the CSR (henceforth referred to as a ‘percent difference’). All the percent differences for each width in the derived range were finally averaged for each single discharge (Q_{eff}, Q_{bf}, $Q_{1.5}$, Q_{s50}, and Q_{s75}) to compare potential designs for each method.

Lastly, an analysis was performed to quantify the potential practical implications of the differences in sediment yield between the CSR and single-discharge designs. If the CSR design is assumed to provide the most encompassing physical basis for channel design, then the differences in sediment yield for designs based on the single discharges can lead to potential erosion or deposition within the channel. The percent differences in sediment yield between the CSR and single-discharge outputs were converted to a potential depth of erosion or sedimentation over a kilometer of river reach. This conversion can give a practical sense of the potential channel effects due to the differences for each design methodology. This conversion was performed for all examples, and three examples that were near 5 and 10% difference were selected with three different incoming sediment loads to represent the spread of results found in the analysis.

3.3.2.2 Regression analysis

Comparisons of the CSR to single-discharge designs and influencing factors used linear regression to examine trends from the scatter plots. Linear trend lines and R^2 values were extracted directly from Excel® and p-values were obtained from running the regression data analysis tool in Excel®.

3.3.2.3 Comparing sand-bed versus gravel-bed behavior

The sensitivity of stable channel design solutions to changes in incoming sediment load were examined for both sand- and gravel-bed examples for means of comparison. To focus on results solely from changes in incoming sediment load and for consistency, an idealized case scenario was created using the same flow record, dimensions, and roughness values to set-up the design reach for the CSR analysis. The bank height was set at 1.25 m, the bank angles at 1.5 H:V with 0.035 Manning’s *n*, and the floodplain angle at 4 H:V with 0.035 Manning’s *n*. The grain size distribution for the sand-bed example only incorporated sand size particles, while the gravel-bed example was comprised of primarily gravel with some cobble and all sand removed. Four incoming sediment loads (10, 50, 100, and 500 tons/day) were manually entered and run in the program to produce four stable channel design curves.

3.4 Results

3.4.1 CSR Tool Development

Testing the CSR Tool with single discharges rather than a full FDC provides a direct comparison to the Copeland method in the HEC-RAS. I found very similar results between HEC-RAS outputs and single-discharge calculations from the CSR Tool, which supports the validity of its algorithms and outputs. For example, the CSR Tool and the Copeland method in HEC-RAS estimated a total sediment concentration of 342 ppm and 343 ppm, respectively, at 50 cms (1,765 cfs) for Big Raccoon Creek in Indiana (Figure 3-3). The average percent difference of the CSR Tool single-discharge output from the Copeland output for this scenario was 0.70% from the minimum slope through the right-side of the curves. Furthermore, out of four scenarios comparing the CSR Tool to the Copeland method using a single discharge, there was an average of 1.02% difference between the solutions from the minimum slope to the outer right of the curves.

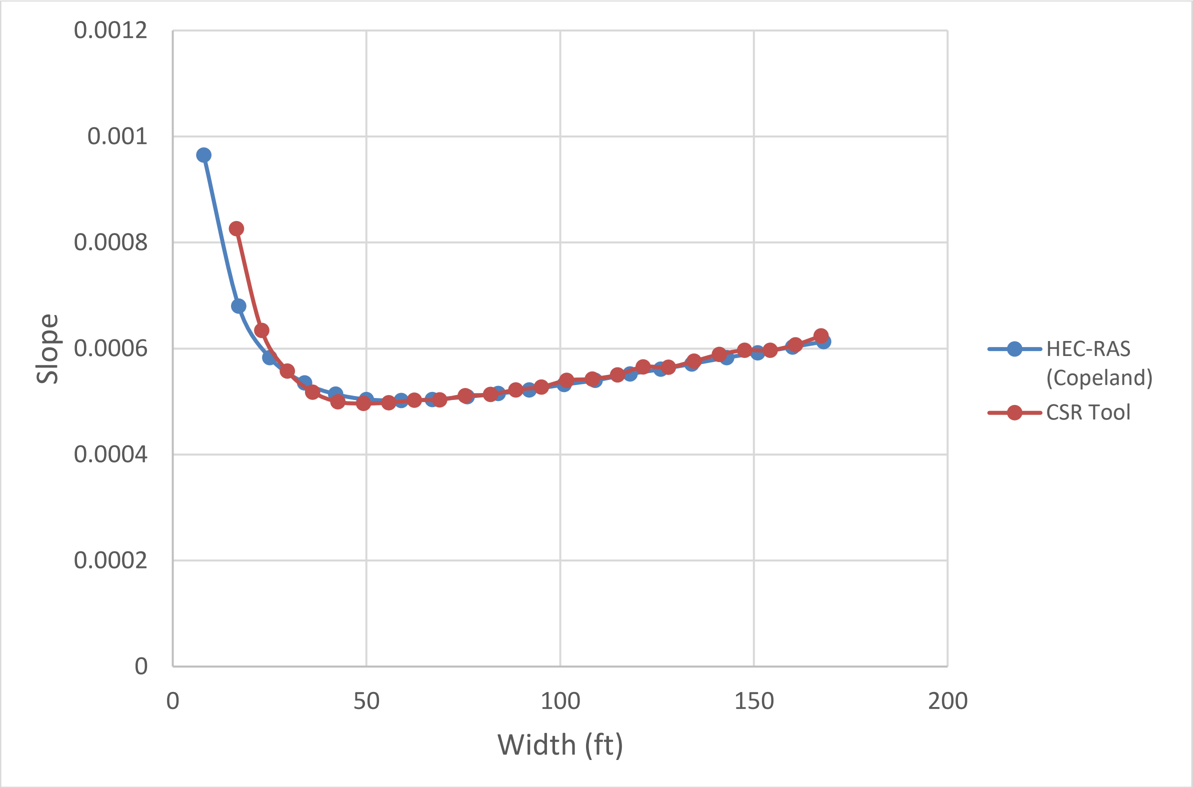


Figure 3-3. Comparison of CSR Tool with HEC-RAS stable channel design using the Copeland method with the same channel dimensions, grain size distribution, and single discharge. Example: Big Raccoon Creek, Indiana.

3.4.2 CSR Tool Applications

Eighteen sand-bed channels were analyzed with the CSR Tool using both the full CSR method and the single-discharge method with Q_{eff}, Q_{bf}, $Q_{1.5}$, Q_{s50}, and Q_{s75} as the design discharges. The average stable slopes within the range given by the downstream hydraulic geometry (Equation (3-2)) from Soar and Thorne (2001) are listed in Table 3-2. The sites below the South River had the Q_{eff} in the first bin from the MFA. The Q_{s50} and Q_{s75} designs were consistently the closest to the CSR design slopes across the eighteen examples. The associated sediment yields of these designs were compared to find the percent differences from the CSR design (Table 3-3, presented and discussed later).

Table 3-2. Average stable slope outputs for each single-discharge and CSR designs.

River Name	CSR	Q_{eff}	Q_{bf}	Q_{s50}	Q_{s75}	$Q_{1.5}$
Big Raccoon Creek	0.000532	0.000537	0.000537	0.000530	0.000533	0.000538
St. Joseph	0.000180	0.000179	0.000181	0.000179	0.000181	0.000182
Tallahala Creek	0.000577	0.000579	0.000579	0.000577	0.000584	0.000577
Fishing Creek	0.000162	0.000152	0.000169	0.000160	0.000170	0.000164
Licking	0.000260	0.000258	0.000248	0.000258	0.000260	0.000258
Rough	0.00011	0.00011	0.00011	0.00011	0.000114	0.00011
South	0.000272	0.000275	0.000270	0.000273	0.000270	0.000269
Mud Creek	0.000275	0.000300	0.000289	0.000287	0.000278	0.000205
Cahaba	0.000446	0.000479	0.000411	0.000466	0.000450	0.000433
East Nishnabotna	0.000696	0.000714	0.000667	0.000691	0.000695	0.000665
Buttahatchee	0.000411	0.000472	0.000399	0.000461	0.000443	0.000215
Wolf	0.000462	0.000421	0.000450	0.000434	0.000461	0.000545
Big Sioux	0.000267	0.000283	0.000270	0.000277	0.000266	0.000271
Cossatot	0.000809	0.000829	0.000799	0.000806	0.000793	0.000793
Rock	0.000556	0.000575	0.000552	0.000557	0.000546	0.000553
Red	0.000411	0.000427	0.000394	0.000415	0.000407	0.000389
Sugar Creek	0.000413	0.000446	0.000433	0.000421	0.000402	0.000395
Washita	0.000450	0.000442	0.000457	0.000449	0.000443	0.000445

The Q_{s50} and Q_{s75} single-discharge designs had sediment yields that were the most similar to the CSR designs at 40% of the sites for both discharges. In comparisons of the total average percent difference for each single discharge to the CSR output for all eighteen sites, Q_{s75} was consistently the closest (3.8%), followed closely by Q_{s50} (4.0%), and then Q_{bf} (4.6%), with Q_{eff} and $Q_{1.5}$ the farthest at 7.6% and 10.5%, respectively.

In general, the Q_{s50}, Q_{s75}, and Q_{bf} design slopes and sediment yields were closest to the CSR designs and were on average within 5% across all eighteen examples. These single-discharge designs only produced one instance of a difference > 10%. In contrast, the Q_{eff} and $Q_{1.5}$ designs showed the greatest departures with average percent deviations from 5 to 10%. The Q_{eff} and $Q_{1.5}$ designs had differences greater than 10% in six and three scenarios, respectively. Eleven of the eighteen designs based on Q_{eff} had the Q_{eff} in the first bin of the MFA and had almost three times more deviation with a total average deviation of 6.3%. In the other seven Q_{eff} designs, the design discharge did not occur in the first bin the total average deviation was 2.4%.

The Q_{eff} and Q_{s50} designs tended to be closer together and over-estimate the slope and sediment yield of the CSR design, while the Q_{s75} and Q_{bf} designs were more similar and tended to underestimate the slope and sediment yield of the CSR design. The Q_{s50} and Q_{s75} designs were often close to matching the CSR result or bracketing the CSR result. On average, Q_{s50} and Q_{s75} either matched (within 0.2% tolerance) or bracketed the CSR design for fifteen out of eighteen sand-bed sites.

The practical implications of the percent differences in Table 3-3 with respect to potential aggradation or degradation varied widely across the eighteen sites. The most influential factor on the resulting depth of erosion or deposition based on the comparison of single-discharge designs to the CSR designs is the incoming sediment load. For example, the potential erosion or deposition over a 1-km reach due to differences between single-discharge and CSR designs can be illustrated with Sugar Creek, the Buttahatchee River, and the Washita River, each of which had single-discharge sediment yields that differed from the CSR yield by approximately 5% and 10% (Table 3-4). These sites have incoming sediment yields that differ by orders of magnitude, so a 5% difference in design sediment yield can result in potential erosion or deposition of 0.03 m/yr for Sugar Creek (93 tons/day incoming sediment yield) and 2.6 m/yr for the Washita River (13588 tons/day incoming sediment yield).

Table 3-3. Summary of sediment yield comparisons of CSR to single-discharge designs.

	Q_{eff}	Q_{bf}	Q_{s50}	Q_{s75}	$Q_{1.5}$
Number of times closest to CSR	0	2	7	7	2
Average % difference	7.6%	4.6%	4.0%	3.8%	10.5%
Number of times (<5%)	8	10	12	13	9
Number of times (5 to 10%)	4	7	5	4	6
Number of times (>10%)	6	1	1	1	3

Table 3-4. Potential erosion or deposition for varying incoming sediment loads over one kilometer of river reach.

Stream Name	Single-design Discharge	Average % Difference	Incoming Sediment Yield [tons/day]	Erosion/ Deposition [m/yr]
Sugar Creek	Q_{s75}	4.9	93	0.03
Buttahatchee River	Q_{bf}	4.9	1013	0.8
Washita River	Q_{s50}	5.6	13588	2.6
Sugar Creek	Q_{bf}	9.8	93	0.06
Buttahatchee River	Q_{s75}	10.9	1013	1.9
Washita River	Q_{s75}	9.6	13588	5.8

The R-B Index was compared to many other variables influencing the CSR analysis to make inferences about the robustness of the single-discharge designs. Figure 3-4 shows the deviation of single discharges Q_{eff}, $Q_{1.5}$, Q_{s50}, and Q_{s75} relative to Q_{bf} with a change in R-B Index. This can reveal the sensitivity of these discharges ability to estimate Q_{bf} with changes in 'flashiness'. Departures between field-identified bankfull discharge and Q_{eff} show a significant positive correlation ($R^2 = 0.31$, $p < 0.02$) with an increase in R-B Index; however, Q_{s75}, Q_{s50}, and $Q_{1.5}$ are much less sensitive than Q_{eff} ($R^2 < 0.11$, $p > 0.17$). Q_{s75} and $Q_{1.5}$ were the least sensitive to changes in R-B flashiness. Interestingly, the ratio of the 2-yr instantaneous peak flow (Q_2) to the mean annual discharge (Q_m) is highly correlated ($R^2 = 0.88$, $p < 10^{-7}$) with the R-B Index (Figure 3-5).

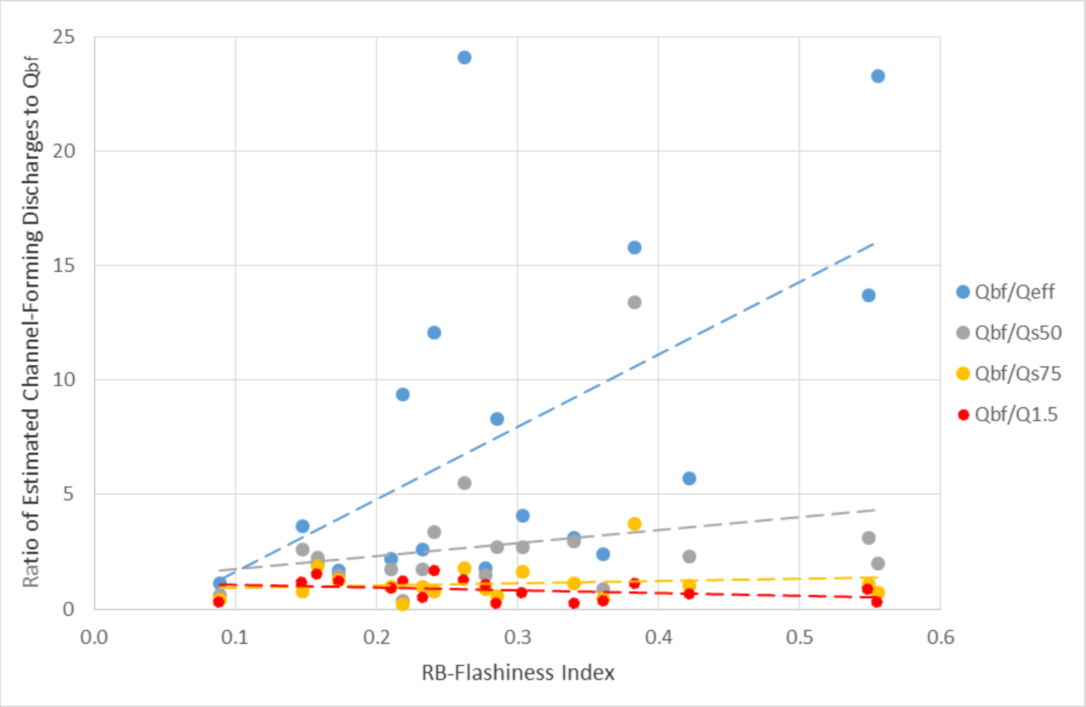


Figure 3-4. Sensitivity of departures between field-identified bankfull discharge versus Q_{eff}, Q_{s50}, Q_{s75}, and $Q_{1.5}$ with changes in R-B Index.

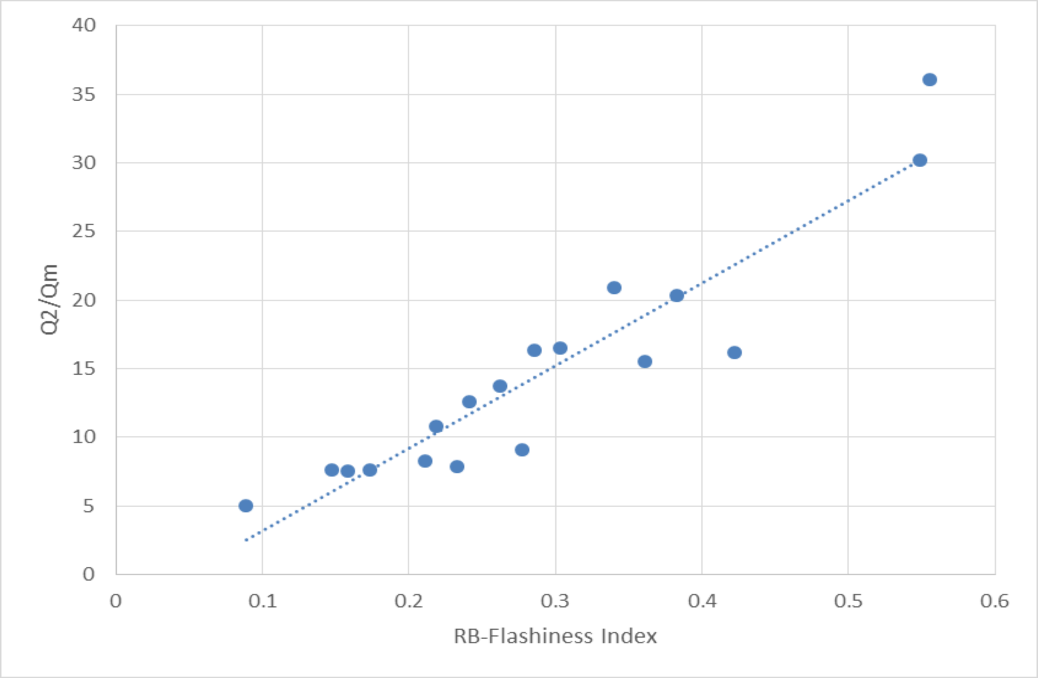
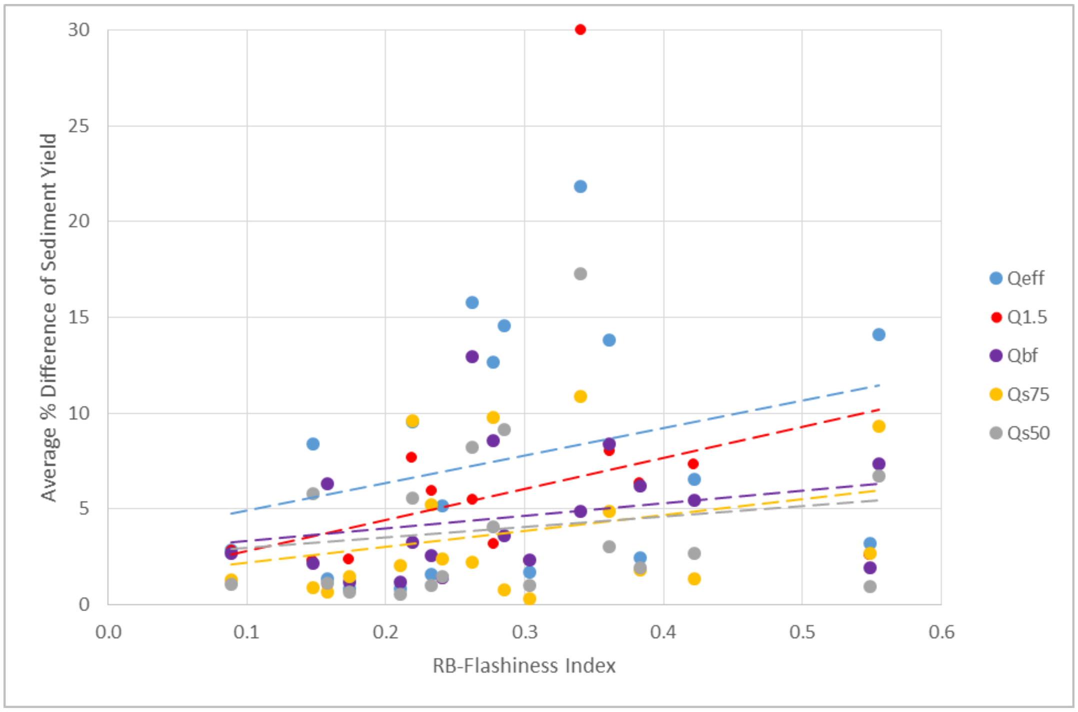


Figure 3-5. Relationship between the ratio of the 2-yr instantaneous peak flow (Q_2) to the mean annual discharge (Q_m) and R-B Index.

In general, the R-B Index and the width-to-depth ratio (derived from field estimates of bankfull top width and bankfull depth for each site) were strong indicators of the deviation between single-discharge designs and the CSR result (Figure 3-4). The Q_{eff} and $Q_{1.5}$ deviations are most sensitive to changes in R-B flashiness and width-to-depth ratio followed by Q_{s50} with Q_{bf}, and Q_{s75} the least sensitive (Figures 3-6(a) and 3-6(b)). More-detailed comparisons show that the average R-B Index tends to be higher when the Q_{eff} is in the first bin (average R-B Index = 0.34) than when not (average R-B Index = 0.21).

(a)



(b)

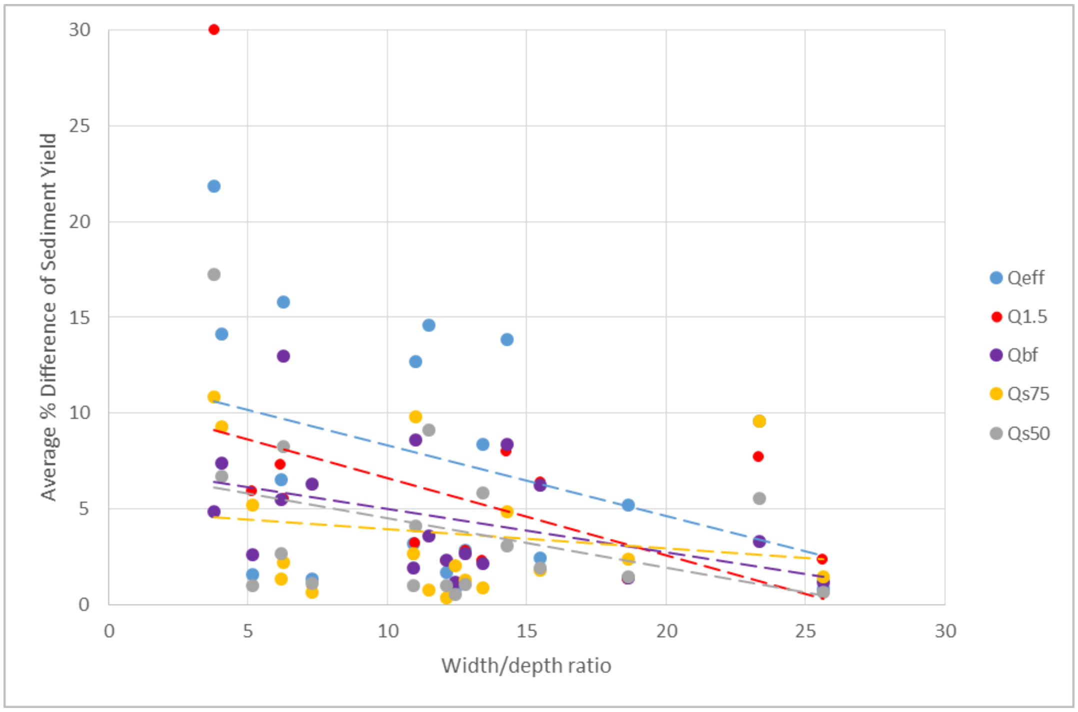


Figure 3-6. Total average percent difference in sediment yield computed from single-discharge designs to those computed with CSR designs for all eighteen sites with changes in (a) R-B Index and (b) width-to-depth ratio. R-B Index relationship with $Q_{1.5}$ is significant at $p < 0.05$, all others have $p > 0.10$. Width-to-depth ratio relationship with $Q_{1.5}$ and Q_{bf} is significant at $p < 0.10$, all others have $p > 0.10$.

3.4.3 Comparing Sand-bed versus Gravel-bed

The differences between the stable channel design curves for examples of each channel type (sand versus gravel/cobble) are apparent with changes to incoming sediment load. The stability curves for each channel type were produced using 10, 50, 100, and 500 tons/day of inflowing sediment load for the sand-bed example (Figure 3-7(a)) and gravel-bed example (Figure 3-7(b)). As stated above, the solutions that are often most viable for design on the stable channel design curve are from the lowest slope (minimum specific stream power) to the outer right of the curve. Comparing this part of the curves in Figure 3-7 indicates the change in slope is more sensitive for the idealized sand-bed example with changes of inflowing sediment load. There was an average percent difference of 72.6% and 65.1% between the sand-bed solutions, and 51.2% and 40.0% between the gravel-bed solutions with a change of 10 to 100 tons/day and 100 to 500 tons/day of incoming sediment load, respectively (Figure 3-7).

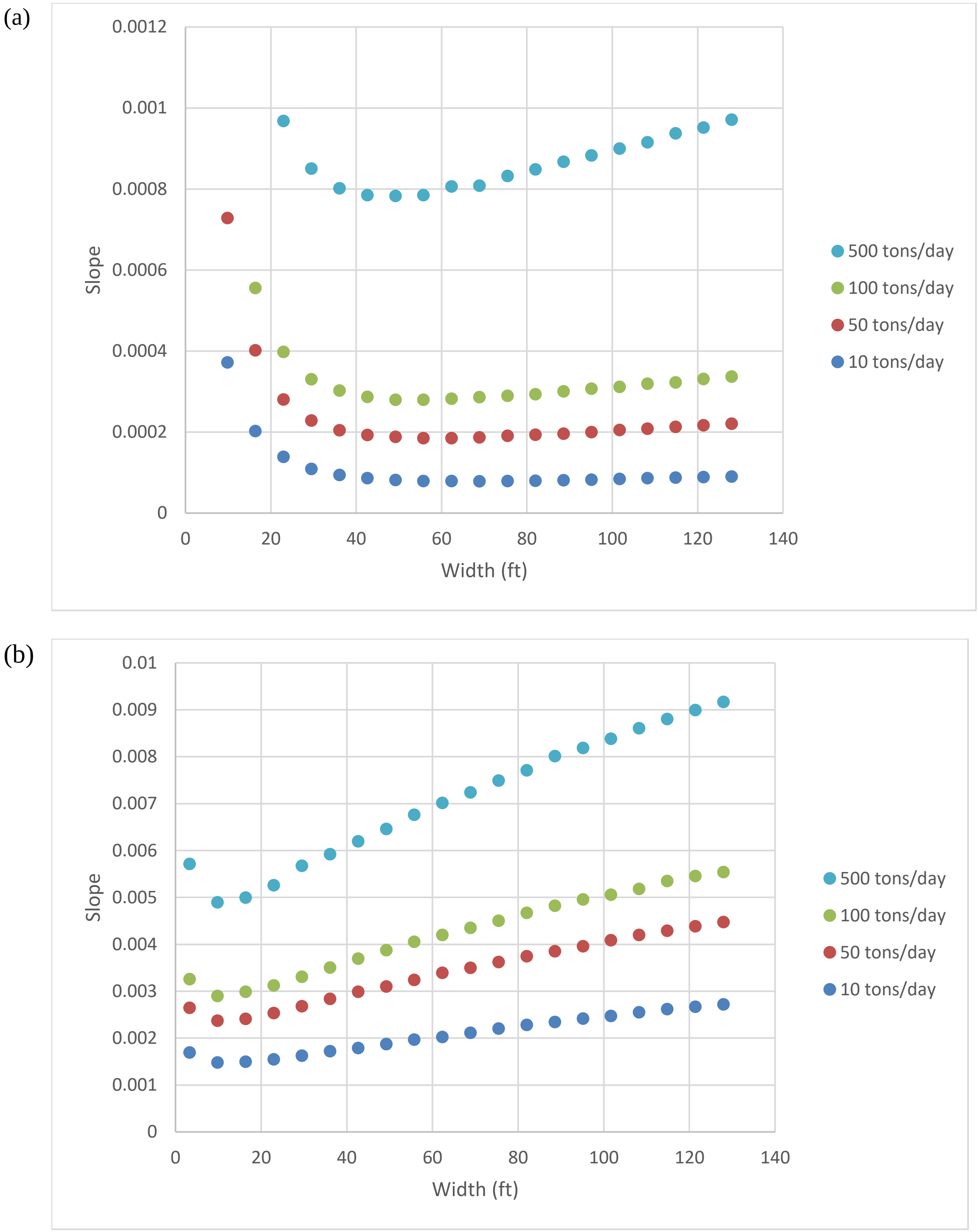


Figure 3-7. Comparison of the sensitivity of stable channel designs to changes in incoming sediment load for idealized (a) sand-bed example, and (b) gravel-bed example.

3.5 Discussion

The CSR Tool was developed to perform full spectrum analytical channel designs using the CSR analysis. The tool produces a family of stable channel design solutions that balances the continuity of water and sediment across the entire FDC rather just a single discharge. The general methodology of the tool followed the Copeland method in HEC-RAS and was compared for accuracy. Unique additions to the CSR Tool include modeling overbank flow and the ability to perform the analysis on sand-bed and gravel- / cobble-bed streams. The analysis of the CSR Tool was aimed at sand-bed streams because there is less material in the literature that focuses on the design of these channels, and the CSR was deemed more necessary for this channel type. Furthermore, other researchers have already found single-discharge designs such as the Q_{eff} to match Q_{bf} well in gravel- / cobble-bed streams without large sand fractions (Andrew 1980; Emmett and Wolman 2001; Shield et al. 2003).

3.5.1 CSR Tool Development

3.5.1.1 Code validation

Comparisons of the CSR Tool output using a single-discharge to the stable channel design tool using the Copeland method in HEC-RAS show close resemblance (Figure 3-3). The main deviation between the two sets of solutions is in the lower widths where the curves curl-up steeply. These deviations can be explained by the difference in channel partitioning between the two tools. The CSR Tool uses the same methodology to partition the channel as the Copeland method for in-channel flow; however, this technique is inapplicable for overbank flows so the method had to be altered. For the single-discharge comparison (Figure 3-3), the flow is not overbank for the supply reach bank height; however, when the program cycles through the entire range of widths to find stable channel solutions the flow is overbank at the lowest widths. Thus, even though the bank and floodplain angles were matched in the examples to model a single trapezoid, the different overbank partitioning method changes the lower width solution slightly. Although, as previously stated, the solutions on this part of the curve are often less realistic than the solutions on the right-side of the curve, since they usually do not fall within the realm of most downstream hydraulic geometry equations and field observations of how width scales with bankfull discharge.

3.5.1.2 Strengths and weaknesses of the CSR Tool model

The CSR Tool has many features that improve the physical basis of stable channel design, but still has many caveats that can potentially limit its applicability. In general, the approach requires specification of an incoming sediment load to the design reach to calculate the sediment balance. In the context of this tool, this requires the user to have a stable upstream supply reach that will be representative of the incoming sediment load into the design reach. This can introduce many uncertainties and may be impossible in some situations. Secondly, the sediment balance is based on estimates from sediment transport equations which have inherent uncertainties; however, these are alleviated to some extent because solutions are based on a relative balance from the same equation rather than relying on any absolute magnitude.

The CSR approach adds the complexity of modeling sediment transport across the entire FDC rather than relying on a single representative discharge. This approach is much more representative of the full spectrum of effective flows the actual channel conveys through time, but still requires assumptions in the design process. First, the flow record used must be available for a stable upstream supply reach and be representative of inflows to the design reach of interest, or the user must use a derived FDC that is often based on regionalized curves and extrapolation to ungaged sites that can add uncertainty. Secondly, the ‘effectiveness’ or the estimated total sediment transported for the channel is computed with a binning procedure and average discharges which can substantively change the output depending on the binning method used. Lastly, the CSR Tool has many fundamental assumptions as do all hydraulic models. The underlying hydraulic relationships are based on 1-D cross-section averaged, steady flow, sediment transport is assumed to occur only on the bed for in-channel and overbank flow, and the cross section is trapezoidal. Overall, the CSR Tool can offer a more physically realistic representation of the full range of geomorphically effective flows over the single-discharge methods, but remains a highly simplified representation of a complex system that provides one line of evidence in the overall design process.

3.5.2 CSR Tool Applications

3.5.2.1 **What are the most important influences on the deviation of single-discharge designs from the CSR output?**

In practice, every channel design scenario has different factors and a combination of influences that can lead to departures between a single-discharge design and a full spectrum CSR design. However, the eighteen examples explored in this research revealed a few key variables that had a clear influence on the deviation of single-discharge designs from the CSR output. Numerous factors were examined to identify variables that substantially influence the deviation of single-discharge designs, but only a few could be pinpointed.

My hypothesis that ‘flashiness’ quantified by the R-B Index has a strong influence on the deviation of the CSR from the single-discharge designs is supported by these results. This hypothesis is rooted in the idea that streams with highly variable or ‘flashy’ hydrographs are more likely to have several different flows that are influential to channel form. More specifically, these streams are postulated to have more frequent large flows and floods that can dominate overall sediment yield as proposed by Wolman and Miller (1960), and subsequently demonstrated in fine-bed streams (Soar and Thorne 2001) and coarse-bed streams (Bunte et al. 2013). One representative discharge will often not account for the effectiveness of these other influential flows which may lead to designs prone to excessive erosion or deposition.

I hypothesize that the high sensitivity of Q_{eff} to flashiness is attributed to the dynamic characteristics of labile channels which can skew the estimation of the effective discharge. Wolman and Miller (1960) concluded that the intermediate flows within a flow regime are the most ‘channel-forming’ or effective discharges, because large floods are too infrequent, and frequent low flows lack sufficient capacity to maintain and rework channel form through sediment transport. However, in ‘labile’ channels with highly erodible substrate, others have shown that low flows well below Q_{bf} can have the capacity to rework the channel and be considered the most effective discharges (Soar and Thorne 2001; Hey 1975). A high frequency of low flows with capacity to transport sediment can also skew the effectiveness curve to the lowest discharges in the first bin and potentially lead to underestimating the Q_{eff} (Biedenharn et al. 2000). If the effective discharge is underestimated, then the channel designs based off that discharge will not produce sediment continuity. This causes over-compensation of slope which can lead to degradation in the design reach (Figure 3-2). This effect is very prevalent in the eighteen sand-bed sites analyzed in this research and supports previous research, indicating that Q_{eff} can be underestimated if it is derived from the first bin (Soar and Thorne 2001; Biedenharn et al. 2000). This issue was noted by Biedenharn et al. (2000) who recommended addressing the problem by increasing the number of bins in the hydrologic analysis. The CSR Tool starts at 25 bins and sorts the flows into as many bins as possible without having a zero frequency bin, and thus does not address the first bin issue in its current version. Examining the Q_{eff} in more detail to avoid the first bin issue could increase the potential of this discharge matching the CSR designs closer. Furthermore, it was observed that a stream with a Q_{eff} in the first bin was more likely to have a higher R-B Index which could be another potential explanation for the deviation of these scenarios.

Few previous studies have focused on the theoretical basis of Q_{s50} and Q_{s75} as dominant discharges for design; however, they have separately been found to be good indicators of Q_{bf} in fine-bed streams (Sholtes and Bledsoe 2016; Copeland et al. 2001). These claims are supported by this research which has shown these design discharges to be consistently close to the CSR output and be very insensitive to changes in flashiness which was previously identified as a leading factor in the deviation of single-discharge designs. These discharges are potentially more robust to changes in flashiness, because they do not suffer from the previously discussed binning issues nor misleading field indicators that can hinder Q_{bf} estimation. I hypothesize that the small deviation from the CSR by these designs is self-evident because they are based on sediment transport and are derived from a MFA that is similar to the derivation of the CSR. However, it is also recognized that this can be one of leading downfalls of these design discharges, because a strong estimation of cumulative sediment transport is required which can be limited by data availability. Thus, if these data are available then often a designer could just use the CSR method instead of a single discharge.

Width-to-depth ratio is a strong influence on deviations in sediment yield between single-discharges versus CSR designs. The deviation of the single-discharge designs essentially increase as the stream gets smaller (lower width-to-depth ratio) as seen in Figure 3-6(b). I hypothesize that on a larger context this is attributed to the idea that smaller streams with smaller basins have more potential for flashiness. This aligns directly with Baker et al. (2004) which found a decreasing trend of R-B Index with increasing basin size. The higher flashiness increases the likelihood of having several influential flows that are not accounted for with a single-discharge design.

Furthermore, Q_{eff} is most likely to be underestimated in incised channels and semi-arid environments that often have flashy flow regimes (Biedenharn et al. 2000). This aligns with the presented results for not only Q_{eff} but the other three single-discharge designs as well. The sand-bed streams with low width-to-depth ratios used in this study are likely to have some level of incision, and although none of the sites examined were in semi-arid environments many scenarios had high values of R-B flashiness.

3.5.2.2 Is the CSR analysis needed and, if so, when is it most important to use over a single-discharge design?

One of the most important implications of this research for practical design applications is that the benefits of a CSR analysis depend on the specific design scenario. Riverine ecosystems are so complex, diverse, and dependent on so many variables that there is no direct answer, but this research has identified several important factors such as fine-grain streams, flashiness, low width-to-depth ratio, and high incoming sediment load that can be considered in addressing this question. In addition, the CSR Tool developed in this research provides a means for designers and researchers to explore this question in the context of their specific situation.

In considering the efficacy of single-discharge versus CSR designs, one must make assumptions regarding the goals of a design and how much deviation from the goal is acceptable. Specifically, the overarching goal of analytical channel design is generally consistent: a state of dynamic equilibrium over an engineering time scale. This concept is precisely why I argue for and have used analytical channel design in this research to quantify and predict the potential for a design to be successful, or reach a state of dynamic equilibrium, as it depends on sediment balance (Shields et al. 2003).

Soar and Thorne (2001) suggested having a CSR within 10% of unity to ensure dynamic stability. This research used percent differences in sediment yield to compare deviations so they are scaled with the magnitude of sediment load. However, the outputs of these methods do not explicitly translate to practical erosion or sedimentation potential. This research showed that the percent differences for the single-discharge designs can be substantially sensitive to incoming sediment load and differences in yield can produce large aggradation/degradation potential on the order of meters. This is expected since the same percent difference will have more sediment available for erosion or deposition for a higher incoming sediment load. The influences of incoming sediment load on a potential design is also dependent on many site-specific characteristics such as the size of the river, grain size distribution, and flow regime that will determine the sediment transport capacity of the stream.

It should be noted that all of the scenarios used in this research had idealized cross sections and all channel characteristics matched in order to focus the results solely on the hydrology technique used in the analytical channel design methodology (single Q or full FDC). For these ideal scenarios, my results suggest that there is not a significant difference between designs based on the CSR or single discharge for certain situations. However, in practice, this is ultimately dependent on the site-specific design scenario.

3.5.2.3 What single-discharge design matches the CSR output the closest?

I suggest that the CSR design methodology provides a more encompassing physical basis to produce channel designs that will provide the continuity of water and sediment. However, it is recognized that this methodology is not always applicable or even possible when the required input data do not exist. The single-discharge design method provides the simplicity that can promote the use of analytical channel design in practical design situations that are under great socioeconomic, time, and data availability constraints.

Out of the five single discharges examined in this research, Q_{s50} and Q_{s75} stand out as the single discharges that produce designs that match the CSR designs the closest which aligns with two previous studies. Sholtes and Bledsoe (2016) found Q_{s50} and Copeland et al. (2001) found Q_{s75} to be a good predictor of bankfull discharge in fine-grained streams. This research supports these findings and suggests that both Q_{s50} and Q_{s75} can be robust design discharges as proxies for the full spectrum CSR analysis. There were no clear trends throughout the examples that explained when or why the CSR was closer to Q_{s50} versus Q_{s75}, but these design discharges consistently matched or bracketed the CSR design, which can have useful implications for narrowing down a single discharge in practical design applications. However, as previously stated, the derivation of these discharges can be just as limited by data availability as the CSR.

The field-based bankfull discharge Q_{bf} performed nearly as well as the Q_{s50} and Q_{s75}. This is perhaps unsurprising because observed bankfull conditions may be expected to reflect the flow and sediment regime that a channel experiences. The 1.5-yr recurrence interval discharge ($Q_{1.5}$) performed well in some circumstances and poorly in others (Table 3-3). There were three outliers in the analysis that brought the average percent difference of this design discharge higher overall (10.5% with and 4.0% without). The $Q_{1.5}$ is the easiest single discharge to compute as it only requires an annual maximum peak flow series, and it can predict Q_{bf} well in some gravel- and sand-bed scenarios (Sholtes and Bledsoe 2016); however, it can be a poor predictor of channel-forming conditions for flashy streams (Figure 3-6(a)).

The Q_{bf} designs in this research generally outperformed the Q_{eff} as a design discharge. This is somewhat counterintuitive since there is a large body of research supporting the use of Q_{eff} (e.g., Biedenharn et al. 2000; Doyle et al. 2007; Shields et al. 2003). However, the examples used in this research are scenarios that can be particularly vulnerable to the methodological idiosyncrasies of

Q_{eff}. For example, Q_{eff} can be difficult to estimate in dynamic labile streams, because it can be sensitive to characteristics of these channels such as the flashiness, and the binning techniques that cause the Q_{eff} to be in the first bin (Biedenharn et al. 2000). The high sensitivity of Q_{eff} to Q_{bf} with changes in flashiness can lead to markedly underestimating Q_{bf} and can compromise its utility as a design discharge. The Q_{s50} and Q_{s75} are much less sensitive to flashiness, which results in smaller deviations from CSR designs; however, Q_{bf} had only slightly higher deviations from the CSR in many cases. This supports the idea that direct measurements of Q_{bf} can still be considered helpful metrics assuming expert judgement and sufficient field indicators are present.

Lastly, the strong relationship between the Q_2/Q_m and R-B Index found in this research has implications for practical design applications when continuous streamflow data for calculating the R-B Index are lacking. More specifically, Q_2/Q_m could replace the R-B Index when 15-minute flow data are not available for a highly flashy stream.

3.5.2.4 Differences between sand-bed and gravel-bed solutions

Unlike previous tools, the CSR Tool facilitates comparison of sand- versus gravel-bed designs. In reality, there is not a discrete threshold between sand- and gravel-bed streams, but rather a continuous spectrum of morphological types with different grain size mixtures (Montgomery and Buffington 1997; Schumm 1977). However, there are distinct characteristics exhibited by streams that are dominated by one or the other (Church 2002; Howard 1987), and accordingly, there are clear differences between the solutions for sand- and gravel-bed streams using the CSR analysis. The differences in the sensitivity of stable slopes to incoming sediment load for sand- and gravel-dominated streams are attributed to the balance of different sediment transport characteristics for each channel morphology. More change in slope is required for gravel-dominated streams to produce the difference in sediment yield required to match the inflowing sediment load, because it demands more energy to mobilize the larger grains. However, sand particles are characteristically more easily mobilized than gravel and larger particles thus respond much more drastically to changes in flow characteristics. These traits both contribute towards the sensitivity of change in slope to changes to inflowing sediment load. Sand-bed channels appear more sensitive to incoming sediment load which suggests that designers need to be particularly cautious when designing sand-bed channels, especially for relatively high incoming sediment loads. Additionally, it is known that large sand fractions in gravel streams can greatly increase gravel transport rates which could also lead to those streams exhibiting large sensitivity to changes in inflowing sediment load (Wilcock et al. 2001).

3.5.2.5 New questions and future directions

Upon developing and exploring the outputs of the CSR Tool, many new questions and possible new directions for research arise. The simplifying assumptions in the code methodology mentioned above point to potential improvements that could enhance the physical rigor of the tool. However, such improvements can increase data requirements and complexity. Here I focus on variables and methods to which the tool is particularly sensitive. Then, I explore several new questions and future research directions that have arose from the application of the CSR Tool.

The assumption that the cross-section averaged flow is the same for the bank and bed components (Einstein 1950) is questionable in naturalized channels and alternative methods could produce better results. In the context of the CSR Tool, the Einstein (1950) equation could not be used for overbank flow which results in some inconsistency between models. Future versions could apply the same methodology for both in-channel and overbank flow.

Another main assumption in the model is that sediment transport only occurs over the bed partition. This can be a reasonable assumption in many instances, certainly with in-channel flow over a large bottom width with steep banks; however, with the addition of floodplain modeling, the assumption is stretched even further. One hypothesis of this research is that the CSR method can provide a more encompassing physical basis over single-discharge designs when there are multiple influential flows for sediment transport, and that the most influential flows are often overbank. The current model only accounts for the change in area and roughness for overbank flows and does not consider sediment transported on floodplains. If this process was considered, it could lend support to the aforementioned assumption in some scenarios, although modeling floodplain sediment transport can become very complicated especially when there is heavy vegetation or grain size mixtures that are different than the bed.

The application of the CSR Tool introduced several variables that were strong influences on the deviations of single-discharge designs from the CSR for the eighteen sites examined. Much could be gained from running more sites from a larger physiographic range and more channel morphologies from sand to gravel/cobble to find more influential variables and stronger correlations. Specifically, it would be interesting to extend the analysis to gravel-bed dominated streams with a high sand fraction which are hypothesized in the research to be just as dynamic as sand-bed streams. More effort to amend the first bin issue for Q_{eff} designs that were not considered in this analysis could prove to greatly increase the validity of this design discharge for fine-grain systems. Furthermore, the CSR is theorized to provide a more encompassing physical basis, but there also needs to be research that examines when it might be less preferable to use.

Overall, as with any tool or model, the best way to verify and strengthen its utility is through application and experience in practice. There could be much gained from applying the CSR Tool to case studies in channel design such as the evaluation of the failed restoration design at White Marsh Run in Maryland by Soar and Thorne (2001). Also, using the tool to compare to designs implemented in projects, or using flume studies to test a specific aspect of the CSR analysis.

3.6 Conclusion

The CSR Tool developed in this study performs a full spectrum analytical channel design calculation using the CSR sediment balance concept. Outputs include a family of stable channel design solutions that provide the continuity of water and sediment over the entire FDC. The tool has been verified for accuracy with comparisons to the Copeland method in HEC-RAS with slight deviations that can most likely be explained from the difference in modeling approach for overbank flow. The CSR Tool has the additional feature of floodplain modeling which can increase the fidelity of the model to actual physical processes, and it provides the ability to perform CSR analysis on both sand-bed and gravel-bed streams. Comparisons between the resulting stability curves for sand-bed and gravel-bed examples show that stable slopes for sand are more sensitive to changes of incoming sediment load. This finding supports my hypothesis that the CSR analysis will be more important for finer grain channels.

The CSR Tool was applied to eighteen sand-bed sites to provide insight on comparisons of single-discharge designs to the CSR, when and what influences any differences, and when is it most important to use the CSR analysis. This analysis provides support to more sustainable channel design practice, and has cultivated new questions that can help advance the science of analytical channel design. I suggest that the CSR method can be the preferred technique in many instances since it provides a more rigorous physical basis over single-discharge designs. Four key variables indicating that a CSR design is appropriate are highly erodible substrate, flashy flow regime, small width-to-depth ratio, and large inflowing sediment loads. Highly erodible channels are often sand-bed dominated channels, but also extend to be gravel-bed channels with high sand mixtures that also exhibit ‘labile’ behaviors. The five single-discharge designs diverged with a positive correlation from the CSR result with increasing R-B Index. This is most likely because ‘flashier’ streams have a higher potential to have several influential flows that are not accounted for with a single-discharge design. The single-discharge deviations also had a negative correlation with increasing width-to-depth ratio. This is presumably because smaller streams with smaller basins have a higher potential to have flashy hydrographs.

In general, the single-discharge designs based on Q_{s50} and Q_{s75} as expected were the closest to the CSR followed by Q_{bf}, Q_{eff}, and $Q_{1.5}$. The Q_{eff} can be an inconsistent design metric because of its sensitivity to binning procedures used in the MFA. Q_{bf} can also be challenging to obtain accurately, especially in disturbed systems in need of restoration, because field indicators are often confounding or absent in urban and incised streams, but when field indicators and expert judgement is present it can still prove to be a useful design metric. The $Q_{1.5}$ is the simplest to calculate and can be a useful design metric is some instances, but can be highly dependent on the quality and quantity of available hydrologic data. The Q_{s50} and Q_{s75} are robust single-discharge design metrics because they are based off of cumulative sediment transport distributions and are less sensitive to the common difficulties of estimating the Q_{eff}, $Q_{1.5}$, and Q_{bf} discharges; however, they may also be the most limited by data availability. Furthermore, the majority of sand-bed streams examined in this study showed that the Q_{s50} and Q_{s75} designs matched or bracketed the CSR design which can provide a useful practical reference for choosing a design discharge. Lastly, this research showed that the percent differences for the single-discharge designs can be substantially sensitive to incoming sediment load and differences in yield can produce large aggradation/degradation potential on the order of meters. This is expected since the same percent difference will have more sediment available for erosion or deposition for a higher incoming sediment load.

Rivers and streams are highly complex systems and numerous factors influence their behavior and response. As a result, analytical channel designs that are subject to practical time and socioeconomic constraints necessitate many simplifying assumptions. Designers can only hope to minimize these assumptions to provide the most robust solutions within the constraints of the project. The CSR Tool developed in this research along with the practical insights derived from its application provides a means of improving the physical basis and promoting more sustainable analytical designs within the constraints of a typical river-management project.

REFERENCES

Andrews, E.D. 1980. "Effective and Bankfull Discharges of Streams in the Yampa River Basin, Colorado and Wyoming." *Journal of Hydrology*, Vol. 46, No. 3, pp. 311–330, DOI: 10.1016/0022-1694(80)90084-0.

Baker, D.B., R.P. Richards, T.T. Loftus, and J.W. Kramer. 2004. "A New Flashiness Index: Characteristics and Applications to Midwestern Rivers and Streams." *Journal of the American Water Resources Association*, Vol. 40, No. 2, pp. 503–522, DOI: 10.1111/j.1752-1688.2004.tb01046.x.

Beechie, T.J., D.A. Sear, J.D. Olden, G.R. Pess, J.M. Buffington, H. Moir, P. Roni, and M.M. Pollock. 2010. "Process-based Principles for Restoring River Ecosystems." *BioScience*, Vol. 60, No. 3, pp. 209–222, DOI: 10.1525/bio.2010.60.3.7.

Biedenharn, D.S., R.R. Copeland, C.R. Thorne, P.J. Soar, R.D. Hey, and C.C. Watson. 2000. "Effective Discharge Calculation: A Practical Guide." *Technical Report No. ERDC/CHL TR-00-15*, U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Bledsoe, B.P., D. Baker, P.A. Nelson, T. Rosburg, J. Sholtes, and T.R. Stroth. Submitted 2016. "Design Hydrology for Stream Restoration and Channel Stability at Stream Crossings." Prepared for National Cooperative Highway Research Program (NCHRP) Project 24-40.

Brownlie, W.R. 1981. "Prediction of Flow Depth and Sediment Discharge in Open-channels." *Report No. KH-R-43A*, California Institute of Technology, W.M. Keck Laboratory, Pasadena, CA.

Brunner, G.W. 2010. "HEC-RAS River Analysis System, User's Manual." *Report No. CPD-68*, Version 4.1, U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, 790 p., URL: http://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS_4.1_Users_Manual.pdf.

Bunte, K., K.W. Swingle, S.R. Abt, and D. Cenderelli. 2013. “Steep Gravel Bedload Rating Curves Obtained from Bedload Traps Shift Effective Discharge to Flows Much Higher than ‘Bankfull’.” *ePoster EP41A-0774*, American Geophysical Union, Fall Meeting 2012, San Francisco, CA, December 3-17, 2012.

Church, M. 2002. “Geomorphic Thresholds in Riverine Landscapes.” *Freshwater Biology*, Vol. 47, No. 4, pp. 541–557, DOI: 10.1046/j.1365-2427.2002.00919.x.

Church, M. 2006. “Bed Material Transport and the Morphology of Alluvial River Channels.” *Annual Review of Earth and Planetary Sciences*, Vol. 34, pp. 325–354, DOI: 10.1146/annurev.earth.33.092203.122721.

Copeland, R.R. 1994. “Application of Channel Stability Methods – Case Studies.” *Technical Report HL-94-11*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, September, 60 p., URL: http://www.dtic.mil/dtic/tr/fulltext/u2/a285625.pdf.

Copeland, R.R., D.N. McComas, C.R. Thorne, P.J. Soar, M.M. Jonas, and J.B. Fripp. 2001. “Hydraulic Design of Stream Restoration Projects.” *Technical Report No. ERDC/CHL-TR-01-28*, Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS, URL: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043219.pdf.

Doyle, M.W., D. Shields, K.F. Boyd, P.B. Skidmore, and D. Dominick. 2007. “Channel-forming Discharge Selection in River Restoration Design.” *Journal of Hydraulic Engineering*, Vol. 133, No. 7, pp. 831–837, DOI: 10.1061/(ASCE)0733-9429(2007)133:7(831).

Einstein, H.A. 1950. “The Bed Load Function for Sediment Transport in Open Channel Flows.” *Technical Bulletin No. 1026*, U.S. Department of Agriculture, Soil Conservation Service, Washington, DC.

Emmett, W.W., and M.G. Wolman. 2001. “Effective Discharge and Gravel-bed Rivers.” *Earth Surface Processes and Landforms*, Vol. 26, No. 13, pp. 1369–1380, DOI: 10.1002/esp.303.

Hawley, R.J., B.P. Bledsoe, E.D. Stein, and B.E. Haines. 2012. “Channel Evolution Model of Semiarid Stream Response to Urban-induced Hydromodification.” *Journal of the American Water Resources Association*, Vol. 48, No. 4, pp. 722–744, DOI: 10.1111/j.1752-1688.2012.00645.x.

Hey, R.D. 1975. “Design Discharge for Natural Channels.” Pages 73–88 in R.D. Hey and T.D. Davies (Eds.): *Science, Technology and Environmental Management*, Saxon House, Farnborough.

Howard, A.D. 1987. “Modelling Fluvial Systems: Rock-, Gravel-, and Sand-bed Channels.” Pages 69–94 in K. Richards (Ed.): *River Channels: Environment and Process*, Blackwell, New York, NY.

Limerinos, J.T. 1970. “Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels.” *U.S. Geological Survey Water-Supply Paper 1898-B*, 47 p., U.S. Government Printing Office, Washington, DC, URL: http://pubs.usgs.gov/wsp/1898b/report.pdf.

Montgomery, D.R., and J.M. Buffington. 1997. “Channel-reach Morphology in Mountain Drainage Basins.” *Geological Society of America Bulletin*, Vol. 109, No. 5, pp. 596–611, DOI: 10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2.

Parker, G. 1990a. “Surface-based Bedload Transport Relation for Gravel Rivers.” *Journal of Hydraulic Research*, Vol. 28, No. 4, pp. 417–436, DOI: 10.1080/00221689009499058.

Parker, G. 1990b. “The “acronym” Series of Pascal Programs for Computing Bedload Transport in Gravel Rivers.” *External Memorandum M-220*, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Minneapolis, MN, 24 p.

Parker, G. 2006. “Gary Parker’s Morphodynamics Web Page.” URL: http://hydrolab.illinois.edu/people/parkerg/, accessed April 13.

Piégay, H., M. Cuaz, E. Javelle, and P. Mandier. 1997. “Bank Erosion Management Based on Geomorphological, Ecological and Economic Criteria on the Galaure River, France.” *Regulated Rivers: Research & Management*, Vol. 13, No. 5, pp. 433–448, DOI: 10.1002/(SICI)1099-1646(199709/10)13:5<433::AID-RRR467>3.0.CO;2-L.

Ricciardi, A., and J.B. Rasmussen. 1999. “Extinction Rates of North American Freshwater Fauna.” *Conservation Biology*, Vol. 13, No. 5, pp. 1220–1222, DOI: 10.1046/j.1523-1739.1999.98380.x.

Schumm, S.A. 1977. *The Fluvial System*. Vol. 338, Wiley, New York, NY.

Shields Jr., F.D., R.R. Copeland, P.C. Klingeman, M.W. Doyle, and A. Simon. 2003. “Design for Stream Restoration.” *Journal of Hydraulic Engineering*, Vol. 129, No. 8, pp. 575–584, DOI: 10.1061/(ASCE)0733-9429(2003)129:8(575).

Sholtes, J.S., and B.P. Bledsoe. 2016. “Half-yield Discharge: Process-based Predictor of Bankfull Discharge.” *Journal of Hydraulic Engineering*, Vol. 142, No. 8, DOI: 10.1061/(ASCE)HY.1943-7900.0001137, 04016017.

Skidmore, P.B., F.D. Shields, M.W. Doyle, and D.E. Miller. 2001. “A Categorization of Approaches to Natural Channel Design.” Pages 1–12 in D.F. Hays (Ed.): *Proceedings of* *the 2001 Wetlands Engineering and River Restoration Conference*, Reno, NV, August 27-31, DOI: 10.1061/40581(2001)38.

Soar, P.J., and C.R. Thorne. 2001. "Channel Restoration Design for Meandering Rivers." *Technical Report No. ERDC/CHL CR-01-1*, Coastal and Hydraulics Laboratory, U.S. Army, Engineer Research and Development Center, Vicksburg, MS, URL: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043218.pdf.

Soar, P.J., and C.R. Thorne. 2013. "Design Discharge for River Restoration." Pages 123–150 in A. Simon, S.J. Bennett, and J.M. Castro (Eds.): *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*, Geophysical Monograph Series, Vol. 194, American Geophysical Union, Geopress, Washington, DC.

Strayer, D.L., and D. Dudgeon. 2010. "Freshwater Biodiversity Conservation: Recent Progress and Future Challenges." *Journal of the North American Benthological Society*, Vol. 29, No. 1, pp. 344–358, DOI: 10.1899/08-171.1.

Thomas, W.A., R.R. Copeland, and D.N. McComas. 2002. "SAM Hydraulic Design Package for Channels." Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Vicksburg, MS, URL: http://www.stream.fs.fed.us/fishxing/fplibrary/ACOE_2002_SAM_Hydraulic_Design_Package_for_Channels.pdf.

Trimble, S.W. 1997. "Contribution of Stream Channel Erosion to Sediment Yield from an Urbanizing Watershed." *Science*, Vol. 278, No. 5342, pp. 1442–1444, DOI: 10.1126/science.278.5342.1442.

U.S. Environmental Protection Agency (EPA). 2009. "National Water Quality Inventory: Report to Congress: 2004 Reporting Cycle." *EPA Publication 841-R-08-001*, EPA, Washington, DC, 37 p., URL: https://www.epa.gov/sites/production/files/2015-09/documents/2009_01_22_305b_2004report_2004_305breport.pdf.

Vogel, R.M., J.R. Stedinger, and R.P. Hooper. 2003. "Discharge Indices for Water Quality Loads." *Water Resources Research*, Vol. 39, No. 10, DOI: 10.1029/2002WR001872.

Wilcock, P.R., S.T. Kenworthy, and J.C. Crowe. 2001. "Experimental Study of the Transport of Mixed Sand and Gravel." *Water Resources Research*, Vol. 37, No. 12, pp. 3349–3358, DOI: 10.1029/2001WR000683.

Wilcock, P.R., and J.C. Crowe. 2003. "Surface-based Transport Model for Mixed-size Sediment." *Journal of Hydraulic Engineering*, Vol. 129, No. 2, pp. 120–128, DOI: 10.1061/(ASCE)0733-9429(2003)129:2(120).

Wohl, E., B.P. Bledsoe, R.B. Jacobson, N.L. Poff, S.L. Rathburn, D.M. Walters, and A.C. Wilcox. 2015. "The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management." *Bioscience*, Vol. 65, No. 4, pp. 358–371, DOI: 10.1093/biosci/biv002.

Wolman, M.G., and J.P. Miller. 1960. "Magnitude and Frequency of Forces in Geomorphic Processes." *Journal of Geology*, Vol. 68, No. 1, pp. 54–74, DOI: 10.1086/626637.

CHAPTER 4: THESIS CONCLUSION

The CSR Tool developed in this study performs a full spectrum analytical channel design calculation using the CSR sediment balance concept. Outputs include a family of stable channel design solutions that provide the continuity of water and sediment over the entire FDC. The tool has been verified for accuracy with comparisons to the Copeland method in HEC-RAS with slight deviations that can most likely be explained from the difference in modeling approach for overbank flow. The CSR Tool has the additional feature of floodplain modeling which can increase the fidelity of the model to actual physical processes, and it provides the ability to perform CSR analysis on both sand-bed and gravel-bed streams. Comparisons between the resulting stability curves for sand- and gravel-bed examples show that stable slopes for sand are more sensitive to changes of incoming sediment load. This finding supports my hypothesis that the CSR analysis will be more important for finer grain channels.

The CSR Tool was applied to eighteen sand-bed sites to provide insight on comparisons of single-discharge designs to the CSR, when and what influences any differences, and when is it most important to use the CSR analysis. This analysis provides support to more sustainable channel design practice, and has cultivated new questions that can help advance the science of analytical channel design. I suggest that the CSR method can be the preferred technique in many instances since it provides a more rigorous physical basis over single-discharge designs. Four key variables indicating that a CSR design is appropriate are highly erodible substrate, flashy flow regime, small width-to-depth ratio, and large inflowing sediment loads. Highly erodible channels are often sand-bed dominated channels, but also extend to gravel-bed channels with high sand mixtures that also exhibit ‘labile’ behaviors. The five single-discharge designs diverged with a positive correlation from the CSR result with increasing R-B Index. This is most likely because ‘flashier’ streams have a higher potential to have several influential flows that are not accounted for with a single-discharge design. The single-discharge deviations also had a negative correlation with increasing width-to-depth ratio. This is presumably because smaller streams with smaller basins have a higher potential to have flashy hydrographs.

In general, the single-discharge designs based on Q_{s50} and Q_{s75} as expected were the closest to the CSR followed by Q_{bf}, Q_{eff}, and $Q_{1.5}$. The Q_{eff} can be an inconsistent design metric because of its sensitivity to binning procedures used in the MFA. Q_{bf} can also be challenging to obtain accurately, especially in disturbed systems in need of restoration, because field indicators are often confounding or absent in urban and incised streams, but when field indicators and expert judgement is present it can still prove to be a useful design metric. The $Q_{1.5}$ is the simplest to calculate and can be a useful design metric is some instances, but can be highly dependent on the quality and quantity of available hydrologic data. The Q_{s50} and Q_{s75} are robust single-discharge design metrics because they are based off of cumulative sediment transport distributions and are less sensitive to the common difficulties of estimating the Q_{eff}, $Q_{1.5}$, and Q_{bf} discharges; however, they may also be the most limited by data availability. Furthermore, the majority of sand-bed streams examined in this study showed that the Q_{s50} and Q_{s75} designs matched or bracketed the CSR design which can provide a useful practical reference for choosing a design discharge. Lastly, this research showed that the percent differences for the single-discharge designs can be substantially sensitive to incoming sediment load and differences in yield can produce large aggradation/degradation potential on the order of meters. This is expected since the same percent difference will have more sediment available for erosion or deposition for a higher incoming sediment load.

This thesis presented the development and application of the VBA-based CSR Tool. All stated objectives for the development and application of the CSR Tool were met and completed, and all presented research questions were analyzed and discussed. The development of this tool has provided a streamlined platform for researchers and practitioners to explore and utilize the full spectrum information of the CSR methodology for stable channel design. The applications of the tool presented offer a basis for which sequent research can build off of to advance the science of analytical channel design, and practitioners can apply to aid in sustainable channel design initiatives.

APPENDIX A: REFERENCE MANUAL: CSR STABLE CHANNEL DESIGN TOOL

A.1 Reference Manual for the CSR Tool

This reference manual summarizes the theoretical background and methodology used to develop the CSR Stable Channel Design Tool (CSR Tool) based in Excel® Visual Basic for Applications (VBA). It provides background information, the theoretical basis of the tool's functionalities, the code structure methodology, and how the tool was tested for accuracy.

A.1.1 Analytical Channel Design using Sediment Continuity

The underlying methodology of the CSR Tool uses an analytical channel design procedure to produce stable channel configurations for a reach of interest. This is achieved by estimating sediment continuity within the reach by using empirically derived equations to estimate the sediment transport capacity or potential ability of the reach to transport sediment versus the incoming sediment load delivered from an upstream supply reach. Two approaches to analytical channel design were the main focus in the development of this tool: (1) the Copeland Method from the Stable Channel Design section of HEC-RAS (Copeland 1994), and (2) the CSR method presented by Soar and Thorne (2001). This tool was developed to provide a user-friendly means to use the CSR method for stable channel design. The coding scheme for the tool follows the Copeland method as closely as possible in order to compare between the two approaches. The following sections will give an overview of these methods, the fundamental relationships and equations used, and how they apply to the development of the CSR Tool.

A.1.1.1 Basic hydraulic equations

The continuity equation for 1-D cross-section averaged, steady flow is used in the calculations as follows:

$$Q = VA \tag{A-1}$$

and the Manning's equation:

$$V = \mathrm{c}\frac{R^{2/3}S_f^{1/2}}{n} \qquad \textbf{(A-2)}$$

where:

Q = discharge [m^3/s, ft^3/s];

V = cross-section averaged velocity [m/s, ft/s];

A = cross-sectional area [m^2, ft^2];

R = hydraulic radius [m, ft];

S_f = friction slope [m/m, ft/ft];

n = Manning's roughness coefficient; and

c = constant, conversion factor (1.0 for SI units and 1.486 for English units).

A.1.1.2 Copeland method

The Copeland Method was developed by Dr. Ronald Copeland at the Waterways Experiment Station for use in the SAM software package (Copeland 1994). It is an analytical channel design approach that is based on the use of empirically derived equations. The method was developed solely to design sand-bed channels by estimating sediment continuity in a design reach using the total load sediment transport equation created by Brownlie (1981). For a given design discharge, the model solves for stable depth and slope for a range of bottom widths for trapezoidal cross sections. The Brownlie (1981) relationship used to calculate transport concentration is as follows:

$$C_{ppm} = 9022\left(\frac{V - V_c}{\sqrt{(G-1)gD_{50}}}\right)^{1.978} S_f^{0.6601}\left(\frac{R}{D_{50}}\right)^{-0.3301} \qquad \textbf{(A-3)}$$

where:

C_{ppm} = sediment transport concentration [ppm];

V = cross-section averaged velocity [m/s, ft/s];

V_c = critical velocity [m/s, ft/s];

G = specific gravity of sediment particles;

g = gravitational constant;

D_{50} = median grain size [m, ft];

S_f = friction slope [m/m, ft/ft]; and

R = hydraulic radius [m, ft].

This method calculates a critical velocity to determine how much sediment will be transported. If the cross-section averaged velocity, V is less than the critical velocity (V_c), then no sediment transport is assumed. The critical velocity is calculated by using the following equations:

$$V_c = 4.596 \tau_{*c}^{0.529} S_f^{-0.1405} \sigma_g^{-0.1606} \quad \textbf{(A-4a)}$$

$$\sigma_g = \sqrt{\frac{D_{84}}{D_{16}}} \quad \textbf{(A-4b)}$$

$$\tau_{*c} = 0.22Y + 0.06(10^{-7.7Y}) \quad \textbf{(A-4c)}$$

$$Y = \left(\frac{\sqrt{(G - 1) g D_{50}^3}}{v} \right)^{-0.6} \quad \textbf{(A-4d)}$$

where:

τ_{*c} = dimensionless critical shear stress;

S_f = friction slope [m/m, ft/ft];

σ_g = gradation coefficient;

D_{84} = particle size for which 84% of all sediments is smaller [m, ft];

D_{16} = particle size for which 16% of all sediments is smaller [m, ft];

G = specific gravity of sediment particles;

g = gravitational constant; and

v = kinematic viscosity [m^2/s, ft^2/s].

The critical shear stress is calculated using regression equations of the original Shields diagram. Next, Brownlie developed the following depth predictor equations that take into account the effects of sand-bed forms for lower and upper regimes.

$$R_{bank} = 0.05761(G - 1)^{0.9447} F_g^{1.889} S^{-0.7345} \sigma_g^{0.3034} (D_{50}) \quad \textbf{(A-5a)}$$

$$R_{bank} = 0.03478(G - 1)^{0.8326} F_g^{1.665} S^{-0.7668} \sigma_g^{0.2136} (D_{50}) \quad \textbf{(A-5b)}$$

$$F_g = \frac{Q}{A\sqrt{(G - 1)gD_{50}}} \quad \textbf{(A-5c)}$$

where:

R_{bank} = hydraulic radius of bank partition [m, ft];

G = specific gravity of sediment particles;

F_g = grain-related Froude number;

S = gradient [m/m, ft/ft];

σ_g = gradation coefficient;

D_{50} = median grain size [m, ft]);

Q = discharge [m^3/s, ft^3/s];

A = cross-sectional area [m^2, ft^2];

G = specific gravity of sediment particles; and

g = gravitational constant.

These equations are used in conjunction with the previous equation to find the total estimated sediment transport for different design combinations. The lower and upper regime is determined by regression equations presented by (Brownlie 1981) of the relationship of grain

Froude number versus slope. If the slope of the channel is greater than 0.006 then only upper regime is expected. When the slope is less than 0.006, the maximum velocity of the lower regime can be determined by solving for velocity from the following equation:

$$F_g = 1.25F_g^{'} \tag{A-6a}$$

with:

$$F_g^{'} = 1.74S^{1/3} \tag{A-6b}$$

The channel is partitioned into bed and bank components and sediment transport is assumed to occur only on the bed. The Einstein (1950) equation is utilized to partition the hydraulic parameters of the channel:

$$A = R_{bed}P_{bed} + R_{bank}P_{bank} \tag{A-7}$$

where:

A = cross-sectional area [m^2, ft^2];

R_{bed} = hydraulic radius of bed partition [m, ft];

P_{bed} = bottom width = wetted perimeter of bed partition [m, ft];

R_{bank} = hydraulic radius of bank partition [m, ft]; and

P_{bank} = wetted perimeter of bank partition [m, ft].

This method assumes that the average velocity for the bank and the bed partitions are both equal to the cross-section averaged velocity for the whole channel. Thus, the channel banks can be described by rearranging the Manning’s equation as the following:

$$R_{bank} = \left(\frac{Vn_{bank}}{S^{1/2}}\right) \tag{A-8}$$

where:

R_{bank} = hydraulic radius of bank partition [m, ft];

V = cross-section averaged velocity [m/s, ft/s];

n_{bank} = Manning's roughness coefficient of bank partition; and

S = slope [m/m, ft/ft].

The Manning's n of the banks are required inputs, but the roughness of the bed partition is calculated within the program with the Brownlie (1983) roughness equations:

$$n = \left[1.6940\left(\frac{R}{D_{50}}\right)^{0.1374} S^{0.1112}\sigma^{0.1605}\right]0.034(D_{50})^{0.167} \text{ (lower regime)} \qquad \textbf{(A-9a)}$$

$$n = \left[1.0213\left(\frac{R}{D_{50}}\right)^{0.0662} S^{0.0395}\sigma^{0.1282}\right]0.034(D_{50})^{0.167} \text{ (upper regime)} \qquad \textbf{(A-9b)}$$

where:

n = Manning's roughness coefficient;

R = hydraulic radius [m, ft];

D_{50} = median grain size [m, ft]; and

S = slope [m/m, ft/ft].

In order to run the model, an incoming sediment load must be defined. There are two options to define the sediment supply in HEC-RAS. The user can simply enter an incoming sediment concentration, or the user can have the program estimate the concentration for them using a user-defined trapezoidal cross section that represents an upstream supply reach that will produce the incoming sediment load.

The user must then define the desired characteristics of the design reach and enter a single design discharge that will be used in the equations presented above. This discharge will be assumed to represent the most channel-forming flow that can be seen in the flow record for the channel.

“To date, no generally accepted discharge for stable channel design is agreed upon, therefore, the use of a range of discharges is recommended” (Copeland 1994). The HEC-RAS reference manual further suggests the use of a 2-yr frequency flood (perennial streams), 10-yr frequency flood (ephemeral streams), bankfull discharge, or effective discharge for the design discharge. The program can then solve for depth, slope, and width combinations that will successfully pass the incoming sediment load through the design channel based on its estimated sediment transport potential using Brownlie (1981). The results of the model produce a family of stable channel designs similar to Figure A-1.

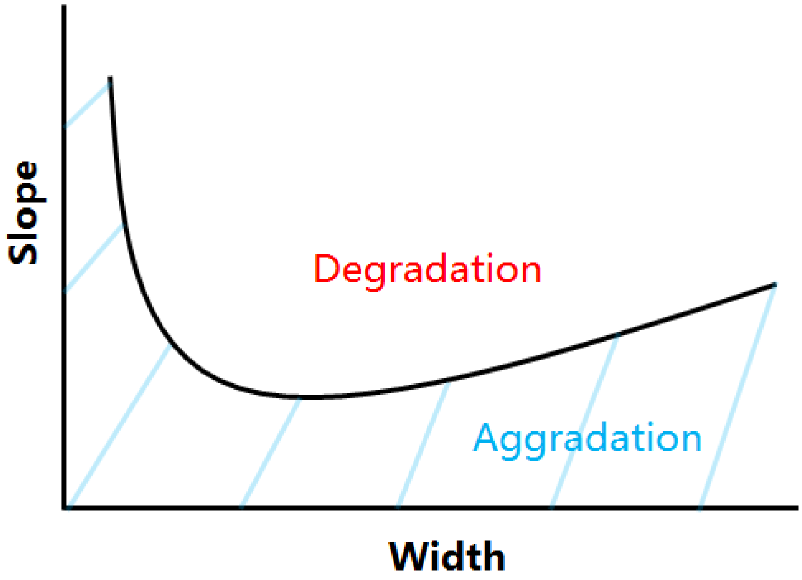


Figure A-1. Slope/width combinations that provide continuity of water and sediment based on the Copeland Method.

This curve represents the stable slope/width combinations that provide continuity of water and sediment for the design channel. If slope/width combinations for the design channel fall above this curve then one can expect degradation because the channel is estimated to have to a higher sediment transport capacity than supply. Alternatively, if the design falls below the curve, aggradation is expected since supply exceeds capacity.

A.1.1.3 CSR method

The Capacity/Supply Ratio (CSR) concept was first introduced by (Soar and Thorne 2001). They used this concept to analyze the faults in a design that led to a failed river restoration project at White Marsh Run in Maryland. The CSR is a simple balance between the ability of a given river reach to transport sediment (capacity), to the sediment that is being transported into the reach of interest (supply). This is the same sediment balance concept as used in the Copeland Method; however, the difference comes from the discharge(s) the sediment transport capacity is calculated with. More specifically, the CSR can be described with the following equation:

$$\mathrm{CSR} = \frac{\int_{\mathrm{time}} \text{transport capacity of Design Reach}}{\int_{\mathrm{time}} \text{transport capacity of Supply Reach}} \qquad \textbf{(A-10)}$$

This equation describes the CSR as the time integrated ratio of sediment transport capacity of a design reach to the incoming sediment supply. In other words, "*The CSR is defined as the bed-material load transported through the river reach by a sequence of flows over an extended time period divided by the bed-material load transported into the reach by the same sequence of flows over the same time period*" (Wohl et al. 2015). Ultimately, the CSR method balances the total average sediment yield over the entire flow record rather than just for a single representative discharge as in the Copeland Method.

If the capacity of the reach to transport sediment exceeds the sediment entering the reach from upstream, then degradation or erosion can be expected in the reach with a CSR > 1. On the other hand, if the sediment entering the reach exceeds the capacity of the reach to transport it, then aggradation or sediment accumulation is expected with a CSR < 1. A CSR within 10% of unity will be the most likely to have sediment balance with minimal aggradation or degradation in the channel (Soar and Thorne 2001):

- CSR > 1 (degradation);
- CSR ≈ 1 (equilibrium); and
- CSR < 1 (aggradation).

A.1.1.4 Effectiveness analysis

In order to find the time integrated sediment transport, a magnitude/frequency analysis (MFA) needs to be performed to find the total ‘effectiveness’ for each reach. In the context of this tool, the sequence of flows over an extended time period is derived from a user-defined flow record, or a flow duration curve (FDC) from another source for the river reach of interest. These flows are used to calculate the probability that a given flow will occur on average in the associated reach in a given day. Then, the potential that the given flow has to move sediment is estimated with an appropriate sediment transport equation. The effectiveness or the sediment transported on average over a period of time is calculated by multiplying the probability of the given flow by the potential sediment that can be transported by that flow. The effectiveness for each flow in the record is summed to get the total effectiveness or time integrated sediment transport capacity of the reach.

A.1.1.5 Hydrology

A more extensive hydrologic analysis is required by the CSR Tool in order to estimate the time integrated sediment transport capacity of the reaches over the entire FDC rather than a single discharge. The CSR Tool can use a flow gage record, or a pre-derived flow duration curve. These flow characteristics are assumed to be the same and representative of the flows seen by the supply and design reach.

If a gage record is chosen for the hydrology data, then the program will sort the discharges using an arithmetic binning procedure. This method splits the flows into a specified number of equal interval bins. A total number of bins must be defined by the user or the program defaults to 25 bins as recommended by Biedenharn et al. (2000). Each bin represents a range of discharges that the flows of the record could fall into. This is defined by the following equation:

$$\mathit{Range}\,Q = \frac{\mathit{Max}\,Q - \mathit{Min}\,Q}{\#\text{ of bins}} \tag{A-11}$$

where:

Range Q = range of discharge in flow record [m^3/s, ft^3/s];

Max Q = maximum discharge in flow record [m^3/s, ft^3/s]; and

Min Q = minimum discharge in flow record [m^3/s, ft^3/s].

The program then counts how many flows from the flow record falls into each range of discharges. The process starts at 25 arithmetic discharge bins and reduces the amount of bins until there are no bins with zero frequency. In cases where there is still zero frequency at 10 bins then the process starts again at 25 bins and combines the discharges above the zero frequency bin into one. The geometric mean of the range of discharges in each bin is calculated to be used later in the sediment transport estimations for that bin. The probability of occurrence for flows in each bin can be calculated by the simple equation also known as the relative frequency:

$$\text{probability} = \frac{\text{frequency of flows in bin}}{\text{total \# of flows in record}} \tag{A-12}$$

Finally, this can be converted to a probability density for each bin by dividing by the discharge range of each bin:

$$\text{probability density} = \frac{\text{frequency of flows in bin}}{\text{total \# of discharges in record} * \mathit{Range}\,Q} \tag{A-13}$$

The most common method to perform a MFA is using a flow record when possible, however, it is rare in practice to have a sufficiently long and representative flow record for a stable reach upstream of the design reach. There has been research that has developed ways to help this by extrapolating FDC's at un-gaged sites and factoring in effects such as land use into the FDC. So, to strengthen and broaden the applicability of this tool a feature was added to allow the user to enter their own FDC rather use a flow record. The program that was focused on for this feature, that is made to produce specialized FDC curves, is SWAT-DEG (channel DEGradation portion of SWAT) in eRams (environmental Risk Assessment & Management System). Instead of entering the flows for a gage record, the user simply enters the values of the FDC. For example, the SWAT-DEG program creates a very detailed FDC and outputs a table of exceedance probabilities versus discharges that can be directly pasted into the CSR Tool. This FDC is very detailed and often thousands of cells long so the user is required to define a lower number of bins to consolidate the FDC for use in sediment calculations. The default is set to 25 bins but the user can choose up to 50 bins. The user can then run the associated tab to consolidate the original FDC. The larger FDC is sampled logarithmically for the user-defined number of bins. To perform this sampling, the range of discharges for the FDC is converted to log space to find a logarithmic interval to sample the data:

$$Min\,Q_{\log} = \frac{\log(Min\,Q)}{\log(10)} \tag{A-14a}$$

$$Max\,Q_{\log} = \frac{\log(Max\,Q)}{\log(10)} \tag{A-14b}$$

$$\text{sampling interval} = \frac{Max\,Q_{\log}\ \text{-}\ Min\,Q_{\log}}{\#\,\text{of bins}} \tag{A-14c}$$

This sampling interval is added to the minimum Q in log space for the given number of bins. These discharges are then converted back from log space to represent the new consolidated range of discharges. The match function of Excel® is then used to search for the exceedance probabilities that are associated with each sampled discharge. The exceedance probabilities of the new consolidated FDC are then converted to non-exceedance probabilities with:

$$\text{non-exceedance probability} = 1 - \text{exceedance probability} \qquad \textbf{(A-15)}$$

Finally, the non-exceedance probabilities and their associated discharges represent the cumulative distribution function (CDF). This CDF can be differentiated to find the associated probability density function (PDF). The differentiation or the slope of the CDF at each discharge point, can be approximated using the central difference method:

$$f'(\text{CDF}) = \frac{P_{<,i+1} - P_{<,i}}{Q_{i+1} - Q_{i+1}} \qquad \textbf{(A-16)}$$

where:

$P_{<,i}$ = non-exceedance probability of each bin.

This PDF can then be used in the sediment transport calculations for the tool.

A.1.1.6 Using the CSR/effectiveness in the context of the tool

The CSR Stable Channel Design Tool requires the input of hydrology information and the dimensions and hydraulic characteristics of a supply reach to perform the CSR analysis. The information is used to perform a MFA for the supply reach to estimate the total effectiveness or sediment supply entering the design reach of interest downstream. The hydrologic information for the supply reach is assumed to be the same for the design reach, and the sediment transported by the supply reach is assumed to be the value that is entering the design reach. The program also requires dimensions and hydraulic characteristics for a potential design reach except a width and slope. Then, the program loops through slope/width combinations that produce an effectiveness that balances with the calculated incoming sediment from the supply reach giving a CSR = 1. This curve is analogous to the stable channel design curve produced by Copeland's method is HEC-RAS. The curve shown in (Figure A-2) represents a family of channel slope/width combinations with a CSR = 1. Any design with a slope/width above this line can expect degradation or erosion, while any below could expect aggradation or sediment accumulation.

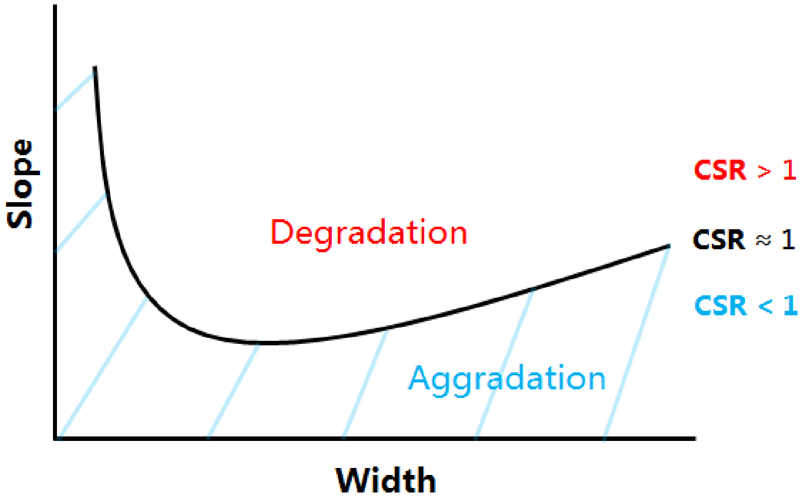


Figure A-2. Family of slope/width combinations which provide continuity of water and sediment.

Figure A-3 shows a visual representation of the methodology behind the tool using a CSR analysis. The figure shows a delineated upstream supply reach and downstream design reach. Each reach shows an idealized flow frequency/ probability distribution (section A), an idealized sediment discharge curve (secton B), and the resulting product of (section A) and (section B) which gives the effectiveness curve (section C). The area under the effectiveness curve represents the total sediment moved on average by each reach and is used to find the sediment balance of the design reach using the CSR. The curves are colored coded to correspond with the CSR equation shown at the top of Figure A-3.

$$\text{Capacity/Supply Ratio(CSR)} = \frac{\int_{\text{time}} \text{Sediment transport capacity of Design Reach}}{\int_{\text{time}} \text{Sediment transport capacity of Supply Reach}}$$

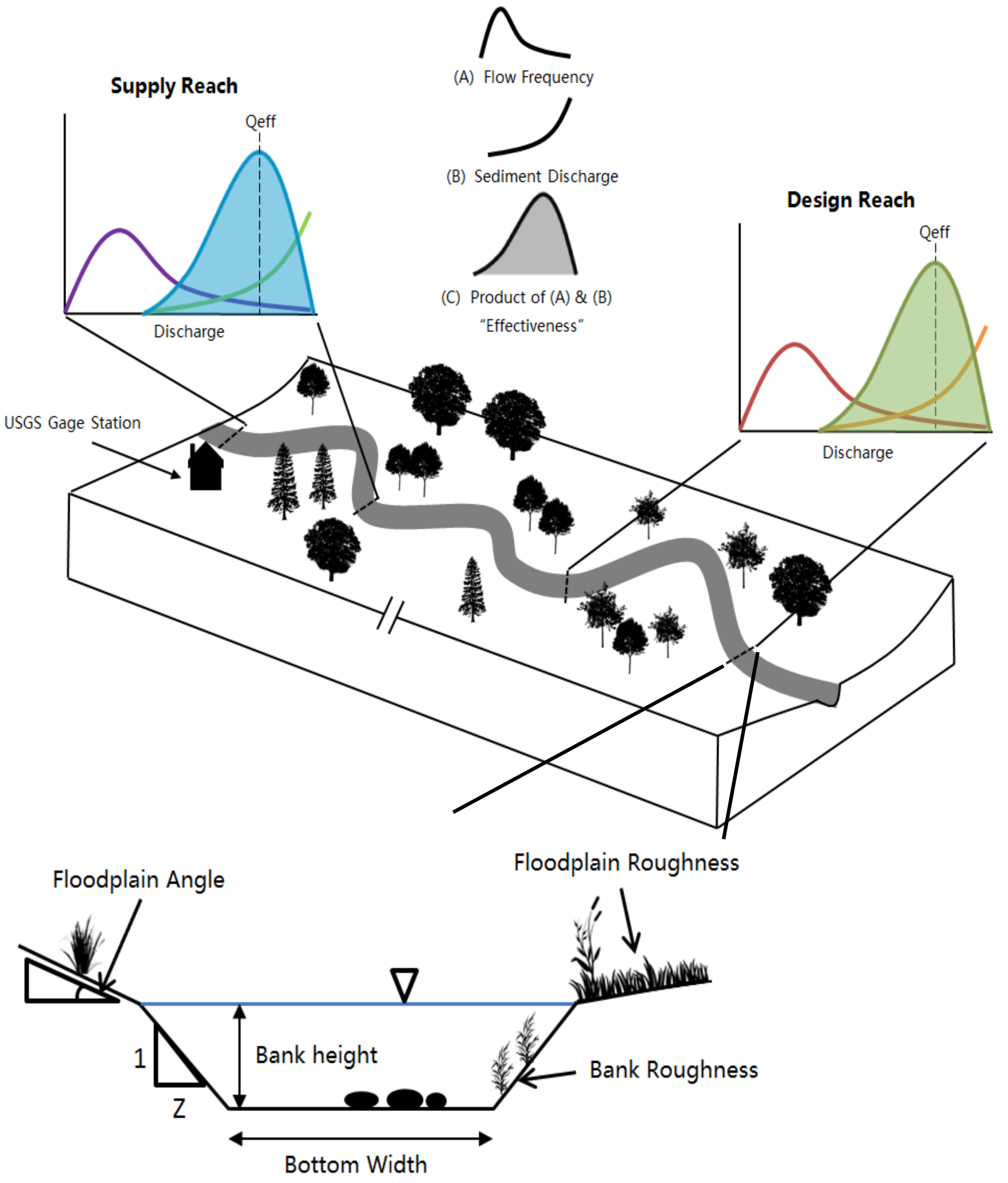


Figure A-3. Visual representation of CSR analysis in tool and simplified trapezoidal features.

A.1.1.7 Simplified trapezoidal channel

The tool uses a simplified trapezoidal channel to represent the supply reach and design reach as shown at the bottom of Figure A-3. All of the trapezoidal dimensions (bank height, bottom width, bank/floodplain angle) and roughness characteristics (bank/floodplain Manning's *n*) are required inputs for the supply reach of the tool. As opposed to the Copeland method in HEC-RAS, The CSR Tool models overbank flow thus requires inputs for floodplain angle and roughness. The bed Manning's *n* is calculated in conjunction with the sediment transport equations. The design reach requires the same inputs except bottom width and slope because these variables are varied by the program to find new channel dimensions that will produce a CSR = 1. The equations used to model the trapezoid channel are shown below:

$$A_{channel} = (b + zh)h \qquad \textbf{(A-17a)}$$

$$P_{Bank} = h(\sqrt{1+z^2}) \qquad \textbf{(A-17b)}$$

$$P_{Bank} = b \qquad \textbf{(A-17c)}$$

$$R_{Bank} = h(\sqrt{1+z^2}) \qquad \textbf{(A-17d)}$$

where:

$A_{channel}$ = cross-sectional area of channel [m^2, ft^2];

b = bottom width [m, ft];

z = bank angle, horizontal to vertical [H:V];

h = depth [m, ft];

P_{bank} = wetted perimeter of bank partition [m, ft]; and

R_{bank} = hydraulic radius of bank partition [m, ft].

A.1.1.8 Channel partitioning

The in-channel partitioning approach for the CSR Tool follows the method used by Copeland in HEC-RAS, which breaks the channel into bed and bank components with separate roughness characteristics (Figure A-4(a)). The bank roughness is specified by the user and the bed roughness is calculated in conjunction with the sediment transport analysis. The Einstein (1950) equation is utilized to partition the components.

Unlike the Copeland method, the CSR Tool also models overbank flow. Once the flow in the channel breaks into overbank flow, the partition approach is altered because the Einstein (1950) method is no longer valid. In contrast to the in-channel method, the partitions are simply delineated by vertical lines as shown in Figure A-4(b). The bed partition is centered over the bed, the bank components over both banks, and the floodplain components over each floodplain (Figure A-4):

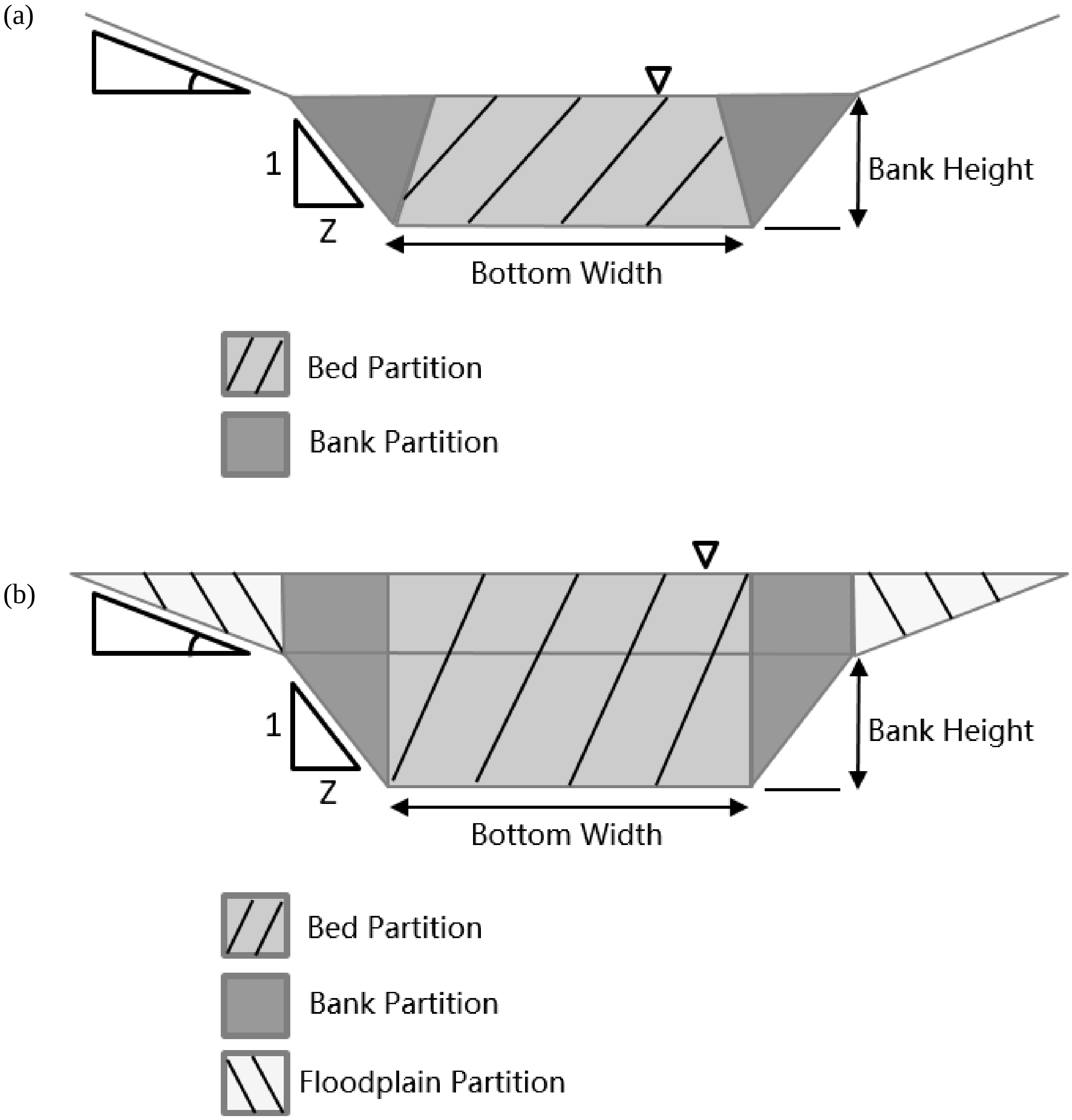


Figure A-4. Visual representation of channel partitioning methodology for the (a) in-channel flow partitioning approach and (b) overbank flow partitioning approach.

Instead, a conveyance method that is used by HEC-RAS (USACE) is utilized to help converge on a depth solution. The conveyance (*K*) of the floodplain partition is calculated with the following:

$$K_{OB} = \frac{1}{n_{floodplain}} A_{OB} R_{OB}^{2/3} \qquad \textbf{(A-18)}$$

where:

K_{OB} = conveyance of bed partition;

$n_{floodplain}$ = Manning's roughness of floodplain partition;

A_{OB} = area of floodplain partition [m^2, ft^2]; and

R_{OB} = hydraulic radius of floodplain partition [m, ft].

This variable is used in solving the system of equations to converge on a depth solution.

A.1.2 Gravel- / Cobble-Bed Analysis

The CSR Tool, as opposed to the Copeland method, can run the CSR analysis to find stable channel design solutions for both sand-bed *and* gravel- / cobble-bed streams.

The sand-bed portion of the tool uses the Brownlie (1981) total load sediment transport equation to estimate transport rate similar to the Copeland method in HEC-RAS except with the full CSR approach. Two bedload sediment transport equations, the Parker (1990) and Wilcock-Crowe (2003) equations are available to estimate sediment transport rates in gravel- / cobble-bed streams. Pre-existing code from Gary Parker was obtained for these equations and implemented/adapted for use in the tool. This includes the addition of an extra tab for the input and sorting of the grain size distribution for calculations. The Parker (1990) bedload equation is appropriate for use with rivers of gravel size (>2 mm diameter) and larger substrate. The Wilcock-Crowe (2003) bedload equation can be used with gravel- / cobble-bed streams that include a sand fraction (<2 mm diameter). Refer to the CSR Tool Guidance Document (Appendix B) for further selection guidance on stream type.

The code methodology for the gravel- / cobble-bed portion was matched as closely as possible to the sand-bed structure. The biggest difference between the methodologies for the calculation of hydraulic parameters is with the hydraulic roughness. The sand-bed portion of the tool uses the Manning's equation and the roughness predictor with bedforms from (Brownlie 1983). It was chosen to use the Manning's and Limerinos (1970) equations to calculate the roughness in the channel for the gravel-bed portion of the tool. The Limerinos (1970) equation was calibrated to account for mostly grain roughness of larger particles from gravels to boulders:

$$n = \frac{(\beta)R^{1/6}}{1.16 + 2.0\log_{10}\left(\frac{R}{D_{84}}\right)} \qquad \textbf{(A-19)}$$

where:

n = Manning's roughness coefficient;

β = conversion factor (0.1129 for SI units and 0.0926 for English units);

R = hydraulic radius (m, ft); and

D_{84} = particle size for which 84% of all sediments is smaller (m, ft).

A.1.2.1 Grain size distribution calculations

To run the CSR analysis for a gravel- / cobble-bed stream the user is required to enter a grain size distribution as the percent finer (%) versus grain size class (mm). The grain size classes are defined by the following for N grain size ranges from i =1 to N + 1:

$$(D_{b,i} * D_{b,i+1}) \qquad \textbf{(A-20)}$$

The characteristic grain size (D_i) and fraction of the surface layer (F_i) is then:

$$D_i = \sqrt{D_{b,i}(D_{b,i+1})} \qquad \textbf{(A-21a)}$$

$$F_i = \frac{F_{f,i} - F_{f,i+1}}{100} \qquad \textbf{(A-21b)}$$

where:

$D_{b,i}$ = grain size representing each size class of the (active) layer of the bed [m, ft].

Each grain size on the base-2 logarithmic ψ scale is computed by the following:

$$\psi_i = \ln(D_i) = \frac{\log_{10}(D_i)}{\log_{10}(2)} \tag{A-22}$$

where:

Ψ_i = each grain size on the base 2 logarithmic ψ scale; and

D_i = characteristic grain size for each size class [m, ft].

Then the geometric mean grain size (D_{sg}) can be calculated with:

$$D_{sg} = 2^{\overline{\psi_s}} \tag{A-23a}$$

$$\overline{\psi_s} = \sum_{i=1}^{N} \psi_i F_i \tag{A-23b}$$

where:

N = grain size ranges from i = 1 to N + 1;

Ψ_i = each grain size on the base 2 logarithmic ψ scale; and

F_i = fraction of grain size in surface layer.

The geometric and arithmetic standard deviations σ_{sg} and σ_s, respectively:

$$\sigma_{sg} = 2^{\sigma} \tag{A-24a}$$

$$\sigma_s^2 = \sum_{i=1}^{N} (\psi_i - \overline{\psi_s})^2 F_i \tag{A-24b}$$

where:

σ_{sg} = geometric standard deviation;

σ_s = arithmetic standard deviation;

N = grain size ranges from i = 1 to N + 1;

Ψ_i = each grain size on the base 2 logarithmic ψ scale; and

F_i = fraction of grain size in surface layer.

A.1.2.2 Bedload sediment transport relationships

The gravel- / cobble-bed portion of the tool has two options for running the CSR analysis. The user can choose the Parker (1990) or Wilcock-Crowe (2003) bedload equation. Both of these equations estimate the total bedload transport rate per unit width. This amount is then converted into an effectiveness for each discharge. The Parker (1990) bedload transport relation can be expressed as the following:

$$W_i^* = 0.00218G\left(\phi_i\right) = \frac{Rgq_{bi}}{F_i u_*^3} \qquad \textbf{(A-25)}$$

where:

$$\phi_i = \omega\phi_{sgo}\left(\frac{D_i}{D_{sg}}\right)^{-0.0951}$$

$$\phi_{sgo} = \frac{\tau_{sg}^*}{\tau_{ssrg}^*}$$

$$\tau_{sg}^* = \frac{u_*^2}{RgD_{sg}}$$

$$\tau_{ssrg}^* = 0.0386$$

$$G(\phi) = \begin{cases} 5474\left(1 - \frac{0.853}{\phi}\right)^{4.5} & \text{for } \phi > 1.59 \\ \exp[14.2(\phi - 1) - 9.28(\phi - 1)^2] & \text{for } 1 \leq \phi \leq 1.59 \\ \phi^{14.2} & \text{for } \phi < 1 \end{cases}$$

$$\omega = 1 + \frac{\sigma_s}{\sigma_O(\phi_{sgo})}\left[\omega_O\left(\phi_{sgo}\right) - 1\right]$$

where:

G = specific gravity of sediment particles;

R = $(\rho_s / \rho) - 1$ = submerged specific density of sediment; where ρ_s = density of sediment [kg/m^3];

g = gravitational constant;

q_{bi} = volume gravel bedload transport per unit width of grains in the ith size range [m^2/s, ft^2/s];

F_i = fraction of grain size in surface layer;

u_* = $\sqrt{\frac{\tau_b}{\rho}}$ = shear velocity on the bed [m/s]; where τ_b = boundary shear stress on the bed [Pa], and ρ = density of water [kg/m^3];

ω = strain function for the Parker (1990) bedload equation;

D_i = characteristic grain size for each size class [m, ft];

D_{sg} = geometric mean grain size [m, ft];

τ_{sg}^* = Shields' stress;

τ_{ssrg}^* = reference Shields' stress; and

σ_s = arithmetic standard deviation.

The functions $\sigma_O(\phi_{sgo})$ and $\omega_O(\phi_{sgo})$ are found from a lookup table representing the strain functions (Figure A-5).

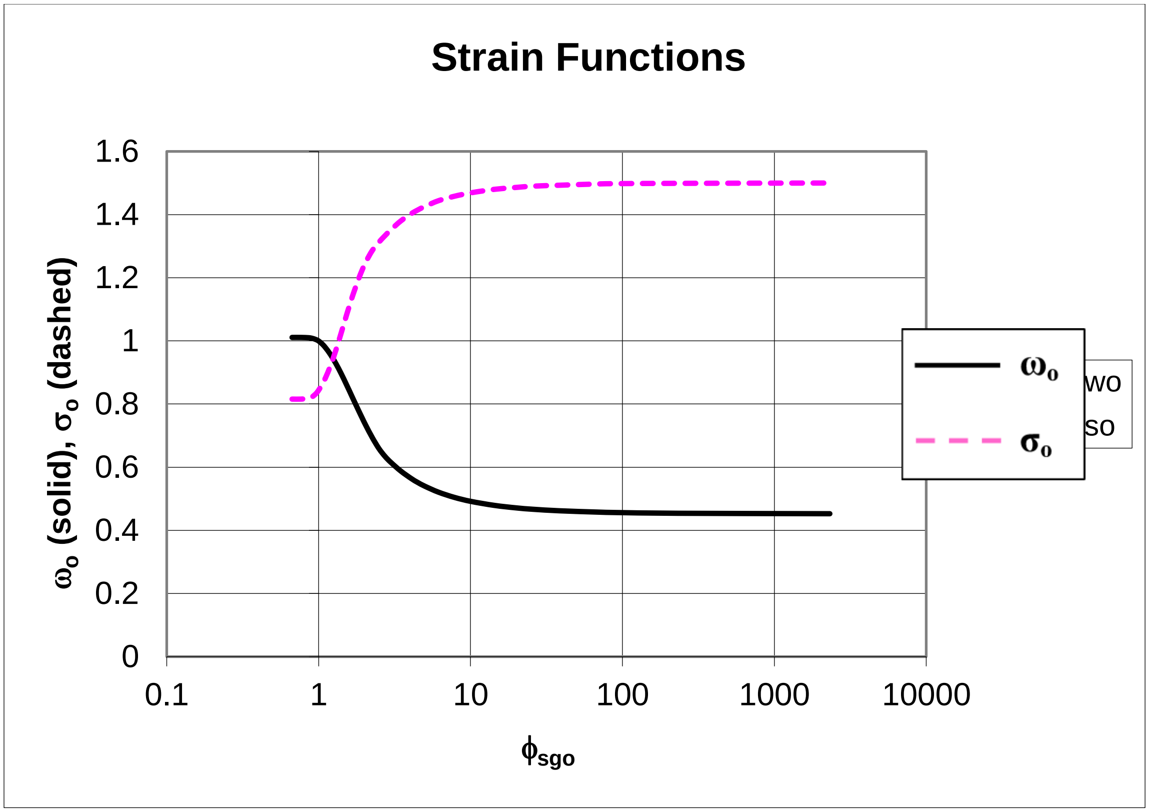


Figure A-5. Strain functions for the Parker (1990) gravel bedload transport relation.

Finally, the total volume bedload transport rate per unit width (q_{bT}) is calculated with:

$$q_{bT} = \sum_{i=1}^{N} q_{bi} \tag{A-26}$$

where:

q_{bT} = total volume gravel bedload transport rate per unit width over all sizes [m^2/s, ft^2/s];

N = grain size ranges from i = 1 to N + 1; and

q_{bi} = volume gravel bedload transport per unit width of grains in the i^{th} size range [m^2/s, ft^2/s].

The Wilcock-Crowe (2003) bedload transport equation is similar to the Parker (1990) equation except it adds the effects of the sand fraction in the mixture on the estimated transport rate. This equation can be expressed as the following:

$$W_i^* = G(\phi_i) = \frac{Rgq_{bi}}{\mathrm{F_i} u_*^3} \qquad \textbf{(A-27)}$$

where:

$$\phi_i = \phi_{sgo} \left(\frac{D_i}{D_{sg}}\right)^{-b}$$

$$\phi_{sgo} = \frac{\tau_{sg}^*}{\tau_{ssrg}^*}$$

$$\tau_{sg}^* = \frac{u_*^2}{RgD_{sg}}$$

$$\tau_{ssrg}^* = 0.021 + 0.015 \exp(-20F_s)$$

$$b = \frac{0.67}{1 + \exp\left(1.5 - \frac{D_i}{D_{sg}}\right)}$$

and

$$G(\phi) = \begin{cases} 0.002\phi^{7.5} & \text{for } \phi < 1.35 \\ 14\left(1 - \frac{0.894}{\phi^{0.5}}\right)^{4.5} & \text{for } \phi \geq 1.35 \end{cases}$$

where:

G = specific gravity of sediment particles;

R = $(\rho_s / \rho) - 1$ = submerged specific density of sediment; where ρ_s = density of sediment [kg/m^3];

g = gravitational constant;

q_{bi} = volume gravel bedload transport per unit width of grains in the i^{th} size range [m^2/s, ft^2/s];

F_i = fraction of grain size in surface layer;

u_* = $\sqrt{\frac{\tau_b}{\rho}}$ = shear velocity on the bed [m/s]; where τ_b = boundary shear stress on the bed [Pa], and ρ = density of water [kg/m^3];

D_i = characteristic grain size for each size class [m, ft];

D_{sg} = geometric mean grain size [m, ft];

τ^*_{sg} = Shields' stress;

τ^*_{ssrg} = reference Shields' stress; and

F_s = fraction of sand on the bed surface.

Finally, just as for the Parker (1990), the total volume bedload transport rate per unit width q_{bT} is calculated with:

$$q_{bT} = \sum_{i=1}^{N} q_{bi} \tag{A-28}$$

where:

q_{bT} = total volume gravel bedload transport rate per unit width over all sizes [m^2/s, ft^2/s];

N = grain size ranges from $i = 1$ to $N + 1$; and

q_{bi} = volume gravel bedload transport per unit width of grains in the i^{th} size range [m^2/s, ft^2/s].

This amount is converted into a total transport load by multiplying by the bottom width (transport assumed to only occur on the bed) and the density of the sediment.

A.1.3 Sediment Transport Equation Selection

Table A-1 summarizes the grain size class delineations of sediment, and Table A-2 lists the boundaries published by the authors, of the associated sediment transport equations, for the development of the relationships. These tables can be referenced to help select the proper 'Stream Type' and 'Transport Relationship' for the CSR Tool analysis. This can also give insight to when these sediment transport equations are more or less appropriate for the analysis of interest. For further guidance on the selection of 'Stream Type' and 'Transport Relationship' for the tool see the CSR Tool Guidance Document (Appendix B).

Table A-1. Grain size class delineations sediment transport equations.

	Class Name	Particle Diameter [mm]	Particle Diameter [ft]
Boulder	Very Large	>2,048	>6.719
	Large	>1,024	>3.360
	Medium	>512	>1.680
	Small	>256	>0.840
Cobble	Large	>128	>0.420
	Small	>64	>0.210
Gravel	Very Coarse	>32	>0.105
	Coarse	>16	>0.0525
	Medium	>8	>0.0262
	Fine	>4	>0.0131
	Very Fine	>2	>0.0066
Sand	Very Coarse	>1	>0.0033
	Coarse	>0.5	>0.0016
	Medium	>0.25	>0.00082
	Fine	>0.125	>0.00041
	Very Fine	>0.0625	>0.00021
Silt	Coarse	>0.031	>0.00010
	Medium	>0.016	>5.25E-05
	Fine	>0.008	>2.62E-05
	Very Fine	>0.004	>1.31E-05
Clay	Coarse	>0.002	>6.56E-06
	Medium	>0.001	>3.28E-06
	Fine	>0.0005	>1.64E-06
	Very Fine	>0.00024	>7.87E-07

Table A-2. Boundaries of sediment transport equations used in tool.

	Variable	Minimum	Maximum
Brownlie (1981)	D_{50}, mm (ft)	0.088 (0.0029)	2.8 (0.0092)
	Unit discharge, $m^3/s/m$ ($ft^2/s/ft$)	0.012 (0.129)	40 (430)
	Discharge, m^3/s (ft^3/s)	0.0032 (0.113)	22,000 (776,900)
	Slope	0.000003	0.037
	Hydraulic radius, m (ft)	0.025 (0.082)	17 (56)
	Temperature, °C (°F)	0 (32)	63 (145)
	Width/depth ratio	≥ 4	≥ 4
	Geometric standard deviation of particles sizes, σ_g	≤ 5	≤ 5
Parker (1990)	Gravel-sized particles, mm (ft)	2 (0.0066)	203 (0.666)
	Sand-sized particles, mm (ft)	sand removed	sand removed
	(%) of sand in mixture	3.3% surface	13% subsurface
Wilcock-Crowe (2003)	Gravel-sized particles, mm (ft)	2 (0.0066)	64 (0.210)
	Sand-sized particles, mm (ft)	0.5 (0.0016)	2 (0.0066)
	(%) of sand in mixture	6.2	34.3
	Depth, m (ft)	0.09 (0.295)	0.12 (0.394)

A.1.4 CSR Analysis Code Structure

The main routine performed by the CSR Tool is running the design reach to perform the CSR analysis and search for stable channel designs. This part of the tool is run after the incoming sediment load is calculated for the supply reach using the given hydrologic information. The CSR Tool code structure went through many iterations to find the most reliable and efficient configuration. The final code methodology for calculating stable channel design solutions is outlined in Figure A-6.

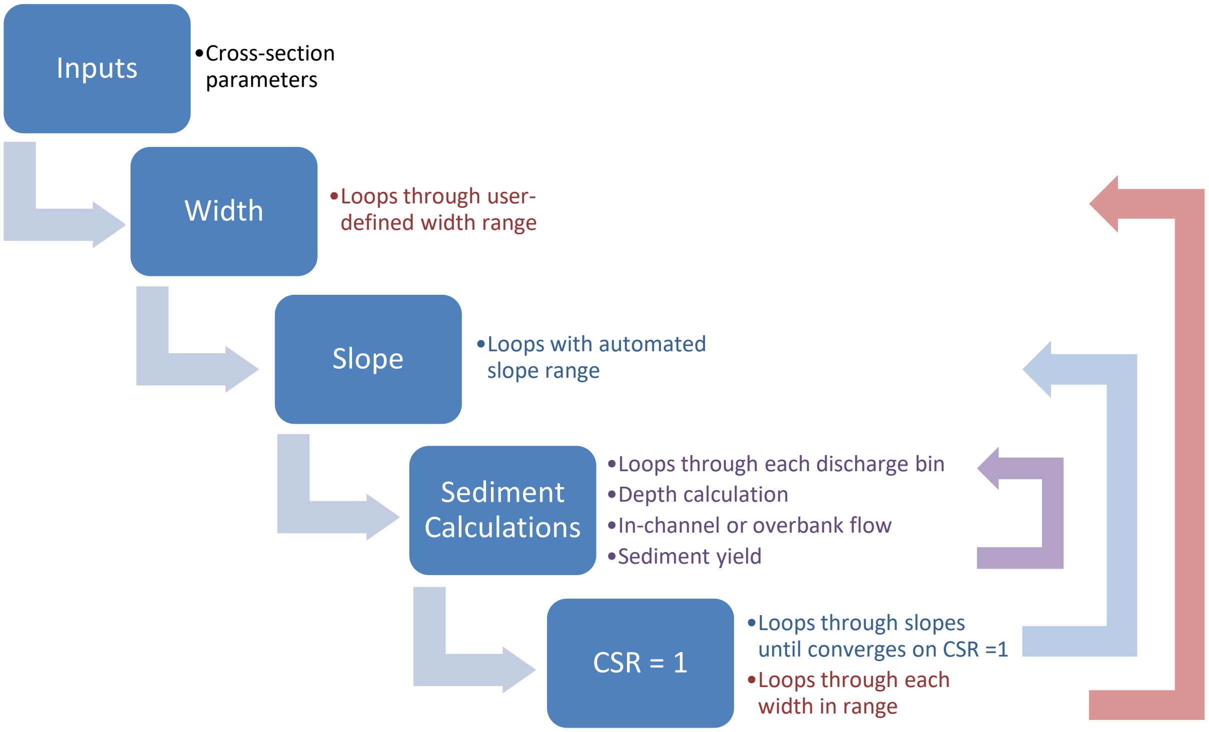
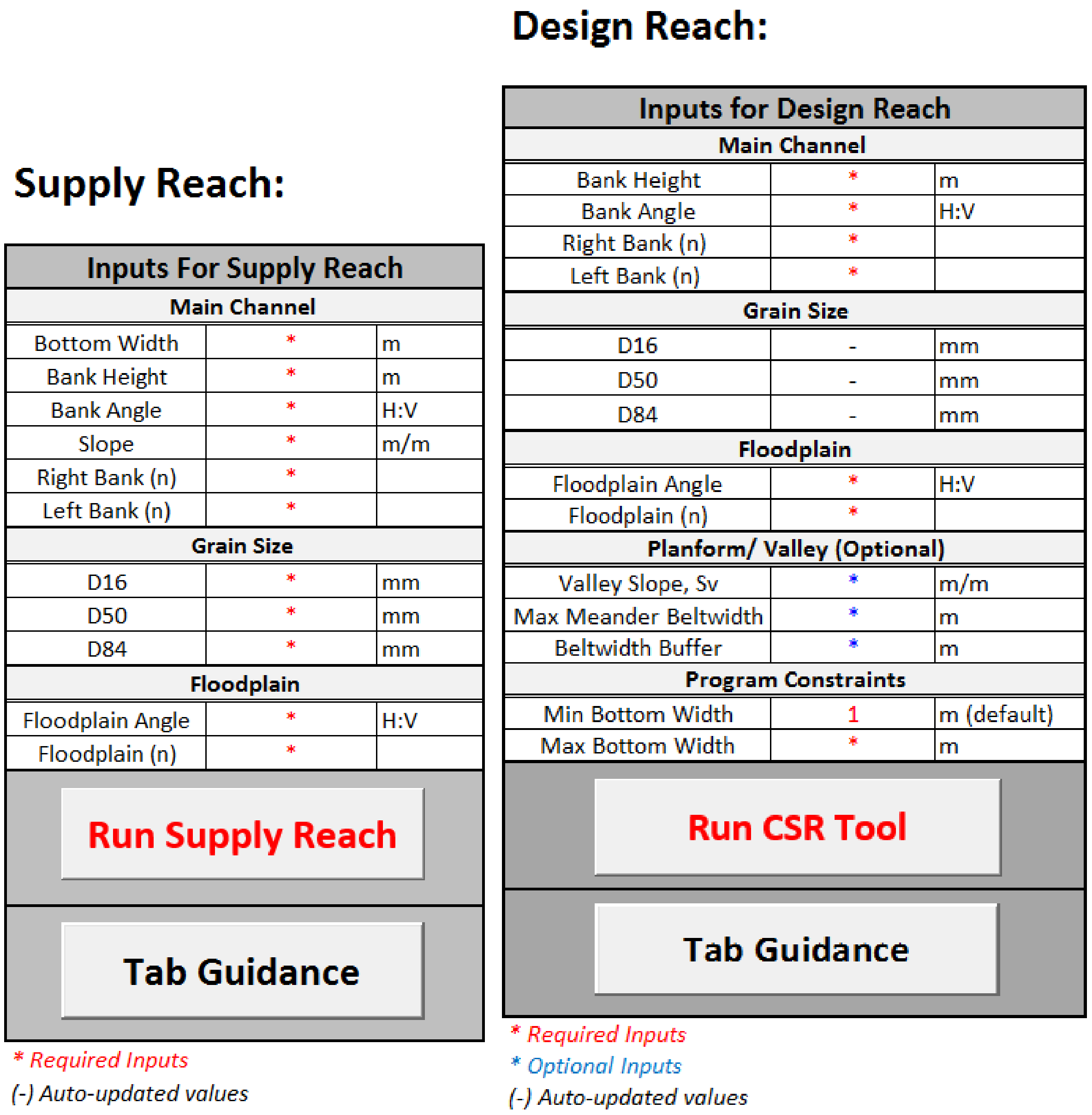


Figure A-6. Schematic of design reach code methodology.

Firstly, the program reads the cross-sectional information entered by the user. Screenshots of the required inputs for the supply and design reaches are shown in (Figure A-7). Next, an outer loop initiates that goes through each width in the user-defined range. The loop proceeds for every other meter in the width range (i.e., 1, 3, 5, 7 m, etc.) if the supply reach bottom width is above 15 m and every meter (i.e., 1, 2, 3, 4 m, etc.) if the supply reach bottom width is below 15 m. This was chosen to be the most efficient set-up while still retaining enough resolution of the outputs. The default for the minimum width in the range is 1 m to produce all possible results and the entire family of stable channel design solutions curve. The program guesses an initial slope and calculates the depth, in channel or overbank flow, and upper and lower regime to calculate sediment yield for each average discharge in the binned FDC. The sediment yield summed over all discharges is compared with the supply reach total sediment yield to calculate the CSR for that slope estimate.

The slope is then updated using a bisection method until it converges on the slope that will give a CSR = 1 within a tolerance of 0.025 for each width in the defined range.



Supply Reach:

Inputs For Supply Reach		
Main Channel		
Bottom Width	*	m
Bank Height	*	m
Bank Angle	*	H:V
Slope	*	m/m
Right Bank (n)	*	
Left Bank (n)	*	
Grain Size		
D16	*	mm
D50	*	mm
D84	*	mm
Floodplain		
Floodplain Angle	*	H:V
Floodplain (n)	*	

* Required Inputs

(-) Auto-updated values

Design Reach:

Inputs for Design Reach		
Main Channel		
Bank Height	*	m
Bank Angle	*	H:V
Right Bank (n)	*	
Left Bank (n)	*	
Grain Size		
D16	-	mm
D50	-	mm
D84	-	mm
Floodplain		
Floodplain Angle	*	H:V
Floodplain (n)	*	
Planform/ Valley (Optional)		
Valley Slope, Sv	*	m/m
Max Meander Beltwidth	*	m
Beltwidth Buffer	*	m
Program Constraints		
Min Bottom Width	1	m (default)
Max Bottom Width	*	m

* Required Inputs

* Optional Inputs

(-) Auto-updated values

Figure A-7. Required inputs for the Supply Reach and the Design Reach of the Stable Channel Design tool.

A.1.5 CSR Tool Validation

When the CSR tool is given a single discharge rather than a full FDC, its results can be directly compared to the implementation of the Copeland method in the HEC-RAS stable channel design tool. Many examples have shown very similar results between HEC-RAS output and single-discharge calculations from the CSR Tool, which fosters confidence in the validity of the tool's output. Figure A-8 is an example of the CSR Tool's output with a single discharge for Big Raccoon Creek in Indiana compared to HEC-RAS's stable channel design using the Copeland method.

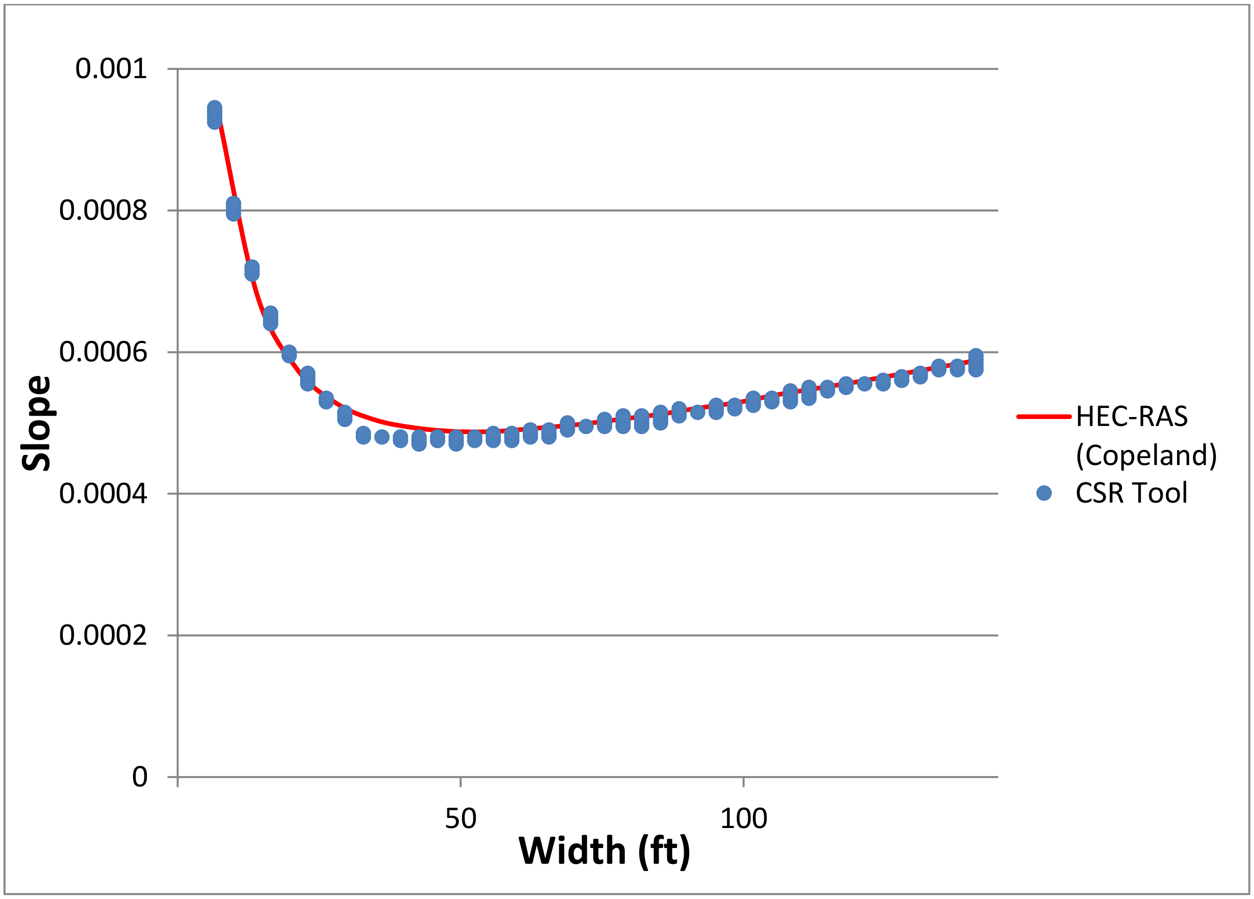


Figure A-8. Comparison of CSR Tool with HEC-RAS stable channel design using the Copeland method with the same channel dimensions, grain size distribution and single discharge.

The CSR Tool estimated a total sediment concentration of 279 ppm at 1,246 cfs and HEC-RAS estimated a total sediment concentration of 286 ppm at 1,246 cfs. The data for this example were taken from Soar and Thorne (2001).

A.1.6 Planform Characteristics

An optional addition to the tool is to include planform characteristics to the design reach output. If a valley slope is entered then the sinuosity, meander belt width, and braiding risk can be calculated for each slope/width solution. The following simple equation is used to calculate the sinuosity for each slope/width combination:

$$\text{sinuosity} = P = \frac{\text{valley slope}}{\text{bed slope}} = \frac{S_v}{S_o} \qquad \textbf{(A-29)}$$

This is an estimate but gives a good indication of what a single-thread channel of the corresponding dimensions would tend toward for meandering. This result can then be used to find the meander belt width and wavelength based off an idealized sine-generated curve, shown in Figure A-9. The sinuosity output could also give indication on the limits a design can have to allow for sediment continuity but also have enough sinuosity for aesthetic appeal that may be desired in a restoration project. The wavelength can be estimated by the following equation. The meander wavelength range represents the 95% confidence interval derived from a data set for 438 streams ranging from nearly straight to tortuous meanders (Soar and Thorne 2001):

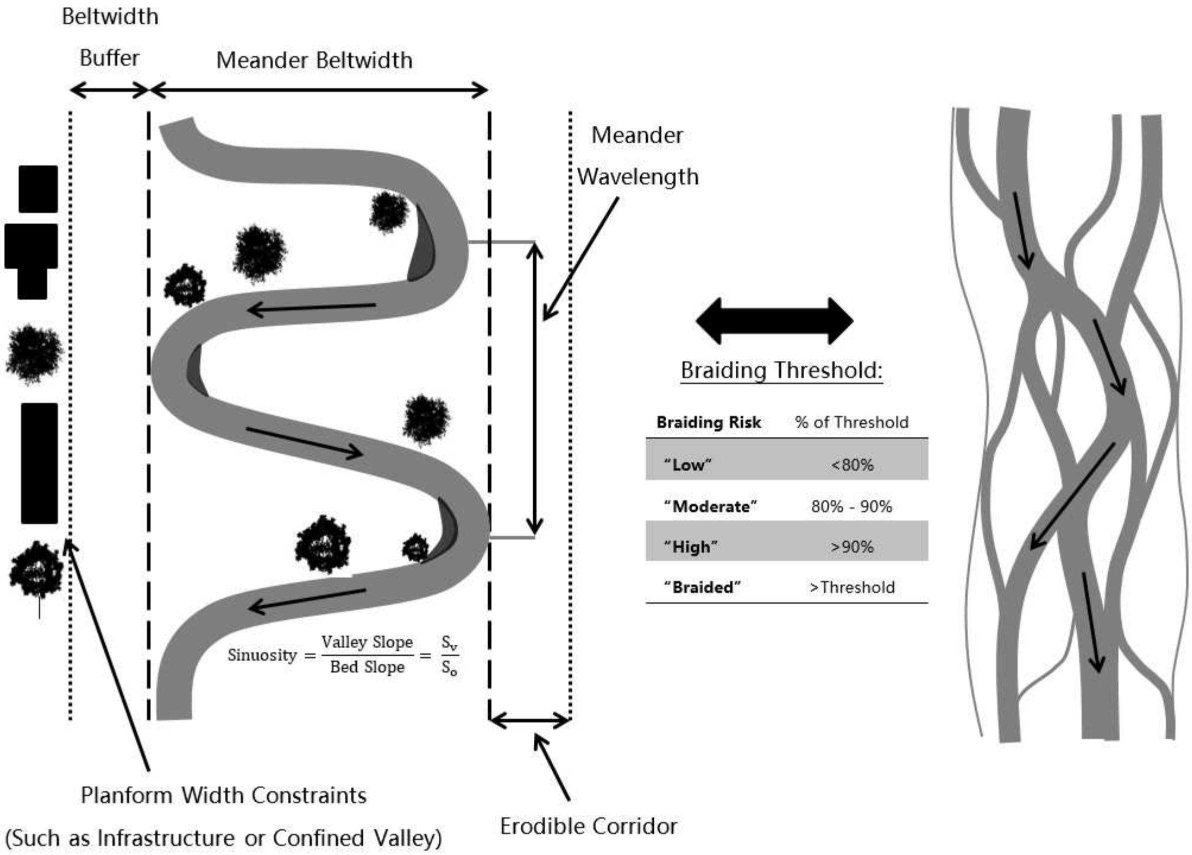
$$\text{meander wavelength } = \lambda \approx (11.26 \text{ to } 12.47) * \text{width} \approx 12(W) \qquad \textbf{(A-30)}$$

The minimum meander belt width produced by the corresponding sinuosity and channel width can be estimated with the following (Hagerman and Williams 2000):

$$\text{minimum belt width } = \lambda(6.0625\varphi^3 - 5.1279\varphi^2 + 2.509\varphi + 0.0005) + \text{width} + \text{buffer} \qquad \textbf{(A-31a)}$$

with:

$$\varphi = \frac{P - 1}{P} \tag{A-31b}$$



Braiding Risk	% of Threshold
"Low"	<80%
"Moderate"	80% - 90%
"High"	>90%
"Braided"	>Threshold

Figure A-9. Visual representation of the planform characteristics included in the tool.

The meander belt width is an estimation of the total planform width the river will span to support the projected dimensions and sinuosity of the design (Hagerman and Williams 2000). This can be useful for visualizing the size of the design and determining whether planform width constraints exist in the design area (Figure A-9). Following this concept, the tool allows the user to specify a maximum allowable meander belt width between the edge of the river and any planform constraint such as infrastructure. If any solution is over this amount then it will be highlighted in red in the outputs, so the user can know which solutions might conflict with this lateral restriction. Additionally, has the equation above suggests, the tool allows the user to enter a buffer to be included in the belt width calculations. The buffer will be added to the calculated belt width and considered in the maximum belt width determination. This buffer aligns with the "room for the river" or "erodible corridor" concept that sets aside extra space around the river to allow for natural movement and adjustments of the channel without compromising the surrounding infrastructure (Piégay et al. 2005; Kondolf 2011).

Lastly, the valley slope can be used to estimate the braiding risk for the channel with the addition of a bankfull discharge (Q_{bf}) and a median grain size (D_{50}) of the design reach. The tool automatically extracts these values to calculate a risk for the design single thread channel to cross the geomorphic threshold to a braided or multi-thread channel, shown in Figure A-9. This is an important consideration in design because channels near the threshold and braided channels are characteristically unstable (Schumm 1977; Bledsoe and Watson 2001). The tool uses the channel braiding relationships developed in van den Berg (1995). Van den Berg analyzed 228 data sets from 192 rivers for their relationships between channel type, channel pattern, and graphed them based on D_{50} grain size and ω unit stream power (Figure A-10).

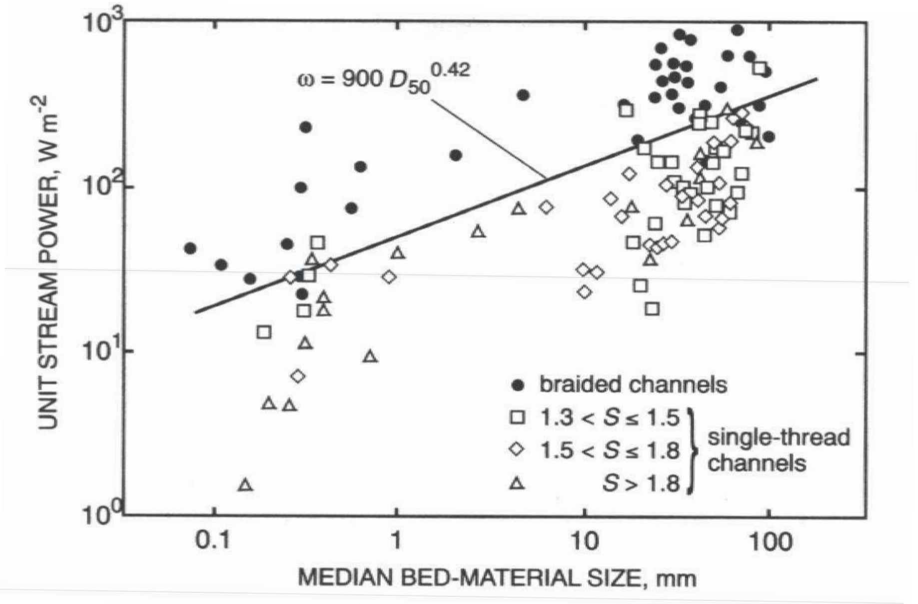


Figure A-10. Braiding threshold on plot of channel pattern in relation to median grain size and potential specific stream power (van den Berg 1995).

Potential specific stream power is calculated with the given reach characteristics with the following equations:

$$\omega_v = 2100\, S_v \sqrt{Q_{bf}} \quad \text{(sand channels)} \tag{A-32a}$$

$$\omega_v = 3300\, S_v \sqrt{Q_{bf}} \quad \text{(gravel channels)} \tag{A-32b}$$

where:

ω_v = potential specific stream power [W/m^2];

S_v = valley slope [m/m, ft/ft]; and

Q_{bf} = bankfull discharge [m^3/s];

These values are then compared to the value calculated using the following equation representing the threshold in Figure A-10:

$$\omega = 900\, D_{50}^{0.42} \tag{A-33}$$

where:

D_{50} = median grain size [m].

The risk for braiding is then denoted by the following categories listed in Table A-3.

Table A-3. The categories for braiding risk in terms of percent from van den Berg (1995) braiding threshold.

Braiding Risk	% of Threshold
"Low"	<80%
"Moderate"	80 – 90%
"High"	>90%
"Braided"	>Threshold

A.1.7 Sediment Yield Percentiles

Additional outputs of sediment yield percentiles are included on the "Detailed Results" tab of the CSR Tool. These percentiles are defined as follows:

- Q_{s50} = discharge associated with 50% of the cumulative sediment yield;
- Q_{s75} = discharge associated with 75% of the cumulative sediment yield;
- Q_{s90} = discharge associated with 90% of the cumulative sediment yield; and
- Q_{eff} = single discharge that moves the most total sediment load.

These percentiles are calculated for the supply reach and each stable slope/width combination for the design reach. An example output of these variables from the tool can be seen in Figure A-12.

A.1.8 Key Differences between CSR and Copeland Stable Channel Design Tools

The CSR Tool is very similar to the Copeland method in HEC-RAS (Copeland 1994), although there are some key differences:

- Sediment transport is calculated using the entire FDC associated with the design reach rather than just a single representative discharge and, therefore, accounts for the morphological influence of the other flows.
- Overbank flow is modeled and considered in transport calculations unlike the Copeland method. This can help avoid overestimating the effectiveness of overbank flows.
- The tool is capable of performing the CSR analysis for not only sand-bed streams but also gravel- / cobble-bed streams using the Wilcock-Crowe (2003) and Parker (1990) equations.
- Additional planform outputs and sediment percentiles are listed for each stable solution.

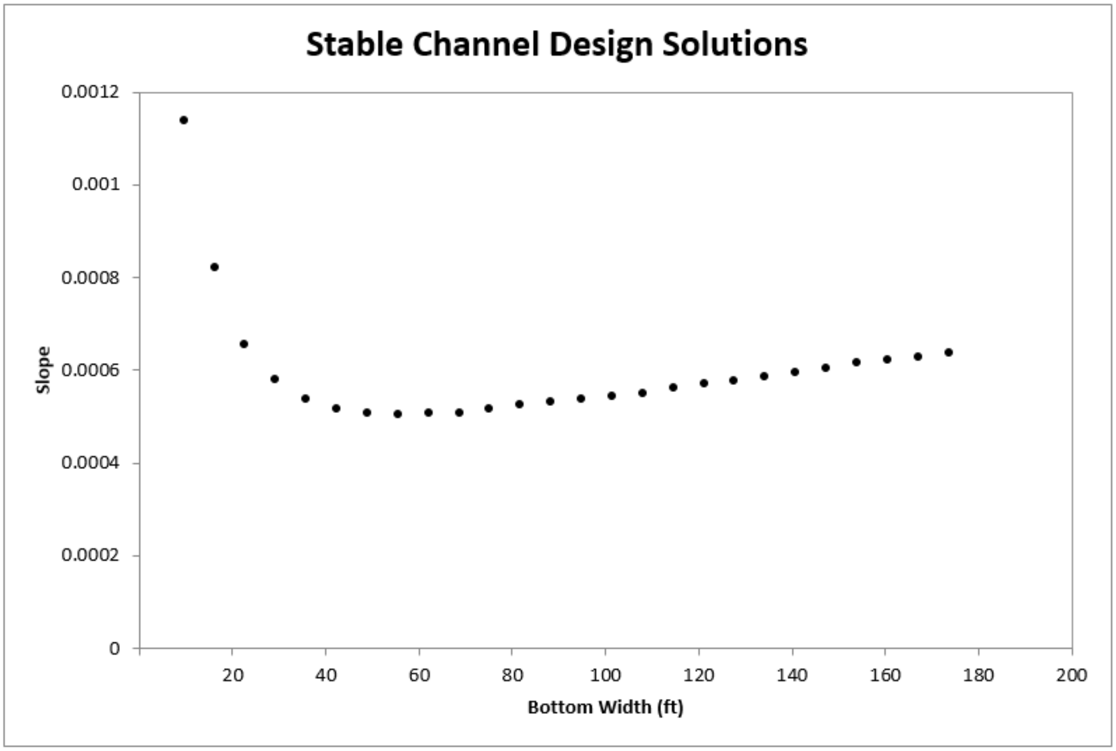
A.1.9 CSR Tool Outputs

The following shows examples of the output solutions produced by the CSR Tool for a sand-bed stream (Figure A-11) and a gravel-bed stream (Figure A-13). Figure A-11(a) shows the plot of the family of channel slope/width combinations which provide continuity of water and sediment (i.e., CSR = 1) for the associated design. Figure A-11(b) shows the associated table of solutions with the planform characteristics listed for each design. These outputs are shown on the 'Results' tab of the CSR Tool. This example was developed using data retrieved from Soar and Thorne (2001) for a reach on Big Raccoon Creek in Indiana.

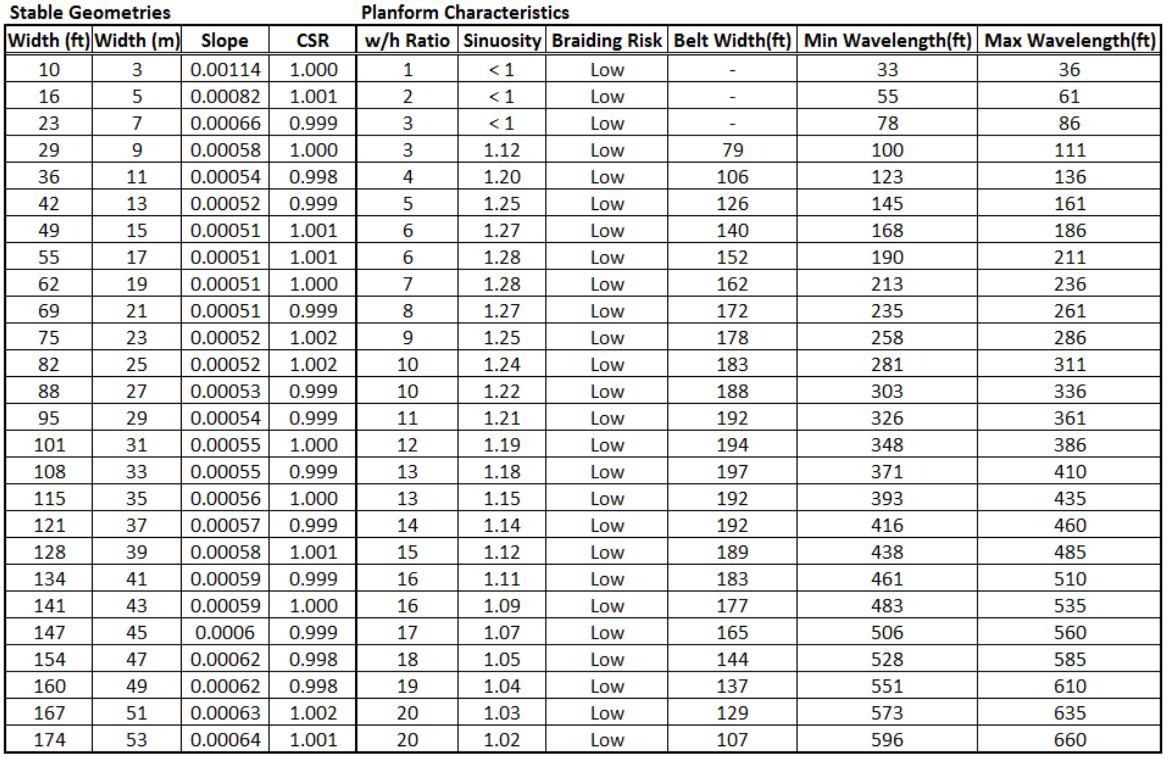
Figure A-12 shows an example output from the 'Detailed Results' tab of the CSR Tool. This is a summary of the 'effectiveness' in tons/day for each average bin discharge for the supply reach. Below the 'effectiveness' table shows the associated sediment percentiles summary (see Sediment Yield Percentiles). The 'Detailed Results' tab of the CSR Tool also displays this same output for each stable slope/width combinations as well.

Figure A-13(a) shows the plot of the family of channel slope/width combinations which provide continuity of water and sediment (i.e., CSR = 1) for the associated design. Figure A-13(b) shows the associated table of solutions with the planform characteristics listed for each design. This example was developed using data retrieved from (King et al. 2004) for a reach on the Red River in Idaho.

(a)

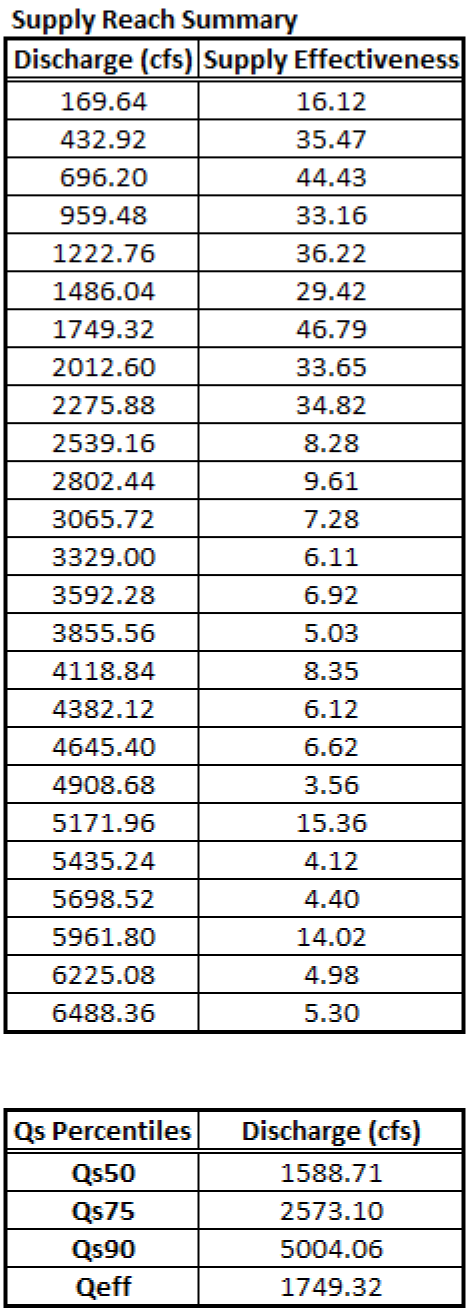


(b)



Stable Geometries				Planform Characteristics					
Width (ft)	Width (m)	Slope	CSR	w/h Ratio	Sinuosity	Braiding Risk	Belt Width(ft)	Min Wavelength(ft)	Max Wavelength(ft)
10	3	0.00114	1.000	1	< 1	Low	-	33	36
16	5	0.00082	1.001	2	< 1	Low	-	55	61
23	7	0.00066	0.999	3	< 1	Low	-	78	86
29	9	0.00058	1.000	3	1.12	Low	79	100	111
36	11	0.00054	0.998	4	1.20	Low	106	123	136
42	13	0.00052	0.999	5	1.25	Low	126	145	161
49	15	0.00051	1.001	6	1.27	Low	140	168	186
55	17	0.00051	1.001	6	1.28	Low	152	190	211
62	19	0.00051	1.000	7	1.28	Low	162	213	236
69	21	0.00051	0.999	8	1.27	Low	172	235	261
75	23	0.00052	1.002	9	1.25	Low	178	258	286
82	25	0.00052	1.002	10	1.24	Low	183	281	311
88	27	0.00053	0.999	10	1.22	Low	188	303	336
95	29	0.00054	0.999	11	1.21	Low	192	326	361
101	31	0.00055	1.000	12	1.19	Low	194	348	386
108	33	0.00055	0.999	13	1.18	Low	197	371	410
115	35	0.00056	1.000	13	1.15	Low	192	393	435
121	37	0.00057	0.999	14	1.14	Low	192	416	460
128	39	0.00058	1.001	15	1.12	Low	189	438	485
134	41	0.00059	0.999	16	1.11	Low	183	461	510
141	43	0.00059	1.000	16	1.09	Low	177	483	535
147	45	0.0006	0.999	17	1.07	Low	165	506	560
154	47	0.00062	0.998	18	1.05	Low	144	528	585
160	49	0.00062	0.998	19	1.04	Low	137	551	610
167	51	0.00063	1.002	20	1.03	Low	129	573	635
174	53	0.00064	1.001	20	1.02	Low	107	596	660

Figure A-11. (a) Plot of family of slope/width combinations which provide continuity of water and sediment, and (b) output table of stable geometries and planform characteristics for each solution. Example: Big Raccoon Creek, Indiana.



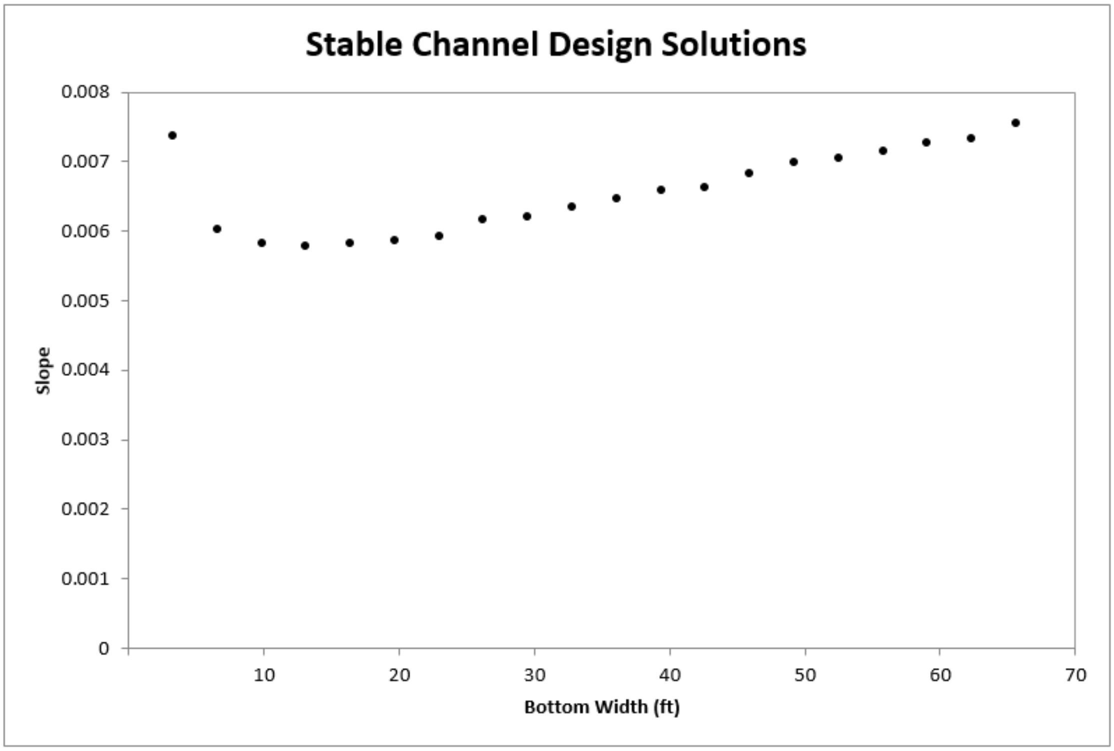
Supply Reach Summary

Discharge (cfs)	Supply Effectiveness
169.64	16.12
432.92	35.47
696.20	44.43
959.48	33.16
1222.76	36.22
1486.04	29.42
1749.32	46.79
2012.60	33.65
2275.88	34.82
2539.16	8.28
2802.44	9.61
3065.72	7.28
3329.00	6.11
3592.28	6.92
3855.56	5.03
4118.84	8.35
4382.12	6.12
4645.40	6.62
4908.68	3.56
5171.96	15.36
5435.24	4.12
5698.52	4.40
5961.80	14.02
6225.08	4.98
6488.36	5.30

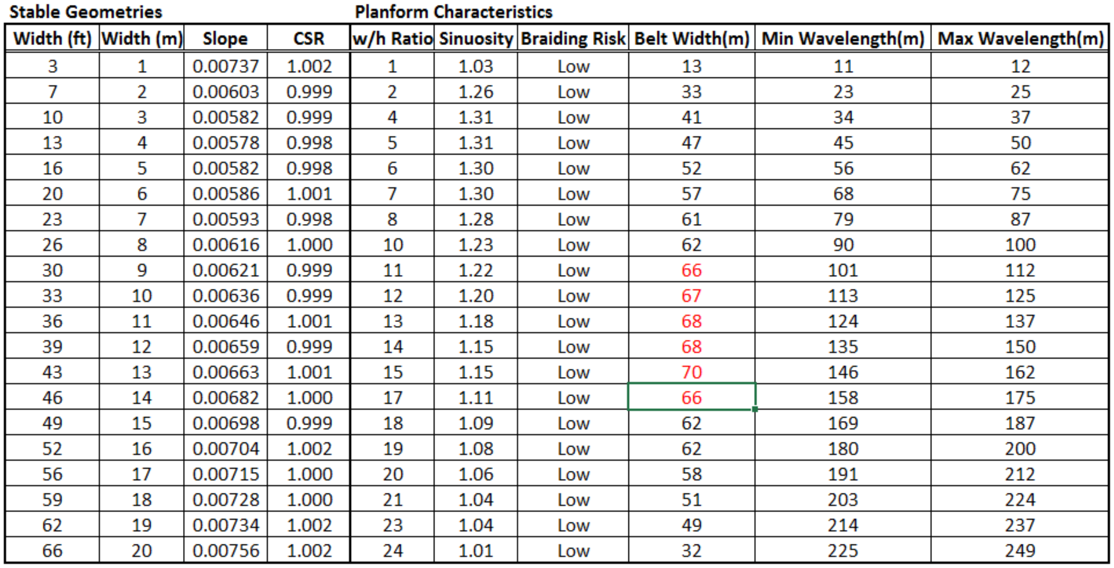
Qs Percentiles	Discharge (cfs)
Qs50	1588.71
Qs75	2573.10
Qs90	5004.06
Qeff	1749.32

Figure A-12. Example output on 'Detailed Results' tab. Example: Big Raccoon Creek, Indiana.

(a)



(b)



Stable Geometries				Planform Characteristics					
Width (ft)	Width (m)	Slope	CSR	w/h Ratio	Sinuosity	Braiding Risk	Belt Width(m)	Min Wavelength(m)	Max Wavelength(m)
3	1	0.00737	1.002	1	1.03	Low	13	11	12
7	2	0.00603	0.999	2	1.26	Low	33	23	25
10	3	0.00582	0.999	4	1.31	Low	41	34	37
13	4	0.00578	0.998	5	1.31	Low	47	45	50
16	5	0.00582	0.998	6	1.30	Low	52	56	62
20	6	0.00586	1.001	7	1.30	Low	57	68	75
23	7	0.00593	0.998	8	1.28	Low	61	79	87
26	8	0.00616	1.000	10	1.23	Low	62	90	100
30	9	0.00621	0.999	11	1.22	Low	66	101	112
33	10	0.00636	0.999	12	1.20	Low	67	113	125
36	11	0.00646	1.001	13	1.18	Low	68	124	137
39	12	0.00659	0.999	14	1.15	Low	68	135	150
43	13	0.00663	1.001	15	1.15	Low	70	146	162
46	14	0.00682	1.000	17	1.11	Low	66	158	175
49	15	0.00698	0.999	18	1.09	Low	62	169	187
52	16	0.00704	1.002	19	1.08	Low	62	180	200
56	17	0.00715	1.000	20	1.06	Low	58	191	212
59	18	0.00728	1.000	21	1.04	Low	51	203	224
62	19	0.00734	1.002	23	1.04	Low	49	214	237
66	20	0.00756	1.002	24	1.01	Low	32	225	249

Figure A-13. (a) Plot of family of slope/width combinations which provide continuity of water and sediment, and (b) output table of stable geometries and planform characteristics for each solution. Example: Red River, Idaho.

REFERENCES

Biedenharn, D.S., R.R. Copeland, C.R. Thorne, P.J. Soar, R.D. Hey, and C.C. Watson. 2000. "Effective Discharge Calculation: A Practical Guide." *Technical Report No. ERDC/CHL TR-00-15*, U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Bledsoe, B.P., and C.C. Watson. 2001. "Logistic Analysis of Channel Pattern Thresholds: Meandering, Braiding, and Incising." *Geomorphology*, Vol. 38, No. 3, pp. 281–300, DOI: 10.1016/S0169-555X(00)00099-4.

Brownlie, W.R. 1981. "Prediction of Flow Depth and Sediment Discharge in Open-channels." *Report No. KH-R-43A*, California Institute of Technology, W.M. Keck Laboratory, Pasadena, CA.

Brownlie, W.R. 1983. "Flow Depth in Sand-bed Channels." *Journal of Hydraulic Engineering*, Vol. 109, No. 7, pp. 959–990, DOI: 10.1061/(ASCE)0733-9429(1983)109:7(959).

Copeland, R.R. 1994. "Application of Channel Stability Methods – Case Studies." *Technical Report HL-94-11*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, September, 60 p., URL: http://www.dtic.mil/dtic/tr/fulltext/u2/a285625.pdf.

Einstein, H.A. 1950. "The Bed Load Function for Sediment Transport in Open Channel Flows." *Technical Bulletin No. 1026*, U.S. Department of Agriculture, Soil Conservation Service, Washington, DC.

Hagerman, J.R., and J.D. Williams. 2000. "Meander Shape and the Design of Stable Meanders." Pages 563–568 in: *Riparian Ecology and Management in Multi-land Use Watersheds*, Proceedings of the American Water Resources Association, Spring Specialty Conference, Anchorage, AK, April 30 - May 4.

King, J.G., W.W. Emmett, P.J. Whiting, R.P. Kenworthy, and J.J. Barry. 2004. "Sediment Transport Data and Related Information for Selected Coarse-Bed Streams and Rivers in Idaho." *General Technical Report RMRS-GTR-131*, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 26 p., URL: http://www.fs.fed.us/rm/pubs/rmrs_gtr131.pdf\.

Kondolf, G.M. 2011. "Setting Goals in River Restoration: When and Where Can the River 'Heal Itself'?" Pages 29–43 in: *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analyses, and Tools*, Geophysical Monograph Series 194, American Geophysical Union, URL: https://institutbeaumont.files.wordpress.com/2007/09/kondolf2011-settinggoals.pdf.

Limerinos, J.T. 1970. "Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels." *U.S. Geological Survey Water-Supply Paper 1898-B*, 47 p., U.S. Government Printing Office, Washington, DC, URL: http://pubs.usgs.gov/wsp/1898b/report.pdf.

Parker, G. 1990. "Surface-based Bedload Transport Relation for Gravel Rivers." *Journal of Hydraulic Research*, Vol. 28, No. 4, pp. 417–436, DOI: 10.1080/00221689009499058.

Piégay, H., S.E. Darby, E. Mosselman, and N. Surian. 2005. "A Review of Techniques Available for Delimiting the Erodible River Corridor: A Sustainable Approach to Managing Bank Erosion." *River Research and Applications*, Vol. 21, No. 7, pp. 773–789, DOI: 10.1002/rra.881.

Schumm, S.A. 1977. *The Fluvial System*. Vol. 338, Wiley, New York, NY.

Soar, P.J., and C.R. Thorne. 2001. "Channel Restoration Design for Meandering Rivers." *Technical Report No. ERDC/CHL CR-01-1*, Coastal and Hydraulics Laboratory, U.S. Army, Engineer Research and Development Center, Vicksburg, MS, URL: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043218.pdf.

van den Berg, J.H. 1995. "Prediction of Alluvial Channel Pattern of Perennial Rivers." *Geomorphology*, Vol. 12, No. 4, pp. 259–279, DOI: 10.1016/0169-555X(95)00014-V.

Wilcock, P.R., and J.C. Crowe. 2003. "Surface-based Transport Model for Mixed-size Sediment." *Journal of Hydraulic Engineering*, Vol. 129, No. 2, pp. 120–128, DOI: 10.1061/(ASCE)0733-9429(2003)129:2(120).

Wohl, E., B.P. Bledsoe, R.B. Jacobson, N.L. Poff, S.L. Rathburn, D.M. Walters, and A.C. Wilcox. 2015. "The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management." *Bioscience*, Vol. 65, No. 4, pp. 358–371, DOI: 10.1093/biosci/biv002.

A.2 Abbreviations

Units of Measure

°C	degree(s) Celsius
°F	degree(s) Fahrenheit

cfs, ft^3/s	cubic feet per second
cms, m^3/s	cubic meter(s) per second
ft	foot or feet
ft/ft	feet per foot
ft/s	feet per second
ft^2	square feet
ft^2/s	square feet per second
$ft^2/s/ft$	square feet per second per foot
H:V	horizontal:vertical
kg/m^3	kilogram(s) per cubic meter
m	meter(s)
m/m	meter(s) per meter
m/s	meter(s) per second
m^2	square meter(s)
m^2/s	square meter(s) per second
$m^3/s/m$	cubic meter(s) per second per meter
mm	millimeter(s)
Pa	Pascal(s)
ppm	part(s) per million
%	percent
W/m^2	Watt(s) per square meter
yr(s)	year(s)

Acronyms

CDF	cumulative distribution function
CSR	Capacity-Supply Ratio

CSR Tool	CSR Stable Channel Design Tool
eRAMS	Environmental Risk Assessment & Management System
FDC	flow duration curve
HEC-RAS	Hydrologic Engineering Centers River Analysis System
NCHRP	National Cooperative Highway Research Program
MFA	magnitude-frequency analysis
PDF	probability density function
SWAT	Soil and Water Assessment Tool
SWAT-DEG	channel DEGradation portion of SWAT
VBA	Visual Basic for Applications

Symbols[1]

A	cross-sectional area [m^2, ft^2]
$A_{channel}$	cross-sectional area of channel [m^2, ft^2]
A_{OB}	area of floodplain partition [m^2, ft^2]
b	bottom width [m, ft]
c	constant, conversion factor (1.0 for SI units and 1.486 for English units)
C_{ppm}	sediment transport concentration [ppm]
D_{50}	median grain size [m, ft]
D_{16}, D_{84}	particle size for which 16% and 84% of all sediments is smaller, respectively [m, ft]
$D_{b,i}$	grain size representing each size class of the (active) layer of the bed [m, ft]
D_i	characteristic grain size for each size class [m, ft]

---

[1] Variables are reported with SI units or English units or both to accommodate equation and/or software input. The software works in both SI and English units.

D_{sg}	geometric mean grain size [m, ft]
F_g	grain-related Froude number
F_i	fraction of grain size in surface layer
F_s	fraction of sand on the bed surface
g	gravitational constant
G	specific gravity of sediment particles
h	depth [m, ft]
K	conveyance
K_{OB}	conveyance of bed partition
$Max\ Q$	maximum discharge in flow record [m^3/s, ft^3/s]
$Min\ Q$	minimum discharge in flow record [m^3/s, ft^3/s]
n	Manning's roughness coefficient
n_{bank}	Manning's roughness coefficient of bank partition
$n_{floodplain}$	Manning's roughness of floodplain partition
N	grain size ranges from i = 1 to N + 1
$P_{<,i}$	non-exceedance probability of each bin
P_{bank}	wetted perimeter of bank partition [m, ft]
P_{bed}	bottom width = wetted perimeter of bed partition [m, ft]
q_{bi}	volume gravel bedload transport per unit width of grains in the i^{th} size range [m^2/s, ft^2/s]
q_{bT}	total volume gravel bedload transport rate per unit width over all sizes [m^2/s, ft^2/s]
Q	discharge [m^3/s, ft^3/s]
Q_{bf}	bankfull discharge [m^3/s]
Q_{eff}	single discharge that moves the most total sediment road (percentile) [m^3/s, ft^3/s]

Q_{s50}	discharge that moves the 50% of the total estimated sediment load (percentile) [m^3/s, ft^3/s]
Q_{s75}	discharge that moves the 75% of the total estimated sediment load (percentile) [m^3/s, ft^3/s]
Q_{s90}	the discharge that moves the 90% of the total estimated sediment load (percentile) [m^3/s, ft^3/s]
R	hydraulic radius [m, ft]
R	$(\rho_s/\rho) - 1$ = submerged specific density of sediment
R_{bank}	hydraulic radius of bank partition [m, ft]
R_{bed}	hydraulic radius of bed partition [m, ft]
R_{OB}	hydraulic radius of floodplain partition [m, ft]
$Range\ Q$	range of discharge in flow record [m^3/s, ft^3/s]
S	slope [m/m, ft/ft]
S_f	friction slope [m/m, ft/ft]
S_o	bed slope [m/m, ft/ft]
S_v	valley slope [m/m, ft/ft]
u_*	$\sqrt{\frac{\tau_b}{\rho}}$ = shear velocity on the bed [m/s, ft/s]
V	cross-section averaged velocity [m/s, ft/s]
V_c	critical velocity [m/s, ft/s]
w/h	width-to-depth ratio
z	bank angle, horizontal to vertical [H:V]
v	kinematic viscosity [m^2/s, ft^2/s]
ρ	density of water [kg/m^3]
ρ_s	density of sediment [kg/m^3]
σ_g	gradation coefficient

σ_s	arithmetic standard deviation
σ_{sg}	geometric standard deviation
τ_b	boundary shear stress on the bed [Pa]
τ_{*c}	dimensionless critical shear stress
τ_{sg}^{*}	Shields’ stress
τ_{ssrg}^{*}	reference Shields’ stress
Ψ_i	each grain size on the base 2 logarithmic ψ scale
ω	strain function for the Parker (1990) bedload equation
ω_v	potential specific stream power [W/m^2]

APPENDIX B: GUIDANCE DOCUMENT: CSR STABLE CHANNEL DESIGN TOOL

B.1 User Guidance for the CSR Tool

This guidance was developed as a quick reference outline to run the CSR Tool based in VBA. It provides a step-by-step guidance for each tab in the workbook, the process necessary to run the program, and two examples running the program (one sand-bed and one gravel-bed stream). For more-detailed information on the hydrologic and hydraulic theory, and code methodology behind the tool refer to the CSR Tool Reference Manual (Appendix A).

This step-by-step guidance reports Steps 1 through 3, which correlate the color-coded numbers in the 'Startup Tabs' numbered subsections with the appropriate numbered boxes that are overlaid onto referenced figures.

B.1.1 Tab-by-tab Guidance

This section of the guidance document provides a step-by-step guide on how to run each tab in the CSR Tool workbook. Figure B-1 shows a decision tree on selecting tabs to use and the order in which to use them to produce stable channel design solutions. The path in the decision table is determined by selections on the startup page that refer to the type of river and hydrologic information.

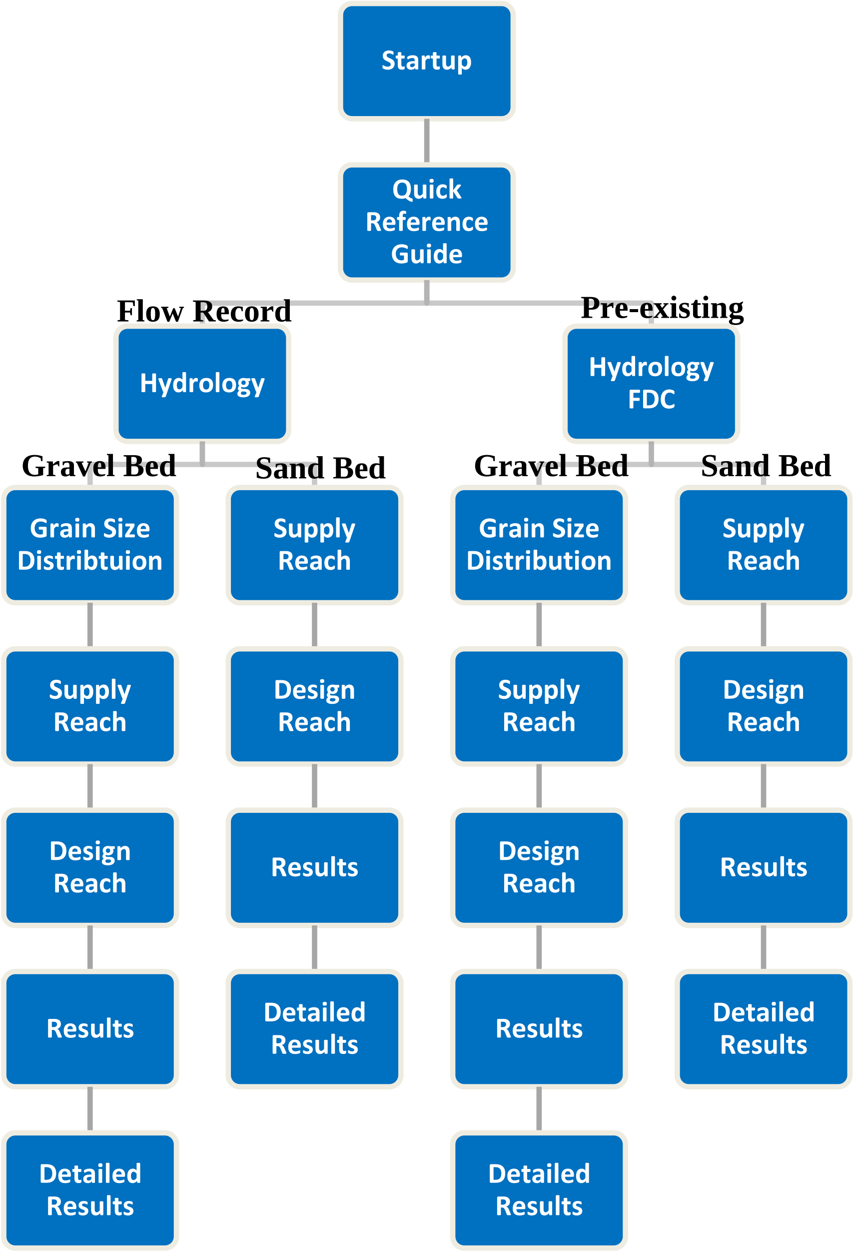
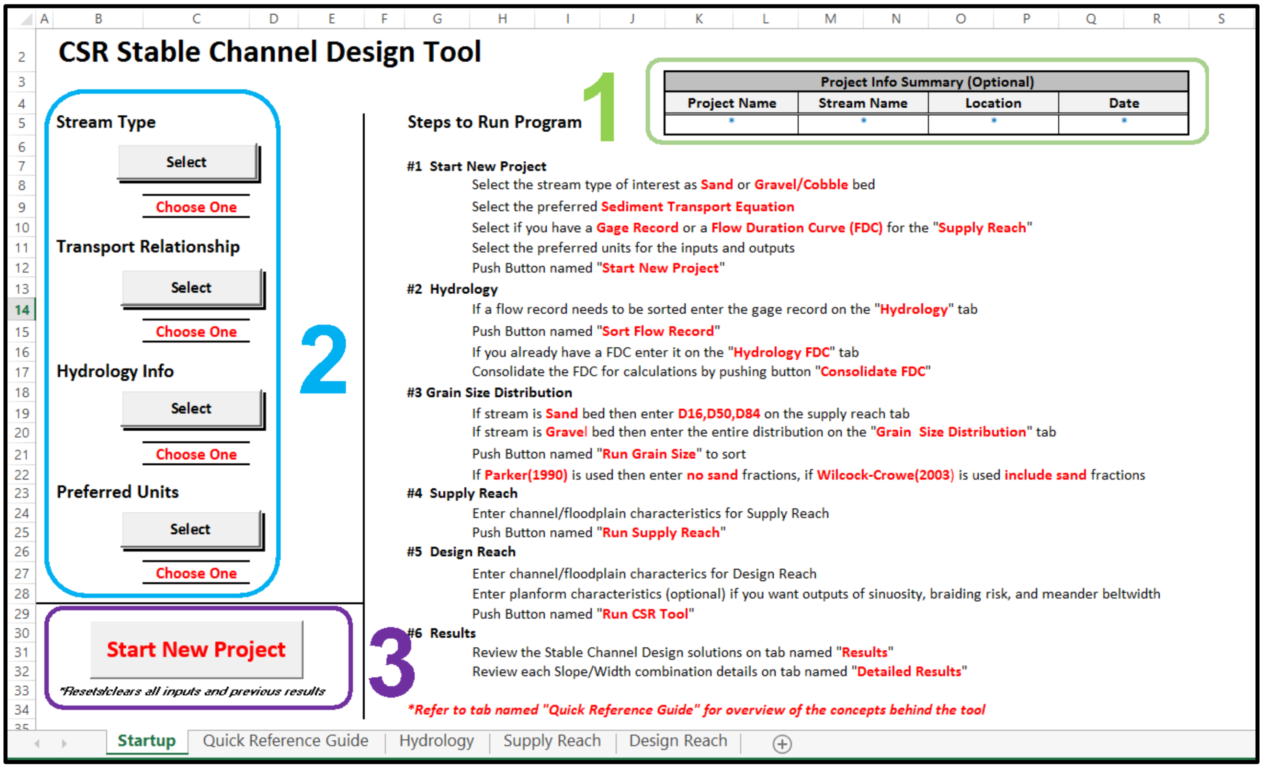


Figure B-1. Decision tree for the tab order and usage in the CSR Tool.

B.1.2 Startup Tab

This tab was created as a platform to set-up a new project and define the project type to run the program. The following will give a step-by-step guide to setting up a new project to run the program. Figure B-2 shows a screenshot of the "Startup" tab pointing out the areas on the sheet that are needed for each step in starting a new project.



CSR Stable Channel Design Tool

Project Info Summary (Optional)			
Project Name	Stream Name	Location	Date
*	*	*	*

Steps to Run Program

#1 Start New Project
Select the stream type of interest as **Sand** or **Gravel/Cobble** bed
Select the preferred **Sediment Transport Equation**
Select if you have a **Gage Record** or a **Flow Duration Curve (FDC)** for the "**Supply Reach**"
Select the preferred units for the inputs and outputs
Push Button named "**Start New Project**"

#2 Hydrology
If a flow record needs to be sorted enter the gage record on the "**Hydrology**" tab
Push Button named "**Sort Flow Record**"
If you already have a FDC enter it on the "**Hydrology FDC**" tab
Consolidate the FDC for calculations by pushing button "**Consolidate FDC**"

#3 Grain Size Distribution
If stream is **Sand** bed then enter **D16,D50,D84** on the supply reach tab
If stream is **Gravel** bed then enter the entire distribution on the "**Grain Size Distribution**" tab
Push Button named "**Run Grain Size**" to sort
If **Parker(1990)** is used then enter **no sand** fractions, if **Wilcock-Crowe(2003)** is used **include sand** fractions

#4 Supply Reach
Enter channel/floodplain characteristics for Supply Reach
Push Button named "**Run Supply Reach**"

#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "**Run CSR Tool**"

#6 Results
Review the Stable Channel Design solutions on tab named "**Results**"
Review each Slope/Width combination details on tab named "**Detailed Results**"

Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

Figure B-2. Screenshot of "Startup" tab with areas delineated for Steps 1–3.

B.1.2.1 <u>Steps for Startup tab</u>

Step 1. Project Information Summary (Optional)

The first step is to enter the project information summary in the area provided (Figure B-2). This is optional and solely for the user's reference and will not be used to run the program.

Step 2. Defining Project Type

The selections made in this step define variables in the program, equations, and inputs needed to perform the CSR analysis. The appropriate tabs required for the specified project type will be automatically unhidden in the workbook. This allows the user to easily follow the order as presented in Figure B-3 to run the program and view the results. The variables selected will be displayed underneath the "Select" button for reference.

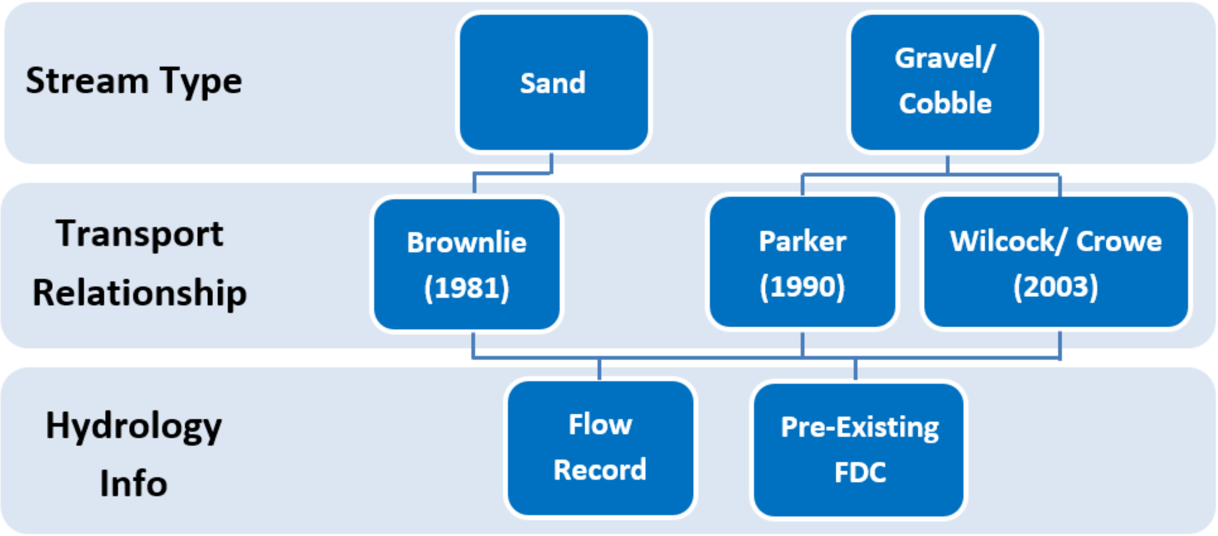


Figure B-3. Decision tree for Step 2 (Defining Project Type) of the "Startup" page.

Stream Type

Press the "Select" button under "Stream Type" to define the stream type of interest for the project. The two choices are "Sand" or "Gravel/Cobble." This distinction is used to constrain the type of sediment transport equations used in the analysis. Sand-bed streams commonly use "total" load sediment transport equations, while gravel- / cobble-bed streams use bedload sediment transport relationships. There is no distinct threshold between these two channel types but rather a continuous spectrum and a mixture of many grain size groups (Montgomery and Buffington 1997). For user reference, a table listing the delineation of all grain size groups is presented in Table B-1. In general, the bed material of a sand-bed stream would primarily consist of sand (0.0625 to 2 mm) size particles in the distribution, and a gravel/cobble stream would primarily consist of gravel (2 to 64 mm) and/or cobble (64 to 256 mm) size particles. In other words, the stream would have a D_{50} within these ranges. More specifically, the user can compare to the sediment distributions used to derive the sediment transport equations that are used in the tool (Table B-2). Comparing to Table B-9 is the most accurate and appropriate way to ensure the integrity of the sediment transport equation output and the resulting design solutions. ****Using the equations outside of the range used to develop them can produce unstable/erroneous solutions from the CSR Tool.****

Table B-1. Grain size class delineations.

	Class Name	Particle Diameter [mm]
Boulder	Very Large	>2,048
	Large	>1,024
	Medium	>512
	Small	>256
Cobble	Large	>128
	Small	>64
Gravel	Very Coarse	>32
	Coarse	>16
	Medium	>8
	Fine	>4
	Very Fine	>2
Sand	Very Coarse	>1
	Coarse	>0.5
	Medium	>0.25
	Fine	>0.125
	Very Fine	>0.0625
Silt	Coarse	>0.031
	Medium	>0.016
	Fine	>0.008
	Very Fine	>0.004
Clay	Coarse	>0.002
	Medium	>0.001
	Fine	>0.0005
	Very Fine	>0.00024

Table B-2. Boundaries of sediment transport equations used in tool.

Equation	Variable	Minimum	Maximum
Brownlie (1981)	D_{50} [mm]	0.088	2.8
	Unit discharge [m^3/s/m]	0.012	40
	Discharge [m^3/s]	0.0032	22,000
	Slope	0.000003	0.037
	Hydraulic radius [m]	0.025	17
	Temperature [ºC]	0	63
	Width/depth ratio	≥ 4	≥ 4
	Geometric standard deviation of particles sizes, σ_g	≤ 5	≤ 5
Parker (1990)	Gravel-sized particles [mm]	2	203
	Sand-sized particles [mm]	sand removed	sand removed
	[%] of sand in mixture	3.3% (surface)	13% (subsurface)
Wilcock-Crowe (2003)	Gravel-sized particles [mm]	2	64
	Sand-sized particles [mm]	0.5	2
	[%] of sand in mixture	6.2	34.3
	Depth [m]	0.09	0.12

Transport Relationship

Press the “Select” button under “Transport Relationship” to define the sediment transport equation that will be used to carry out the CSR analysis for the project (Figure B-2).

If “Sand” was selected for the stream type, then the Brownlie (1981) total load sediment transport equation will be automatically selected. This transport equation was developed to estimate the sediment transported in sand-bed channels. Refer to Table B-2 for the boundaries Brownlie (1981) listed in his publication for developing this equation. This is the same equation that is used for the Copeland method of stable channel design in Hydrologic Engineering Centers River Analysis System (HEC-RAS).

If “Gravel/Cobble” was selected for the stream type, then there will be two choices under “Transport Relationship.” The “Parker (1990)” and “Wilcock-Crowe (2003)” sediment transport equations are bedload equations developed for gravel- / cobble-bed streams. Refer to Table B-2 to review the boundaries listed by the authors in developing these transport relationships. The Parker

(1990) equation is a well-respected bedload equation for streams with primarily gravel/cobble particle sizes and a low fraction of sand (<3 to 5%) in the mixture. This equation is recommended when the grain size distribution consist of primarily gravel/cobble particles with (<3 to 5%) sand fraction. This equation will eliminate all sand fractions (<2 mm) in the distribution prior to calculating the bedload. The Wilcock-Crowe (2003) bedload equation is similar to the Parker (1990) equation but it also considers sand fractions in the calculations. This equation is recommended if there is a significant sand fraction (6 to 34%) in the mixture. This equation will take into account the effects on sediment transport of sand in the gravel/cobble mixture. Sand is known to greatly increase the transport of gravel/cobbles if present in the mixture (Wilcock et al. 2001).

Hydrology Info

Press the "Select" button under "Hydrology Info" to define the source type for the hydrology that will be used in the CSR analysis for the project (Figure B-2). As stated in the CSR Tool Reference Manual (Appendix A), the tool requires a sequence of flows over time for the channel reach of interest in order to perform a magnitude-frequency analysis (MFA) and calculate the associated effectiveness or total sediment yield. The CSR Tool can derive this from a flow record or a pre-derived FDC. The hydrology information input for the upstream supply reach is assumed to be the same for the design reach downstream.

The first selection, "Flow Record," is for users that have a gaging station flow record representing the flows of the supply and design reach. This is the recommended approach for the most accurate analysis, if the flow record is of significant length (>10 to 15 yrs) and representative of both the supply and design reach (Biedenharn et al. 2000). The CSR Tool is optimized to accept USGS gage data directly from the record in cubic feet per second (cfs). The program will automatically eliminate any “Ice” if present in the record. If “Flow Record” is selected, the “Hydrology” tab will appear when a new project is made.

The second selection, “Pre-existing FDC,” is for users that have a pre-derived FDC to enter rather than a flow record. This feature was mainly added to the program to help with the great limitation of needing an extended flow record for the supply reach, which is often absent in many situations. Therefore, this feature should be used when a flow record of significant length is lacking or deemed unrepresentative of the flow regime. The program was optimized for the use of FDCs derived from SWAT-DEG in eRAMS. Further guidance on creating a FDC in ungaged basins can be found in Biedenharn et al. (2000). If “Pre-existing FDC” is selected then the “Hydrology FDC” tab will appear when a new project is made.

Preferred Units

This selection is to choose the preferred units of the inputs and outputs of the program. Note: No matter which unit is selected the grain size will still be entered in millimeters and the flow record will need to be entered in cubic feet per second since these are the most common units for these variables.

Step 3. Start New Project

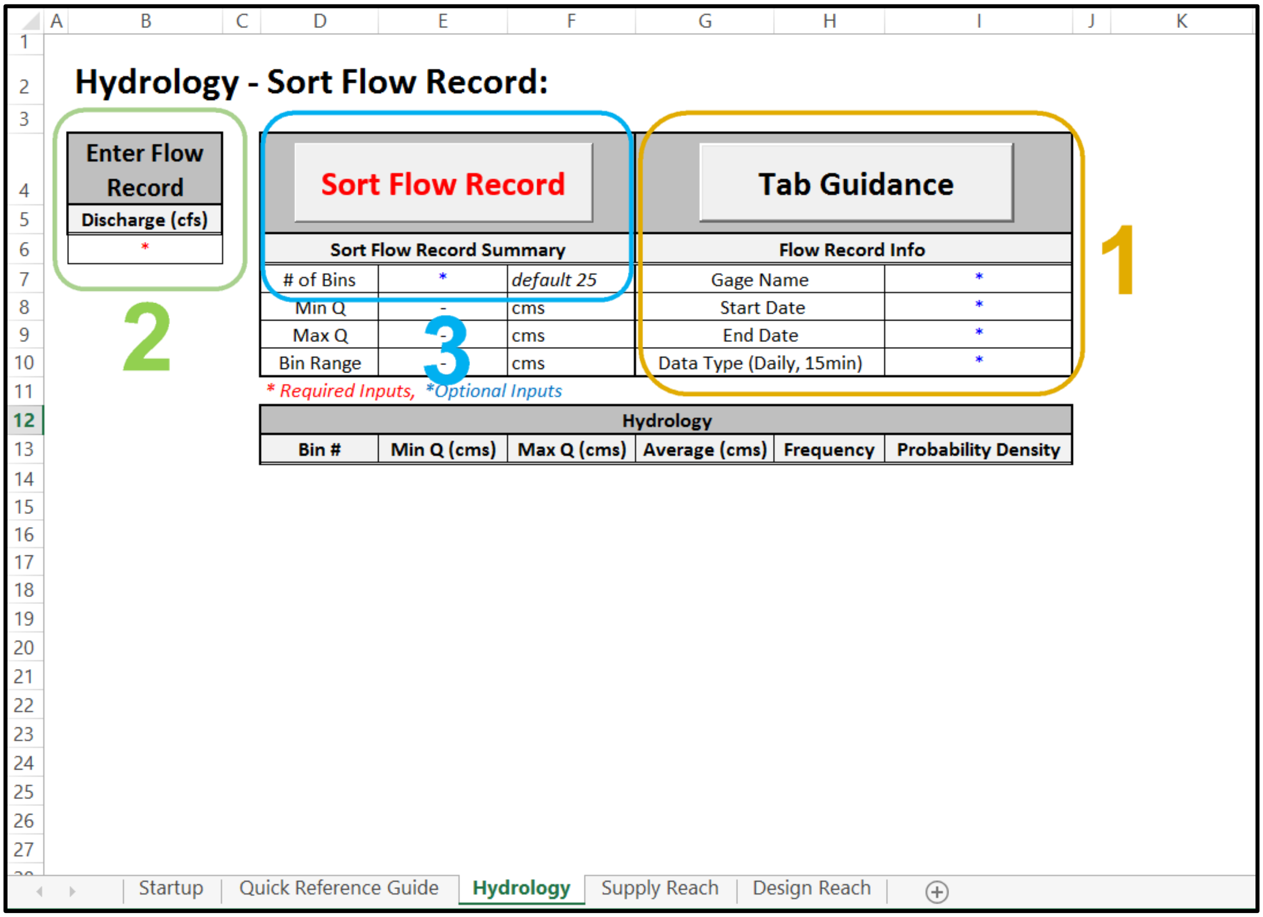
The last step on the “Startup” tab is to start a new project. With Steps 1–2 complete, press the “Start New Project” button as seen in Figure B-2. Note: This will eliminate all previous results of the last project that was run. This will also unhide the tabs necessary to complete the analysis based on the variables defined in Step 2, and highlight the required inputs on the associated cells of each tab.

B.1.3 Quick Reference Guide (Optional) Tab

This tab was created to be a quick visual reference for some of the main concepts behind the CSR Tool analysis as presented in the CSR Tool Reference Manual (Appendix A). There are no required inputs on this tab.

B.1.4 Hydrology Tab

This tab was created to take a flow record and sort it into a specified number of bins to be converted into a probability density function (PDF) of flows to be used in the CSR analysis. The following will give a step-by-step guide on running this tab. Figure B-4 shows a screenshot of the "Hydrology" tab pointing out the areas on the sheet that are needed for each step.



Hydrology - Sort Flow Record:

Enter Flow Record
Discharge (cfs)
*

Sort Flow Record Summary		
# of Bins	*	*default 25*
Min Q	-	cms
Max Q		cms
Bin Range	-	cms

Flow Record Info	
Gage Name	*
Start Date	*
End Date	*
Data Type (Daily, 15min)	*

** Required Inputs, *Optional Inputs*

Hydrology					
Bin #	Min Q (cms)	Max Q (cms)	Average (cms)	Frequency	Probability Density

Figure B-4. Screenshot of "Hydrology" tab with areas delineated for Steps 1–3.

B.1.4.1 Steps for Hydrology tab

Step 1. Flow Record Info / Tab Guidance

The user can enter the flow record information summary in the area provided and/or press the “Tab Guidance” button to access a quick reference on how to run the tab (Figure B-4). This is optional and solely for the user’s reference and will not be used to run the program.

Step 2. Enter Flow Record

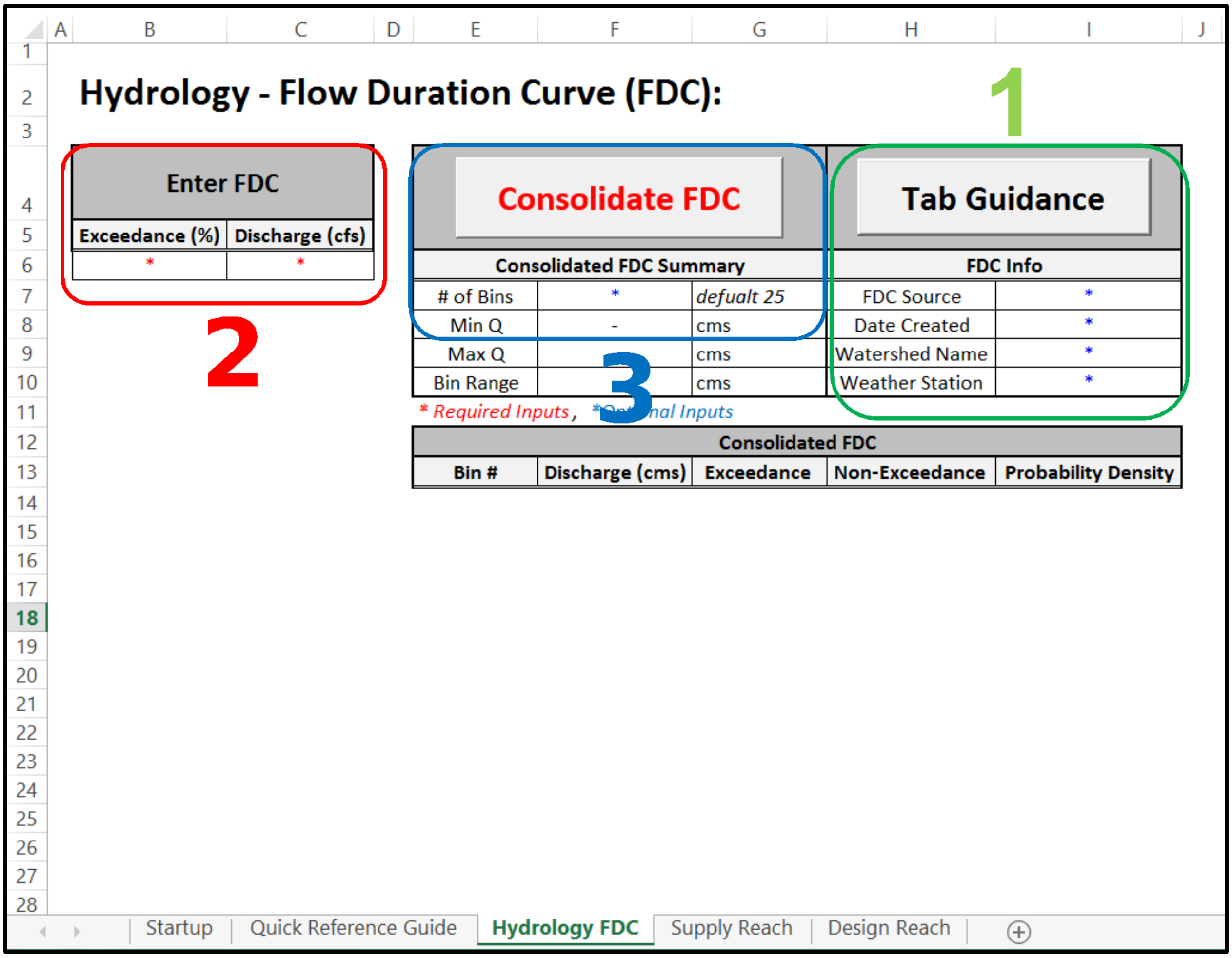
This tab is optimized to import flow records directly from the USGS database, but is also capable of processing flow records from other sources. Select a gaging station for the “Supply Reach” of either mean daily flows or 15-minute flows. 15-minute data may be too large for spreadsheet analysis, although it may be favorable to use. Refer to Rosburg (2015) for further guidance on choosing 15-minute or daily flow data. Enter just the discharge in cubic feet per second from the flow record in Column B under “Enter Flow Record” as seen in Figure B-4.

Step 3. Sort Flow Record

The program defaults to 25 arithmetic bins (recommended) to sort the flow record (Biedenharn et al. 2000). The user can change this number in the “# of Bins” row. The program will decrease that number until no 0 frequency bins are present. In cases where there is still zero frequency at 10 bins, then the process starts again at 25 bins and combines the discharges above the zero frequency bin into one. Press the “Sort Flow Record” button to bin the flows for the analysis. Column B will be sorted from lowest to highest flow and formatted. The required hydrology information will automatically be transferred to the “Supply Reach” and “Design Reach” tabs. (This flow record is assumed to be the same for the Supply and Design Reaches.) Review the summary of the sorting under “Sort Flow Record Summary” and the results per bin under “Hydrology.”

B.1.5 Hydrology FDC Tab

This tab was created to take a pre-derived FDC and consolidate it into a specified number of bins to be converted into a PDF of flows to be used in the CSR analysis. The following will give a step-by-step guide on running this tab. Figure B-5 shows a screenshot of the “Hydrology FDC” tab pointing out the areas on the sheet that are needed for each step.



Hydrology - Flow Duration Curve (FDC):

Exceedance (%)	Discharge (cfs)
*	*

Consolidated FDC Summary		
# of Bins	*	*defualt 25*
Min Q	-	cms
Max Q		cms
Bin Range		cms

FDC Info	
FDC Source	*
Date Created	*
Watershed Name	*
Weather Station	*

** Required Inputs, *Optional Inputs*

Consolidated FDC				
Bin #	Discharge (cms)	Exceedance	Non-Exceedance	Probability Density

Figure B-5. Screenshot of “Hydrology FDC” tab with areas delineated for Steps 1–3.

B.1.5.1 Steps for Hydrology FDC tab

Step 1. FDC Info / Tab Guidance

The user can enter the FDC information summary in the area provided and/or press the "Tab Guidance" button to access a quick reference on how to run the tab (Figure B-5). This is optional and solely for the user's reference and will not be used to run the program.

Step 2. Enter FDC

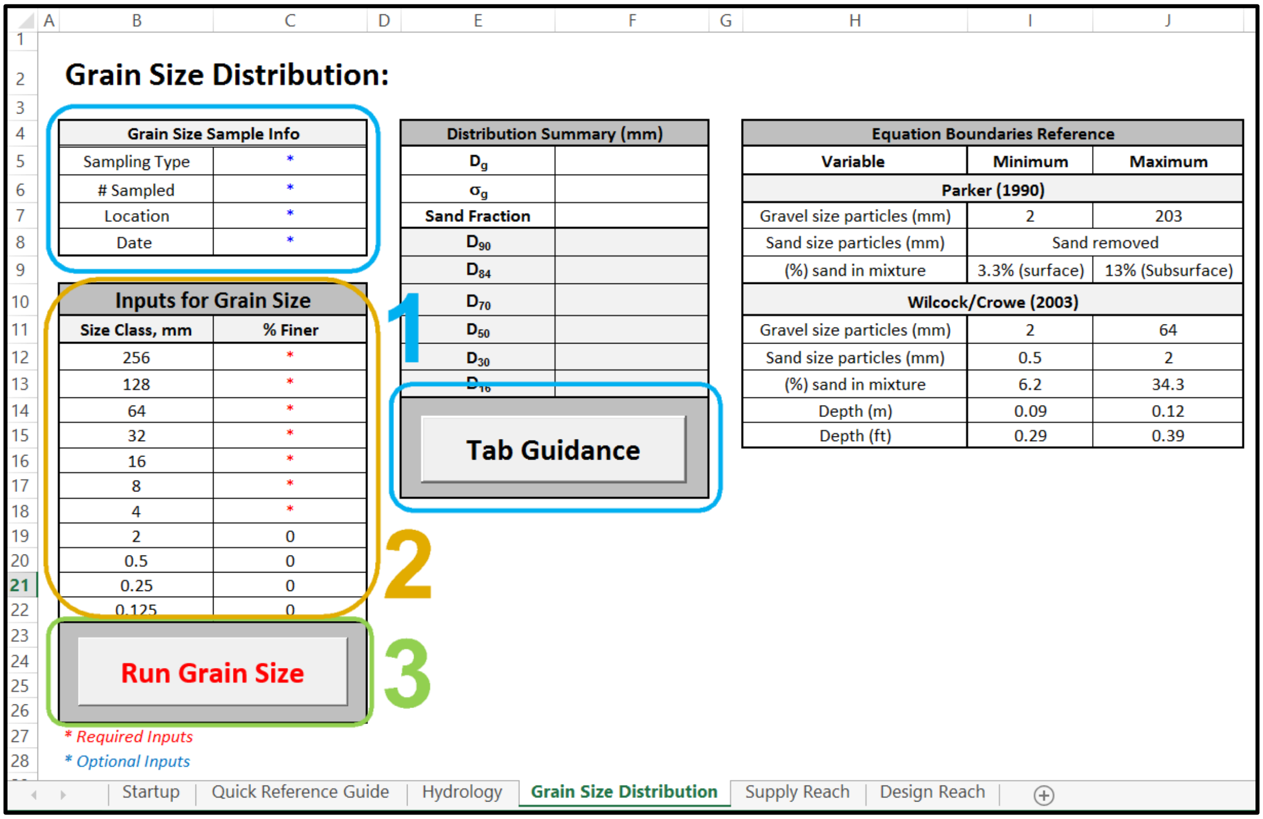
This tab is optimized to import FDCs generated by SWAT-DEG in eRAMS. Other sources of FDCs are compatible as well. Enter the FDC of exceedance probability in percent (%) versus discharge (cfs) under the corresponding labels in Columns B–C of the tab. This tab's main purpose is to consolidate a detailed FDC to a condensed FDC of 25 to 50 bins to be used in the CSR analysis. The user can specify the number of bins to be consolidated to in the "# of Bins" row. The program defaults to 25 bins (recommended) for the CSR analysis (Biedenharn et al. 2000). If the FDC entered is under 50 bins already, then the program simply uses all of the original values rather than sampling.

Step 3. Consolidate FDC

Press the "Consolidate FDC" button to logarithmically sample the original FDC to the specified number of bins. The required hydrology information will automatically be transferred to the "Supply Reach" and "Design Reach" tabs. (This FDC is assumed to be the same for the Supply and Design Reaches.)

B.1.6 Grain Size Distribution Tab

This tab was created to sort a grain size distribution of a gravel- / cobble-bed stream type for the CSR analysis. The distributions are sorted to calculate the necessary statistical parameters to be used in the sediment transport calculations. The following will give a step-by-step guide on running this tab. Figure B-6 shows a screenshot of the “Grain Size Distribution” tab pointing out the areas on the sheet that are needed for each step.



Grain Size Distribution:

Grain Size Sample Info	
Sampling Type	*
# Sampled	*
Location	*
Date	*

Inputs for Grain Size	
Size Class, mm	% Finer
256	*
128	*
64	*
32	*
16	*
8	*
4	*
2	0
0.5	0
0.25	0
0.125	0

Distribution Summary (mm)	
D_g	
σ_g	
Sand Fraction	
D_{90}	
D_{84}	
D_{70}	
D_{50}	
D_{30}	
D_{16}	

Equation Boundaries Reference		
Variable	Minimum	Maximum
Parker (1990)		
Gravel size particles (mm)	2	203
Sand size particles (mm)	Sand removed	
(%) sand in mixture	3.3% (surface)	13% (Subsurface)
Wilcock/Crowe (2003)		
Gravel size particles (mm)	2	64
Sand size particles (mm)	0.5	2
(%) sand in mixture	6.2	34.3
Depth (m)	0.09	0.12
Depth (ft)	0.29	0.39

** Required Inputs*
** Optional Inputs*

Figure B-6. Screenshot of “Grain Size Distribution” tab with areas delineated for Steps 1–3.

B.1.6.1 <u>Steps for Grain Size Distribution tab</u>

Step 1. Grain Size Sample Info / Tab Guidance

The user can enter the grain size sample information summary in the area provided and/or press the “Tab Guidance” button to access a quick reference on how to run the tab (Figure B-6). This is optional and solely for the user’s reference and will not be used to run the program.

Step 2. Inputs for Grain Size

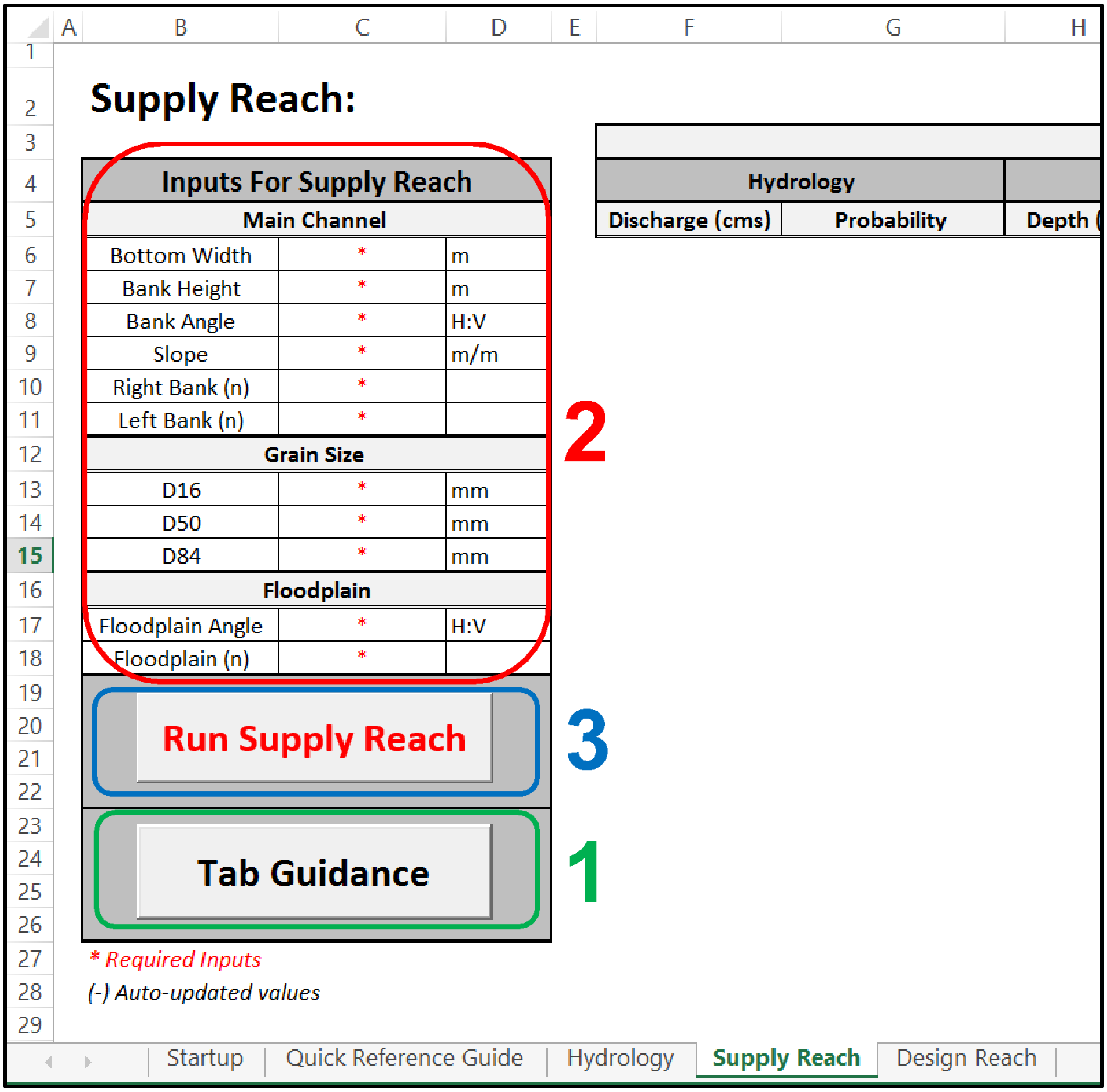
Enter the % finer for each grain size class under “% Finer” in Column C of the tab as seen in Figure B-6. If you selected the Parker (1990) transport equation then all sand fraction size classes (<2 mm) will not be considered in the analysis. If you selected the Wilcock-Crowe (2003) transport equation then all size classes will be considered and you can review the Sand Fraction (%) under “Distribution Summary.” The sediment transport equation development boundaries are summarized on the top right of the tab for reference.

Step 3. Run Grain Size

Press the “Run Grain Size” button to graph the distribution and calculate the distribution percentiles summarized under “Distribution Summary.” The necessary grain size information for the CSR analysis will automatically be transferred to the “Supply Reach” and “Design Reach” tabs. (This grain size distribution is assumed to be the same for the Supply and Design Reaches.)

B.1.7 Supply Reach Tab

The main purpose of this tab is to calculate the incoming sediment load produced by the supply reach entering the design reach of interest for the CSR analysis. The following will give a step-by-step guide on running this tab. Figure B-7 shows a screenshot of the “Supply Reach” tab pointing out the areas on the sheet that are needed for each step.



Supply Reach:

Inputs For Supply Reach		
Main Channel		
Bottom Width	*	m
Bank Height	*	m
Bank Angle	*	H:V
Slope	*	m/m
Right Bank (n)	*	
Left Bank (n)	*	
Grain Size		
D16	*	mm
D50	*	mm
D84	*	mm
Floodplain		
Floodplain Angle	*	H:V
Floodplain (n)	*	

** Required Inputs*

(-) Auto-updated values

Hydrology		
Discharge (cms)	Probability	Depth (

Figure B-7. Screenshot of "Supply Reach" tab with areas delineated for Steps 1–3.

B.1.7.1 <u>Steps for Supply Reach tab</u>

Step 1. Tab Guidance

The user can press the "Tab Guidance" button to access a quick reference on how to run the tab (Figure B-7). This is optional and solely for the user's reference and will not be used to run the program.

Step 2. Inputs for Supply Reach

Main Channel

Enter the main channel dimensions and characteristics of the supply reach in Cells C6–C11. The bottom width, bank height (bankfull), and bank angle are dimensions of a simplified trapezoid that represents the actual supply reach cross-sectional geometry (see Figure B-19 for a visual). The channel slope can be simplified as a bed slope with the steady, uniform flow assumption, but can also be entered more accurately as a water surface slope or friction slope. Right and left banks (n) correspond to the Manning's n roughness characteristics of each bank. For a sand-bed stream type the roughness of the bed is calculated within the roughness predictors produced in Brownlie (1983) which accounts for sand-bed forms. For a gravel/cobble stream type the roughness of the bed is calculated in conjunction with the bedload equations with the Limerinos (1970) equation.

Grain Size

If the channel type is sand bed then D_{16}, D_{50}, and D_{84} are required inputs that need to be specified by the user for the sediment calculations. If the channel type is gravel/cobble then D_{16}, D_{50}, and D_{84} are an auto-updated summary from the "Grain Size Distribution" tab. (For both channel types, these values are assumed to be the same for the design reach and automatically transferred to the "Design Reach" tab.)

Floodplain

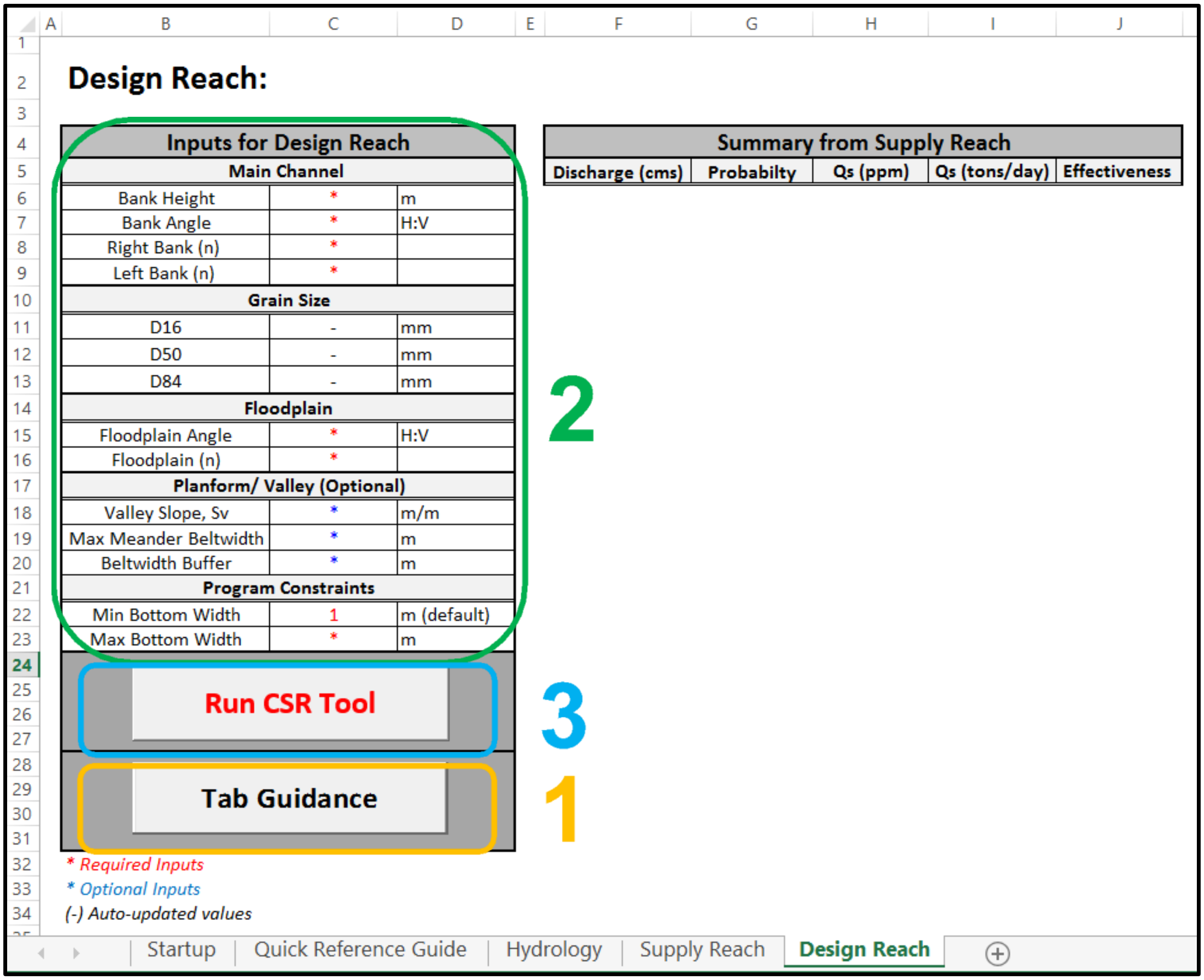
Enter the floodplain angle and roughness characteristics of the supply reach in Cells C17–C18. This program models flows that break onto the floodplain as opposed to the Copeland method of HEC-RAS. The roughness and angle specified is assumed to be the same on both sides of the channel. Column I of the results will show if the flow was modeled as overbank (True) or not (False).

Step 3. Run Supply Reach

Press the “Run Supply Reach” button to run sediment transport calculations for the supply reach. The hydrology results will be auto-updated in Columns F–G. Review the hydraulic output for each bin discharge in Columns H–N and the sediment transport outputs in Columns O–Q. The effectiveness or the total sediment transported on average in a given year for each bin discharge will be plotted in the bottom left, and a diagram that shows the visual representation of the supply reach channel geometry in the bottom right. The channel geometry diagram is on a generic scale, but all lengths and angles are proportional to each other.

B.1.8 Design Reach Tab

The main purpose of this tab is to define the desired design reach characteristics and set-up the CSR analysis to produce stable channel design solutions. The following will give a step-by-step guide on running this tab. Figure B-8 shows a screenshot of the “Design Reach” tab pointing out the areas on the sheet that are needed for each step.



Design Reach:

Inputs for Design Reach		
Main Channel		
Bank Height	*	m
Bank Angle	*	H:V
Right Bank (n)	*	
Left Bank (n)	*	
Grain Size		
D16	-	mm
D50	-	mm
D84	-	mm
Floodplain		
Floodplain Angle	*	H:V
Floodplain (n)	*	
Planform/ Valley (Optional)		
Valley Slope, Sv	*	m/m
Max Meander Beltwidth	*	m
Beltwidth Buffer	*	m
Program Constraints		
Min Bottom Width	1	m (default)
Max Bottom Width	*	m

Summary from Supply Reach				
Discharge (cms)	Probabilty	Qs (ppm)	Qs (tons/day)	Effectiveness

* Required Inputs

* Optional Inputs

(-) Auto-updated values

Figure B-8. Screenshot of "Design Reach" tab with areas delineated for Steps 1–3.

B.1.8.1 <u>Steps for Design Reach tab</u>

Step 1. Tab Guidance

The user can press the "Tab Guidance" button to access a quick reference on how to run the tab (Figure B-8). This is optional and solely for the user's reference and will not be used to run the program.

Step 2. Inputs for Design Reach

Main Channel

Enter the main channel dimensions and characteristics of the design reach in Cells C6–C9. The bank height is a bankfull depth that the program needs in order to know when the flow is overbank. This value can be iterated to find the right value for the design. The bank angle is for a simplified trapezoid that represents the cross-sectional geometry of the design reach (see Figure B-19 for visual). Right and left banks (*n*) correspond to the Manning's *n* roughness characteristics of each bank just like the supply reach. The bottom width and slope inputs are absent because these are the two variables that are varied by the program to find stable channel design solutions (CSR = 1).

Grain Size

The values for D_{16}, D_{50}, and D_{84} are auto-updated from previous tabs and assumed to be the same as the supply reach.

Floodplain

Enter the floodplain angle and roughness characteristics of the design reach in Cells C15–C16. The program will model overbank flows the same as the supply reach. The roughness and angle specified is assumed to be the same on both sides of the channel.

Planform/Valley (Optional)

Enter "Planform/Valley" characteristics to include them in the outputs. Entering a valley slope will allow the program to calculate the sinuosity, meander belt width, and channel braiding risk for each stable channel design solution. Setting a maximum belt width and buffer will tell the program to highlight the solutions in red that fall outside of these bounds. Review the "Planform

Characteristics" section of the CSR Tool Reference Manual (Appendix A) for a detailed overview of these concepts and Figure B-19 for a visual representation of the concepts.

Program Constraints

Enter the program width constraints. The minimum width is defaulted to 1 m or 3 ft to produce the entire 'family of solutions' even though it is an impractical solution. Set the maximum width (1.5 to 2 times) for the supply reach bottom width to produce a full family of solutions. The program will loop through this width range in conjunction with an automated range of slope guesses to find design channels with a CSR = 1.

Step 3. Run Design Reach

Press the "Run CSR Tool" button to produce a family of stable channel slope/width combinations (Figure B-8) for the design reach that can pass the incoming sediment load from the supply reach with minimal aggradation or degradation (i.e., CSR = 1). Review the solutions on the "Results" tab and each slope/width combination details on the "Detailed Results" tab. There is a diagram showing the design reach channel dimensions on the "Results" tab. All angles and lengths are proportional except the bottom width is set at a generic length because this value varies for each solution.

B.1.9 Results Tab

The "Results" tab will display the main results of the CSR Tool. This tab will have a plot of the 'family of width and slope combinations' the program found that provide continuity of water and sediment (i.e., CSR = 1). These solutions will traditionally take a shape as seen in Figure B-9. A shape similar to this should be expected for sand-bed channel types, and one can expect less curl up at lower widths and a generally flatter curve for gravel- / cobble-bed channel types.

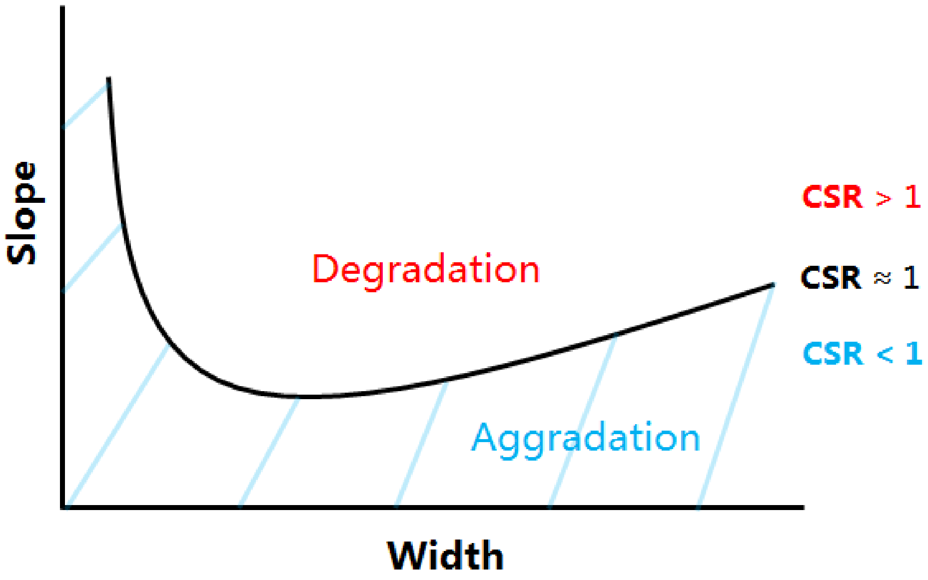


Figure B-9. Family of slope/width combinations which provide continuity of water and sediment.

B.1.10 Detailed Results Tab

The “Detailed Results” tab will display more specific results for each slope/width combination from the “Results” page. The far left of the tab displays the discharges per bin used in the analysis and the associated effectiveness for each from the supply reach. These results are displayed for reference to be compared to the bin-by-bin effectiveness of each slope and width solution for the design reach. Furthermore, a table of the sediment percentiles for each slope/width combination is displayed below each effectiveness table. For more information on sediment percentiles refer to the CSR Tool Reference Manual (Appendix A).

B.2 CSR Tool Examples

The following will present two examples of using the CSR Tool with screenshots. One example will be a sand-bed river using U.S. customary units and the other will be a gravel-bed river using metric units. The *Tab-by-tab Guidance* section of this document focused on explaining the inputs and functions required by the user to run the CSR Tool. This section will focus on giving a visual and explanations on each tab for the output of the tool through examples.

B.2.1 Sand Bed

This example is for a reach on Big Raccoon Creek, Indiana (Figure B-10). The data used for this example are from Soar and Thorne (2001; Appendix B – U.S. sand-bed river data).

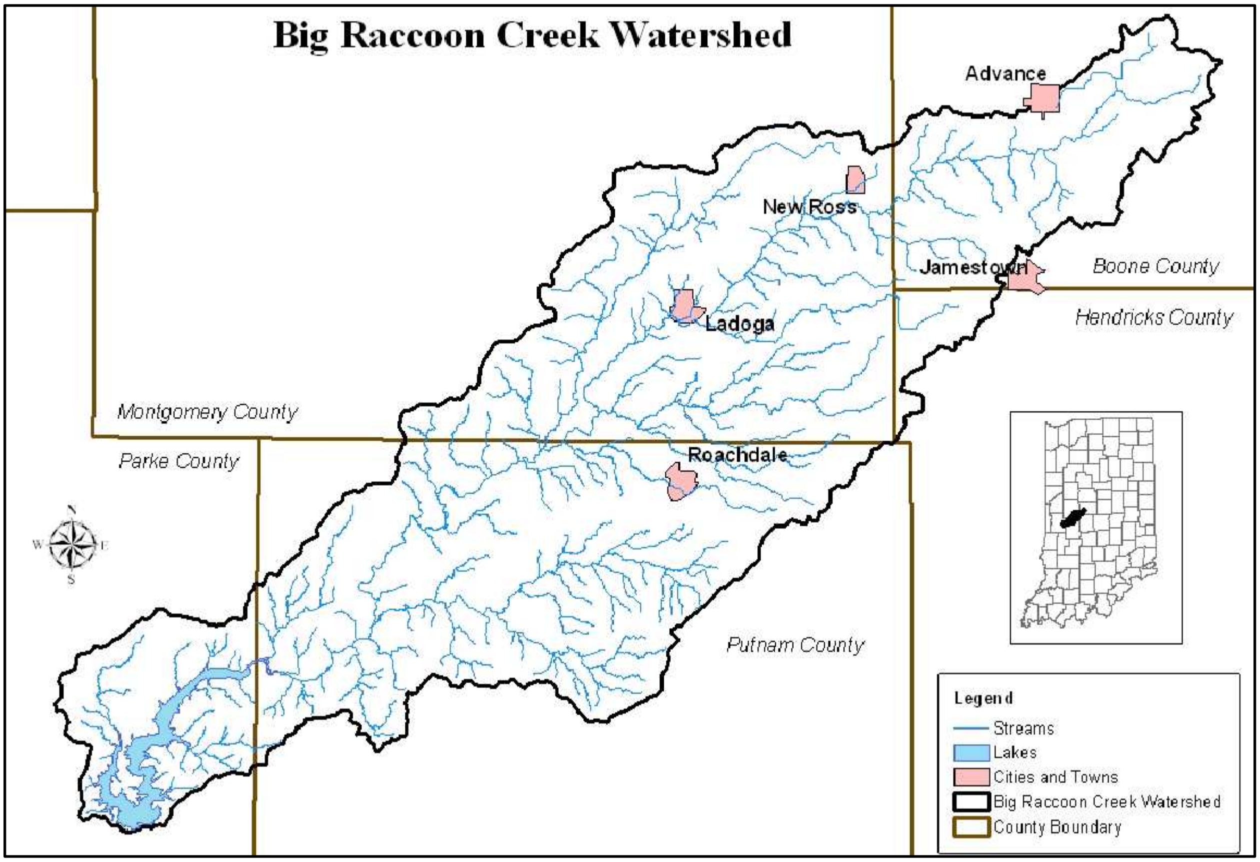
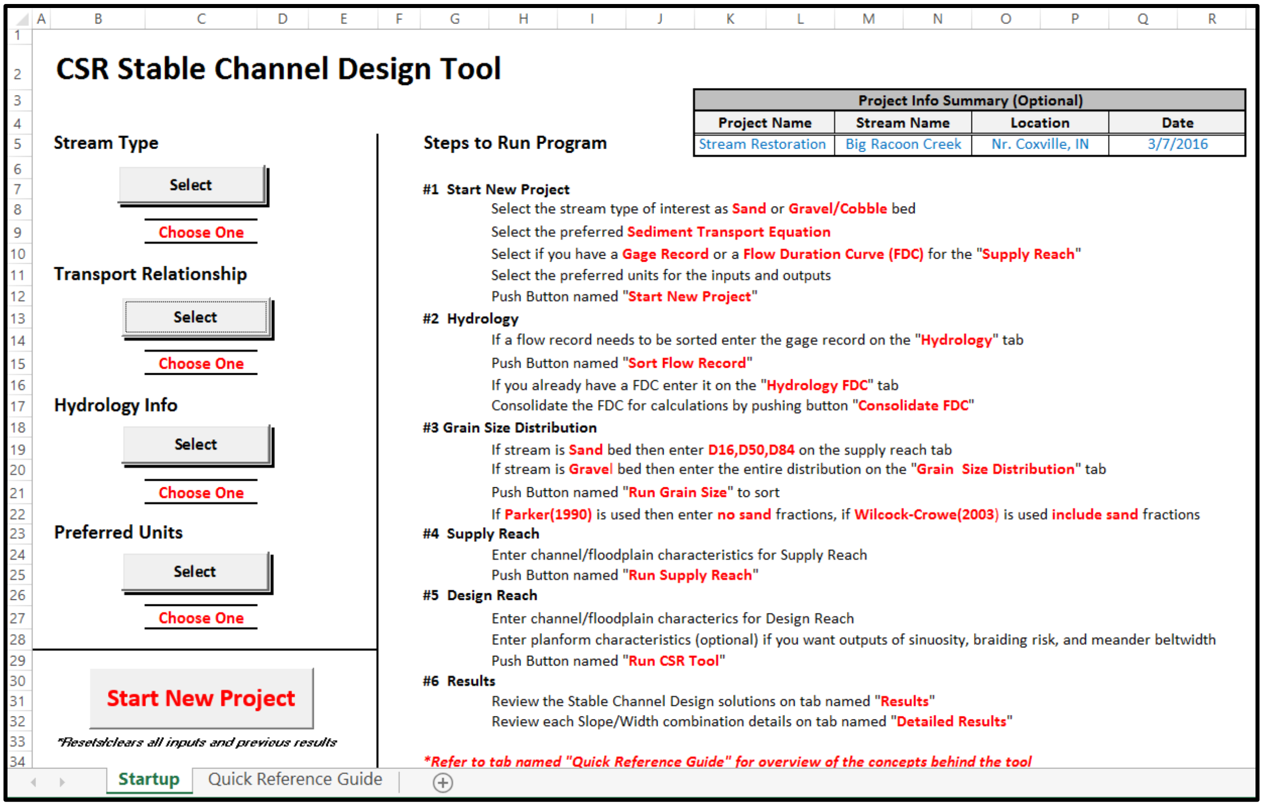


Figure B-10. Map of Big Raccoon Creek watershed in Indiana (Indiana Department of Environmental Management (IDEM) 2013).

B.2.1.1 <u>Startup page</u>

The CSR Tool initial screen is shown in Figure B-11. The project information summary is optionally entered in the top right of the tab.



CSR Stable Channel Design Tool

Project Info Summary (Optional)			
Project Name	**Stream Name**	**Location**	**Date**
Stream Restoration	Big Racoon Creek	Nr. Coxville, IN	3/7/2016

*Resets/clears all inputs and previous results

Steps to Run Program

#1 Start New Project
Select the stream type of interest as **Sand** or **Gravel/Cobble** bed
Select the preferred **Sediment Transport Equation**
Select if you have a **Gage Record** or a **Flow Duration Curve (FDC)** for the "**Supply Reach**"
Select the preferred units for the inputs and outputs
Push Button named "**Start New Project**"

#2 Hydrology
If a flow record needs to be sorted enter the gage record on the "**Hydrology**" tab
Push Button named "**Sort Flow Record**"
If you already have a FDC enter it on the "**Hydrology FDC**" tab
Consolidate the FDC for calculations by pushing button "**Consolidate FDC**"

#3 Grain Size Distribution
If stream is **Sand** bed then enter **D16,D50,D84** on the supply reach tab
If stream is **Gravel** bed then enter the entire distribution on the "**Grain Size Distribution**" tab
Push Button named "**Run Grain Size**" to sort
If **Parker(1990)** is used then enter **no sand** fractions, if **Wilcock-Crowe(2003)** is used **include sand** fractions

#4 Supply Reach
Enter channel/floodplain characteristics for Supply Reach
Push Button named "**Run Supply Reach**"

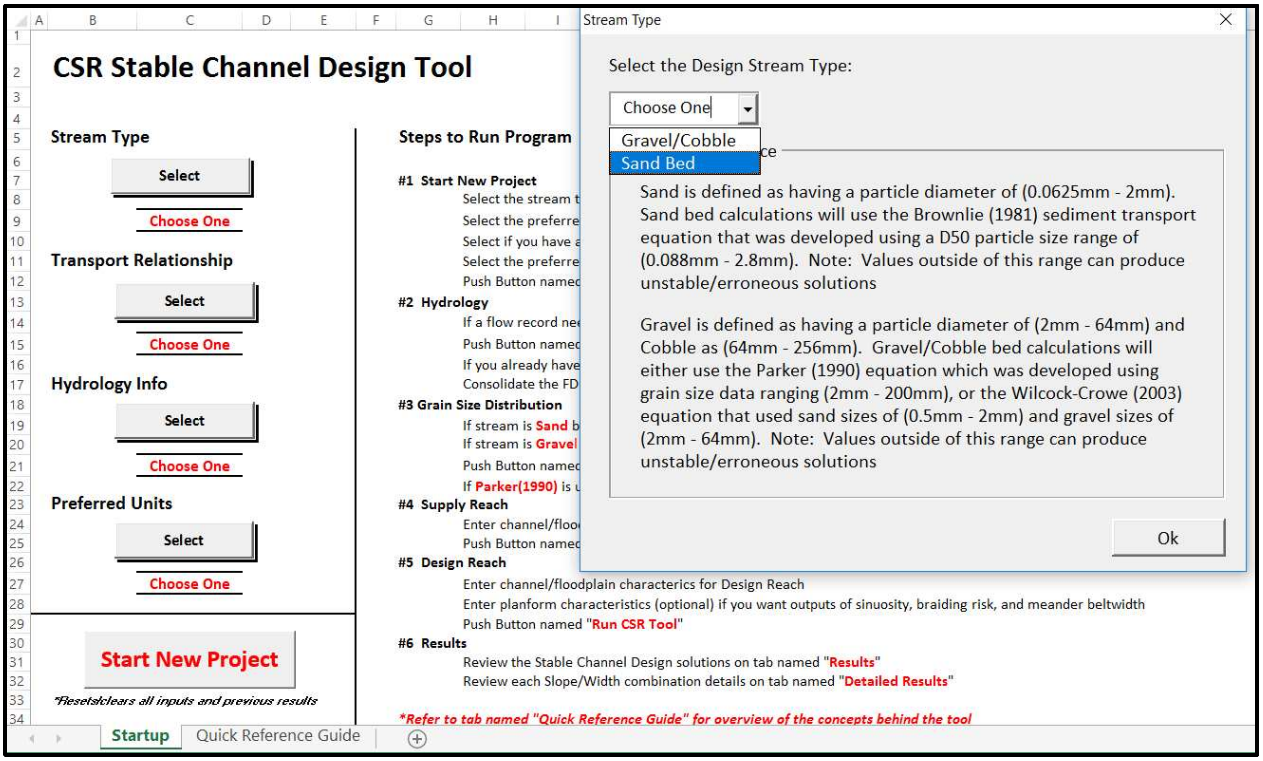
#5 Design Reach
Enter channel/floodplain charactercics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "**Run CSR Tool**"

#6 Results
Review the Stable Channel Design solutions on tab named "**Results**"
Review each Slope/Width combination details on tab named "**Detailed Results**"

Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

Figure B-11. “Startup” page of the CSR Tool.

The stream type is selected as “Sand Bed” because the D_{50} for this stream is 0.5 mm which is within the range given in Table B-2 for the sand-bed transport equation “Brownlie (1981).” This range is also provided in the selection guidance window as shown in Figure B-12. The selection for each field will display for reference below the “Select” buttons.



#1 Start New Project
Select the stream t
Select the preferre
Select if you have a
Select the preferre
Push Button named

#2 Hydrology
If a flow record ne
Push Button named
If you already have
Consolidate the FD

#3 Grain Size Distribution
If stream is **Sand** b
If stream is **Gravel**
Push Button named
If **Parker(1990)** is u

#4 Supply Reach
Enter channel/floo
Push Button named

#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "**Run CSR Tool**"

#6 Results
Review the Stable Channel Design solutions on tab named "**Results**"
Review each Slope/Width combination details on tab named "**Detailed Results**"

****Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool***

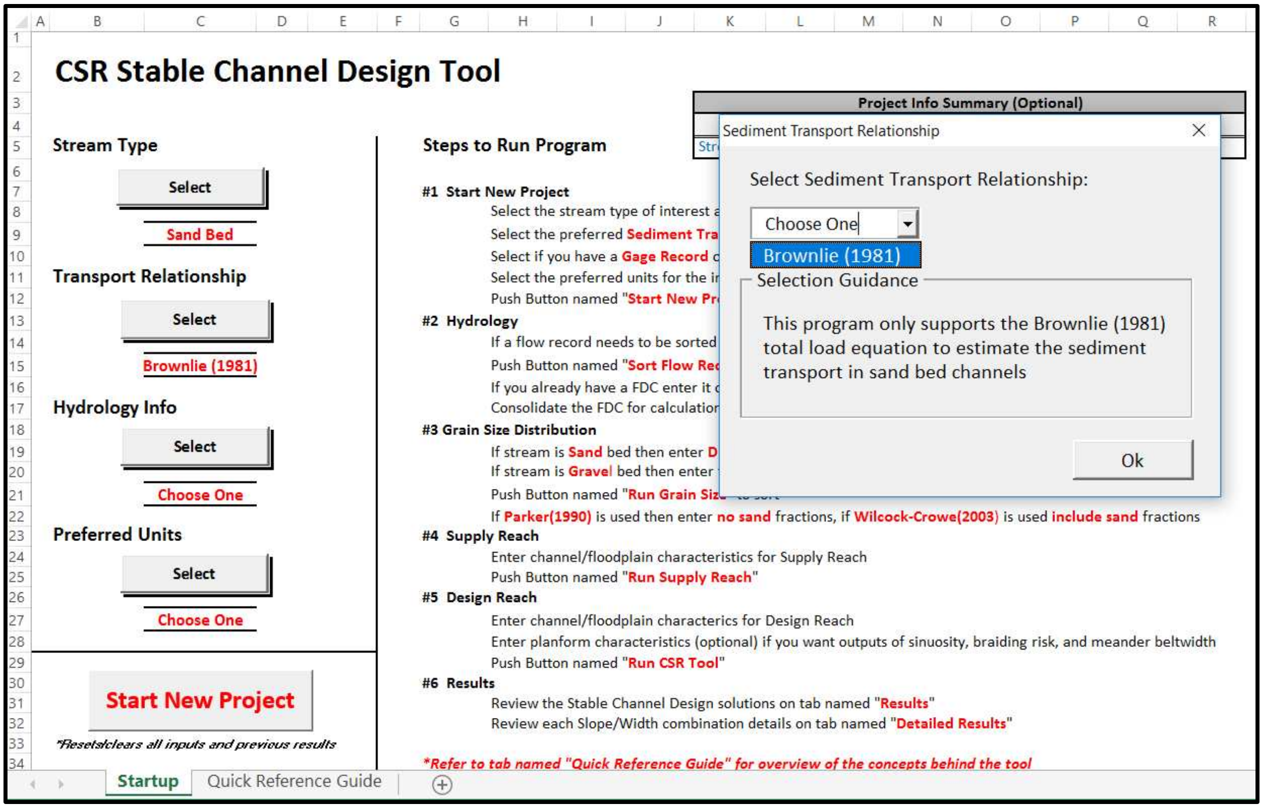
Select the Design Stream Type:

Sand is defined as having a particle diameter of (0.0625mm - 2mm). Sand bed calculations will use the Brownlie (1981) sediment transport equation that was developed using a D50 particle size range of (0.088mm - 2.8mm). Note: Values outside of this range can produce unstable/erroneous solutions

Gravel is defined as having a particle diameter of (2mm - 64mm) and Cobble as (64mm - 256mm). Gravel/Cobble bed calculations will either use the Parker (1990) equation which was developed using grain size data ranging (2mm - 200mm), or the Wilcock-Crowe (2003) equation that used sand sizes of (0.5mm - 2mm) and gravel sizes of (2mm - 64mm). Note: Values outside of this range can produce unstable/erroneous solutions

Figure B-12. Selecting "Stream Type" on "Startup" tab.

The selection of a sand-bed stream type will automatically choose the "Brownlie (1981)" equation for the transport relationship since this is the only sand-bed transport equation available for the CSR Tool. The user can also select the equation manually as shown in Figure B-13.



CSR Stable Channel Design Tool

Stream Type
Sand Bed

Transport Relationship
Brownlie (1981)

Hydrology Info
Choose One

Preferred Units
Choose One

*Resets/clears all inputs and previous results

Project Info Summary (Optional)

Str

Steps to Run Program

#1 Start New Project
Select the stream type of interest a
Select the preferred **Sediment Tra**
Select if you have a **Gage Record** c
Select the preferred units for the ir
Push Button named "**Start New Pr**

#2 Hydrology
If a flow record needs to be sorted
Push Button named "**Sort Flow Rec**
If you already have a FDC enter it c
Consolidate the FDC for calculatior

#3 Grain Size Distribution
If stream is **Sand** bed then enter **D**
If stream is **Gravel** bed then enter
Push Button named "**Run Grain Siz**
If **Parker(1990)** is used then enter **no sand** fractions, if **Wilcock-Crowe(2003)** is used **include sand** fractions

#4 Supply Reach
Enter channel/floodplain characteristics for Supply Reach
Push Button named "**Run Supply Reach**"

#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "**Run CSR Tool**"

#6 Results
Review the Stable Channel Design solutions on tab named "**Results**"
Review each Slope/Width combination details on tab named "**Detailed Results**"

Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

Sediment Transport Relationship

Select Sediment Transport Relationship:

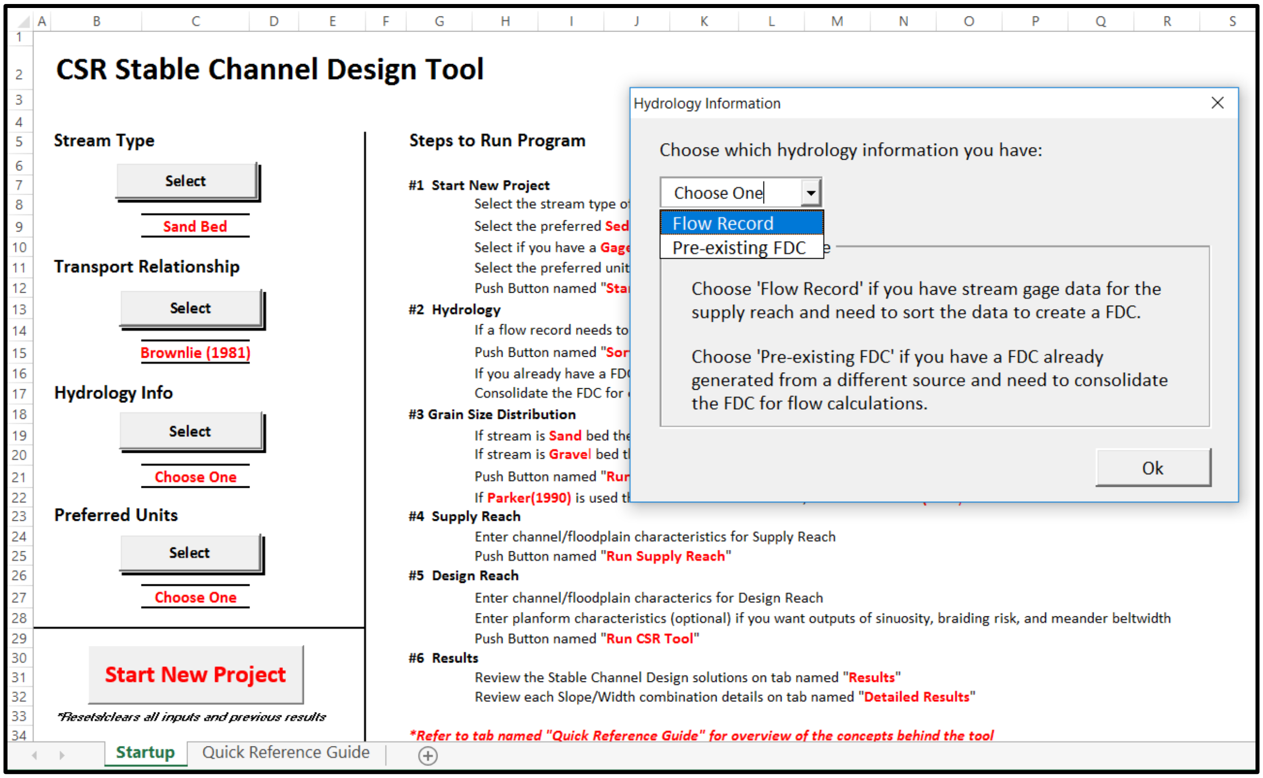
Choose One
Brownlie (1981)

Selection Guidance

This program only supports the Brownlie (1981) total load equation to estimate the sediment transport in sand bed channels

Figure B-13. Selecting "Transport Relationship" on "Startup" tab.

This example reach has USGS gage data of significant length (26 yrs) available to represent the hydrology of the channel for calculations, so the "Flow Record" option was selected for "Hydrology Info" (Figure B-14).



CSR Stable Channel Design Tool

Stream Type

Sand Bed

Transport Relationship

Brownlie (1981)

Hydrology Info

Choose One

Preferred Units

Choose One

*Resets/clears all inputs and previous results

Steps to Run Program

#1 Start New Project
Select the stream type o
Select the preferred Sed
Select if you have a Gag
Select the preferred unit
Push Button named "Sta

#2 Hydrology
If a flow record needs to
Push Button named "Sor
If you already have a FD
Consolidate the FDC for

#3 Grain Size Distribution
If stream is Sand bed the
If stream is Gravel bed t
Push Button named "Ru
If Parker(1990) is used t

#4 Supply Reach
Enter channel/floodplain characteristics for Supply Reach
Push Button named "Run Supply Reach"

#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "Run CSR Tool"

#6 Results
Review the Stable Channel Design solutions on tab named "Results"
Review each Slope/Width combination details on tab named "Detailed Results"

*Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

Hydrology Information

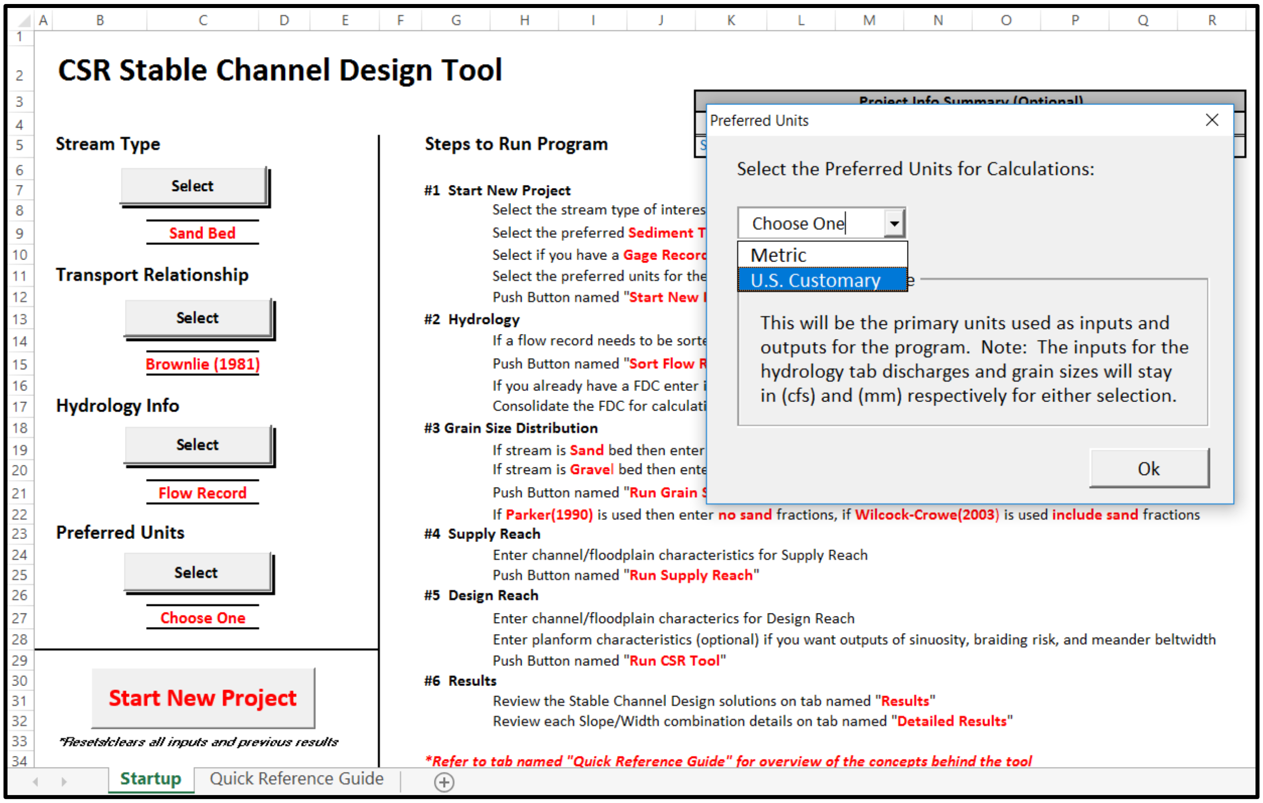
Choose which hydrology information you have:

Choose 'Flow Record' if you have stream gage data for the supply reach and need to sort the data to create a FDC.

Choose 'Pre-existing FDC' if you have a FDC already generated from a different source and need to consolidate the FDC for flow calculations.

Figure B-14. Selecting "Hydrology Info" on "Startup" tab.

Lastly, the preferred units are selected as "U.S. Customary" for this example. This selection will update and format the tabs to accept inputs and produce outputs in this unit of choice (Figure B-15).



CSR Stable Channel Design Tool

Stream Type

Sand Bed

Transport Relationship

Brownlie (1981)

Hydrology Info

Flow Record

Preferred Units

Choose One

*Resets/clears all inputs and previous results

Steps to Run Program

#1 Start New Project
Select the stream type of interes
Select the preferred **Sediment T**
Select if you have a **Gage Recor**
Select the preferred units for the
Push Button named "**Start New**

#2 Hydrology
If a flow record needs to be sorte
Push Button named "**Sort Flow R**
If you already have a FDC enter i
Consolidate the FDC for calculati

#3 Grain Size Distribution
If stream is **Sand** bed then enter
If stream is **Gravel** bed then ente
Push Button named "**Run Grain S**
If **Parker(1990)** is used then enter **no sand** fractions, if **Wilcock-Crowe(2003)** is used **include sand** fractions

#4 Supply Reach
Enter channel/floodplain characteristics for Supply Reach
Push Button named "**Run Supply Reach**"

#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "**Run CSR Tool**"

#6 Results
Review the Stable Channel Design solutions on tab named "**Results**"
Review each Slope/Width combination details on tab named "**Detailed Results**"

Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

Project Info Summary (Optional)

Preferred Units

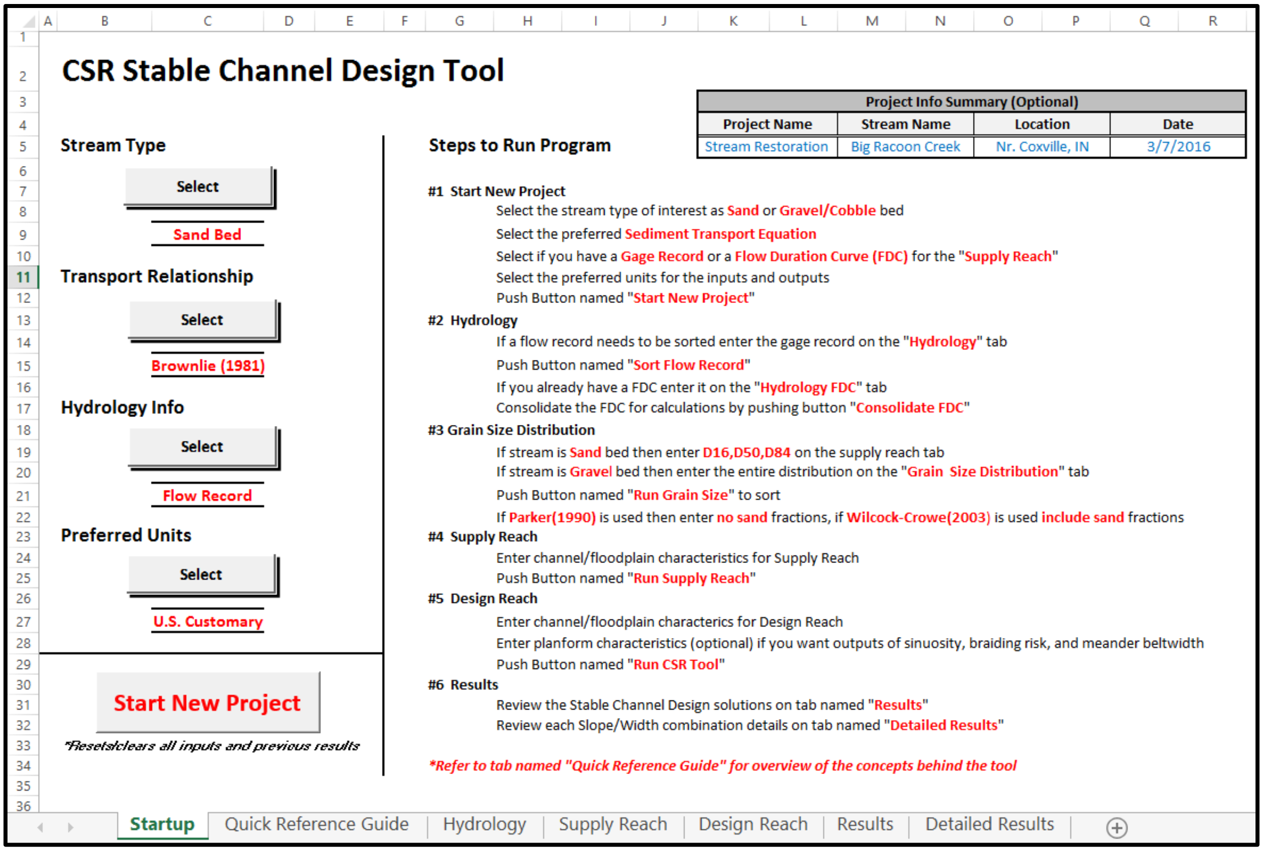
Select the Preferred Units for Calculations:

Choose One
Metric
U.S. Customary

This will be the primary units used as inputs and outputs for the program. Note: The inputs for the hydrology tab discharges and grain sizes will stay in (cfs) and (mm) respectively for either selection.

Figure B-15. Selecting "Preferred Units" on "Startup" tab.

After the preceding four selections are made and the "Start New Project" button is pressed, the next required tabs necessary to run the program are displayed in the workbook as shown on the bottom of Figure B-16.



Project Info Summary (Optional)			
Project Name	Stream Name	Location	Date
Stream Restoration	Big Racoon Creek	Nr. Coxville, IN	3/7/2016

Steps to Run Program

#1 Start New Project
Select the stream type of interest as Sand or Gravel/Cobble bed
Select the preferred Sediment Transport Equation
Select if you have a Gage Record or a Flow Duration Curve (FDC) for the "Supply Reach"
Select the preferred units for the inputs and outputs
Push Button named "Start New Project"

#2 Hydrology
If a flow record needs to be sorted enter the gage record on the "Hydrology" tab
Push Button named "Sort Flow Record"
If you already have a FDC enter it on the "Hydrology FDC" tab
Consolidate the FDC for calculations by pushing button "Consolidate FDC"

#3 Grain Size Distribution
If stream is Sand bed then enter D16,D50,D84 on the supply reach tab
If stream is Gravel bed then enter the entire distribution on the "Grain Size Distribution" tab
Push Button named "Run Grain Size" to sort
If Parker(1990) is used then enter no sand fractions, if Wilcock-Crowe(2003) is used include sand fractions

#4 Supply Reach
Enter channel/floodplain characteristics for Supply Reach
Push Button named "Run Supply Reach"

#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "Run CSR Tool"

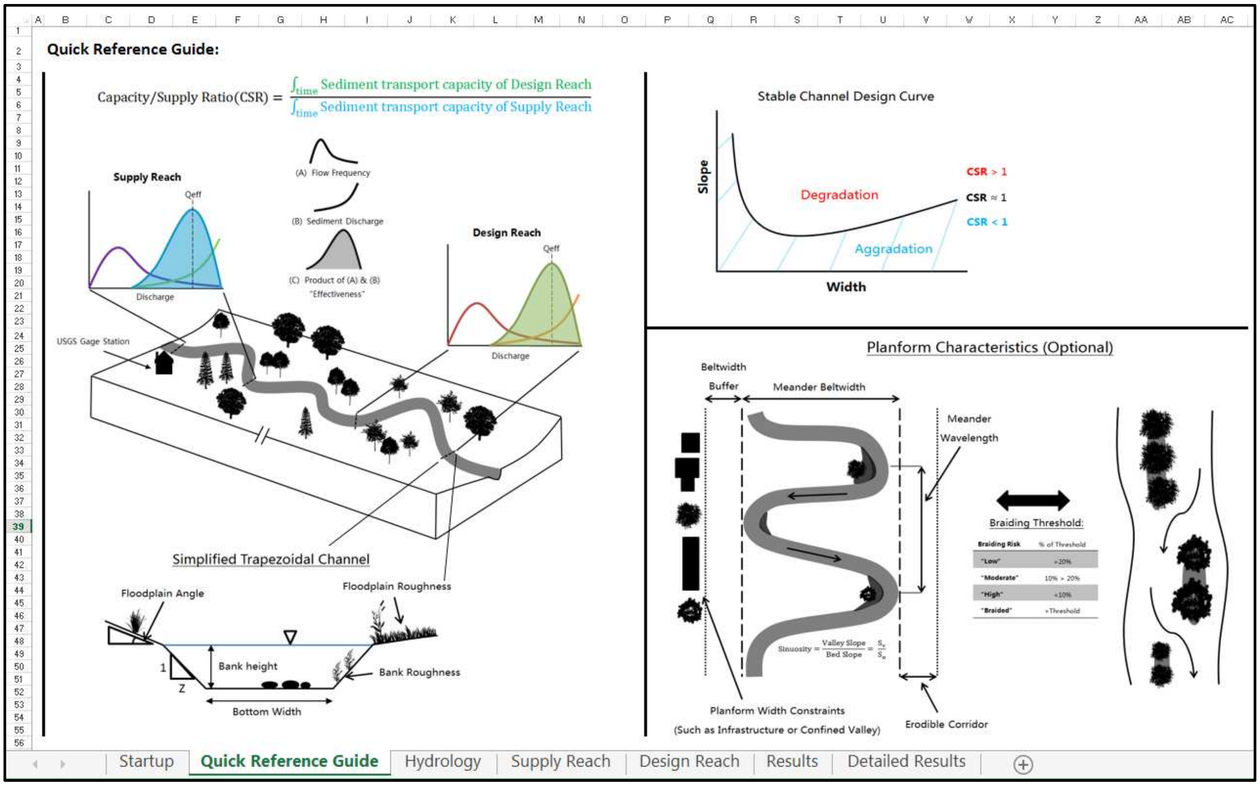
#6 Results
Review the Stable Channel Design solutions on tab named "Results"
Review each Slope/Width combination details on tab named "Detailed Results"

**Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool*

Figure B-16. "Startup" tab with "Start New Project" defined.

B.2.1.2 Quick Reference Guide tab

The "Quick Reference Guide" tab can be viewed at any time to obtain a visual representation of the underlying concepts behind the tool (Figure B-17).



$$\text{Capacity/Supply Ratio(CSR)} = \frac{\int_{\text{time}} \text{Sediment transport capacity of Design Reach}}{\int_{\text{time}} \text{Sediment transport capacity of Supply Reach}}$$

Braiding Risk	% of Threshold
"Low"	>20%
"Moderate"	10% > 20%
"High"	<10%
"Braided"	>Threshold

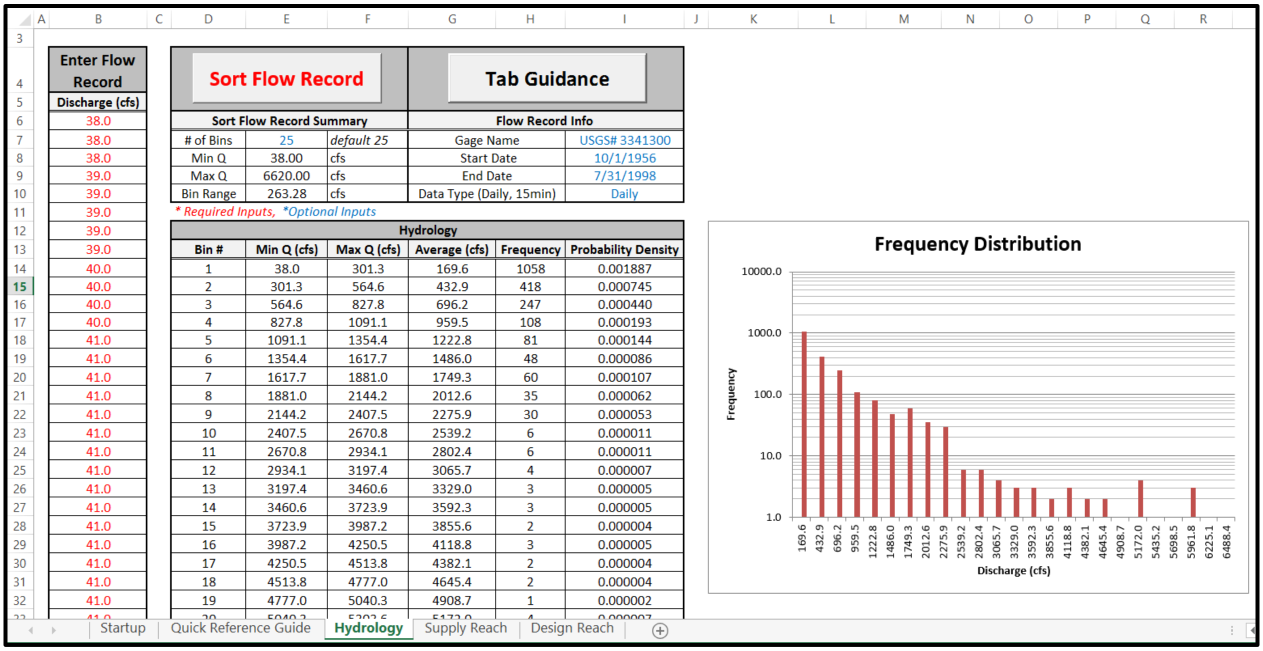
Figure B-17. "Quick Reference Guide" tab of CSR Tool.

B.2.1.3 Hydrology tab

Following the steps provided in the *Tab-by-tab Guidance* section of this report, the flow record information is first entered if desired, then just the discharges of the flow record are entered in cubic feet per second. Subsequently, the "Sort Flow Record" button is pressed to produce results.

Hydrology Results

This example uses the default 25 bins to sort the data which is displayed in Column D under "Bin #" (Figure B-18). An arithmetic binning process is used in the program to produce equal intervals of discharges represented in each bin. The range for each bin and the associated average discharge is displayed in Columns E–G. Column H shows the frequency or total number of flows from the record that fall into the range for the associated bin. Column I displays the probability density for the flows in each bin. The frequency versus each discharge bin is graphed on the right-side of the tab.



Enter Flow Record Discharge (cfs)
38.0
38.0
38.0
39.0
39.0
39.0
39.0
39.0
40.0
40.0
40.0
40.0
41.0
41.0
41.0
41.0
41.0
41.0
41.0
41.0
41.0
41.0
41.0
41.0
41.0
41.0
41.0

Sort Flow Record Summary		
# of Bins	25	*default 25*
Min Q	38.00	cfs
Max Q	6620.00	cfs
Bin Range	263.28	cfs

Flow Record Info	
Gage Name	USGS# 3341300
Start Date	10/1/1956
End Date	7/31/1998
Data Type (Daily, 15min)	Daily

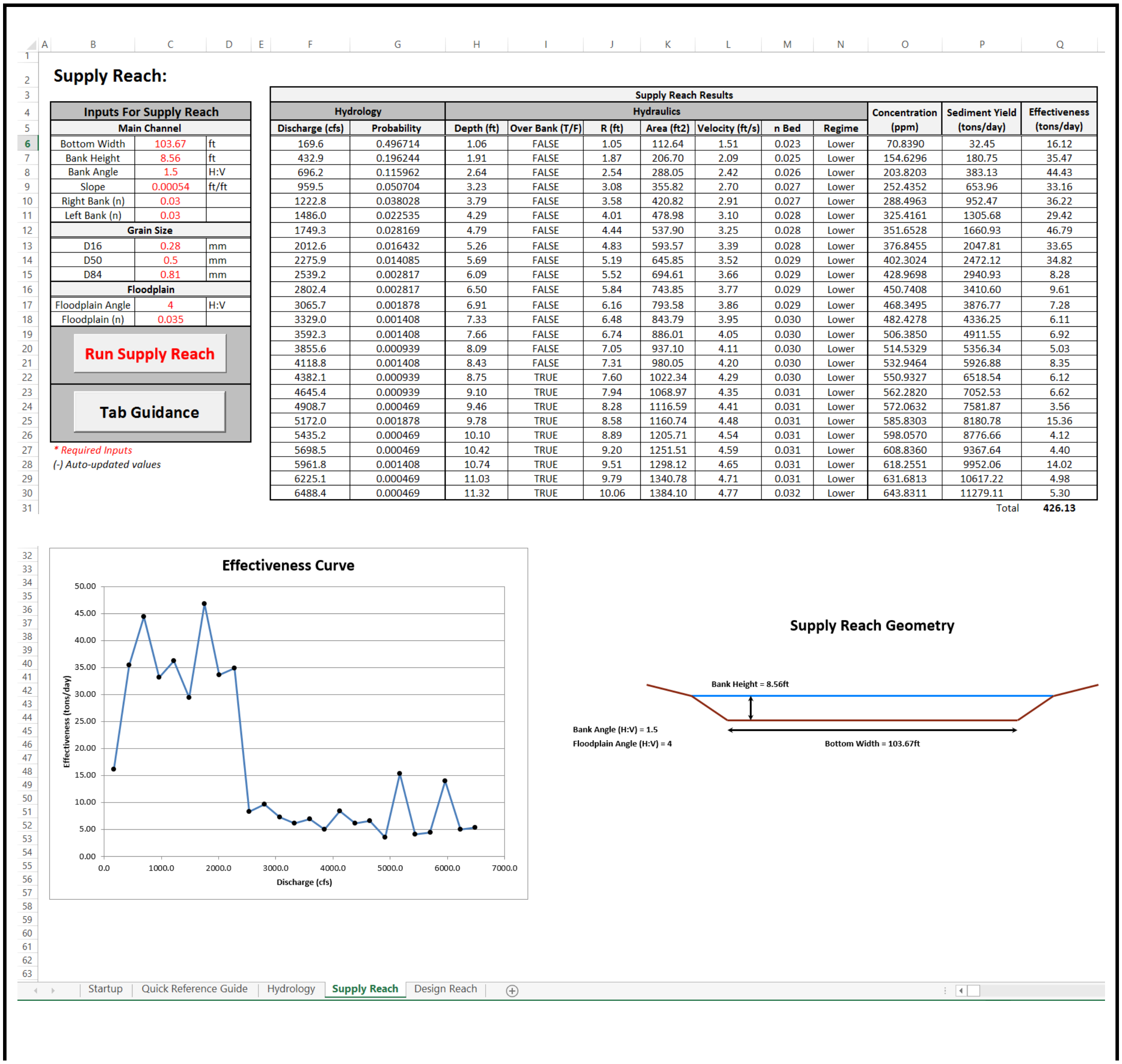
** Required Inputs, *Optional Inputs*

Hydrology					
Bin #	**Min Q (cfs)**	**Max Q (cfs)**	**Average (cfs)**	**Frequency**	**Probability Density**
1	38.0	301.3	169.6	1058	0.001887
2	301.3	564.6	432.9	418	0.000745
3	564.6	827.8	696.2	247	0.000440
4	827.8	1091.1	959.5	108	0.000193
5	1091.1	1354.4	1222.8	81	0.000144
6	1354.4	1617.7	1486.0	48	0.000086
7	1617.7	1881.0	1749.3	60	0.000107
8	1881.0	2144.2	2012.6	35	0.000062
9	2144.2	2407.5	2275.9	30	0.000053
10	2407.5	2670.8	2539.2	6	0.000011
11	2670.8	2934.1	2802.4	6	0.000011
12	2934.1	3197.4	3065.7	4	0.000007
13	3197.4	3460.6	3329.0	3	0.000005
14	3460.6	3723.9	3592.3	3	0.000005
15	3723.9	3987.2	3855.6	2	0.000004
16	3987.2	4250.5	4118.8	3	0.000005
17	4250.5	4513.8	4382.1	2	0.000004
18	4513.8	4777.0	4645.4	2	0.000004
19	4777.0	5040.3	4908.7	1	0.000002

Figure B-18. "Hydrology" tab, Big Raccoon Creek example results.

B.2.1.4 <u>Supply Reach tab</u>

The inputs required for the supply reach are entered in the cells that are highlighted with red-font asterisks (Figure B-19). The channel dimensions including the bottom width, bank height, bank angle, and floodplain angle are used to create a simplified trapezoidal channel that represents the actual cross section of the channel (see "Quick Reference Guide" tab). The roughness inputs are Manning's *n* values. Only the bank roughness is required for the channel because the roughness of the bed is calculated within the sediment transport calculations. When the inputs have been entered and the "Run Supply Reach" button pressed, the results for the supply reach will be displayed to the right.



Supply Reach:

Inputs For Supply Reach		
Main Channel		
Bottom Width	103.67	ft
Bank Height	8.56	ft
Bank Angle	1.5	H:V
Slope	0.00054	ft/ft
Right Bank (n)	0.03	
Left Bank (n)	0.03	
Grain Size		
D16	0.28	mm
D50	0.5	mm
D84	0.81	mm
Floodplain		
Floodplain Angle	4	H:V
Floodplain (n)	0.035	

** Required Inputs*

(-) Auto-updated values

Supply Reach Results											
Hydrology		Hydraulics							Concentration (ppm)	Sediment Yield (tons/day)	Effectiveness (tons/day)
Discharge (cfs)	Probability	Depth (ft)	Over Bank (T/F)	R (ft)	Area (ft2)	Velocity (ft/s)	n Bed	Regime			
169.6	0.496714	1.06	FALSE	1.05	112.64	1.51	0.023	Lower	70.8390	32.45	16.12
432.9	0.196244	1.91	FALSE	1.87	206.70	2.09	0.025	Lower	154.6296	180.75	35.47
696.2	0.115962	2.64	FALSE	2.54	288.05	2.42	0.026	Lower	203.8203	383.13	44.43
959.5	0.050704	3.23	FALSE	3.08	355.82	2.70	0.027	Lower	252.4352	653.96	33.16
1222.8	0.038028	3.79	FALSE	3.58	420.82	2.91	0.027	Lower	288.4963	952.47	36.22
1486.0	0.022535	4.29	FALSE	4.01	478.98	3.10	0.028	Lower	325.4161	1305.68	29.42
1749.3	0.028169	4.79	FALSE	4.44	537.90	3.25	0.028	Lower	351.6528	1660.93	46.79
2012.6	0.016432	5.26	FALSE	4.83	593.57	3.39	0.028	Lower	376.8455	2047.81	33.65
2275.9	0.014085	5.69	FALSE	5.19	645.85	3.52	0.029	Lower	402.3024	2472.12	34.82
2539.2	0.002817	6.09	FALSE	5.52	694.61	3.66	0.029	Lower	428.9698	2940.93	8.28
2802.4	0.002817	6.50	FALSE	5.84	743.85	3.77	0.029	Lower	450.7408	3410.60	9.61
3065.7	0.001878	6.91	FALSE	6.16	793.58	3.86	0.029	Lower	468.3495	3876.77	7.28
3329.0	0.001408	7.33	FALSE	6.48	843.79	3.95	0.030	Lower	482.4278	4336.25	6.11
3592.3	0.001408	7.66	FALSE	6.74	886.01	4.05	0.030	Lower	506.3850	4911.55	6.92
3855.6	0.000939	8.09	FALSE	7.05	937.10	4.11	0.030	Lower	514.5329	5356.34	5.03
4118.8	0.001408	8.43	FALSE	7.31	980.05	4.20	0.030	Lower	532.9464	5926.88	8.35
4382.1	0.000939	8.75	TRUE	7.60	1022.34	4.29	0.030	Lower	550.9327	6518.54	6.12
4645.4	0.000939	9.10	TRUE	7.94	1068.97	4.35	0.031	Lower	562.2820	7052.53	6.62
4908.7	0.000469	9.46	TRUE	8.28	1116.59	4.41	0.031	Lower	572.0632	7581.87	3.56
5172.0	0.001878	9.78	TRUE	8.58	1160.74	4.48	0.031	Lower	585.8303	8180.78	15.36
5435.2	0.000469	10.10	TRUE	8.89	1205.71	4.54	0.031	Lower	598.0570	8776.66	4.12
5698.5	0.000469	10.42	TRUE	9.20	1251.51	4.59	0.031	Lower	608.8360	9367.64	4.40
5961.8	0.001408	10.74	TRUE	9.51	1298.12	4.65	0.031	Lower	618.2551	9952.06	14.02
6225.1	0.000469	11.03	TRUE	9.79	1340.78	4.71	0.031	Lower	631.6813	10617.22	4.98
6488.4	0.000469	11.32	TRUE	10.06	1384.10	4.77	0.032	Lower	643.8311	11279.11	5.30
										Total	**426.13**

Figure B-19. "Supply Reach" tab, Big Raccoon Creek example results.

Hydrology

Columns F–G show a summary of the hydrology results transferred from the "Hydrology" tab. The discharge is the average for the associated bin range along with the probability of those flows occurring.

Hydraulics

Columns H–N display the hydraulic characteristics calculated by the program for the associated bin discharge flowing through the simplified trapezoidal channel defined by the inputs. If the depth shown in Column H is less than the bank height specified in the inputs, then Column I will display a “False” and if it is over then “True” will be displayed showing the program modeled those flows as overbank. Column J is the channel hydraulic radius, Column K is the cross-sectional flow area, and Column L is the associated cross-section averaged flow velocity. Column M is the calculated Manning’s *n* for the bed of the channel. The Brownlie (1983) roughness equations estimate the roughness by taking into account the form roughness produced by sand-bed forms in the channel associated with the regimes (Upper or Lower) that are displayed in Column N.

Sediment Transport

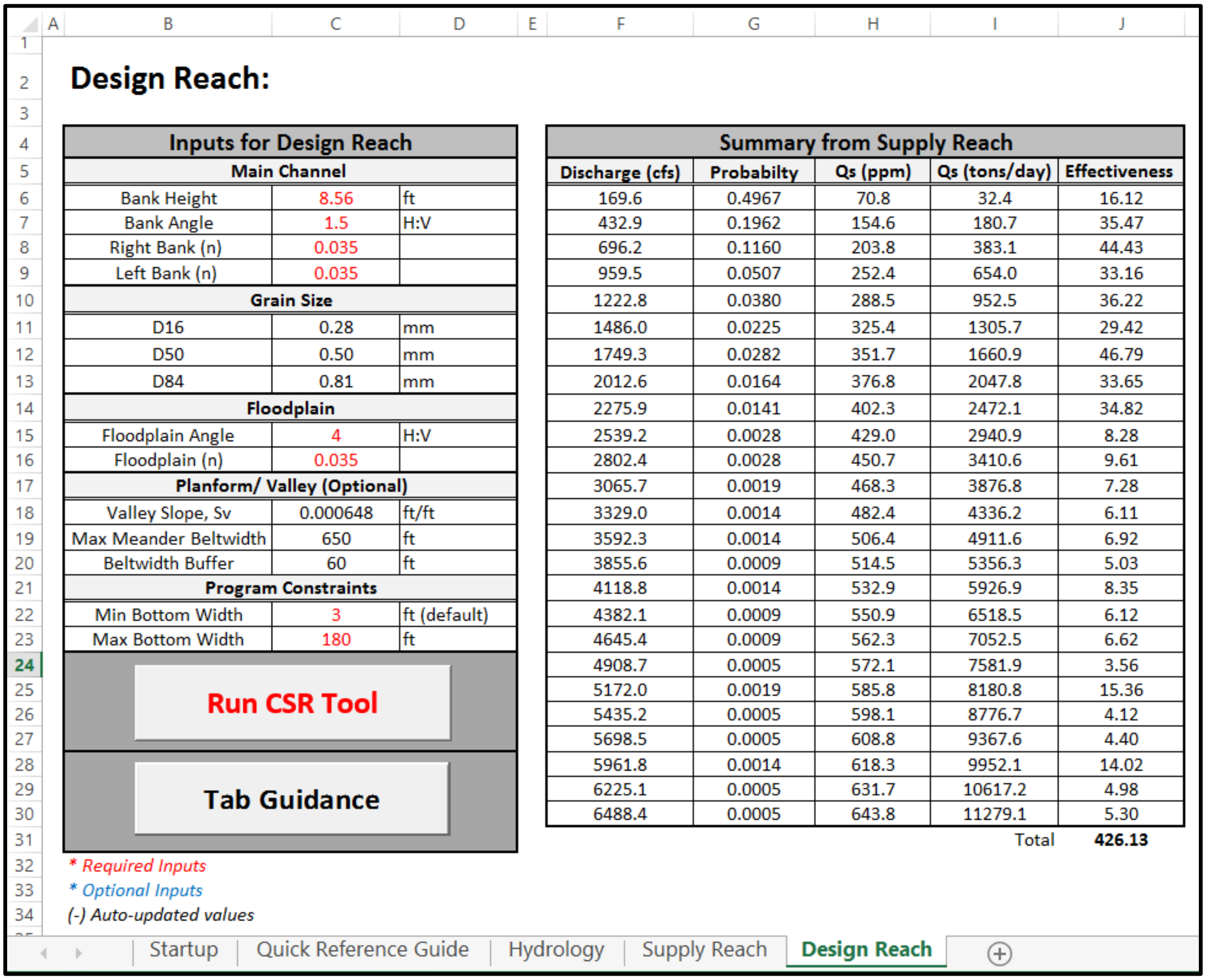
Columns O–Q display the sediment transport results for each bin. Column O shows the concentration or estimated sediment yield in parts per million (ppm) which is the direct output from the Brownlie (1981) equation. Column P converts the sediment yield to tons/day. Columns O–P represent the potential sediment yield by the average flow of the associated bin in Column F. Column Q multiplies Column P by Column G, the probability of flows. The result is the “effectiveness” or total sediment transported on average in a given day based on the probability of daily flows in the flow record. The total effectiveness or total sediment transported on average in a given day is the sum of the individual effectiveness for each bin which is displayed at the bottom of Column Q. Underneath these results, the effectiveness is graphed in the bottom left of the tab for each discharge.

Supply Reach Geometry

In the bottom right, a visual representation of the simplified trapezoidal channel defined by the input dimensions is shown and labeled. The supply reach geometry is on an arbitrary scale, but all dimensions are proportional to each other. This feature is for the user's reference to get a visual of the geometry used in the calculations.

B.2.1.5 Design Reach tab

The required inputs denoted by red-font asterisks, are entered for the design reach (Figure B-20). For this example, the channel dimensions and grain size are assumed to be the same as the supply reach. The planform characteristics are optional, but are included in this example to show the functionality of this option. The valley slope is required to perform the planform calculations. The maximum meander belt width is an optional input that represents the maximum width the valley has to support the channel design laterally. This value should take into account lateral constraints such as a confined valley or infrastructure, etc. If the estimated belt width exceeds this amount, then it will be highlighted in red on the "Results" tab. Another optional input is the belt width buffer. This is the total extra room on both sides of the river that can be used as a safety factor of the estimated belt width and/or room for the river to move (see "Quick Reference Guide" tab for a visual). This amount is added to the calculated belt width. Lastly, the program constraints are defined. This will be the range of widths the program will loop through to attempt to find associated slopes that will produce a CSR = 1. The default minimum of 3 ft is used to produce a full family of solutions. The maximum width is set over the supply reach bottom width usually (1.5 to 2 times) to produce results with widths greater than the supply reach. Pressing the "Run CSR Tool" button will run the program to find slope/width combinations that balance the sediment capacity of the supply and design reach and produce a CSR = 1. This will create a “Results” tab and a “Detailed Results” tab.



Design Reach:

Inputs for Design Reach		
Main Channel		
Bank Height	8.56	ft
Bank Angle	1.5	H:V
Right Bank (n)	0.035	
Left Bank (n)	0.035	
Grain Size		
D16	0.28	mm
D50	0.50	mm
D84	0.81	mm
Floodplain		
Floodplain Angle	4	H:V
Floodplain (n)	0.035	
Planform/ Valley (Optional)		
Valley Slope, Sv	0.000648	ft/ft
Max Meander Beltwidth	650	ft
Beltwidth Buffer	60	ft
Program Constraints		
Min Bottom Width	3	ft (default)
Max Bottom Width	180	ft

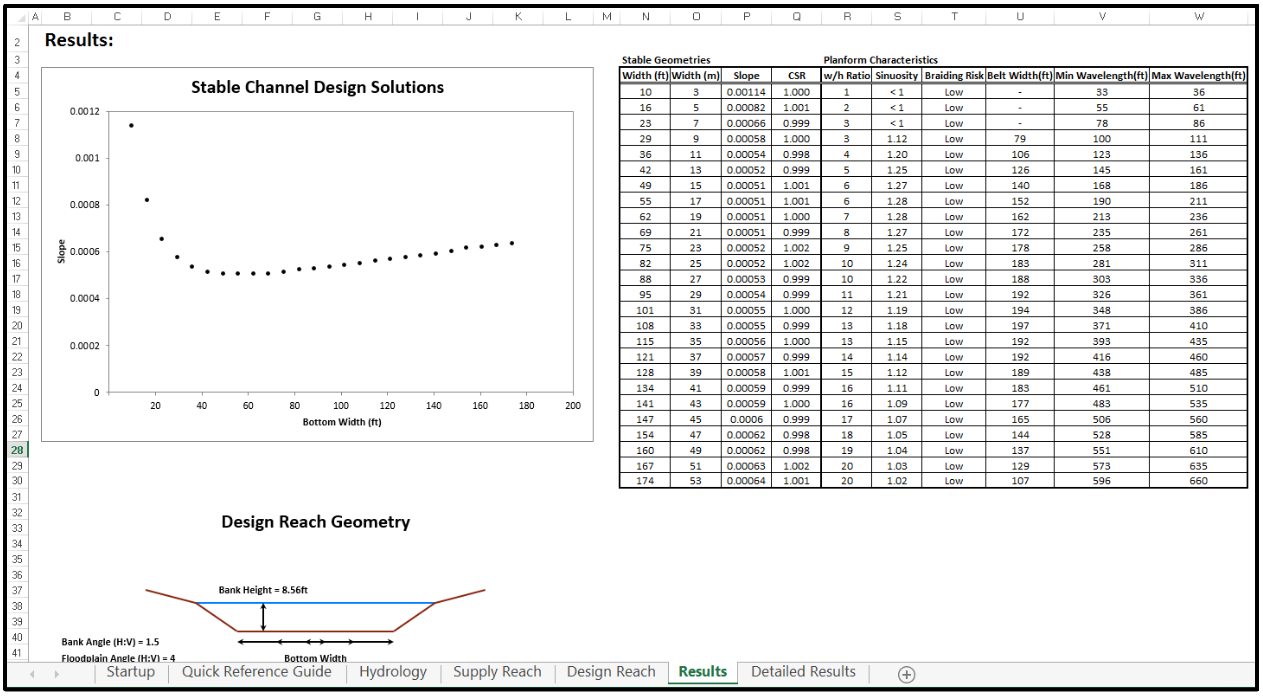
Summary from Supply Reach				
Discharge (cfs)	**Probabilty**	**Qs (ppm)**	**Qs (tons/day)**	**Effectiveness**
169.6	0.4967	70.8	32.4	16.12
432.9	0.1962	154.6	180.7	35.47
696.2	0.1160	203.8	383.1	44.43
959.5	0.0507	252.4	654.0	33.16
1222.8	0.0380	288.5	952.5	36.22
1486.0	0.0225	325.4	1305.7	29.42
1749.3	0.0282	351.7	1660.9	46.79
2012.6	0.0164	376.8	2047.8	33.65
2275.9	0.0141	402.3	2472.1	34.82
2539.2	0.0028	429.0	2940.9	8.28
2802.4	0.0028	450.7	3410.6	9.61
3065.7	0.0019	468.3	3876.8	7.28
3329.0	0.0014	482.4	4336.2	6.11
3592.3	0.0014	506.4	4911.6	6.92
3855.6	0.0009	514.5	5356.3	5.03
4118.8	0.0014	532.9	5926.9	8.35
4382.1	0.0009	550.9	6518.5	6.12
4645.4	0.0009	562.3	7052.5	6.62
4908.7	0.0005	572.1	7581.9	3.56
5172.0	0.0019	585.8	8180.8	15.36
5435.2	0.0005	598.1	8776.7	4.12
5698.5	0.0005	608.8	9367.6	4.40
5961.8	0.0014	618.3	9952.1	14.02
6225.1	0.0005	631.7	10617.2	4.98
6488.4	0.0005	643.8	11279.1	5.30
			Total	**426.13**

** Required Inputs*
** Optional Inputs*
(-) Auto-updated values

Figure B-20. “Design Reach” tab, Big Raccoon Creek example inputs.

B.2.1.6 Results tab

The “Results” tab will automatically be selected after the tool is run. This tab will have a summary of the major results for the analysis. The family of stable channel designs solutions found by the program with CSRs = 1 is graphed at the top left of the tab (Figure B-21). This is analogous to the output of Copeland’s stable channel design tool in HEC-RAS.



Results:

Stable Geometries				Planform Characteristics					
Width (ft)	**Width (m)**	**Slope**	**CSR**	**w/h Ratio**	**Sinuosity**	**Braiding Risk**	**Belt Width(ft)**	**Min Wavelength(ft)**	**Max Wavelength(ft)**
10	3	0.00114	1.000	1	< 1	Low	-	33	36
16	5	0.00082	1.001	2	< 1	Low	-	55	61
23	7	0.00066	0.999	3	< 1	Low	-	78	86
29	9	0.00058	1.000	3	1.12	Low	79	100	111
36	11	0.00054	0.998	4	1.20	Low	106	123	136
42	13	0.00052	0.999	5	1.25	Low	126	145	161
49	15	0.00051	1.001	6	1.27	Low	140	168	186
55	17	0.00051	1.001	6	1.28	Low	152	190	211
62	19	0.00051	1.000	7	1.28	Low	162	213	236
69	21	0.00051	0.999	8	1.27	Low	172	235	261
75	23	0.00052	1.002	9	1.25	Low	178	258	286
82	25	0.00052	1.002	10	1.24	Low	183	281	311
88	27	0.00053	0.999	10	1.22	Low	188	303	336
95	29	0.00054	0.999	11	1.21	Low	192	326	361
101	31	0.00055	1.000	12	1.19	Low	194	348	386
108	33	0.00055	0.999	13	1.18	Low	197	371	410
115	35	0.00056	1.000	13	1.15	Low	192	393	435
121	37	0.00057	0.999	14	1.14	Low	192	416	460
128	39	0.00058	1.001	15	1.12	Low	189	438	485
134	41	0.00059	0.999	16	1.11	Low	183	461	510
141	43	0.00059	1.000	16	1.09	Low	177	483	535
147	45	0.0006	0.999	17	1.07	Low	165	506	560
154	47	0.00062	0.998	18	1.05	Low	144	528	585
160	49	0.00062	0.998	19	1.04	Low	137	551	610
167	51	0.00063	1.002	20	1.03	Low	129	573	635
174	53	0.00064	1.001	20	1.02	Low	107	596	660

Figure B-21. “Results” tab, Big Raccoon Creek example.

Stable Geometries

To the right of the plot, the individual stable slope/width combinations are listed in Columns N–P. Column Q shows the associated CSR for each solution. The solutions are selected because they are within 0.025 of a CSR = 1 which will pass the incoming sediment load from the supply reach with minimal degradation or aggradation. In this example, the dimensions and channel characteristics were matched for the supply and design reach to verify the accuracy of the program output. If these characteristics are matched, then the bottom width and slope of the supply reach should be a solution in the family of stable channel design solutions since the same channel could pass the same sediment yield. This can be seen for this example in Figure B-21. The bottom width for the supply reach is 103.67 ft and the slope is 0.00054. This solution lies between Rows 19–20 for the solutions in Columns N–P.

Planform Characteristics

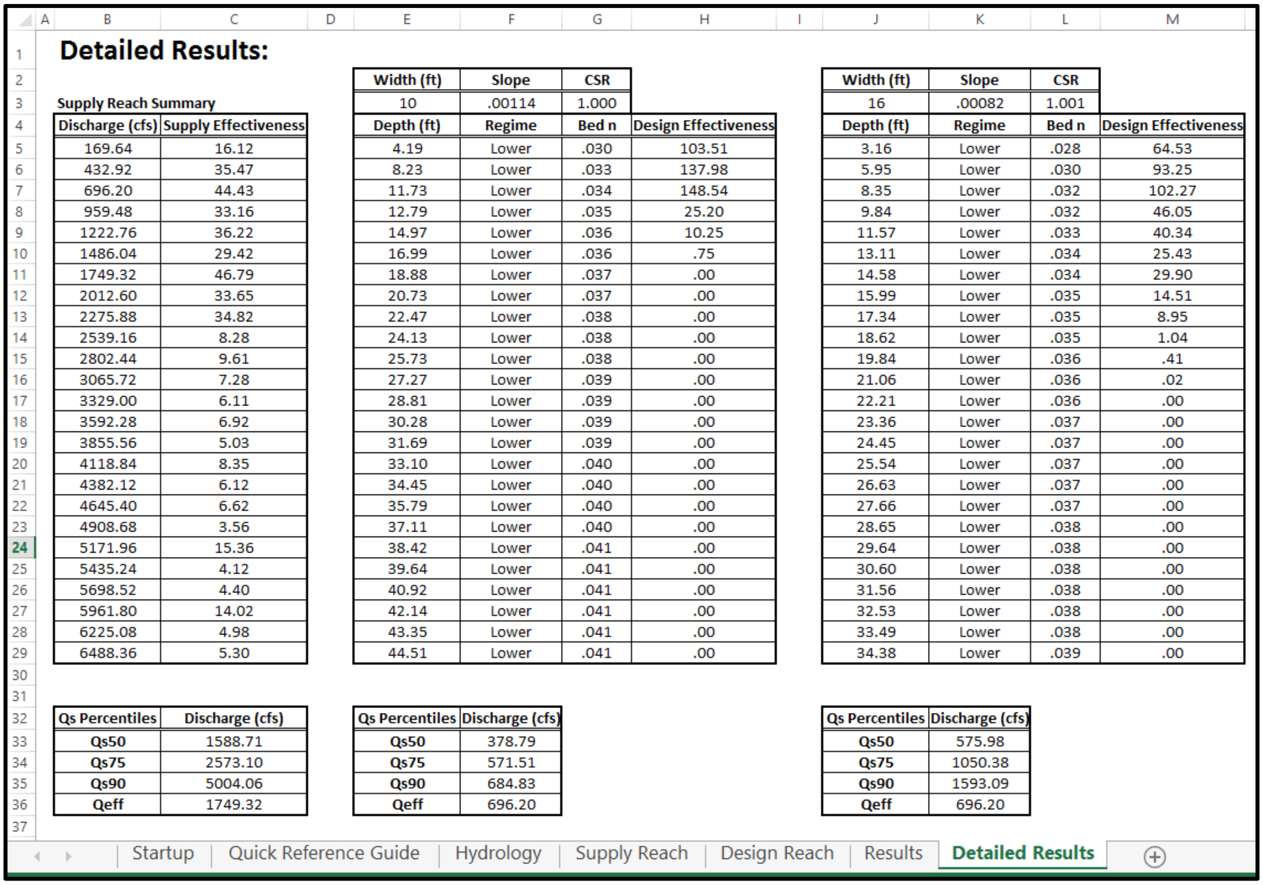
The outputs for planform calculations are displayed in Columns R–W. Column R is the width versus bankfull depth based on the bank height specified on the design reach tab. The input of the valley slope for the stream allows the program to calculate the sinuosity (Column S), the braiding risk (Column T), and the belt width (Column U) for each solution. Rows 18–23 in Column U is highlighted red because the estimated belt width + buffer is larger than the maximum meander belt width that was specified on the design reach inputs. The estimate for the wavelength based on the 95% confidence interval presented by Soar and Thorne (2001) is displayed in Columns V–W. See ‘Planform Characteristics’ in the CSR Tool Reference Manual (Appendix A) and the ”Quick Reference Guide” tab for more information on the planform concepts.

Design Reach Geometry

Similar to the supply reach, a visual of the simplified trapezoidal channel used in the calculations is displayed for the design reach. All dimensions are proportional and labeled except the bottom width. For the design reach, the bottom width varies for each stable solution, so the width is set at an arbitrary length.

B.2.1.7 Detailed Results tab

In addition to the “Results” tab, a “Detailed Results” tab is also created when the CSR analysis is run (Figure B-22). This tab exhibits more-detailed outputs of the analysis per discharge bin for each stable channel solution. Columns B–C of the tab give a summary of the average discharge of each bin used for the supply and design reach calculations and the supply reach effectiveness for each bin. To the right of this summary are the detailed results for each stable channel design solution. The slope/width and CSR is displayed at the top of each result box. The results report the depth, regime, Manning’s *n* of the channel bed, and the effectiveness calculated for each discharge bin. The lower width solutions are often implausible if the minimum width was chosen for the program constraints, but it allows the program to show the entire family of solutions. These results can show very unrealistic solutions for some bins. The Manning's *n* of the bed is labeled as ">0.1" if the roughness goes over this value in an unrealistic situation where the depth in very high for the smallest widths.



Detailed Results:

Supply Reach Summary

Discharge (cfs)	Supply Effectiveness
169.64	16.12
432.92	35.47
696.20	44.43
959.48	33.16
1222.76	36.22
1486.04	29.42
1749.32	46.79
2012.60	33.65
2275.88	34.82
2539.16	8.28
2802.44	9.61
3065.72	7.28
3329.00	6.11
3592.28	6.92
3855.56	5.03
4118.84	8.35
4382.12	6.12
4645.40	6.62
4908.68	3.56
5171.96	15.36
5435.24	4.12
5698.52	4.40
5961.80	14.02
6225.08	4.98
6488.36	5.30

Width (ft)	Slope	CSR	
10	.00114	1.000	
Depth (ft)	**Regime**	**Bed n**	**Design Effectiveness**
4.19	Lower	.030	103.51
8.23	Lower	.033	137.98
11.73	Lower	.034	148.54
12.79	Lower	.035	25.20
14.97	Lower	.036	10.25
16.99	Lower	.036	.75
18.88	Lower	.037	.00
20.73	Lower	.037	.00
22.47	Lower	.038	.00
24.13	Lower	.038	.00
25.73	Lower	.038	.00
27.27	Lower	.039	.00
28.81	Lower	.039	.00
30.28	Lower	.039	.00
31.69	Lower	.039	.00
33.10	Lower	.040	.00
34.45	Lower	.040	.00
35.79	Lower	.040	.00
37.11	Lower	.040	.00
38.42	Lower	.041	.00
39.64	Lower	.041	.00
40.92	Lower	.041	.00
42.14	Lower	.041	.00
43.35	Lower	.041	.00
44.51	Lower	.041	.00

Width (ft)	Slope	CSR	
16	.00082	1.001	
Depth (ft)	**Regime**	**Bed n**	**Design Effectiveness**
3.16	Lower	.028	64.53
5.95	Lower	.030	93.25
8.35	Lower	.032	102.27
9.84	Lower	.032	46.05
11.57	Lower	.033	40.34
13.11	Lower	.034	25.43
14.58	Lower	.034	29.90
15.99	Lower	.035	14.51
17.34	Lower	.035	8.95
18.62	Lower	.035	1.04
19.84	Lower	.036	.41
21.06	Lower	.036	.02
22.21	Lower	.036	.00
23.36	Lower	.037	.00
24.45	Lower	.037	.00
25.54	Lower	.037	.00
26.63	Lower	.037	.00
27.66	Lower	.037	.00
28.65	Lower	.038	.00
29.64	Lower	.038	.00
30.60	Lower	.038	.00
31.56	Lower	.038	.00
32.53	Lower	.038	.00
33.49	Lower	.038	.00
34.38	Lower	.039	.00

Qs Percentiles	Discharge (cfs)
Qs50	1588.71
Qs75	2573.10
Qs90	5004.06
Qeff	1749.32

Qs Percentiles	Discharge (cfs)
Qs50	378.79
Qs75	571.51
Qs90	684.83
Qeff	696.20

Qs Percentiles	Discharge (cfs)
Qs50	575.98
Qs75	1050.38
Qs90	1593.09
Qeff	696.20

Figure B-22. "Detailed Results" tab, Big Raccoon Creek example.

Below each solution, there are separate boxes that give a summary of the sediment transport percentiles for each solution (see Sediment Percentiles in the CSR Tool Reference Manual (Appendix A)). The effective discharge (Q_{eff}) or the discharge bin that moves the most sediment is presented. Also, the discharges corresponding to the percentiles Q_{s50}, Q_{s75}, and Q_{s90} are linearly interpolated from the effectiveness curve for each solution; these discharges represent the discharges that move 50%, 75%, and 90% of the total sediment yield, respectively.

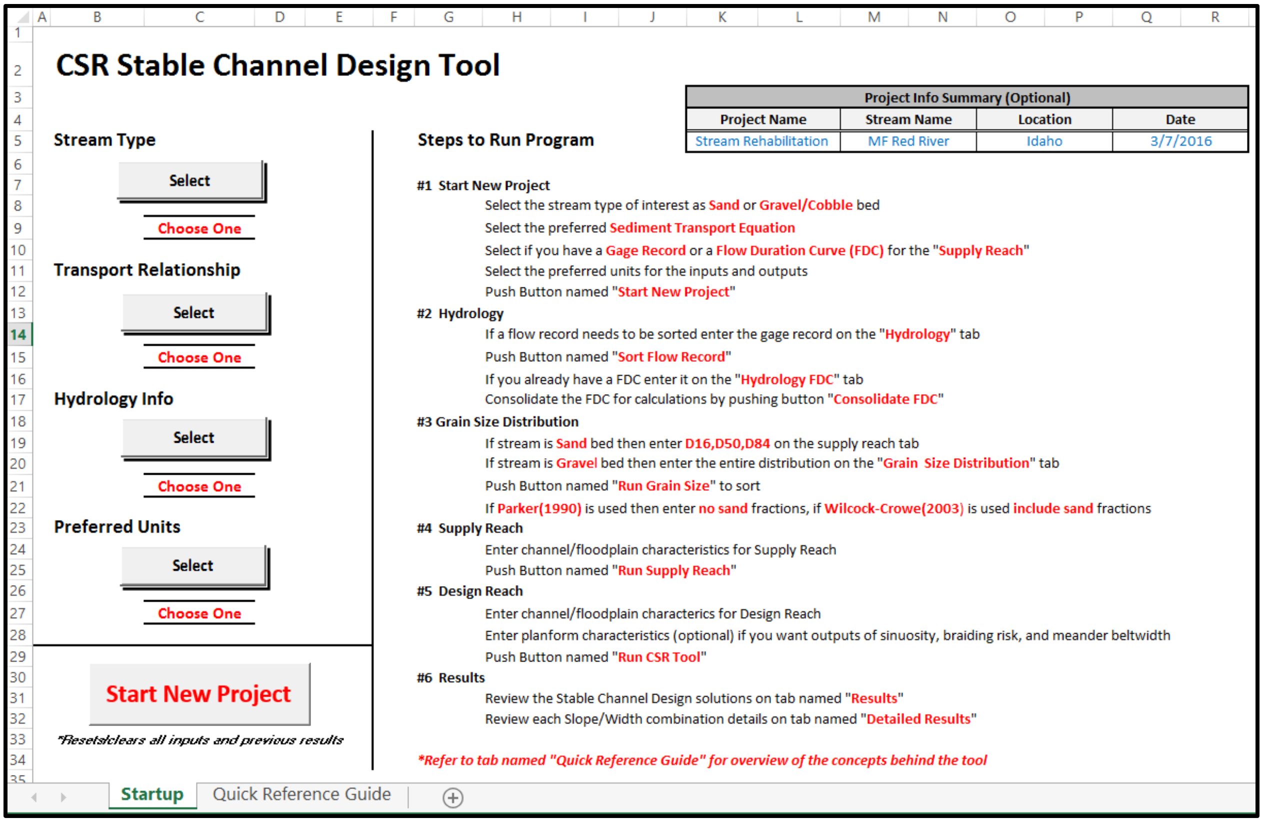
B.2.2 Gravel/Cobble Bed

This example is for a reach on the Main Fork Red River, Idaho (Figure B-23). The data used for this example are from surveys done by the U.S. Forest Service for the Rocky Mountain Research Station in Idaho (King et al. 2004).

Figure B-23. Main Fork Red River looking downstream from upper end of study reach (King et al. 2004).

B.2.2.1 Startup page

The CSR Tool looks like the following when first opened (Figure B-24). The project information summary is optionally entered in the top right of the tab.



CSR Stable Channel Design Tool

Project Info Summary (Optional)			
Project Name	Stream Name	Location	Date
Stream Rehabilitation	MF Red River	Idaho	3/7/2016

Stream Type

Transport Relationship

Hydrology Info

Preferred Units

Resets/clears all inputs and previous results

Steps to Run Program

#1 Start New Project
Select the stream type of interest as Sand or Gravel/Cobble bed
Select the preferred Sediment Transport Equation
Select if you have a Gage Record or a Flow Duration Curve (FDC) for the "Supply Reach"
Select the preferred units for the inputs and outputs
Push Button named "Start New Project"

#2 Hydrology
If a flow record needs to be sorted enter the gage record on the "Hydrology" tab
Push Button named "Sort Flow Record"
If you already have a FDC enter it on the "Hydrology FDC" tab
Consolidate the FDC for calculations by pushing button "Consolidate FDC"

#3 Grain Size Distribution
If stream is Sand bed then enter D16,D50,D84 on the supply reach tab
If stream is Gravel bed then enter the entire distribution on the "Grain Size Distribution" tab
Push Button named "Run Grain Size" to sort
If Parker(1990) is used then enter no sand fractions, if Wilcock-Crowe(2003) is used include sand fractions

#4 Supply Reach
Enter channel/floodplain characteristics for Supply Reach
Push Button named "Run Supply Reach"

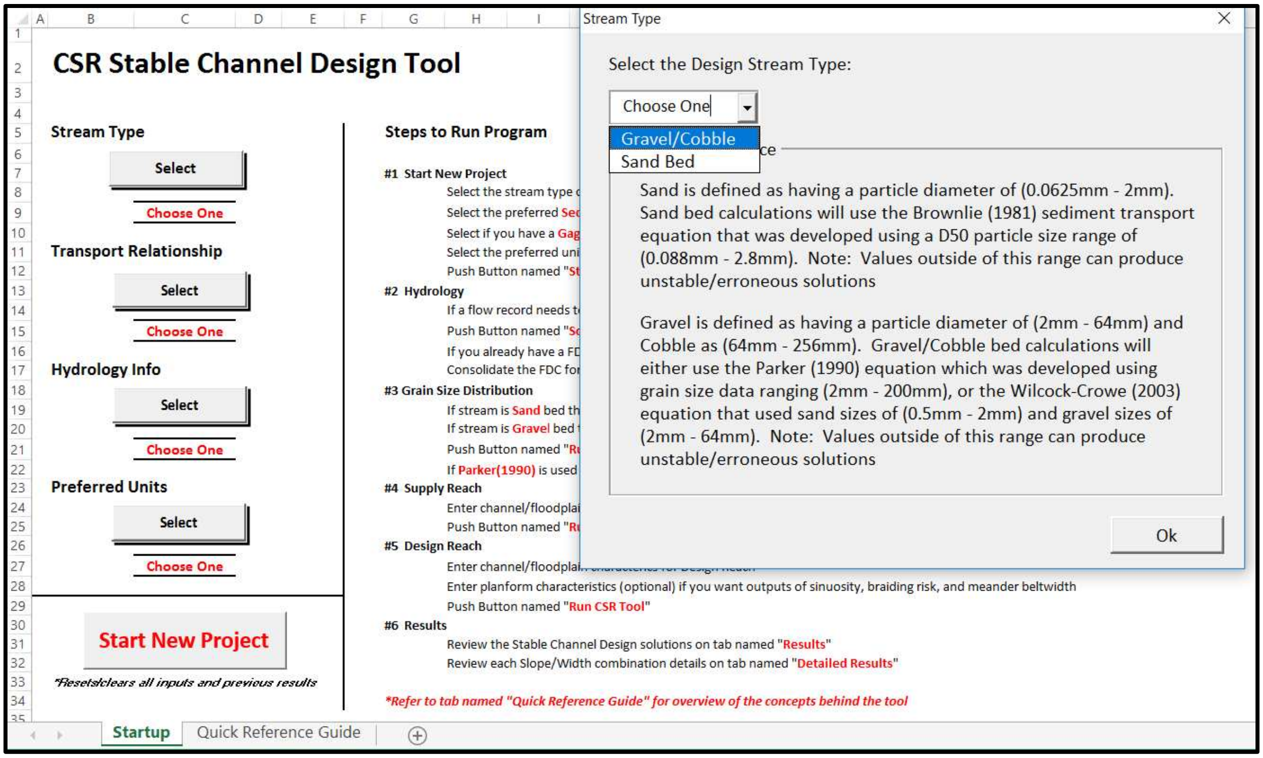
#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "Run CSR Tool"

#6 Results
Review the Stable Channel Design solutions on tab named "Results"
Review each Slope/Width combination details on tab named "Detailed Results"

Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

Figure B-24. "Startup" page of the CSR Tool.

The stream type is selected as "Gravel/Cobble" because the D_{50} for this stream is 20.59 mm which falls within the "Coarse Gravel" category in Table B-1. Also, this is well above the range for the Brownlie (1981) equation, but within the ranges used for Parker (1990) and Wilcock-Crowe (2003) equations (Table B-2). These ranges are also summarized in the selection guidance window as shown in Figure B-25. The selection for each field will display the answer chosen below the "Select" button.



CSR Stable Channel Design Tool

Stream Type

Transport Relationship

Hydrology Info

Preferred Units

*Resets\clears all inputs and previous results

Steps to Run Program

#1 Start New Project
Select the stream type
Select the preferred Se
Select if you have a Gag
Select the preferred uni
Push Button named "St

#2 Hydrology
If a flow record needs t
Push Button named "S
If you already have a FD
Consolidate the FDC for

#3 Grain Size Distribution
If stream is Sand bed th
If stream is Gravel bed
Push Button named "R
If Parker(1990) is used

#4 Supply Reach
Enter channel/floodplai
Push Button named "R

#5 Design Reach
Enter channel/floodplai
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "Run CSR Tool"

#6 Results
Review the Stable Channel Design solutions on tab named "Results"
Review each Slope/Width combination details on tab named "Detailed Results"

*Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

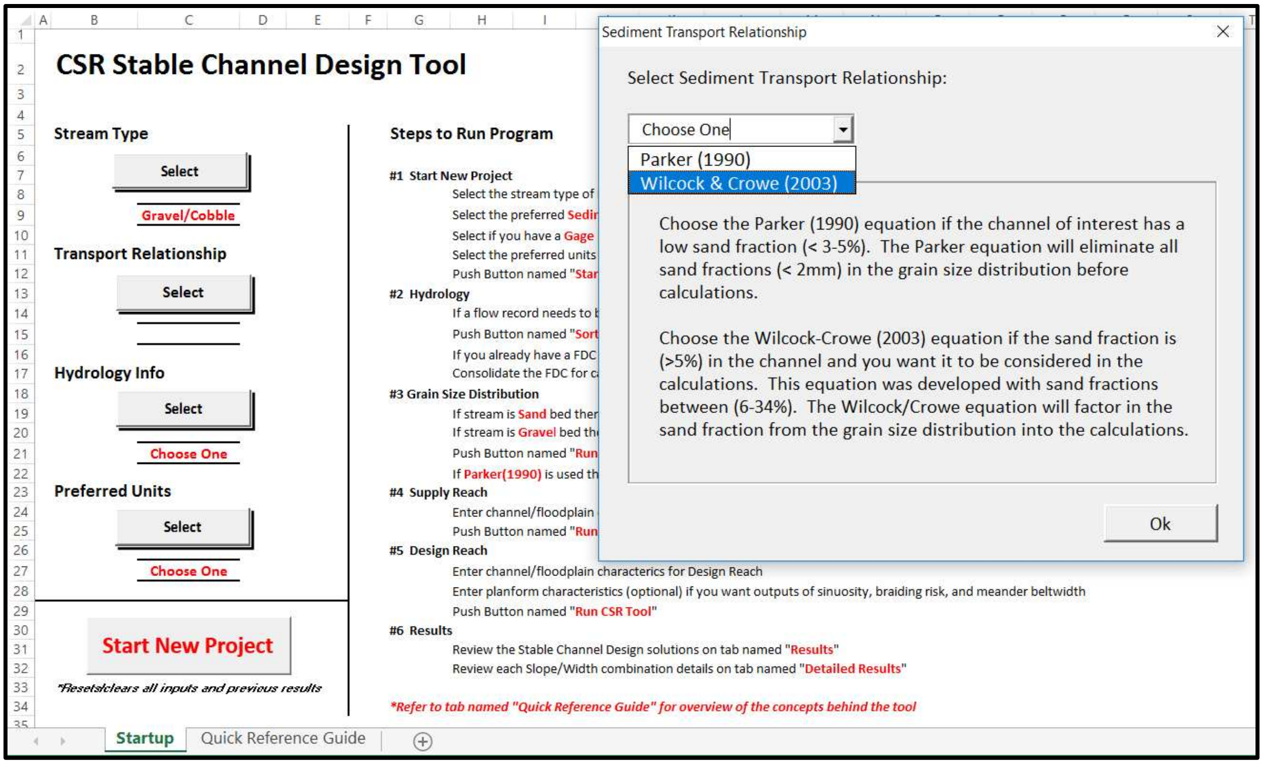
Select the Design Stream Type:

Sand is defined as having a particle diameter of (0.0625mm - 2mm). Sand bed calculations will use the Brownlie (1981) sediment transport equation that was developed using a D50 particle size range of (0.088mm - 2.8mm). Note: Values outside of this range can produce unstable/erroneous solutions

Gravel is defined as having a particle diameter of (2mm - 64mm) and Cobble as (64mm - 256mm). Gravel/Cobble bed calculations will either use the Parker (1990) equation which was developed using grain size data ranging (2mm - 200mm), or the Wilcock-Crowe (2003) equation that used sand sizes of (0.5mm - 2mm) and gravel sizes of (2mm - 64mm). Note: Values outside of this range can produce unstable/erroneous solutions

Figure B-25. Selecting "Stream Type" on "Startup" tab.

Unlike the sand-bed stream type, there is more than one "Transport Relationship" option for the "Gravel/Cobble" bed stream type. For this example, the "Wilcock-Crowe (2003)" equation was selected for the analysis. This was chosen because the sand fraction for the distribution is 10% which is well outside the range used for the Parker (1990) equation. Since the Parker (1990) equation will not consider sand fractions, this equation was deemed the less accurate choice for the "Transport Relationship." In addition, the grain size distribution falls mostly within the bounds used to create the Wilcock-Crowe (2003) equation (Table B-2). The D_{90} for this example is 55.39 mm and the non-sand distribution range used to produce the Wilcock-Crowe (2003) equation is 2 to 64 mm. These ranges are also summarized in the selection guidance windows for the user's reference (Figures B-25 and B-26).



CSR Stable Channel Design Tool

Stream Type

Gravel/Cobble

Transport Relationship

Hydrology Info

Choose One

Preferred Units

Choose One

*Resets/clears all inputs and previous results

Steps to Run Program

#1 Start New Project
Select the stream type of
Select the preferred Sedir
Select if you have a Gage
Select the preferred units
Push Button named "Star

#2 Hydrology
If a flow record needs to b
Push Button named "Sort
If you already have a FDC
Consolidate the FDC for c

#3 Grain Size Distribution
If stream is Sand bed ther
If stream is Gravel bed th
Push Button named "Run
If Parker(1990) is used th

#4 Supply Reach
Enter channel/floodplain
Push Button named "Run

#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "Run CSR Tool"

#6 Results
Review the Stable Channel Design solutions on tab named "Results"
Review each Slope/Width combination details on tab named "Detailed Results"

*Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

Sediment Transport Relationship

Select Sediment Transport Relationship:

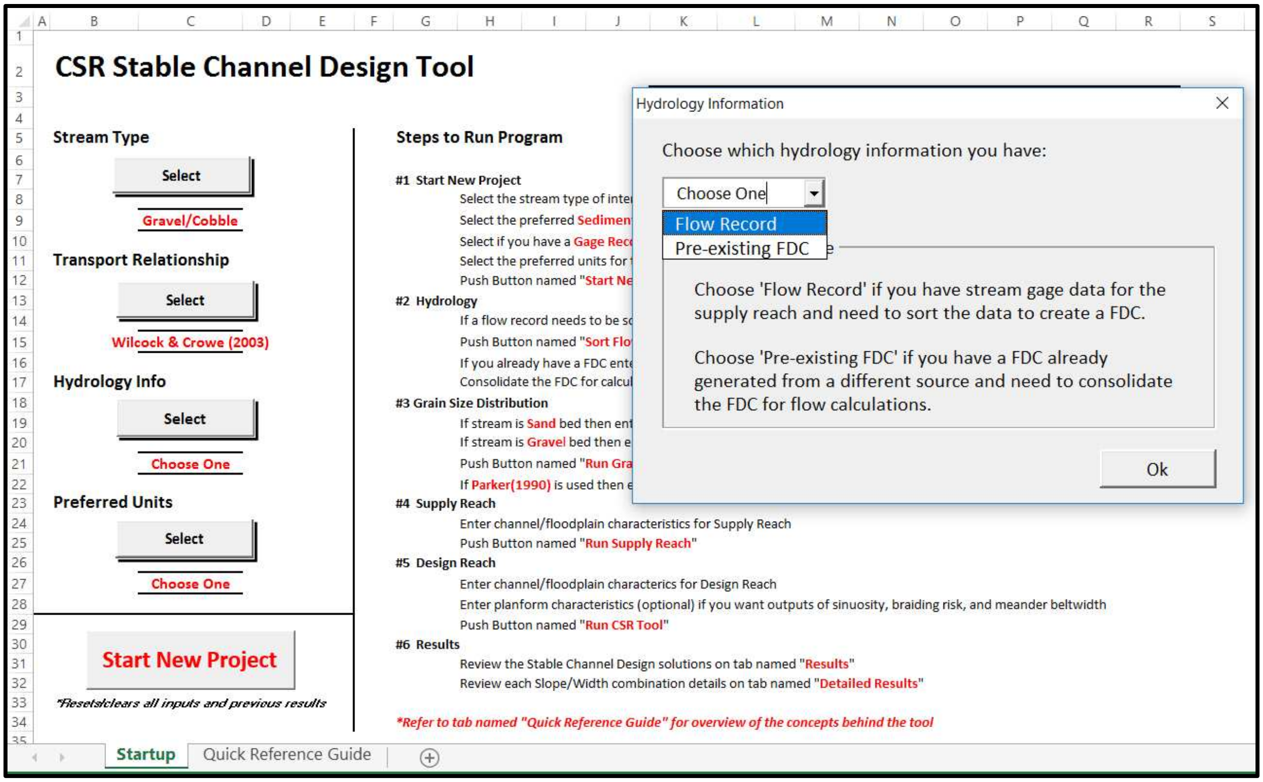
Choose One
Parker (1990)
Wilcock & Crowe (2003)

Choose the Parker (1990) equation if the channel of interest has a low sand fraction (< 3-5%). The Parker equation will eliminate all sand fractions (< 2mm) in the grain size distribution before calculations.

Choose the Wilcock-Crowe (2003) equation if the sand fraction is (>5%) in the channel and you want it to be considered in the calculations. This equation was developed with sand fractions between (6-34%). The Wilcock/Crowe equation will factor in the sand fraction from the grain size distribution into the calculations.

Figure B-26. Selecting "Transport Relationship" on "Startup" tab.

This example reach has discharge data of significant length (35 yrs) from a U.S. Forest Service gaging station to represent the hydrology of the channel for calculations, so the "Flow Record" option was selected for "Hydrology Info" (Figure B-27).



CSR Stable Channel Design Tool

Stream Type: Gravel/Cobble

Transport Relationship: Wilcock & Crowe (2003)

Hydrology Info: Choose One

Preferred Units: Choose One

*Resets/clears all inputs and previous results

Steps to Run Program

#1 Start New Project
Select the stream type of inte
Select the preferred Sedimen
Select if you have a Gage Rec
Select the preferred units for
Push Button named "Start Ne

#2 Hydrology
If a flow record needs to be so
Push Button named "Sort Flo
If you already have a FDC ente
Consolidate the FDC for calcul

#3 Grain Size Distribution
If stream is Sand bed then ent
If stream is Gravel bed then e
Push Button named "Run Gra
If Parker(1990) is used then e

#4 Supply Reach
Enter channel/floodplain characteristics for Supply Reach
Push Button named "Run Supply Reach"

#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "Run CSR Tool"

#6 Results
Review the Stable Channel Design solutions on tab named "Results"
Review each Slope/Width combination details on tab named "Detailed Results"

*Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

Hydrology Information

Choose which hydrology information you have:

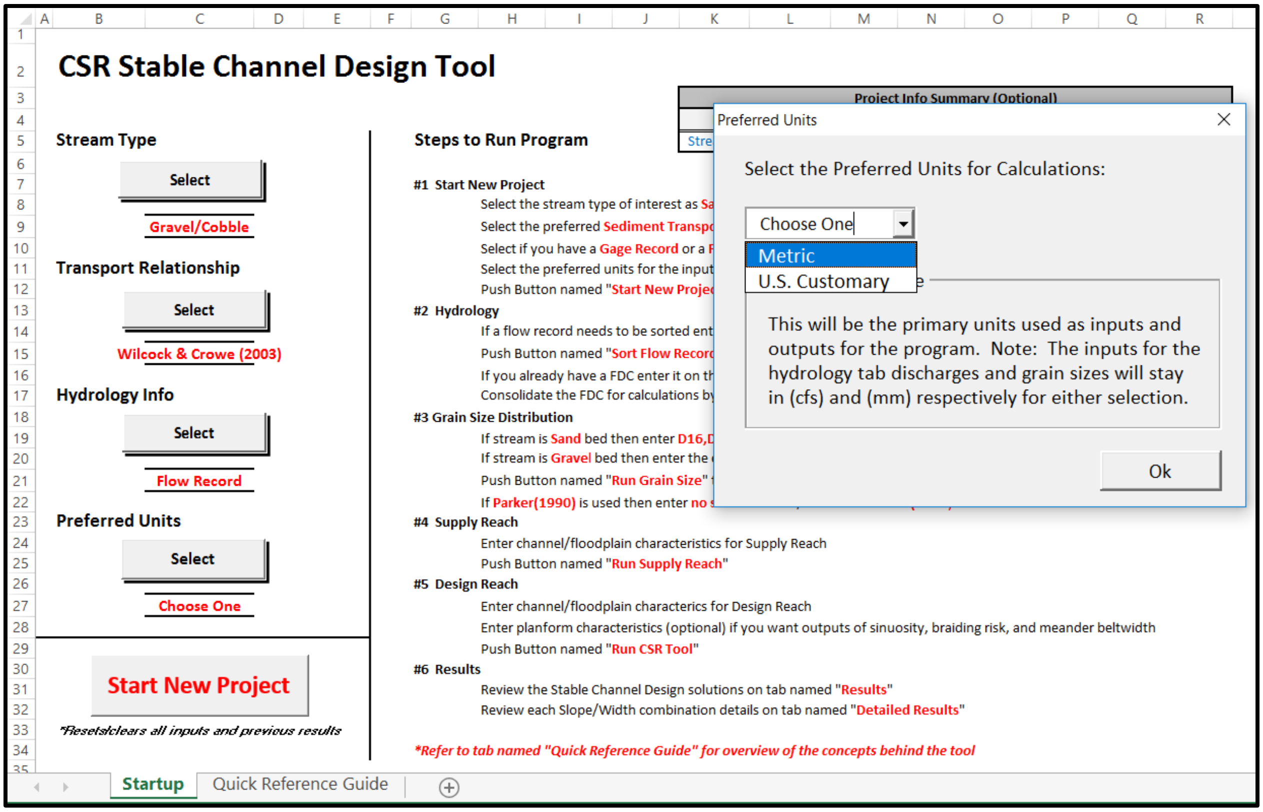
Choose One
Flow Record
Pre-existing FDC

Choose 'Flow Record' if you have stream gage data for the supply reach and need to sort the data to create a FDC.

Choose 'Pre-existing FDC' if you have a FDC already generated from a different source and need to consolidate the FDC for flow calculations.

Figure B-27. Selecting "Hydrology Info" on "Startup" tab.

Lastly, the preferred units are selected as "Metric" for this example (Figure B-28). This selection will update and format the tabs to accept inputs and produce outputs in this unit of choice.


CSR Stable Channel Design Tool

Project Info Summary (Optional)

Stre

Stream Type

Select

Gravel/Cobble

Transport Relationship

Select

Wilcock & Crowe (2003)

Hydrology Info

Select

Flow Record

Preferred Units

Select

Choose One

Start New Project

*Resets/clears all inputs and previous results

Steps to Run Program

#1 Start New Project

Select the stream type of interest as Sa

Select the preferred Sediment Transpo

Select if you have a Gage Record or a F

Select the preferred units for the input

Push Button named "Start New Projec

#2 Hydrology

If a flow record needs to be sorted ent

Push Button named "Sort Flow Record

If you already have a FDC enter it on th

Consolidate the FDC for calculations by

#3 Grain Size Distribution

If stream is Sand bed then enter D16,D

If stream is Gravel bed then enter the

Push Button named "Run Grain Size"

If Parker(1990) is used then enter no

#4 Supply Reach

Enter channel/floodplain characteristics for Supply Reach

Push Button named "Run Supply Reach"

#5 Design Reach

Enter channel/floodplain characterics for Design Reach

Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth

Push Button named "Run CSR Tool"

#6 Results

Review the Stable Channel Design solutions on tab named "Results"

Review each Slope/Width combination details on tab named "Detailed Results"

Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool

Preferred Units

Select the Preferred Units for Calculations:

Choose One

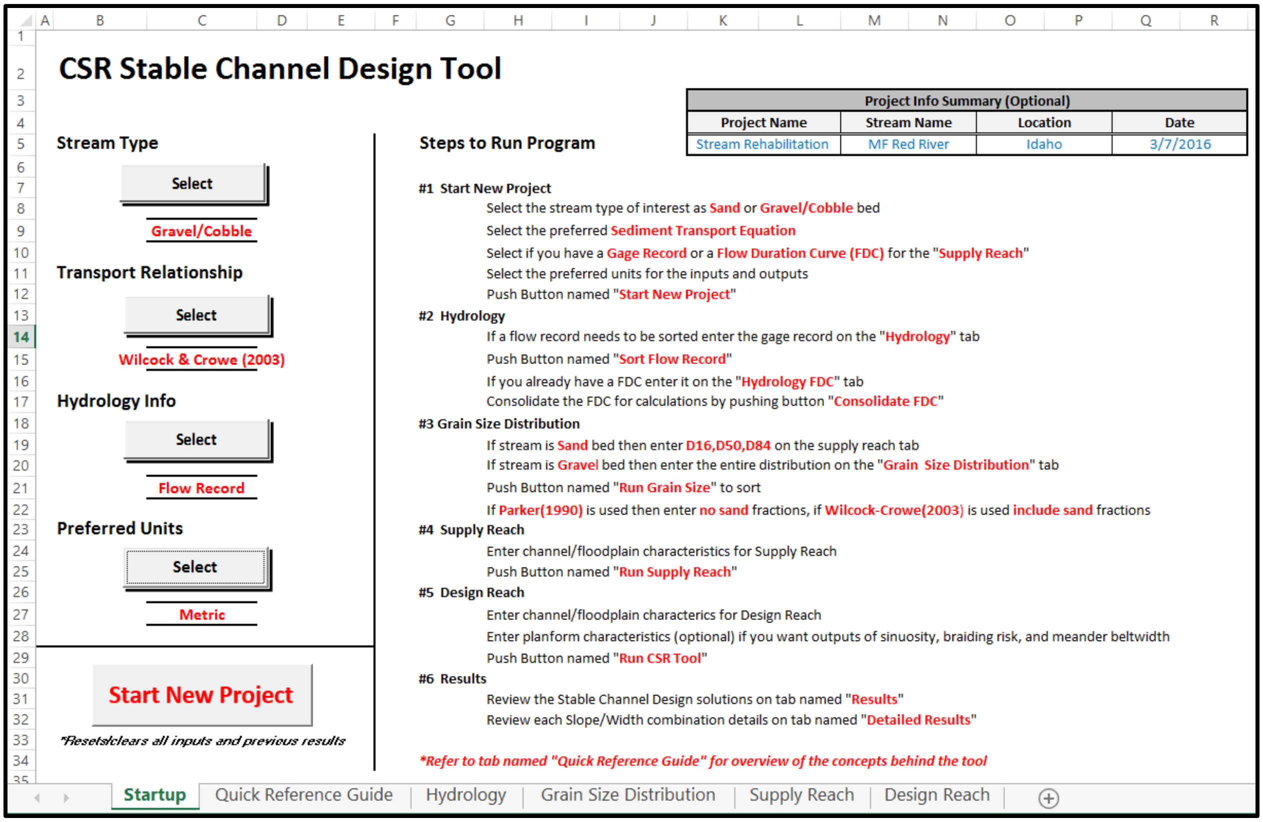
Metric

U.S. Customary

This will be the primary units used as inputs and outputs for the program. Note: The inputs for the hydrology tab discharges and grain sizes will stay in (cfs) and (mm) respectively for either selection.

Figure B-28. Selecting “Preferred Units” on “Startup” tab.

After the preceding four selections are made and the “Start New Project” button is pressed, the next required tabs necessary to run the program are displayed in the workbook as shown at the bottom of Figure B-29.



CSR Stable Channel Design Tool

Stream Type
Gravel/Cobble

Transport Relationship
Wilcock & Crowe (2003)

Hydrology Info
Flow Record

Preferred Units
Metric

**Resets/clears all inputs and previous results*

Project Info Summary (Optional)			
Project Name	**Stream Name**	**Location**	**Date**
Stream Rehabilitation	MF Red River	Idaho	3/7/2016

Steps to Run Program

#1 Start New Project
Select the stream type of interest as **Sand** or **Gravel/Cobble** bed
Select the preferred **Sediment Transport Equation**
Select if you have a **Gage Record** or a **Flow Duration Curve (FDC)** for the "**Supply Reach**"
Select the preferred units for the inputs and outputs
Push Button named "**Start New Project**"

#2 Hydrology
If a flow record needs to be sorted enter the gage record on the "**Hydrology**" tab
Push Button named "**Sort Flow Record**"
If you already have a FDC enter it on the "**Hydrology FDC**" tab
Consolidate the FDC for calculations by pushing button "**Consolidate FDC**"

#3 Grain Size Distribution
If stream is **Sand** bed then enter **D16,D50,D84** on the supply reach tab
If stream is **Gravel** bed then enter the entire distribution on the "**Grain Size Distribution**" tab
Push Button named "**Run Grain Size**" to sort
If **Parker(1990)** is used then enter **no sand** fractions, if **Wilcock-Crowe(2003)** is used **include sand** fractions

#4 Supply Reach
Enter channel/floodplain characteristics for Supply Reach
Push Button named "**Run Supply Reach**"

#5 Design Reach
Enter channel/floodplain characterics for Design Reach
Enter planform characteristics (optional) if you want outputs of sinuosity, braiding risk, and meander beltwidth
Push Button named "**Run CSR Tool**"

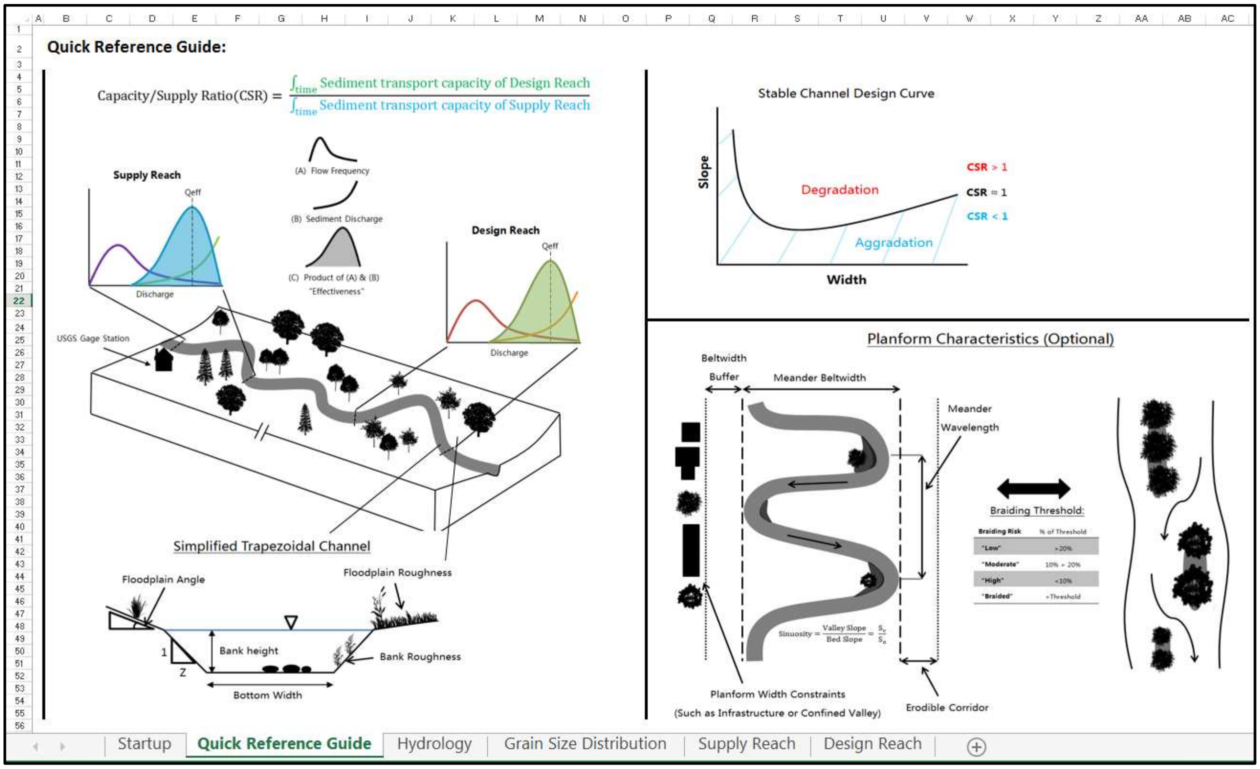
#6 Results
Review the Stable Channel Design solutions on tab named "**Results**"
Review each Slope/Width combination details on tab named "**Detailed Results**"

****Refer to tab named "Quick Reference Guide" for overview of the concepts behind the tool***

Figure B-29. “Startup” tab with “Start New Project” defined.

B.2.2.2 Quick Reference Guide tab

The “Quick Reference Guide” tab can be viewed at any time to obtain a visual representation of the underlying concepts behind the tool (Figure B-30).

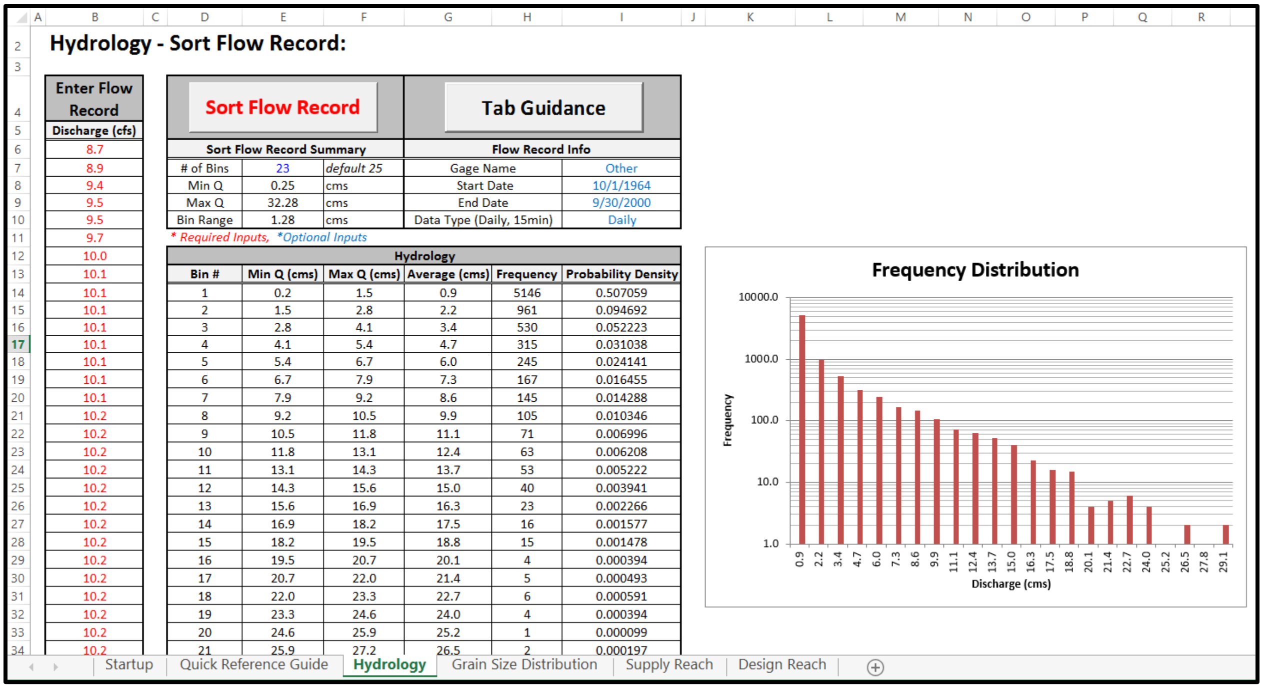


Braiding Risk	% of Threshold
"Low"	>20%
"Moderate"	10% > 20%
"High"	<10%
"Braided"	>Threshold

Figure B-30. "Quick Reference Guide" tab of CSR Tool.

B.2.2.3 Hydrology tab

Following the steps provided in the *Tab-by-tab Guidance* section of this report, the flow record information is first entered if desired, then just the discharges of the flow record are entered in cubic feet per second (Figure B-31). Subsequently, the "Sort Flow Record" button is pressed to produce results.



Hydrology - Sort Flow Record:

Enter Flow Record
Discharge (cfs)
8.7
8.9
9.4
9.5
9.5
9.7
10.0
10.1
10.1
10.1
10.1
10.1
10.1
10.1
10.1
10.2
10.2
10.2
10.2
10.2
10.2
10.2
10.2
10.2
10.2
10.2
10.2
10.2
10.2
10.2

Sort Flow Record Summary		
# of Bins	23	*default 25*
Min Q	0.25	cms
Max Q	32.28	cms
Bin Range	1.28	cms

Flow Record Info	
Gage Name	Other
Start Date	10/1/1964
End Date	9/30/2000
Data Type (Daily, 15min)	Daily

** Required Inputs, *Optional Inputs*

Hydrology					
Bin #	Min Q (cms)	Max Q (cms)	Average (cms)	Frequency	Probability Density
1	0.2	1.5	0.9	5146	0.507059
2	1.5	2.8	2.2	961	0.094692
3	2.8	4.1	3.4	530	0.052223
4	4.1	5.4	4.7	315	0.031038
5	5.4	6.7	6.0	245	0.024141
6	6.7	7.9	7.3	167	0.016455
7	7.9	9.2	8.6	145	0.014288
8	9.2	10.5	9.9	105	0.010346
9	10.5	11.8	11.1	71	0.006996
10	11.8	13.1	12.4	63	0.006208
11	13.1	14.3	13.7	53	0.005222
12	14.3	15.6	15.0	40	0.003941
13	15.6	16.9	16.3	23	0.002266
14	16.9	18.2	17.5	16	0.001577
15	18.2	19.5	18.8	15	0.001478
16	19.5	20.7	20.1	4	0.000394
17	20.7	22.0	21.4	5	0.000493
18	22.0	23.3	22.7	6	0.000591
19	23.3	24.6	24.0	4	0.000394
20	24.6	25.9	25.2	1	0.000099
21	25.9	27.2	26.5	2	0.000197

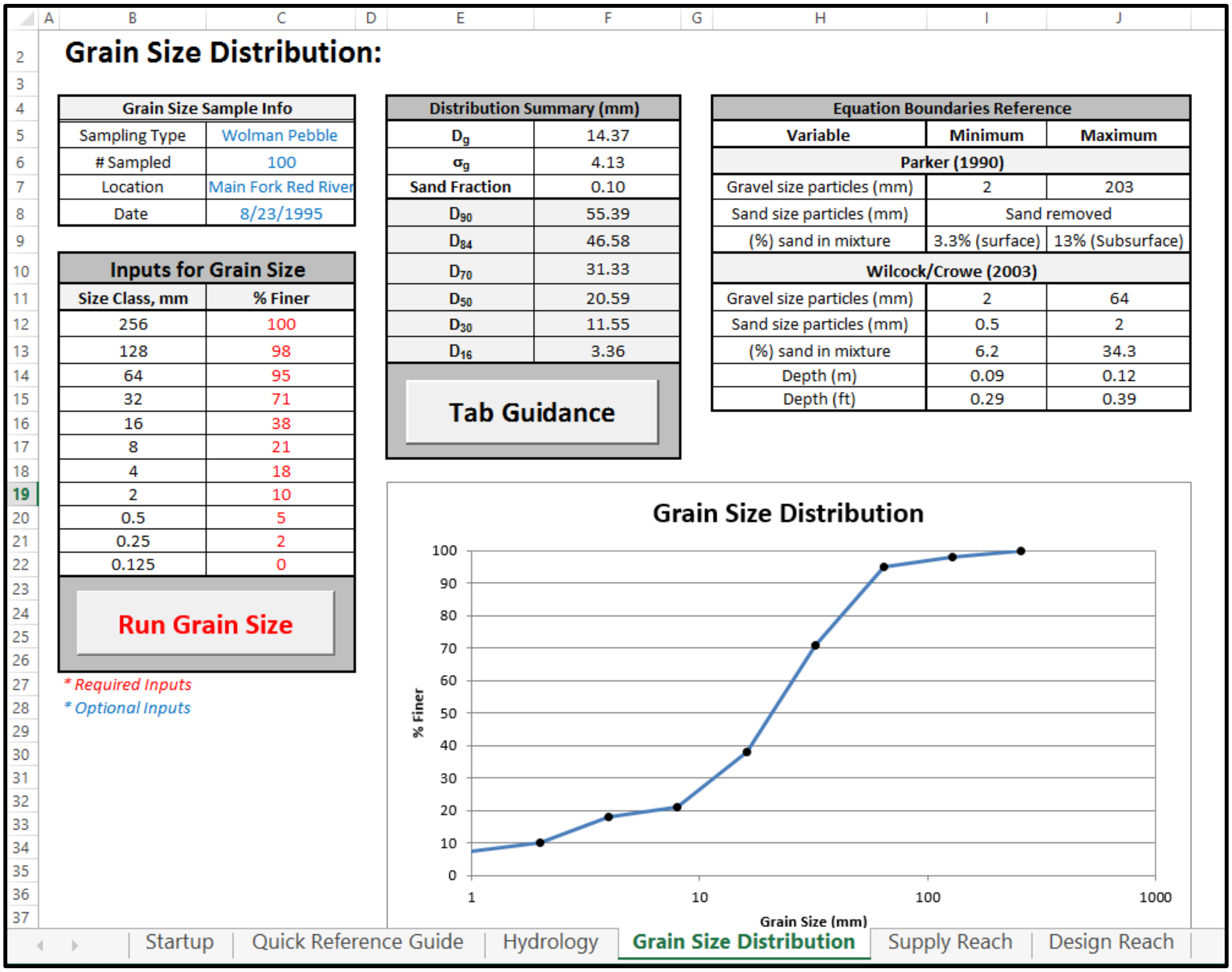
Figure B-31. "Hydrology" tab, Red River example results.

Hydrology Results

This example uses the default 25 bins to sort the data which are displayed in Column D under "Bin #." The resulting total number of bins is 23, because the program found zero frequency bins and then lowered the bin number from 25 until there were no zero frequency bins. An arithmetic binning process is used in the program to produce equal intervals of discharges represented in each bin. The range for each bin and the associated average discharge is displayed in Columns E–G. Column H shows the frequency or total number of flows from the record that fall into the range for the associated bin. Column I displays the probability density for the flows in each bin. The frequency versus each discharge bin is graphed on the right-side of the tab.

B.2.2.4 Grain Size Distribution tab

The "Grain Size Distribution" tab is displayed and required for this example because it is a "Gravel/Cobble" bed stream type. The "Grain Size Sample Info" is first entered at the top left of the tab if desired by the user. Then, the % finer for each grain size class is entered for each required field denoted by red-font asterisks. Since the Wilcock-Crowe (2003) equation was selected for the analysis, every grain size class has a required input because the sand fraction is considered. When the inputs have been entered and the “Run Grain Size” button pressed, the distribution is analyzed to produce the necessary parameters to run the program. Outputs are displayed under “Distribution Summary (mm)” and the percent finer versus grain size class is plotted in Figure B-32.



Grain Size Distribution:

Grain Size Sample Info	
Sampling Type	Wolman Pebble
# Sampled	100
Location	Main Fork Red River
Date	8/23/1995

Inputs for Grain Size	
Size Class, mm	% Finer
256	100
128	98
64	95
32	71
16	38
8	21
4	18
2	10
0.5	5
0.25	2
0.125	0

* Required Inputs

* Optional Inputs

Distribution Summary (mm)	
D_g	14.37
σ_g	4.13
Sand Fraction	0.10
D_{90}	55.39
D_{84}	46.58
D_{70}	31.33
D_{50}	20.59
D_{30}	11.55
D_{16}	3.36

Equation Boundaries Reference		
Variable	Minimum	Maximum
Parker (1990)		
Gravel size particles (mm)	2	203
Sand size particles (mm)	Sand removed	
(%) sand in mixture	3.3% (surface)	13% (Subsurface)
Wilcock/Crowe (2003)		
Gravel size particles (mm)	2	64
Sand size particles (mm)	0.5	2
(%) sand in mixture	6.2	34.3
Depth (m)	0.09	0.12
Depth (ft)	0.29	0.39

Figure B-32. “Grain Size Distribution” tab, Red River example results.

Distribution Summary

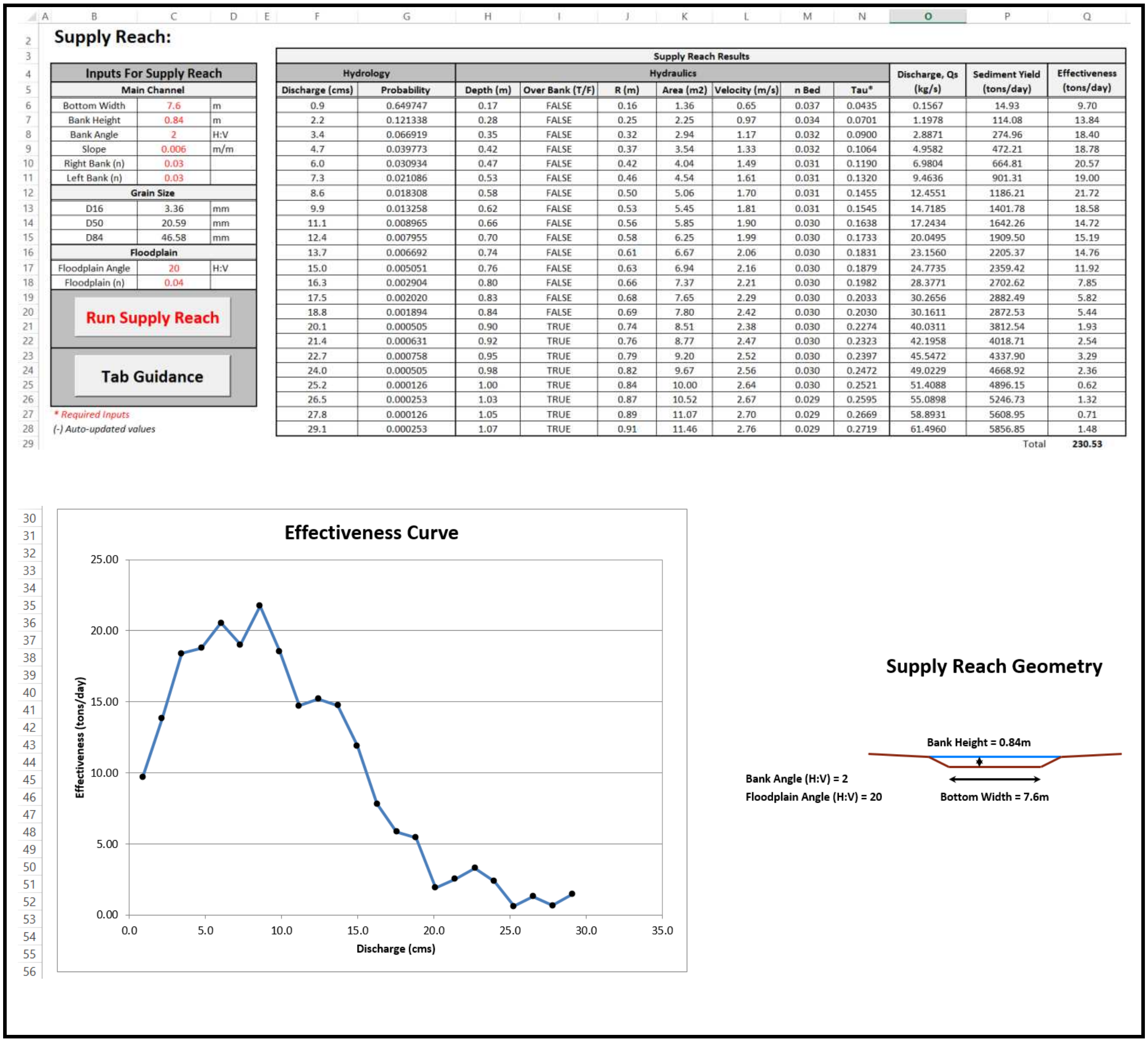
The distribution summary presents the results of the “Grain Size Distribution” tab (Figure B-32). Rows 5–6 show the geometric mean grain diameter (D_g) and the geometric standard deviation (σ_g), Row 7 shows the sand fraction, which in this example is 0.1 or 10%. Rows 8–13 show common grain size percentiles representing the particle diameter for which 16%, 30%, 50%, 70%, 84%, and 90% of all sediment in the distribution is smaller.

Equation Boundaries Reference

The ranges presented by Parker (1990) and Wilcock and Crowe (2003) to develop the equations, as shown in Table B-2, are summarized again for reference under "Equation Boundaries Reference." This can be used to help check if the transport equation selected for the analysis is the most desired choice.

B.2.2.5 Supply Reach tab

The inputs required for the supply reach are entered in the cells that are highlighted with red-font asterisks. The channel dimensions including the bottom width, bank height, bank angle, and floodplain angle are used to create a simplified trapezoidal channel that represents the actual cross section of the channel (see "Quick Reference Guide" tab). The roughness inputs are Manning's *n* values. Only the bank roughness is required for the channel because the roughness of the bed is calculated within the sediment transport calculations. When the inputs have been entered and the "Run Supply Reach" button pressed, the results for the supply reach will be displayed to the right (Figure B-33).



Supply Reach:

Inputs For Supply Reach		
Main Channel		
Bottom Width	7.6	m
Bank Height	0.84	m
Bank Angle	2	H:V
Slope	0.006	m/m
Right Bank (n)	0.03	
Left Bank (n)	0.03	
Grain Size		
D16	3.36	mm
D50	20.59	mm
D84	46.58	mm
Floodplain		
Floodplain Angle	20	H:V
Floodplain (n)	0.04	

** Required Inputs*

(-) Auto-updated values

Supply Reach Results

Hydrology		Hydraulics							Discharge, Qs (kg/s)	Sediment Yield (tons/day)	Effectiveness (tons/day)
Discharge (cms)	Probability	Depth (m)	Over Bank (T/F)	R (m)	Area (m2)	Velocity (m/s)	n Bed	Tau*			
0.9	0.649747	0.17	FALSE	0.16	1.36	0.65	0.037	0.0435	0.1567	14.93	9.70
2.2	0.121338	0.28	FALSE	0.25	2.25	0.97	0.034	0.0701	1.1978	114.08	13.84
3.4	0.066919	0.35	FALSE	0.32	2.94	1.17	0.032	0.0900	2.8871	274.96	18.40
4.7	0.039773	0.42	FALSE	0.37	3.54	1.33	0.032	0.1064	4.9582	472.21	18.78
6.0	0.030934	0.47	FALSE	0.42	4.04	1.49	0.031	0.1190	6.9804	664.81	20.57
7.3	0.021086	0.53	FALSE	0.46	4.54	1.61	0.031	0.1320	9.4636	901.31	19.00
8.6	0.018308	0.58	FALSE	0.50	5.06	1.70	0.031	0.1455	12.4551	1186.21	21.72
9.9	0.013258	0.62	FALSE	0.53	5.45	1.81	0.031	0.1545	14.7185	1401.78	18.58
11.1	0.008965	0.66	FALSE	0.56	5.85	1.90	0.030	0.1638	17.2434	1642.26	14.72
12.4	0.007955	0.70	FALSE	0.58	6.25	1.99	0.030	0.1733	20.0495	1909.50	15.19
13.7	0.006692	0.74	FALSE	0.61	6.67	2.06	0.030	0.1831	23.1560	2205.37	14.76
15.0	0.005051	0.76	FALSE	0.63	6.94	2.16	0.030	0.1879	24.7735	2359.42	11.92
16.3	0.002904	0.80	FALSE	0.66	7.37	2.21	0.030	0.1982	28.3771	2702.62	7.85
17.5	0.002020	0.83	FALSE	0.68	7.65	2.29	0.030	0.2033	30.2656	2882.49	5.82
18.8	0.001894	0.84	FALSE	0.69	7.80	2.42	0.030	0.2030	30.1611	2872.53	5.44
20.1	0.000505	0.90	TRUE	0.74	8.51	2.38	0.030	0.2274	40.0311	3812.54	1.93
21.4	0.000631	0.92	TRUE	0.76	8.77	2.47	0.030	0.2323	42.1958	4018.71	2.54
22.7	0.000758	0.95	TRUE	0.79	9.20	2.52	0.030	0.2397	45.5472	4337.90	3.29
24.0	0.000505	0.98	TRUE	0.82	9.67	2.56	0.030	0.2472	49.0229	4668.92	2.36
25.2	0.000126	1.00	TRUE	0.84	10.00	2.64	0.030	0.2521	51.4088	4896.15	0.62
26.5	0.000253	1.03	TRUE	0.87	10.52	2.67	0.029	0.2595	55.0898	5246.73	1.32
27.8	0.000126	1.05	TRUE	0.89	11.07	2.70	0.029	0.2669	58.8931	5608.95	0.71
29.1	0.000253	1.07	TRUE	0.91	11.46	2.76	0.029	0.2719	61.4960	5856.85	1.48
										Total	**230.53**

Figure B-33. “Supply Reach” tab, Red River example results.

For this example, a trapezoid was fit to the actual cross-sectional data of the channel in order to estimate the dimensions entered for the supply reach as shown in Figure B-34. From the data points, the bottom width is estimated as 7.6 m, the bank height as 0.84 m, bank angle 2:1 (note the figure axes are not proportional), and the floodplain angle as 20:1. The bed slope used for the calculations was estimated from the longitudinal bed profile of the stream as seen in Figure B-35.

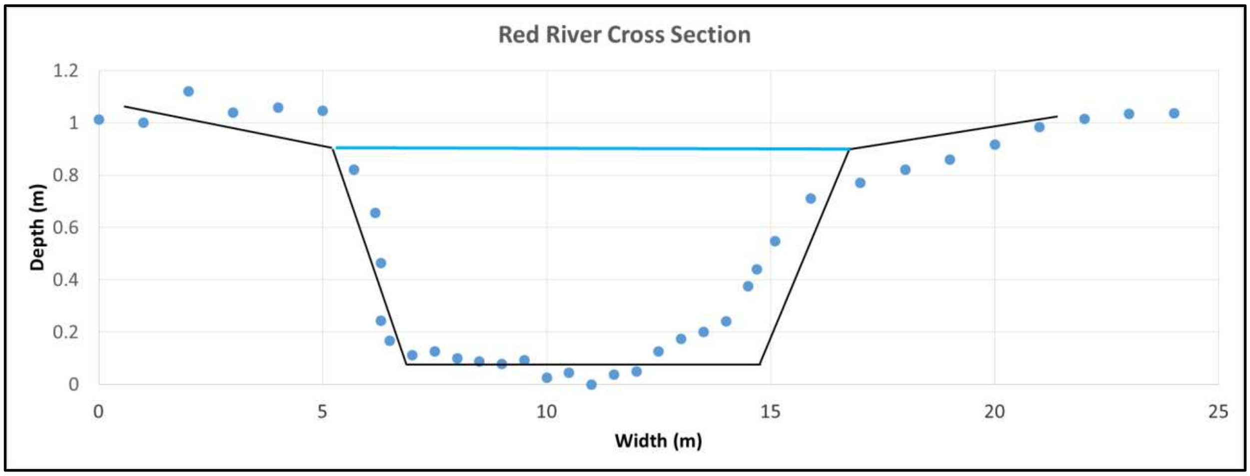


Figure B-34. Fitted trapezoid cross section for supply reach of Red River from actual survey (King et al. 2004).

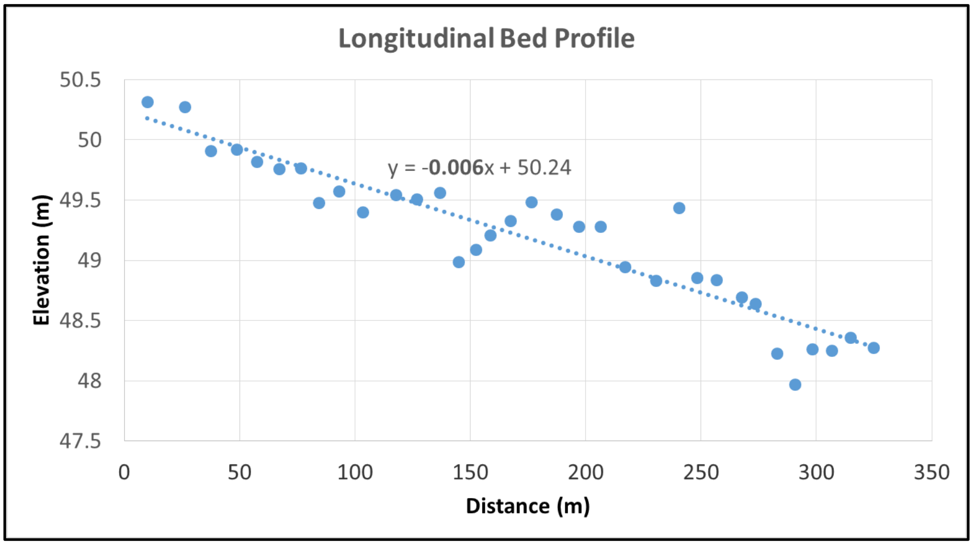


Figure B-35. Red River longitudinal bed profile with fitted trend line to find bed slope (King et al. 2004).

Hydrology

Columns F–G show a summary of the hydrology results transferred from the "Hydrology" tab (Figure B-33). The discharge is the average for the associated bin range along with the probability of those flows occurring.

Hydraulics

Columns H–N display the hydraulic characteristics calculated by the program for the associated bin discharge flowing through the simplified trapezoidal channel defined by the inputs. If the depth shown in Column H is less than the bank height specified in the inputs, then Column I will display a "False," and if it is over then "True" will be displayed showing the program modeled those flows as overbank. Column J is the channel hydraulic radius, Column K is the cross-sectional flow area, and Column L is the associated cross-section averaged flow velocity. Column M is the calculated Manning's *n* for the bed of the channel. The roughness of the bed is calculated using Limerinos (1970) equation for "Gravel/Cobble" bed stream types. Column N displays the dimensionless shear stress of the bed or the Shields' stress based on the surface geometric grain size.

Sediment Transport

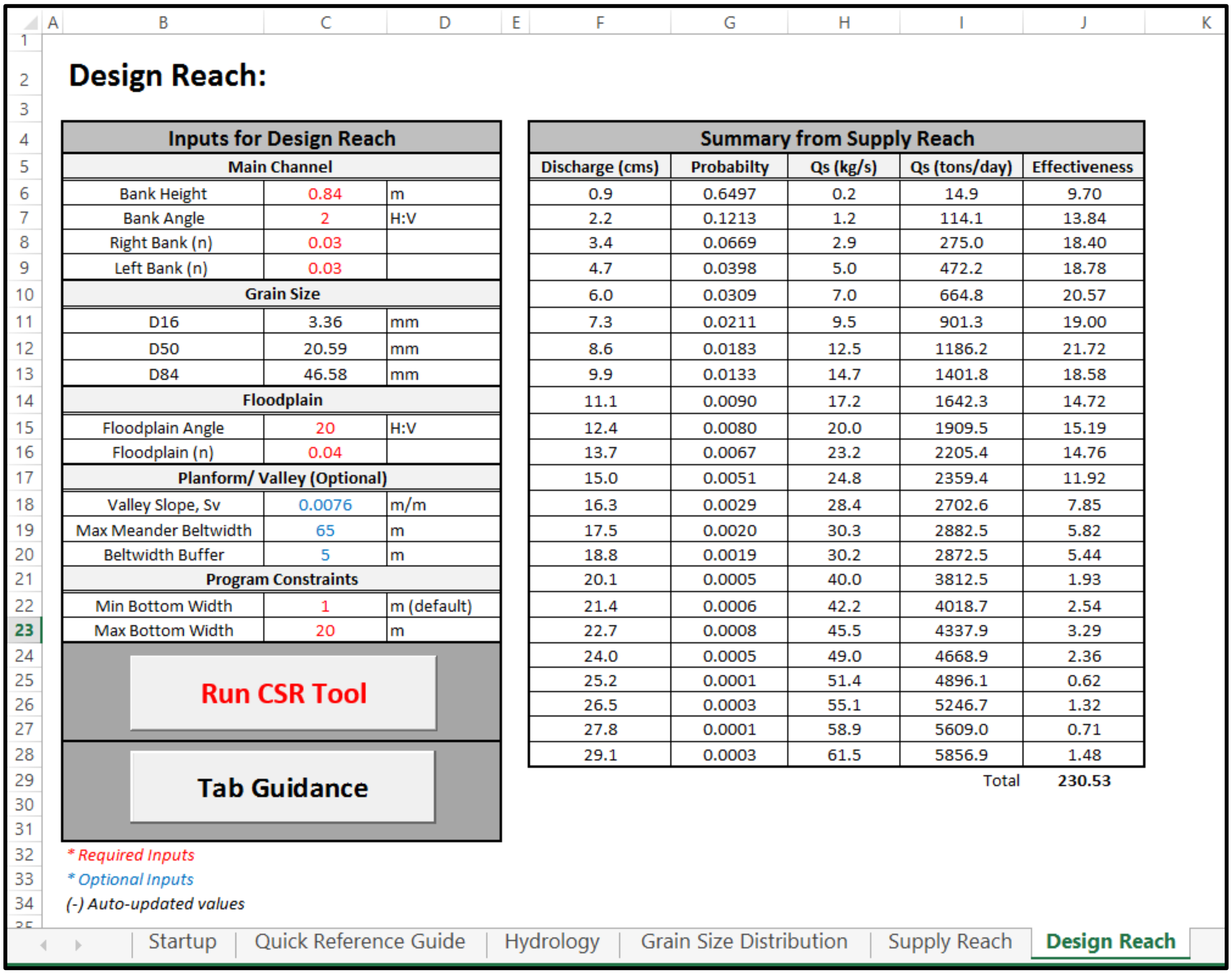
Columns O–Q display the sediment transport results for each bin. Column O shows the estimated sediment discharge in kilograms per second from the bedload transport equation. Column P converts this value to a sediment yield in tons/day. Column P represents the potential sediment yield by the average flow of the associated bin in Column F. Column Q multiplies Column P by Column G, the probability of flows. The result is the "effectiveness" or total sediment transported on average in a given day based on the probability of daily flows in the flow record. The total effectiveness or total sediment transported on average in a given day is the sum of the individual effectiveness for each bin which is displayed at the bottom of Column Q. Underneath these results, the effectiveness is graphed in the bottom left of the tab for each discharge.

Supply Reach Geometry

In the bottom right, a visual representation of the simplified trapezoidal channel defined by the input dimensions is shown and labeled. The supply reach geometry is on an arbitrary scale, but all dimensions are proportional to each other. This feature is for the user's reference to get a visual of the geometry used in the calculations.

B.2.2.6 Design Reach Tab

The required inputs denoted by red-font asterisks, are entered for the design reach (Figure B-36). For this example, the channel dimensions and grain size are assumed to be the same as the supply reach. The planform characteristics are optional, but are included in this example to show the functionality of this option. The valley slope is required to perform the planform calculations. The maximum meander belt width is an optional input that represents the maximum width the valley has to support the channel design laterally. This value should take into account lateral constraints such as a confined valley, or infrastructure, etc. If the estimated belt width exceeds this amount then it will be highlighted in red on the "Results" tab. Another optional input is the belt width buffer. This is the total extra room on both sides of the river that can be used as a safety factor of the estimated belt width and/or room for the river to move (see "Quick Reference Guide" tab for a visual). This amount is added to the calculated belt width. Lastly, the program constraints are defined. This will be the range of widths the program will loop through to attempt to find associated slopes that will produce a CSR = 1. The default minimum of 1 m is used to produce a full family of solutions. The maximum width is set over the supply reach bottom width usually (1.5 to 2 times) to produce results with widths greater than the supply reach. Pressing the "Run CSR Tool" button will run the program to find slope/width combinations that balance the sediment capacity of the supply and design reach and produce a CSR = 1. This will create a “Results” tab and a “Detailed Results” tab.



Design Reach:

Inputs for Design Reach		
Main Channel		
Bank Height	0.84	m
Bank Angle	2	H:V
Right Bank (n)	0.03	
Left Bank (n)	0.03	
Grain Size		
D16	3.36	mm
D50	20.59	mm
D84	46.58	mm
Floodplain		
Floodplain Angle	20	H:V
Floodplain (n)	0.04	
Planform/ Valley (Optional)		
Valley Slope, Sv	0.0076	m/m
Max Meander Beltwidth	65	m
Beltwidth Buffer	5	m
Program Constraints		
Min Bottom Width	1	m (default)
Max Bottom Width	20	m

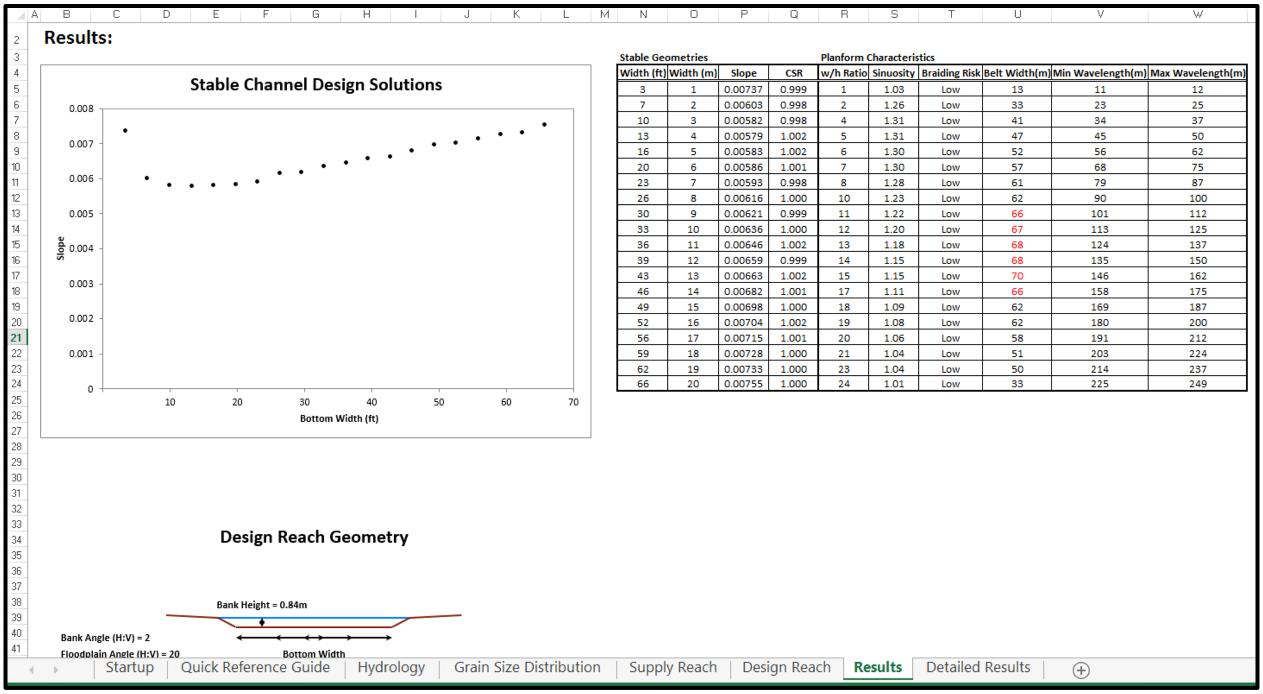
** Required Inputs*
** Optional Inputs*
(-) Auto-updated values

Summary from Supply Reach				
Discharge (cms)	**Probabilty**	**Qs (kg/s)**	**Qs (tons/day)**	**Effectiveness**
0.9	0.6497	0.2	14.9	9.70
2.2	0.1213	1.2	114.1	13.84
3.4	0.0669	2.9	275.0	18.40
4.7	0.0398	5.0	472.2	18.78
6.0	0.0309	7.0	664.8	20.57
7.3	0.0211	9.5	901.3	19.00
8.6	0.0183	12.5	1186.2	21.72
9.9	0.0133	14.7	1401.8	18.58
11.1	0.0090	17.2	1642.3	14.72
12.4	0.0080	20.0	1909.5	15.19
13.7	0.0067	23.2	2205.4	14.76
15.0	0.0051	24.8	2359.4	11.92
16.3	0.0029	28.4	2702.6	7.85
17.5	0.0020	30.3	2882.5	5.82
18.8	0.0019	30.2	2872.5	5.44
20.1	0.0005	40.0	3812.5	1.93
21.4	0.0006	42.2	4018.7	2.54
22.7	0.0008	45.5	4337.9	3.29
24.0	0.0005	49.0	4668.9	2.36
25.2	0.0001	51.4	4896.1	0.62
26.5	0.0003	55.1	5246.7	1.32
27.8	0.0001	58.9	5609.0	0.71
29.1	0.0003	61.5	5856.9	1.48
			Total	**230.53**

Figure B-36. “Design Reach” tab, Red River example inputs.

B.2.2.7 Results Tab

The “Results” tab will automatically be selected after the tool is run (Figure B-37). This tab will have a summary of the major results for the analysis. The family of stable channel design solutions found by the program with CSRs = 1 is graphed at the top left of the tab. This is analogous to the output of Copeland’s Stable Channel Design Tool in HEC-RAS.



Stable Geometries				Planform Characteristics					
Width (ft)	Width (m)	Slope	CSR	w/h Ratio	Sinuosity	Braiding Risk	Belt Width(m)	Min Wavelength(m)	Max Wavelength(m)
3	1	0.00737	0.999	1	1.03	Low	13	11	12
7	2	0.00603	0.998	2	1.26	Low	33	23	25
10	3	0.00582	0.998	4	1.31	Low	41	34	37
13	4	0.00579	1.002	5	1.31	Low	47	45	50
16	5	0.00583	1.002	6	1.30	Low	52	56	62
20	6	0.00586	1.001	7	1.30	Low	57	68	75
23	7	0.00593	0.998	8	1.28	Low	61	79	87
26	8	0.00616	1.000	10	1.23	Low	62	90	100
30	9	0.00621	0.999	11	1.22	Low	66	101	112
33	10	0.00636	1.000	12	1.20	Low	67	113	125
36	11	0.00646	1.002	13	1.18	Low	68	124	137
39	12	0.00659	0.999	14	1.15	Low	68	135	150
43	13	0.00663	1.002	15	1.15	Low	70	146	162
46	14	0.00682	1.001	17	1.11	Low	66	158	175
49	15	0.00698	1.000	18	1.09	Low	62	169	187
52	16	0.00704	1.002	19	1.08	Low	62	180	200
56	17	0.00715	1.001	20	1.06	Low	58	191	212
59	18	0.00728	1.000	21	1.04	Low	51	203	224
62	19	0.00733	1.000	23	1.04	Low	50	214	237
66	20	0.00755	1.000	24	1.01	Low	33	225	249

Figure B-37. "Results" tab, Red River example.

Stable Geometries

To the right of the plot, the individual stable slope/width combinations are listed in Columns N–P. Column Q shows the associated CSR for each solution. The solutions are selected because they are within 0.025 of a CSR = 1 which will pass the incoming sediment load from the supply reach with minimal degradation or aggradation. In this example, the dimensions and channel characteristics were matched for the supply and design reach to verify the accuracy of the program output. If these characteristics are matched, then the bottom width and slope of the supply reach should be a solution in the family of stable channel design solutions since the same channel could pass the same sediment yield. This can be seen for this example in Figure B-37. The bottom width for the supply reach is 7.6 m and the slope is 0.006. This solution lies between Rows 11–12 for the solutions in Columns N–P.

Planform Characteristics

The outputs for planform calculations are displayed in Columns R–W. Column R is the width versus bankfull depth based on the bank height specified on the design reach tab. The input of the valley slope for the stream allows the program to calculate the sinuosity (Column S), the braiding risk (Column T), and the belt width (Column U) for each solution. Rows 13–18 in Column U is highlighted red because the estimated belt width + buffer is larger than the maximum meander belt width that was specified on the design reach inputs. The estimate for the wavelength based on the 95% confidence interval presented by Soar and Thorne (2001) is displayed in Columns V–W. See ‘Planform Characteristics’ in the CSR Tool Reference Manual (Appendix A) and the ”Quick Reference Guide” tab for more information on the planform concepts.

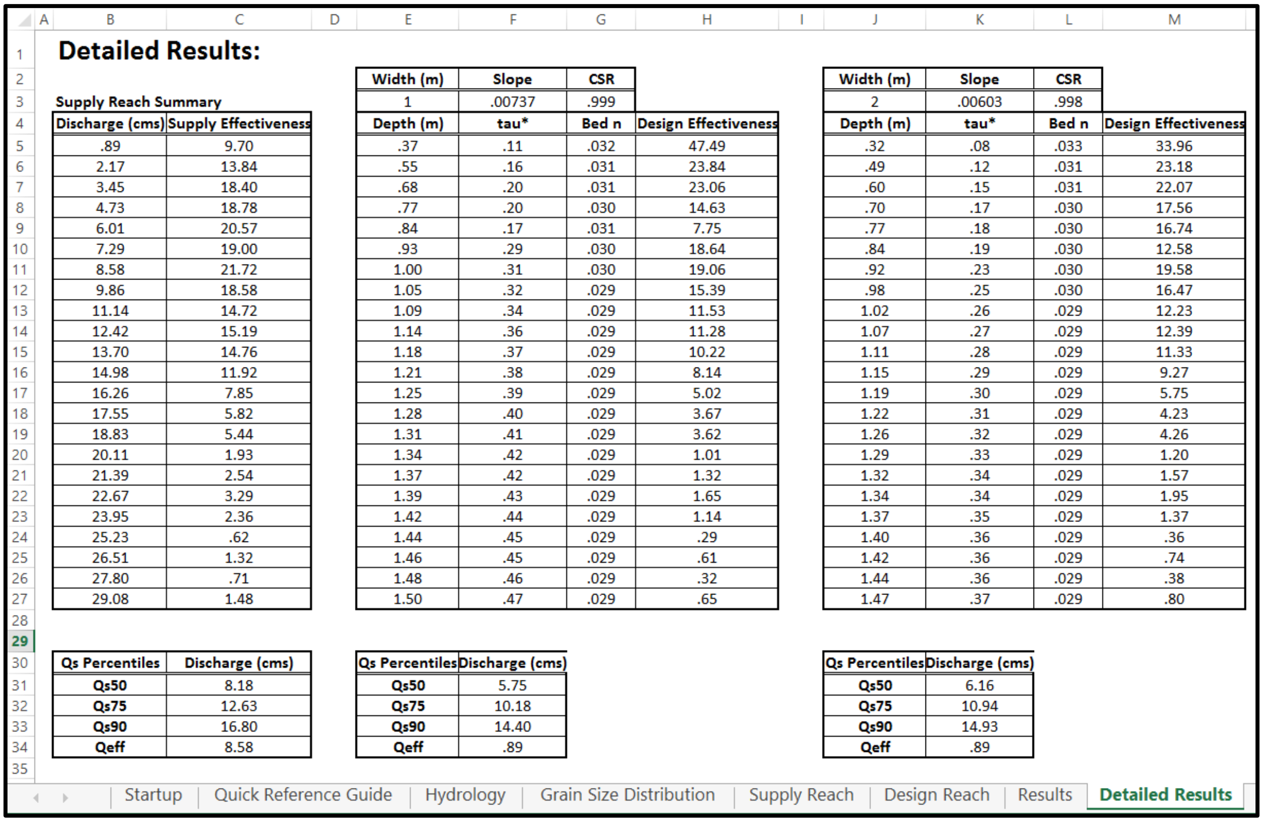
Design Reach Geometry

Similar to the supply reach, a visual of the simplified trapezoidal channel used in the calculations is displayed for the design reach. For the design reach, the bottom width varies for each stable solution, so the width is set at an arbitrary length.

B.2.2.8 Detailed Results tab

In addition to the “Results” tab, a “Detailed Results” tab is also created when the CSR analysis is run (Figure B-38). This tab exhibits more-detailed outputs of the analysis per discharge bin for each stable channel solution. Columns B–C of the tab give a summary of the average discharge of each bin used for the supply and design reach calculations and the supply reach effectiveness for each bin. To the right of this summary are the detailed results for each stable channel design solution. The slope/width and CSR is displayed at the top of each result box. The results report the depth, dimensionless shear stress (τ^*), Manning’s *n* of the channel bed, and the effectiveness calculated for each discharge bin.

Below each solution, there are separate boxes that give a summary of the sediment transport percentiles for each solution (see Sediment Percentiles in the CSR Tool Reference Manual (Appendix A)). The effective discharge (Q_{eff}) or the discharge bin that moves the most sediment is presented. Also, the discharges corresponding to the percentiles Q_{s50}, Q_{s75}, and Q_{s90} are linearly interpolated from the effectiveness curve for each solution. These discharges represent the discharges that move 50%, 75%, and 90% of the total sediment yield, respectively.



Detailed Results:

Supply Reach Summary

Discharge (cms)	Supply Effectiveness
.89	9.70
2.17	13.84
3.45	18.40
4.73	18.78
6.01	20.57
7.29	19.00
8.58	21.72
9.86	18.58
11.14	14.72
12.42	15.19
13.70	14.76
14.98	11.92
16.26	7.85
17.55	5.82
18.83	5.44
20.11	1.93
21.39	2.54
22.67	3.29
23.95	2.36
25.23	.62
26.51	1.32
27.80	.71
29.08	1.48

Width (m)	Slope	CSR
1	.00737	.999

Depth (m)	tau*	Bed n	Design Effectiveness
.37	.11	.032	47.49
.55	.16	.031	23.84
.68	.20	.031	23.06
.77	.20	.030	14.63
.84	.17	.031	7.75
.93	.29	.030	18.64
1.00	.31	.030	19.06
1.05	.32	.029	15.39
1.09	.34	.029	11.53
1.14	.36	.029	11.28
1.18	.37	.029	10.22
1.21	.38	.029	8.14
1.25	.39	.029	5.02
1.28	.40	.029	3.67
1.31	.41	.029	3.62
1.34	.42	.029	1.01
1.37	.42	.029	1.32
1.39	.43	.029	1.65
1.42	.44	.029	1.14
1.44	.45	.029	.29
1.46	.45	.029	.61
1.48	.46	.029	.32
1.50	.47	.029	.65

Width (m)	Slope	CSR
2	.00603	.998

Depth (m)	tau*	Bed n	Design Effectiveness
.32	.08	.033	33.96
.49	.12	.031	23.18
.60	.15	.031	22.07
.70	.17	.030	17.56
.77	.18	.030	16.74
.84	.19	.030	12.58
.92	.23	.030	19.58
.98	.25	.030	16.47
1.02	.26	.029	12.23
1.07	.27	.029	12.39
1.11	.28	.029	11.33
1.15	.29	.029	9.27
1.19	.30	.029	5.75
1.22	.31	.029	4.23
1.26	.32	.029	4.26
1.29	.33	.029	1.20
1.32	.34	.029	1.57
1.34	.34	.029	1.95
1.37	.35	.029	1.37
1.40	.36	.029	.36
1.42	.36	.029	.74
1.44	.36	.029	.38
1.47	.37	.029	.80

Qs Percentiles	Discharge (cms)
Qs50	8.18
Qs75	12.63
Qs90	16.80
Qeff	8.58

Qs Percentiles	Discharge (cms)
Qs50	5.75
Qs75	10.18
Qs90	14.40
Qeff	.89

Qs Percentiles	Discharge (cms)
Qs50	6.16
Qs75	10.94
Qs90	14.93
Qeff	.89

Figure B-38. “Detailed Results” tab, Red River example.

REFERENCES

Biedenharn, D.S., R.R. Copeland, C.R. Thorne, P.J. Soar, R.D. Hey, and C.C. Watson. 2000. "Effective Discharge Calculation: A Practical Guide." *Technical Report No. ERDC/CHL TR-00-15*, U.S. Army Corps of Engineers, Engineer Research and Development Center, Vicksburg, MS.

Brownlie, W.R. 1981. "Prediction of Flow Depth and Sediment Discharge in Open-channels." *Report No. KH-R-43A*, California Institute of Technology, W.M. Keck Laboratory, Pasadena, CA.

Brownlie, W.R. 1983. "Flow Depth in Sand-bed Channels." *Journal of Hydraulic Engineering*, Vol. 109, No. 7, pp. 959–990, DOI: 10.1061/(ASCE)0733-9429(1983)109:7(959).

Indiana Department of Environmental Management (IDEM). 2013. "Escherichia Coli and Impaired Biotic Community Total Maximum Daily Load Report for the Big Raccoon Creek Watershed." Prepared for the U.S. Environmental Protection Agency Region 5, 148 p., Draft URL: http://www.in.gov/idem/nps/files/tmdl_big_raccoon_report.pdf.

King, J.G., W.W. Emmett, P.J. Whiting, R.P. Kenworthy, and J.J. Barry. 2004. "Sediment Transport Data and Related Information for Selected Coarse-Bed Streams and Rivers in Idaho." *General Technical Report RMRS-GTR-131*, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 26 p., URL: http://www.fs.fed.us/rm/pubs/rmrs_gtr131.pdf\.

Montgomery, D.R., and J.M. Buffington. 1997. "Channel-reach Morphology in Mountain Drainage Basins." *Geological Society of America Bulletin*, Vol. 109, No. 5, pp. 596–611, DOI: 10.1130/0016-7606(1997)109<0596:CRMIMD>2.3.CO;2.

Parker, G. 1990. “Surface-based Bedload Transport Relation for Gravel Rivers.” *Journal of Hydraulic Research*, Vol. 28, No. 4, pp. 417–436, DOI: 10.1080/00221689009499058.

Rosburg T. 2015. “Flow Duration Curves and Sediment Yield Estimation for Urbanizing Watersheds.” M.S. Thesis, Colorado State University, Department of Civil and Environmental Engineering, Fort Collins, CO.

Soar, P.J., and C.R. Thorne. 2001. ”Channel Restoration Design for Meandering Rivers.” *Technical Report No. ERDC/CHL CR-01-1*, Coastal and Hydraulics Laboratory, U.S. Army, Engineer Research and Development Center, Vicksburg, MS, URL: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043218.pdf.

Wilcock, P.R., and J.C. Crowe. 2003. “Surface-based Transport Model for Mixed-size Sediment.” *Journal of Hydraulic Engineering*, Vol. 129, No. 2, pp. 120–128, DOI: 10.1061/(ASCE)0733-9429(2003)129:2(120).

Wilcock, P.R., S.T. Kenworthy, and J.C. Crowe. 2001. “Experimental Study of the Transport of Mixed Sand and Gravel.” *Water Resources Research*, Vol. 37, No. 12, pp. 3349–3358, DOI: 10.1029/2001WR000683.

B.3 Abbreviations and Symbols

Acronyms

CSR	Capacity-Supply Ratio
CSR Tool	CSR Stable Channel Design Tool
eRAMS	Environmental Risk Assessment & Management System
FDC	flow duration curve
HEC-RAS	Hydrologic Engineering Centers River Analysis System
IDEM	Indiana Department of Environmental Management
PDF	probability density function
SWAT	Soil and Water Assessment Tool
SWAT-DEG	channel DEGradation portion of SWAT
VBA	Visual Basic for Applications
USGS	U.S. Geological Survey

Symbols

D_{16}, D_{84}, D_{90}	particle size for which 16%, 84%, and 90% of all sediments is smaller, respectively
D_{50}	median grain diameter of the bed material (m)
D_g	geometric mean
n	Manning's roughness coefficient
Q	water discharge rate
$Qeff$	effective discharge
Q_{s50}, Q_{s75}, Q_{s90}	discharge associated with 25%, 50%, 75%, and 90% of cumulative sediment transport over the sorted flow record, respectively
σ_g	geometric standard deviation of particles sizes

Units of Measure

°C	degree(s) Celsius
cfs	cubic feet per second
ft	foot or feet
m	meter(s)
m^3/s	cubic meter(s) per second
$m^3/s/m$	cubic meter(s) per second per meter
mm	millimeter(s)
ppm	part(s) per million
%	percent
yr(s)	year(s)

LIST OF ABBREVIATIONS

CSR	Capacity/Supply Ratio
CSR Tool	CSR Stable Channel Design Tool
eRAMS	Environmental Risk Assessment & Management System
EPA	U.S. Environmental Protection Agency
FDC	flow duration curve
HEC-RAS	Hydrologic Engineering Center – River Analysis System
MFA	magnitude-frequency analysis
R-B Index	Richards-Baker Flashiness Index
SAM	Hydraulic Design Package for Channels
SWAT	Soil and Water Assessment Tool
SWAT-DEG	channel DEGradation portion of SWAT
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VBA	Visual Basic for Applications