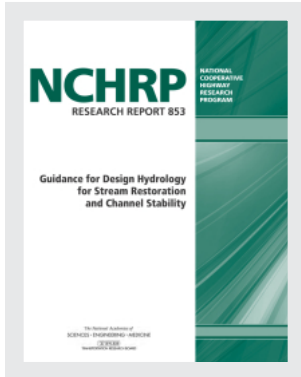


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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 853

**Guidance for Design Hydrology
for Stream Restoration
and Channel Stability**

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2017

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Dr. Brian Bledsoe, P.E. (Professor), was the project director and primary principal investigator; Dr. Peter Nelson (Assistant Professor) and Dr. Daniel Baker (Research Scientist) were co-principal investigators. The other authors of this report are graduate research assistants: Tyler Rosburg (MS candidate), Joel Sholtes (PhD candidate), and Travis Stroth (MS candidate) at CSU. The work was done under the general supervision of the primary principal investigator and two co-principal investigators.


FOREWORD

By **Waseem Dekelbab**

Staff Officer

Transportation Research Board

This guidance describes scientifically supported methods for defining the design hydrology for stream restoration and channel stability at stream crossings with a set of decision support tools that are both science-based and practical in guiding users to an appropriate combination of design tools and depth of analysis for design hydrology in a given hydrologic and geomorphic setting. Specifically, the guidance and tools provide support in: (1) assessing the current conditions adjacent to a stream crossing and in the upstream watershed to determine design effort, (2) performing the appropriate hydrological and geomorphic analysis using a set of analytical and analog tools, and (3) designing the channel through the stream crossing for stability and sediment balance. The hydrologic metrics and tools developed in this project provide a general framework and stronger physical basis for design hydrology at stream crossings, including locations where watershed land use is changing. This report will be of immediate interest to hydraulic engineers.

Significant resources are being applied by public and private highway and rail organizations to design and construct restored streams in disturbed watersheds as well as to provide for stable transportation crossings (bridges and culverts) of streams. Lacking in this effort was a scientifically supported method for (1) defining the design hydrology for such efforts and (2) understanding how that design hydrology might change with land use changes.

Much stream restoration and stream stability work is performed at sites where the upstream watershed is experiencing changes in land use and runoff characteristics. These changes affect not only peak discharges, but also flow duration relationships, total runoff volume, stream power, sediment supply, and sediment transport. Increases or decreases in net sediment transport potential imply changes in the character of channel-forming discharge, consequently affecting both the geometry and stability of existing stream channels.

Understanding how hydrology may vary over time or with changes in the watershed is a weak link in protecting highway infrastructure from the effects of stream instability. Research was needed to quantify the effect of these hydrologic changes on the channel-forming discharges and the resulting channel geometry that are important in designing culverts and bridges for long-term performance.

Research was performed under NCHRP Project 24-40 by Colorado State University to develop guidance based on a scientifically supported method for determining the design hydrology for stream restoration and channel stability at stream crossings and for understanding how that design hydrology might change over time. Several decision support/analysis tools were developed to improve and facilitate design hydrology analyses: (1) a decision tree to be used with web-based hydrologic analysis tools (erams.com) for generating design hydrology metrics under existing and future land use scenarios, (2) guidance on relating

channel response potential to an appropriate level of design analysis, (3) guidance on selecting analog reaches, (4) guidance on performing rapid geomorphic assessments of channel instability in the field, and (5) a spreadsheet-based Capacity Supply Ratio Tool (CSR Tool) for computing analytical channel designs that account for the full spectrum of sediment transporting events.

This research report is Appendix C of the research agency's final report, which documents the entire research effort. The research agency's final report including Appendices A, B, and D is available on the summary web page for *NCHRP Research Report 853*. The three appendices are titled as follow:

- Appendix A—Site-Specific Information for Study Sites
- Appendix B—Tutorials for the use of eRAMS (the Environmental Resource Assessment & Management System)
- Appendix D—Reference Manual: CSR Tool

The CSR Tool and two illustrative examples for different stream types (sand bed and gravel/cobble bed) are also available on the summary web page for *NCHRP Research Report 853*.



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CHAPTER 1

Introduction

Significant resources are being applied by public and private road and rail organizations to design and construct restored streams in disturbed watersheds, as well as to provide for stable transportation crossings (bridges and culverts) of streams. Lacking in this effort is a scientifically supported method for defining the design hydrology for such efforts along with an understanding of how that design hydrology might change with land use changes.

Current practice in hydrologic design of stable channels at stream crossings focuses on a single “dominant” discharge that is assumed to be a reasonable surrogate for the entire range and temporal sequence of channel-forming flows. The channel-forming discharge is typically identified and “bankfull” field indicators (a challenging task even in minimally disturbed channels), recurrence interval analysis of peak flows (often extrapolated from gaged to ungaged sites), regional flood regression relationships, or a combination of these methods. Such methods can be problematic because they oversimplify the physical controls on channel form and response, and frequently result in channel designs that are unstable.

A more robust alternative to stable channel design hydrology has converged on the idea that a sediment continuity or “sediment impact analysis” should underpin the design of most alluvial channels (Copeland et al. 2005; Soar and Thorne 2001, 2011; Natural Resources Conservation Service (NRCS) 2007; Shields et al. 2003, 2008; Doyle et al. 2007), especially fine-grained or “labile” channels. One of the greatest impediments to adoption of these methods in practice has been the lack of (1) decision support and analysis tools for discerning which design situations require such an analysis and (2) practical tools generating key inputs and performing the analyses. This document addresses this gap by summarizing guidance and a set of decision support tools that are scientifically based and practical. The decision support tools presented herein are intended to be flexible and efficient in guiding users to an appropriate combination of design tools and depth of analysis for design hydrology in a given hydrologic and geomorphic setting. Additional data and effort are only required when necessary for the channel type and design situation of interest.



CHAPTER 2

The Design Hydrology Process

2.1 Overview of the Design Hydrology Process

There are two primary phases to the design hydrology for stream restoration and channel stability at stream crossings (hereafter “design hydrology”) process:

- **Phase 1: Assess the Current Conditions Adjacent to the Stream Crossing and in the Watershed to Determine Design Effort.** This phase includes gathering available data related to hydrology, land use, stream bed material, and current channel conditions, as well as the availability of a stable analog reach, to determine the appropriate level of design hydrology analysis.
- **Phase 2: Design the Stream Channel Through the Stream Crossing.** After the appropriate type of analysis has been determined, a set of analytical and analog tools are used to perform the appropriate hydrological analysis and ultimately design a stable channel.

Each phase relies on a mix of decision support and software tools, and requires input from desktop, field, and design phases. Additional details on the scientific basis and development of these tools are provided in Colorado State University’s final report for NCHRP Project 24-40 [downloadable from the *NCHRP Research Report 853* summary page on the TRB website (www.trb.org)]. The goal of this process is to identify the appropriate tools and level of analysis given the conditions of each stream crossing.

The first step in hydrologic design for stream crossings is to define goals and objectives with respect to channel stability, sediment continuity, flood conveyance, environmental considerations, and many other factors. Once goals and objectives are defined, the two phases can be initiated.

2.2 Overview of Phases 1 and 2

The following subsections present the design hydrology processes for Phases 1 and 2:

- **Phase 1** (Section 2.3):
 - Subsection 2.3.1: Bed Material versus Flashiness
 - Subsection 2.3.2: ω^* Versus Flashiness
 - Subsection 2.3.3: Simplified Rapid Geomorphic Assessment
 - Subsection 2.3.4: Analog Reach Guidance
 - Subsection 2.3.5: Selection of the Design Hydrology Approach
- **Phase 2** (Section 2.4):
 - Subsection 2.4.1: Establish a Sediment Supply Reach
 - Subsection 2.4.2: Evaluate Whether Additional Field Reconnaissance Is Needed
 - Subsection 2.4.3: Perform Channel Design Using the Set of Recommended Methods
 - Subsection 2.4.4: Compare Channel Designs to Analog Design(s)
 - Subsection 2.4.5: Select a Robust Design

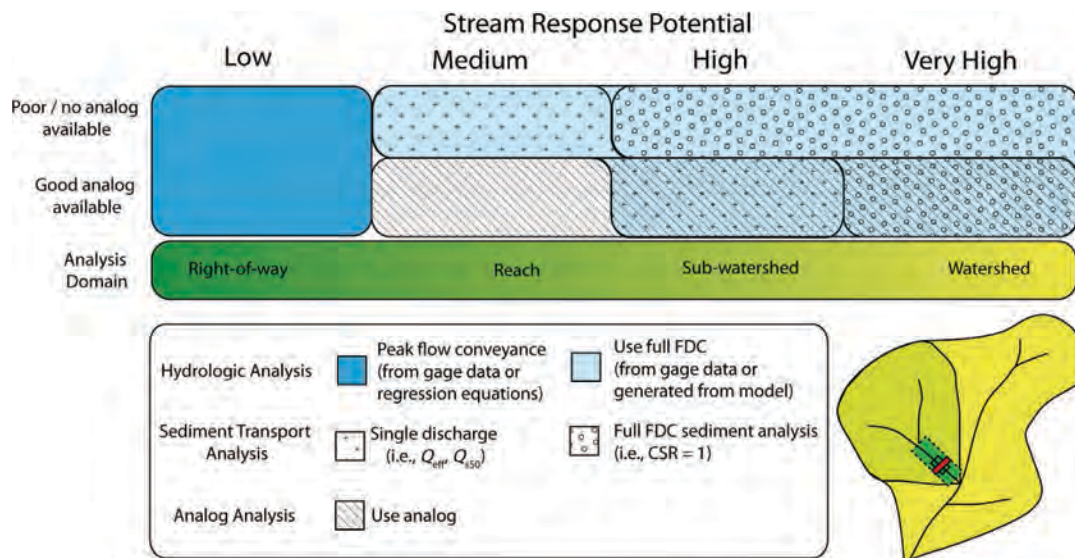
2.3 Phase 1: Assess the Current Conditions Adjacent to the Stream Crossing and in the Watershed to Determine Design Effort

Both Phases 1 and 2 can be related to the overall decision table found in Figure 2-1. Phase 1 is the process of relating stream response potential (SRP) and the availability of an analog reach (also referred to as a reference reach) to determine the appropriate level of design analysis. This phase incorporates the following questions: (1) How does the availability of an analog reach change the level of design guidance? (2) What level of hydrologic analysis should be undertaken? (3) Is it appropriate to perform sediment transport analysis, and, if so, what type of analysis is needed? (4) What spatial domain (i.e., how far upstream and/or downstream from the project location) is recommended for conducting the analysis? The fundamental philosophy underlying this approach is that, as SRP increases, it becomes necessary to conduct a deeper analysis over a larger area of the stream and its watershed.

At the core of this phase is the evaluation of SRP, which is positively correlated with the amount of design effort (Figure 2-2). The multiple methods to evaluate SRP are discussed in the following subsections.

2.3.1 Bed Material Versus Flashiness

The first-cut estimate of the SRP is based upon a visual quantification of the channel bed material adjacent to the stream crossing and the flow regime flashiness (i.e., the frequency and rapidity of short-term changes in streamflow)—as computed in the desktop phase. The general trend related in Table 2-1 is that less erosive bed material and low levels of flashiness typically result in lower SRP than live-bed systems with high flashiness.



FDC = flow duration curve; Q_{eff} = effective discharge;

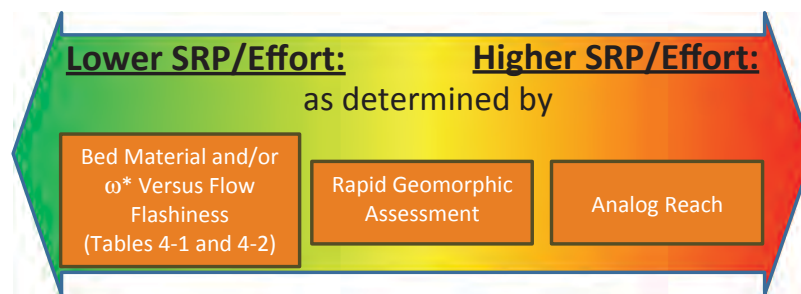
Q_{s50} = discharge associated with 50% of cumulative sediment transport over the sorted flow record;

CSR = capacity-supply ratio.

If a field rapid geomorphic assessment indicates high or very high susceptibility and response potential in the design reach, then shift to the next higher level of stream response potential and design analysis.

Figure 2-1. Decision table providing guidance on the level of design hydrology analysis.

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The boxes at the bottom of the arrow are multiple methods to help evaluate the stream response potential. ω^* is defined as the dimensionless specific stream power.

Figure 2-2. Determination of system risk and associated design effort.

2.3.2 ω^* Versus Flashiness

A fundamental physical relationship that is missing from Table 2-1 is a ratio of flow energy relative to boundary material resistance. A more physically based alternative to Table 2-1 quantifies flow energy relative to dominant bed grain size using dimensionless specific stream power (ω^*), a robust predictor of sediment transport capacity. However, the tradeoff is that field data on grain size will be required for the accurate estimation of dimensionless specific stream power. When it is feasible to collect representative grain size data, the following approach can provide a more rigorous assessment of response potential.

Dimensionless specific stream power is defined as:

$$\omega^* = \frac{\omega}{\rho[g(G-1)D_{50}]^{3/2}} \tag{2-1}$$

where:

ω = specific stream power [W/m^2] = $\rho gQS/w$; where: ρ = density of the fluid mixture [kg/m^3], g = gravitational acceleration [m/s^2], Q = median annual peak flow (Q_2) [m^3/s], S = channel slope [m/m], and w = channel top width [m];

Table 2-1. SRP decision table used to define classes corresponding to different design hydrology strategies based on bed material and flow regime flashiness.

Bed Material ^a	Flow Regime Flashiness ^b		
	R-B Index ^c ≤ 0.2	0.2 < R-B Index ≤ 0.5	0.5 < R-B Index
Boulder / resistant hard pan	Low	Low	Medium
Armored cobble / coarse gravel with assorted sizes tightly packed, overlapping, and possibly imbricated; most material > 4 mm (0.16 in.); $F_s < 20\%$, mostly boulders / cobbles / coarse gravel	Medium	Medium	High
Transitional: unarmored containing moderately packed to loose assortment with $20\% < F_s < 50\%$	Medium	High	Very High
Live bed: very loose assortment with no packing; large amounts of material < 4 mm (0.16 in.); $F_s > 50\%$, mostly sand and finer	High	Very High	Very High

^a F_s = approximate fraction of sand in bed sediments.

^b For braiding and/or rapid urbanization (~10% increase in urban land cover per decade), move to next higher category.

^c R-B Index = Richards-Baker Flashiness Index.

G = specific gravity of sediment (2.65 is typically assumed); and
 D_{50} = median grain diameter of the bed material [m].

Note that for live-bed channels with fine bed materials dominated by sands, silts, and clays, it is recommended to defer to the susceptibility class from Table 2-1 as opposed to computing the class associated with specific stream power (Table 2-2). Discussion and specifications on how grain sizes are sampled are found in Bunte and Abt (2001); note that approaches differ between channel types (e.g., sand versus armored gravel). Also, for guidance on combining sieve and pebble count data, see Bunte and Abt (2001).

If Table 2-1 and/or Table 2-2 indicate a low SRP and the system shows no signs of instability based on *Hydraulic Engineering Circular No. 20* (HEC-20; Lagasse et al. 2012), it may be possible to proceed to Phase 2. However, if the appropriate SRP for the stream crossing is still unclear, the tools described in Subsections 2.3.3 and 2.3.4 provide additional lines of evidence to support making a decision on the appropriate level of design.

2.3.3 Simplified Rapid Geomorphic Assessment

The guidance and figures in this subsection support rapid geomorphic assessments (RGAs) of channel instability and susceptibility at stream crossings. This overtly simple approach is intended to complement more comprehensive and rigorous methods, most notably HEC-20, by orienting engineers to some key considerations during field reconnaissance early in the design hydrology process. **If the RGA indicates high or very high susceptibility and response potential in the design reach, then it is recommended that the designer shift to the next higher level of SRP and design analysis.**

To develop a simplified RGA, the research team reduced a large pool of potential indicators to four:

- (1) Current stability status—Channel Evolution Model (CEM; Schumm et al. 1984) stage, braiding, alluvial fan
- (2) Dominant bed material/armoring potential
- (3) Distance to downstream hardpoint/grade control
- (4) Bank strength

High ratings of stream susceptibility based on these indicators trigger a higher level of design hydrology analysis as defined by the design decision table in Figure 2-1, and underscore the need for a greater stability analysis using more rigorous and comprehensive tools such as HEC-20.

A further understanding of the SRP for a stream crossing can be developed through an RGA. The first consideration in the simplified RGA procedure is to identify early “off-ramps” (Figure 2-3)—characteristics that are indicative of fluvial geomorphic extremes. Streams not

Table 2-2. SRP decision table used to define classes corresponding to different design hydrology strategies based on dimensionless specific stream power at the median annual peak flow (Q_2) and flow regime flashiness.

Flow Power at Q_2 Relative to Bed Material (ω^*)	Flow Regime Flashiness		
	R-B Index ≤ 0.2	$0.2 < \text{R-B Index} \leq 0.5$	$0.5 < \text{R-B Index}$
$\omega^* \ll O[0.1]$	Low	Low	Medium
$\omega^* \sim O[0.1]$	Medium	Medium	High
$\omega^* \sim 0.3$ to $O[1]$	Medium	High	Very High
$\omega^* \sim O[1]$ or higher	High	Very High	Very High

O = on the order of.

ω^* = dimensionless specific stream power.

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Low	Medium	High	Very High
Boulder			Sand/Fine Gravel
			CEM Stage III
			Braiding

Figure 2-3. Early off-ramps in the RGA of low risk (boulder-dominated stream beds) and very high risk [sand/fine gravel-dominated stream beds, CEM Stage III (channel incised past critical bank height for geotechnical failure and mass wasting), or active braiding].

exhibiting the early off-ramp conditions would warrant examination of the secondary factors. For example, a stream bed dominated by medium to coarse gravels could be as sensitive as a very high risk category if its banks were weak (alluvium lacking vegetation) and it lacked grade control. However, the same stream bed could be low risk if it had strong banks (bedrock/boulder) and frequently spaced grade control. Cases in between would be either medium or high risk according to Figure 2-3. Likewise, bed material dominated by small cobbles/very coarse gravels would range from low to high risk depending on bank strength and hardpoint frequency, and beds dominated by large cobbles would range from low to medium risk (Figure 2-4).

Channel responses may propagate for significant distances downstream (and sometimes upstream) from a point of influence such as a stormwater outfall or stream crossing. Accordingly, it may be necessary to conduct field reconnaissance across a domain spanning multiple channel segments and property owners. The research team recommends that the typical analysis

Bed Material = Medium to Coarse Gravel			
Frequency of Hardpoint(s)	Strong Banks (bedrock/boulder/ coarse cobble)	Moderate (cohesive/ well vegetated)	Weak Banks (alluvium/ poorly vegetated)
None/infrequent	High	High	Very High
Intermediate	Med	High	High
Frequent	Low	Med	High

Bed Material = Small Cobbles/Very Coarse Gravel			
Frequency of Hardpoint(s)	Strong Banks (bedrock/boulder/ large cobble)	Moderate (cohesive/ well vegetated)	Weak Banks (alluvium/ poorly vegetated)
None/infrequent	Med	Med	High
Intermediate	Low	Med	Med
Frequent	Low	Low	Med

Bed Material = Large Cobbles			
Frequency of Hardpoint(s)	Strong Banks (bedrock/boulder/ large cobble)	Moderate (cohesive/ well vegetated)	Weak Banks (alluvium/ poorly vegetated)
None/infrequent	Low	Med	Med
Intermediate	Low	Low	Med
Frequent	Low	Low	Low

Figure 2-4. RGA risk categories for beds ranging from coarse gravels to large cobbles across a gradient of bank strength and hardpoint (grade control) frequency.

domain for conducting the RGA should be at least 20 channel widths upstream and downstream in accordance with the recent Caltrans (2015) guidance.

Begin by defining the points or zones along the channel reach(es) where changes in discharge or channel type are likely to occur (e.g., potential locations of outfalls or tributary inputs). Document any observed outfalls for final desktop synthesis and define the minimum upstream and downstream extents of analysis as follows:

- **Upstream**—for a distance equal to 20 channel widths *or* to grade control in good condition—whichever comes first. Within that reach, identify (1) hardpoints that could check headward migration and (2) evidence that headcutting is active or could propagate unchecked upstream.
- **Downstream**—until reaching the closest of the following:
 - At least one reach downstream of the first grade control point (but preferably the second downstream grade control location)
 - Tidal backwater/lentic waterbody
 - Equal-order tributary (Strahler 1952)¹
 - A two-fold increase in drainage area²

This (practicality-driven) guidance should not supersede the consideration of local conditions and sound engineering judgment.

Within the analysis domain, there may be several reaches that should be assessed independently based on either length or change in physical characteristics. In more urban settings, segments may be logically divided by other stream crossings, which may offer grade control, create discontinuities in the conveyance of water or sediment, etc. In more rural settings, changes in valley/channel type, natural hardpoints, and tributary confluences may be more appropriate for delineating assessment reaches. In general, the following criteria should trigger delineation of a new reach and hence a separate susceptibility assessment:

- 200 m or *ca.* 20 bankfull widths—it is difficult to integrate observations in the field over longer distances
- Distinct or abrupt change in grade or slope due to either natural or artificial features
- Distinct or abrupt change in dominant bed material or sediment conveyance
- Distinct or abrupt change in valley setting or confinement
- Distinct or abrupt change in channel type, bed form, or planform

2.3.4 Analog Reach Guidance

The analogy method has sometimes been used recklessly in design: Streams from different watersheds and even different physiographic regions with disparate hydrologic and sediment supply characteristics were used to define channel geometry in dissimilar settings. The decision support tool in Tables 2-3 and 2-4 helps users to identify upstream analogs that are very similar in terms of key criteria—such as the valley setting, boundary conditions, and inflowing loads of water and sediment—and to define supply reaches for sediment continuity analysis.

A good analog reach can serve to inform the level of analysis that is appropriate for a project's design hydrology; however, finding a suitable analog can be challenging. The four criteria in

¹In the absence of proximate downstream grade control or backwater, the confluence of an “equal-order tributary” should correspond to substantial increases in flow and channel capacity that should, in theory, correspond to significant flow attenuation; however, there is no scientific basis to assume that downstream channels of higher stream order are less susceptible than their upstream counterparts.

²An increase in drainage area greater than or equal to 100% would roughly correspond to the addition of an equal-order tributary.

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Table 2-3 are *required* to be met. If the analyst is unable to find an appropriate analog reach with a similar drainage area, similar channel type, and similar hydrology and that is stable, then exclusive reliance on an analytical design method is recommended. The eight criteria in Table 2-4 are *important*; hence, it is recommended that at least six of these criteria are satisfied to ensure the analog reach is an appropriate analog. If the analog reach is not on the same river, then the first question in Table 2-4 does not apply and that criterion is not met.

The research team defines “stable” after Biedenharn et al. (1997): “In summary, a stable river, from a geomorphic perspective, is one that has adjusted its width, depth, and slope such that there is no significant aggradation or degradation of the stream bed or significant planform changes (meandering to braided, etc.) within the engineering time frame (generally less than about 50 years).”

2.3.5 Selection of the Design Hydrology Approach

Phase 1 culminates in selection of the design hydrology approach. Use (1) the SRP for the stream crossing, (2) the existence (or absence) of a good analog reach, and (3) the outcome

Table 2-3. Required criteria for analog reach selection. The analog reach must meet 100% (4/4) of the criteria.

Topic	Question	Criterion Met If:	Context	References
Flow Regime	Do the sites have similar drainage area (within 20%)?	Yes	Rivers and streams are scaled in size by their drainage areas.	<ul style="list-style-type: none"> Environmental Resource Assessment & Management System (eRAMS; erams.com) online tool for delineation (simplified version in development) StreamStats online tool [U.S. Geological Survey (USGS) 2012] Arc Hydro Tools ArcGIS Toolkit
Flow Regime	Is the hydro-climatic system the same (i.e., how and when does the precipitation come: snow, winter rain, convective rain, monsoon)?	Yes	This is often less troublesome if the analog reach is close to the restoration reach, but can become an issue in mountainous areas with strong orographic effects (i.e., wet and dry side of the mountains).	<ul style="list-style-type: none"> Cheng et al. (2012) Poff (1996) Reidy Liermann et al. (2012) Sawicz et al. (2014)
Channel Type	Are the channel types the same?	Yes	Target channel type represents: (1) prevailing historical channel type that was previously stable (diagnose why departure occurred) in that location under current land use; OR (2) channel type is stable under same current land use, flow, and sediment supply in analog reach.	<ul style="list-style-type: none"> See Table 3-2 Church (2006) Lagasse et al. (2012) Montgomery and Buffington (1997) Rosgen (1994)
Stability	Is the analog reach largely stable?	Yes	CEM Stage I or V per Schumm et al. (1984) banks stable, no evidence of trends in aggradation/degradation, planform change, etc. over engineering time scales.	<ul style="list-style-type: none"> Lagasse et al. (2012) Schumm et al. (1984) Hawley et al. (2012)

Table 2-4. Important criteria for analog reach selection. The analog reach must meet 75% (6/8) of the criteria.

Topic	Question	Criterion Met If:	Context	References
Location	If on the same river, is the analog reach upstream of the project reach? (If analog reach is not on the same river, that criterion is not met.)	Yes	Restoration is often in response to disequilibrium (or instability), thus if instability exists at the restoration site, it is likely that this instability may persist downstream.	Learn more about the National Hydrography Dataset Viewer (http://nhd.usgs.gov/index.html)
Flow/Sediment Regime Alterations	Are there any noteworthy tributaries, dams, or intervening flow augmentations or extractions?	No	Tributaries, dams, and flow augmentations or extractions can initiate changes in the flow and sediment regimes.	Learn more about the National Hydrography Dataset Viewer (http://nhd.usgs.gov/index.html)
Valley Type Energy	Is the valley stream power (defined as the $S_v * Q_2^{0.5}$, where S_v = valley slope and Q_2 = 2-year return interval discharge) similar (within 20%)?	Yes	Stream power is the stream's ability to do work including the entrainment and transport of sediment.	Desktop estimates for the required parameters can be performed using: <ul style="list-style-type: none"> Valley slope from mapping tool that includes elevation (e.g., Google® Earth™) and Q_2 (for most locations in the United States) → StreamStats (USGS 2012) Bledsoe and Watson (2001) van den Berg (1995)
Valley Type Lateral Constraints	Are the lateral constraints (i.e., the influence or connectivity of the valley walls) similar? (Is the ratio of floodplain width to channel width within 30% between the analog and project reaches?)	Yes	The narrower and steeper the valley walls, the more connection (and influence) they will have on a river's planform, sediment inputs, and ability to self-adjust.	<ul style="list-style-type: none"> Desktop estimates can come from Google Earth imagery Nanson and Croke (1992) Whiting and Bradley (1993)
Flow Regime	Same hydrologic flashiness (within 30%)?	Yes	Flashiness (i.e., the frequency and rapidity of short-term changes in streamflow) influences the stability of a river channel.	<ul style="list-style-type: none"> Estimates for gaged sites can be found using the Flow Analysis toolkit in eRAMS (variable currently in downloadable data summary) Baker et al. (2004)
Land Use	Are the extent and nature of land use (e.g., curve number) similar between the two watersheds (within 20%)?	Yes	Watershed land use influences both flow regime and sediment supply in a river.	<ul style="list-style-type: none"> Can use SWAT-DEG (Soil and Water Assessment Tool—channel DEGradation) in eRAMS (currently in beta version) to estimate composite curve number for a watershed NRCS (1986)
Geologic Setting	Analogous physiographical region / geologic setting with respect to topography / valley slopes, soil types, and vegetation cover?	Yes	These watershed characteristics influence the magnitude and timing of runoff.	<ul style="list-style-type: none"> Booth et al. (2010) Reid and Dunne (1996) Vigil et al. (2000)
Bed Surface Sediment Characteristics	Are the bed surface grain size distributions similar (do not differ by more than ± one half phi class for D_{50} and D_{84})	Yes	The bed surface grain size is linked to sediment supply [e.g., Dietrich et al. (1989)].	<ul style="list-style-type: none"> Bunte and Abt (2001)

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from the RGA analysis to select the most appropriate combination of analyses (Figure 2-1) and transition to **Phase 2: Design the Stream Channel Through the Stream Crossing**. Note that if the RGA indicates high or very high susceptibility and response potential in the design reach, then it is recommended that the designer shift to the next higher level of SRP and analysis.

2.4 Phase 2: Design the Stream Channel Through the Stream Crossing

Phase 2 begins when the design analysis has been specified and includes a broad range of tools each targeted to a specific type of design. It is important for the designer to keep in mind that there are a range of channel design tools that each have their own inherent strengths, weaknesses, and assumptions. Thus, as the overall project risk increases, it is recommended that the number of evidence lines used in the final design increase as well (Figure 2-5).

2.4.1 Establish a Sediment Supply Reach

If flow duration curve (FDC)/half-load discharge ($Q_{.50}$) or FDC/capacity-supply ratio (CSR) sediment analysis is recommended based on Figure 2-5 and RGA, establish a sediment supply reach in the zone upstream of the crossing. This step includes collecting bed-material data and channel geometry [profile and cross section(s)] within the sediment supply reach. If the upstream reach is currently unstable, attempt to collect data within a subreach that appears closest to stability (if possible). Try to select a reach that (1) appears to be transporting its sediment without appreciable downcutting or aggradation and (2) is far enough upstream from hard-points (culverts, exposed bedrock, etc.) to avoid a depositional reach that could have overly fine bed material (Figure 2-6). If the sediment supply reach is currently stable, it may serve as the best analog reach for the design (i.e., there is no need to find another analog). If the sediment supply reach cannot also serve as the analog reach, establish an analog reach to meet as many suitability criteria as possible (Tables 2-3 and 2-4), and survey the analog if existing analog data are insufficient.

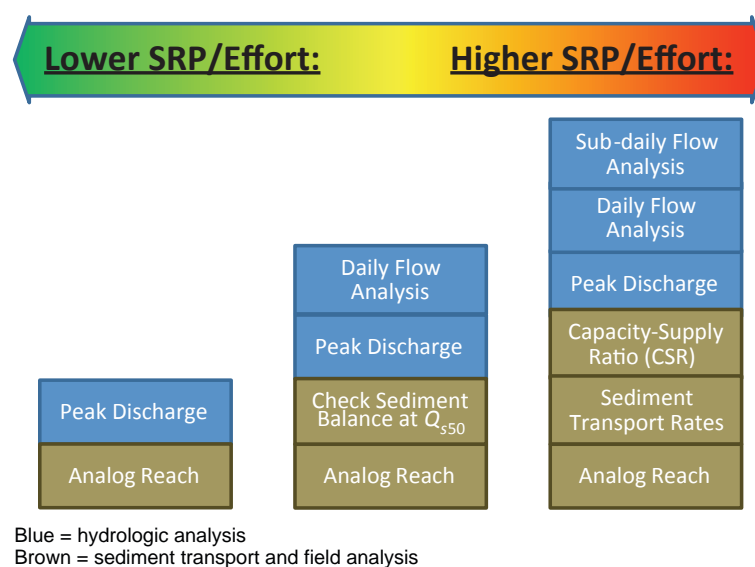
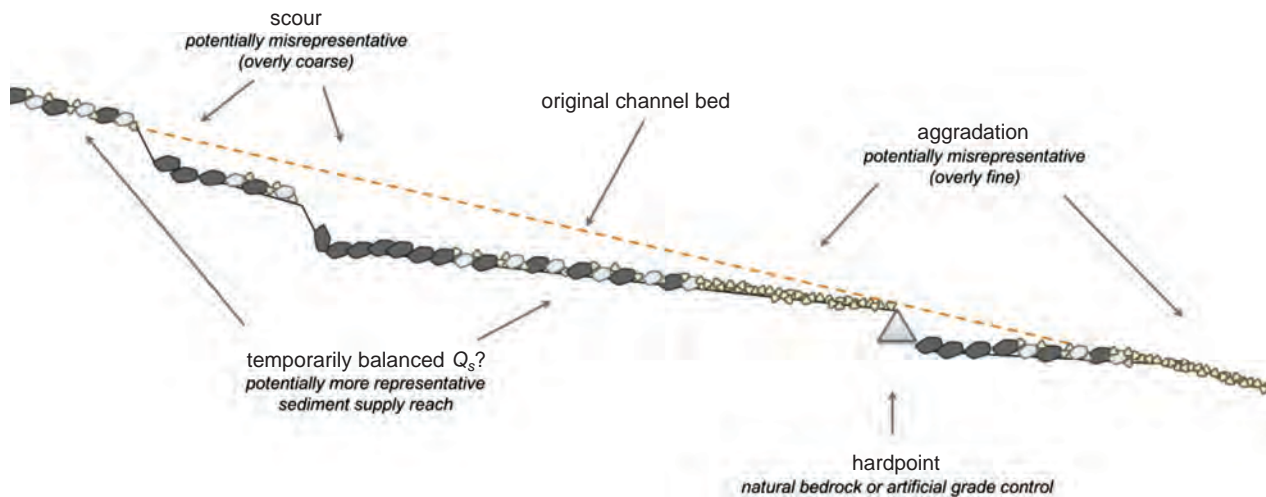


Figure 2-5. Lines of evidence required for design increase with stream response potential.



When selecting the sediment supply reach, the designer should use the reach or subreach that is most representative for sediment continuity. Avoid scour areas immediately downstream of headcuts or hardpoints, as well as aggradational areas immediately upstream of hardpoints. Subreaches that appear to be transporting their bedload without incision or aggradation (even temporarily) are more representative than segments that are more clearly downcutting or aggrading.

Figure 2-6. *Selecting the sediment supply reach.*

2.4.2 Evaluate Whether Additional Field Reconnaissance Is Needed

Additional field reconnaissance may be needed to provide requisite data for performing the recommended level of analysis [see Subsection 3.3 for the input requirements for the CSR Stable Channel Design Tool (CSR Tool)]. Perform additional bed material and geometric surveys as necessary. The field reconnaissance steps described previously are not intended to supplant engineering judgment and existing guidance. Instead, this approach is designed to be a relatively simple and user-friendly complement to the more comprehensive procedures described in HEC-20 (Lagasse et al. 2012).

2.4.3 Perform Channel Design Using the Set of Recommended Methods

For FDC/ Q_{50} design, apply the decision tree in Figure 2-7 and Environmental Resource Assessment & Management System (eRAMS; erams.com) guidance to compute Q_{50} . For full FDC sediment analysis design based on CSR, apply the CSR Stable Channel Design Tool (Subsection 3.3 and Chapter 4).

Details on how to approach each node in the decision tree, and examples of how Q_{50} is calculated using the decision tree and the tools, are provided in Subsection 3.2. Note that $Q_{1.5}$ is typically a reasonable surrogate for Q_{50} in coarse-/armored-bed channels. If CSR design is recommended, generate FDC using eRAMS or other means and apply the CSR Stable Channel Design Tool using appropriate inputs and selected sediment transport equation per guidance (in Subsection 3.3 and Chapter 4). The decision tree presents a series of questions regarding land use change, potential non-stationarity of the flow record, and the availability of stream gage data and sediment transport measurements to guide the user toward the best approach for calculating Q_{50} .

2.4.4 Compare Channel Designs to Analog Design(s)

Compare channel designs, via the Q_{50} and/or CSR Tool under current design hydrology, to analog design(s), if available. The FDC input to the CSR Tool can reflect current or projected

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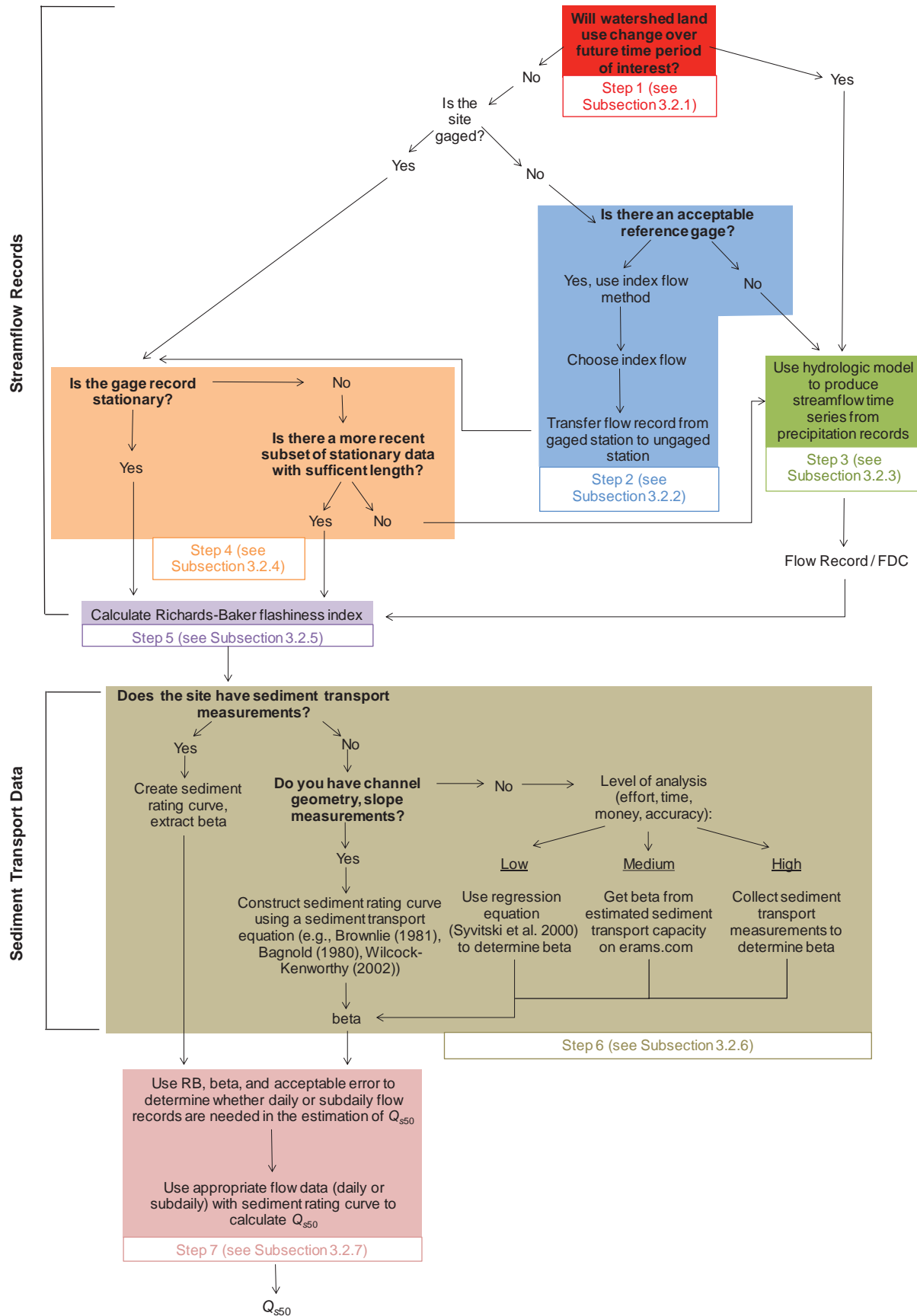


Figure 2-7. Decision tree supporting Q_{50} calculations.

future flow regimes that result from land use change. If hydrology is non-stationary, scenario analysis that examines sediment and water continuity of both near bankfull and overbank flood flows under both current and potential future hydrologic conditions [e.g., Soil and Water Assessment Tool—channel DEgradation (SWAT-DEG), Storm Water Management Model] is recommended. Additionally, if the sediment supply reach is currently unstable or there is uncertainty in its representativeness for future conditions, consider computing channel designs using several sediment supply reaches.

2.4.5 Select a Robust Design

Use weight of evidence to select a robust design and incorporate other design considerations per Soar and Thorne (2001), NRCS (2007), Shields et al. (2008), Hotchkiss and Frei (2007), and U.S. Forest Service (2008). Acknowledge other objectives, such as flood conveyance, managing debris, aquatic organism habitat and passage, etc., and use sound engineering judgment to make final recommendation.

2.5 Limits to the Application of This Process

The hydrology, form, and conditions of streams vary widely. As such the research team attempted to make the guidance as general as possible but, in the end, had to define the limits of applicability for the toolset. Table 2-5 summarizes the types of streams to which the guidance and tools apply and those to which they do not apply.

Table 2-5. Streams and situations to which the guidance and tools apply and situations where they are not directly applicable.

Applies:	Does Not Apply:
<ul style="list-style-type: none"> • Alluvial channels • Dune/ripple, pool-riffle, plane bedforms • Single-thread channels • Channel slope $\leq \sim 0.03$ • D_{50} of sand and larger • Near-perennial flow 	<ul style="list-style-type: none"> • Non-alluvial channels • Multi-thread, braided, fan channels • Channel slope $> \sim 0.03$ • Ephemeral, dryland rivers • Abrupt transitions • Channels that lack capacity to transport inflowing sediment load at valley slope • Severely backwatered/tidal situations • CSR Tool does not apply to boulders



CHAPTER 3

Guidance/Examples

3.1 Guidance/Examples Overview

The following subsections provide some guidance and step-by-step examples for several of the tools:

- Subsection 3.2: Guidance for Calculating the Half-Load Discharge (Q_{50})
- Subsection 3.3: Examples
 - Subsection 3.3.1: **Example 1:** Projecting hydrologic changes caused by changing land use for the Fourmile Creek watershed in central Iowa (Step 1)
 - Subsection 3.3.2: **Example 2:** Rainfall-Runoff Modeling of Box Elder Creek (Step 3)
 - Subsection 3.3.3: **Example 3:** Using eRAMS to calculate the Richards-Baker Flashiness Index of the Iowa River near Iowa City, Iowa (Step 5)
 - Subsection 3.3.4: **Example 4:** Using the Q_{50} decision tree for determining Q_{50} for the Iowa River near Iowa City, Iowa (Steps 1 Through 5)

Chapter 4 provides step-by-step guidance for each tab in the CSR Tool workbook. Chapter 5 presents two examples (sand bed and gravel/cobble bed) using the CSR Tool.

3.2 Guidance for Calculating the Half-Load Discharge

3.2.1 Step 1: Projecting Future Streamflow Behavior Caused by Changing Land Use

If a substantial change in land use in the basin is expected over the time period of interest, historical streamflow records may not act as a good predictor of future streamflow behavior. Hydrological models can be used to assess how much the flow regime is likely to change with changes in land use, and, if significant changes are likely to occur, models may be used to generate streamflow data consistent with future land use.

Many hydrological models have been applied to evaluate potential hydrologic impacts of basin-scale climate change and urban development (Praskievicz and Chang 2009), and some state agencies employ their own models for continuous hydrologic simulation (e.g., the Western Washington Continuous Simulation Hydrology Model 2012). Regardless of the chosen hydrological model, the hydrologic importance of potential future land use change may be evaluated by comparing model-predicted FDCs for current and projected land use scenarios. If a shift in the FDC due to land use change is predicted, it may be more appropriate to use the model-predicted FDC than historical streamflow records. Although uncalibrated models may accurately predict the direction of change in streamflow associated with land use change, accurate prediction of the magnitude of those changes likely requires a spatially calibrated model (Niraula et al. 2015).

See Example 1 for an illustration of how the SWAT-DEG tool in eRAMS may be used to assess shifts in an FDC due to potential land use changes.

3.2.2 Step 2: Choosing a Reference Streamflow Gage and Indexing Flow Records

At locations in which streamflow gaging records are unavailable, it becomes necessary to synthesize streamflow data from another source. The research team proposes using the index flow method to transfer streamflow records from a gaged location to an ungaged location. The reliability of this method is a function of the quality of the gaged record and the physiographical similarity of the watersheds.

Is There an Acceptable Reference Gage?

To produce a streamflow record for an ungaged basin using the index flow method, a reference gage is needed. The selection of a good reference gage is critical as its flow record will be scaled to the ungaged location using an index discharge. The reference gage should be located in a climate similar to the ungaged location as climate impacts both the magnitude and slope of a basin's FDC (Castellarin et al. 2012). Characteristics such as topography, vegetation, land use, soils, and watershed shape shall also impact FDC characteristics (Fennessey and Vogel 1990; Burt and Swank 1992; Musiak et al. 1975) and should be similar among analog and ungaged watersheds. Other factors being equal, nearby gages provide better relations for indexing streamflow records than remote stations (Searcy 1959). However, usable relations have been established between stations as far apart as 50 miles (Searcy 1959). Professional judgment is required to make a determination of whether an "acceptable" reference gage exists.

Choosing the Index Flow

When indexing an FDC for an ungaged basin, consideration must be given to selecting an appropriate index flow. Commonly used index flows include the mean annual runoff (Smakhtin 1997; Ganora et al. 2009), median daily runoff (Ley et al. 2011), and 2-year discharge (Watson et al. 1997). The index flow must be able to be estimated for the ungaged location; often, this is accomplished with regional regression equations (USGS 2012).

Estimating Streamflow Records at Ungaged Stations

[summarized from Biedenharn et al. (2000)]

1. Use a streamflow record from a gaged site in a physiographically similar watershed.
2. Divide the discharge series by the index discharge for the gaged site. This creates a dimensionless flow record for the gaged site. If more than one reference gage site is available, an average dimensionless flow record for all the sites can be developed. This step can be completed using eRAMS. The flow analysis tool within eRAMS allows users to create a dimensionless FDC from a number of stream gages. This tool is useful because it allows users to visually compare the slope and shape of FDCs they are considering using in their analysis. Ideally, the gages selected for creating the regional FDC will have a similar shape and collapse onto each other when indexed.

3. Compute the index flow for the ungaged site using regional regression equations (available from the National Streamflow Statistics Program: <http://water.usgs.gov/osw/programs/nss/index.html>).
4. Calculate the streamflow record for the ungaged site by multiplying the dimensionless flow record by the index discharge for the ungaged site.

3.2.3 Step 3: Using a Hydrologic Model to Produce Streamflow Time Series from Precipitation Records

See Example 2 for an example application of rainfall-runoff modeling using the SWAT-DEG tool in eRAMS.

Many methods and software packages exist for rainfall-runoff modeling, for an introduction, see Beven (2011). The SWAT-DEG Tool within eRAMS is a great resource for developing streamflow records from climatic data for watersheds throughout the country. An example of this application is given in Subsection 3.3.2 for Box Elder Creek in northern Colorado.

3.2.4 Step 4: Checking the Stationarity of Streamflow Records

The R-B Index can be calculated at gaged sites using the eRAMS Flow Analysis Tool. This is illustrated in Example 3.

Because some regions may be experiencing changes in climate that render historical hydrologic records less effective (Milly 2007), it is critical that the stationarity of a hydrologic record be checked before it is used. Methods for testing the stationarity of historical hydrologic records include Mann-Kendall testing (Hamed 2008; Kumar et al. 2009), Spearman's rank correlation method (Villarini et al. 2009; Kahya and Kalayci 2004), and Sen's slope (Kahya and Kalayci 2004). If the streamflow record is highly non-stationary, a hydrologic model may be appropriate for developing streamflow records. For gaged sites, a flow record of at least 15 to 20 years is needed to detect non-stationary behavior, especially for watersheds with inherently high values of R-B Index (see next subsection) and coefficient of variation.

3.2.5 Step 5: Calculating the Richards-Baker Flashiness Index

The R-B Index is calculated by first calculating the path length of flow changes over a given period of time. The path length is equal to the sum of the absolute values of day-to-day changes in discharge. This path length 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. The R-B Index is shown in Equation 3-1:

$$\text{R-B Index} = \frac{\sum_{i=1}^n |q_i - q_{i-1}|}{\sum_{i=1}^n q_i} \quad (3-1)$$

where:

q = daily-averaged discharge [m^3/s];

i = day; and

n = total number of days in the flow record.

3.2.6 Step 6: Obtaining a Sediment Rating Curve

Gaged Sites

If sediment transport measurements exist at a given site for a range of discharges, a sediment rating curve can be constructed. Sediment rating curves often take the form of a simple power

function: $Q_s = aQ^b$; where Q_s = sediment discharge rate, Q = water discharge rate [m^3/s], and a , b = best-fit regression parameters (Asselman 2000).

Ungaged Sites

For sites in which sediment transport measurements are not available, a range of options exist for synthesizing a sediment rating curve. If the channel geometry and slope measurements are available at the site, bedload or total load sediment transport equations can be used to create a sediment rating curve as appropriate based on the bed material and hydraulic conditions. Such equations provide an estimate of sediment transport rate for a given discharge and, by estimating the sediment transport at a range of discharges, a sediment rating curve can be established. It is very important to use an equation that is calibrated and tested for the conditions to which it is applied.

In instances where channel geometry measurements are not available, and collecting sediment transport data is cost or time prohibitive, other methods exist for estimating sediment rating curve parameters. The eRAMS platform has the functionality to provide sediment transport capacity estimates at varying discharges for either extracted or imported cross sections. To make these estimates, eRAMS allows the user to use either the Brownlie (1981), Bagnold (1980), or Wilcock-Kenworthy (2002) equations. The eRAMS platform will also perform the necessary regression and provide the user with the resultant sediment rating curve parameters. These capabilities are located within the channel cross-section analysis application (currently available at <https://beta.erams.com/>).

Sediment rating curves can also be estimated using generalized regression equations for ungaged sites (e.g., Syvitski et al. 2000). While rating curve coefficients and exponents may be predicted based on factors such as basin relief, mean annual air temperature, and latitude, such an approach is susceptible to large errors and may not reflect important local sources of sediment in a particular watershed context.

3.2.7 Step 7: Determining the Appropriate Resolution of Streamflow Data

Streamflow gaging stations in the United States generally provide data in both daily-averaged and 15-minute increments. Daily-averaged discharges, while convenient to use, may not always be appropriate for sediment transport calculations. Streams in urban areas or arid climates, or with small drainage areas, may exhibit rapid short-term variations in streamflow (Ågren et al. 2007; Graf 1977; Walsh et al. 2005). This type of streamflow is often termed “flashy.” Flashy streams may have flood events lasting only a few hours, causing the peak discharge to be much greater than the corresponding mean daily discharge (Biedenharn et al. 2000). In these situations, sediment transport can be underestimated. The degree of underestimation is a function of stream flashiness and the logarithmic slope of the sediment rating curve, b (Rosburg 2015). Using Figure 3-1, one can estimate the underestimation in Q_{s50} that would result from using daily-averaged flow data, instead of hourly flow data, as a function of the R-B Index (Baker et al. 2004) and sediment rating curve parameter, b .

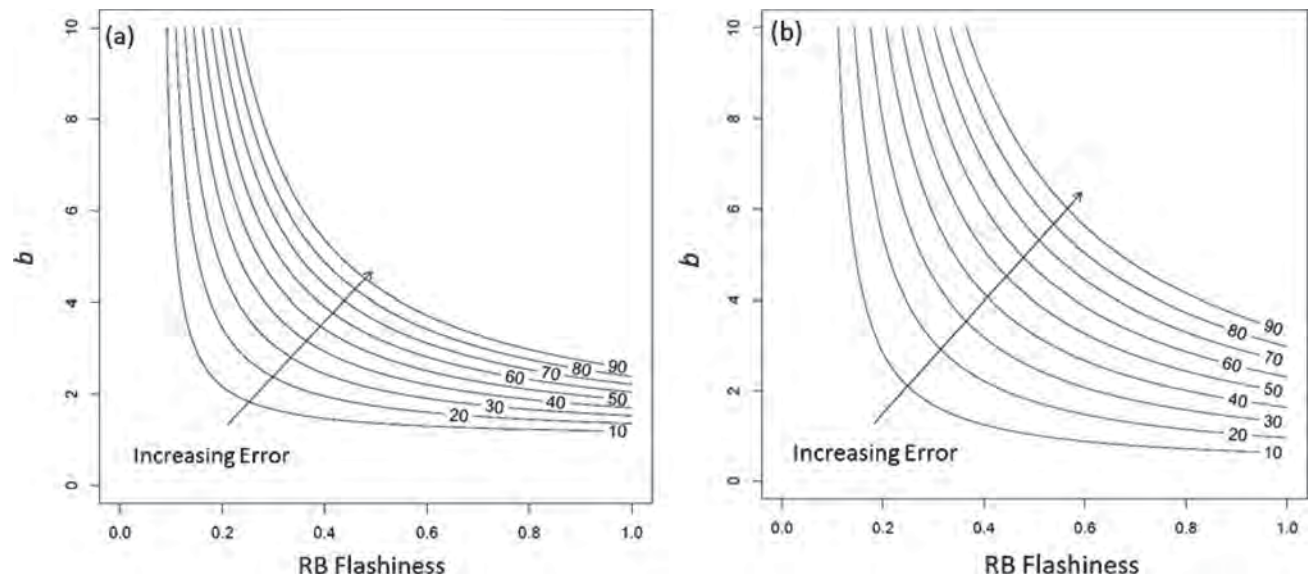


Figure 3-1. Percentage of underestimation of the half-load discharge (Q_{50}) (values labeled at the top of contours) when it is calculated with daily-averaged flow data instead of hourly flow data for (a) bedload sites and (b) suspended-load sites.

3.3 Examples

Much of the analysis needed to determine Q_{50} for a given site can be facilitated using tools built into eRAMS. These capabilities are illustrated in the following four examples.

3.3.1 Example 1: Projecting Hydrologic Changes Caused by Changing Land Use for the Fourmile Creek Watershed in Central Iowa (Step 1)

The Fourmile Creek watershed is a 300 km² basin located north and east of Des Moines, Iowa (Figure 3-2). This example explores the hydrologic sensitivity of Fourmile Creek to urbanization using the eRAMS SWAT-DEG Tool. As of the year 2010, 36% of the watershed was classified as urban, and it is expected that the proportion of urban area will increase. Therefore, two hypothetical scenarios were developed to explore how increases in urban area would impact hydrologic conditions. In Scenario 1, urban area was increased to 50% of watershed area and cropland decreased to 38%. In Scenario 2, urban area was increased to 75% of watershed area and cropland was decreased to 13% (Table 3-1).

Running SWAT-DEG within eRAMS requires, at a minimum, watershed information, channel information, and climate data for the time period of interest. Once a new project has been created, the user can populate the watershed properties by extracting data from a user-defined watershed, or can simply enter the data directly if they are known. To facilitate the use of climate data, eRAMS allows users to download daily climate observations from the Global Historical Climatology Network—Daily (GHCND). The eRAMS interface where the data are input is shown in Figure 3-3.

Following the data input, the user can click “Run SWAT-DEG” to run the model and view the results. The “Results” tab displays the various scenarios the user created and allows the user

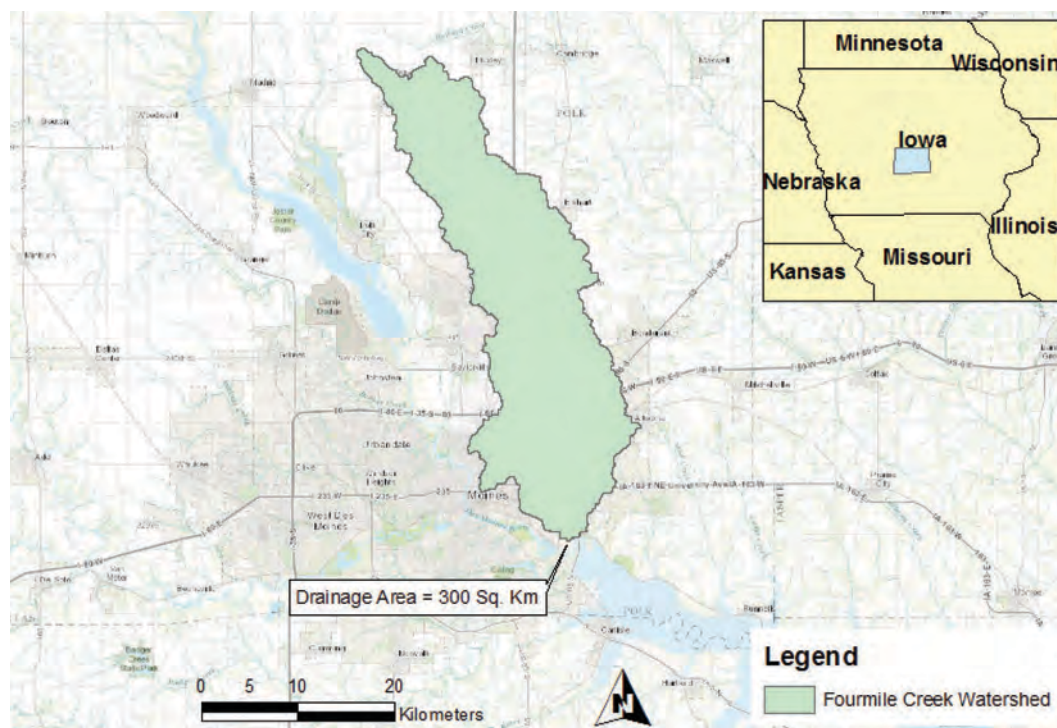


Figure 3-2. Fourmile Creek watershed.

to choose and graph outputs. Outputs can also be downloaded in a variety of formats for post-processing. The research team’s investigation into the hydrologic impacts of urbanization for Fourmile Creek suggests that increases in urbanization will likely cause increases in the magnitude of the FDC across nearly all exceedance levels (Figure 3-4). This demonstrates that historic streamflow records may not be appropriate for future land use conditions.

3.3.2 Example 2: Rainfall-Runoff Modeling of Box Elder Creek (Step 3)

Box Elder Creek is a 750 km² watershed located in northern Colorado and southern Wyoming (Figure 3-5). Because the creek is ungaged, streamflow records are unavailable. Additionally, because the southern portion of the basin is undergoing rapid urbanization, indexing a flow

Table 3-1. Current and future land use scenarios.

Land Use	Year 2010*	Future Scenario 1	Future Scenario 2
Urban and Rural Residential	36%	50%	75%
Forest	1%	1%	1%
Crop Land	52%	38%	13%
Pasture/Grassland	11%	11%	11%
Other	0%	0%	0%

* Adapted from Snyder & Associates Inc. (2013).

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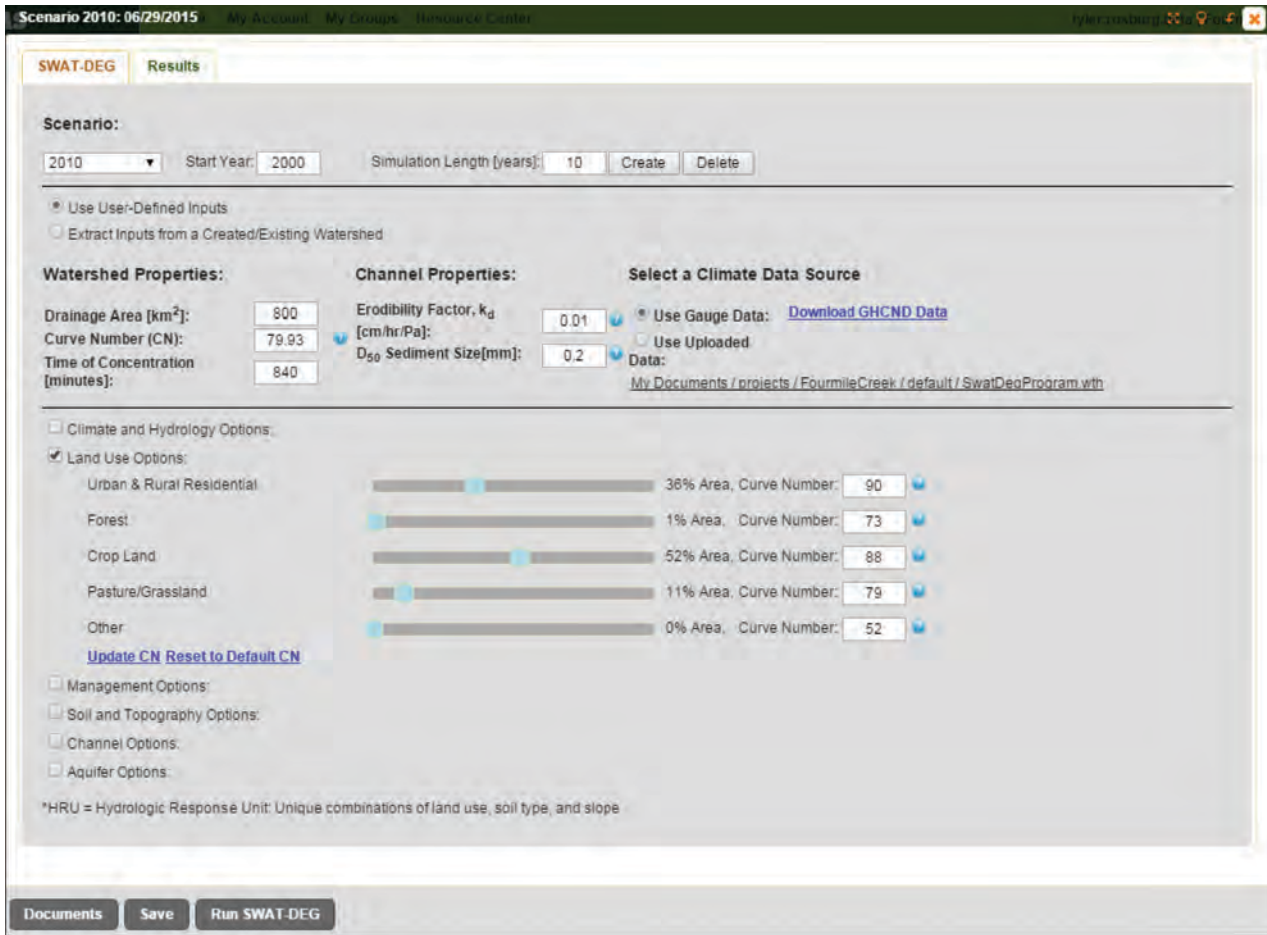
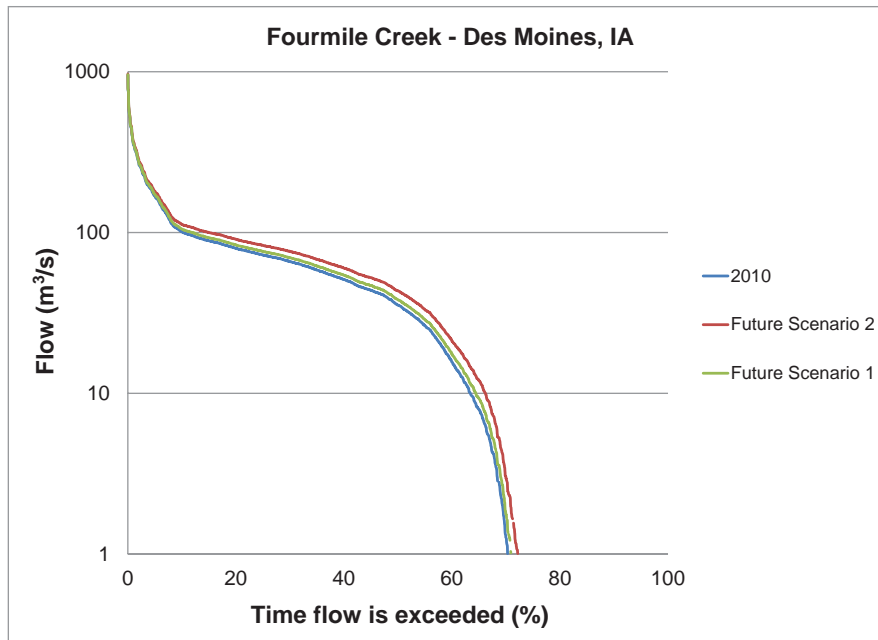


Figure 3-3. eRAMS SWAT-DEG interface.



Created with data produced by eRAMS SWAT-DEG Tool.

Figure 3-4. Comparison of current and future land use FDCs for Fourmile Creek.

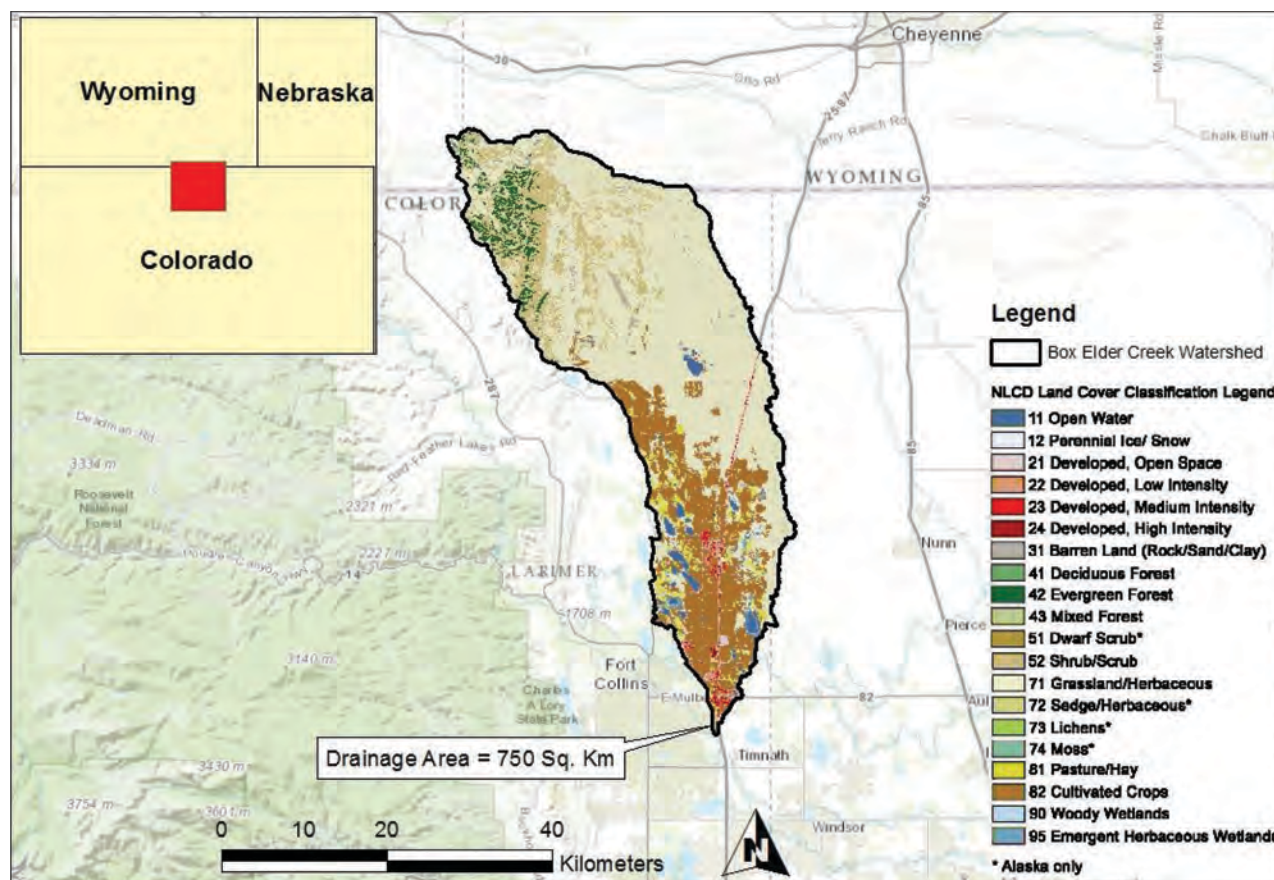


Figure 3-5. Box Elder Creek watershed.

record from a similar and nearby gage is not the best option. This leaves hydrologic modeling as the best remaining option for obtaining a streamflow series at this site.

After logging into eRAMS and starting a new SWAT-DEG project, the user is required to input watershed properties, channel information, and climate data for the time period of interest. The user can populate the watershed properties by extracting data from a user-defined watershed or can simply enter the data directly if they are known. To obtain climate data, eRAMS allows users to download GHCND data. The required input information for Box Elder Creek is shown in Figure 3-6.

After fully populating the input screen, the user can run the model by clicking “Run SWAT-DEG.” This runs the model and launches the output screen. Streamflow data can then be obtained by selecting the appropriate scenario and output parameter and clicking “Graph Output.” A plot of the streamflow time series will then be made available as shown in Figure 3-7. The start and end of the streamflow time series correspond to the start year and simulation length selected when the scenario was developed. It is important to note that the user is required to have climatology data for the entire simulation period.

After the model runs, the raw streamflow data can be downloaded by clicking in the upper right-hand corner of the graph and choosing a preferred file format. Currently, streamflow data are only available in millimeters per day. This can be converted to cubic meters per second by multiplying by the drainage area (m^2) and 86.4. Future versions of eRAMS will do this conversion automatically and provide streamflow in cubic meters per second.

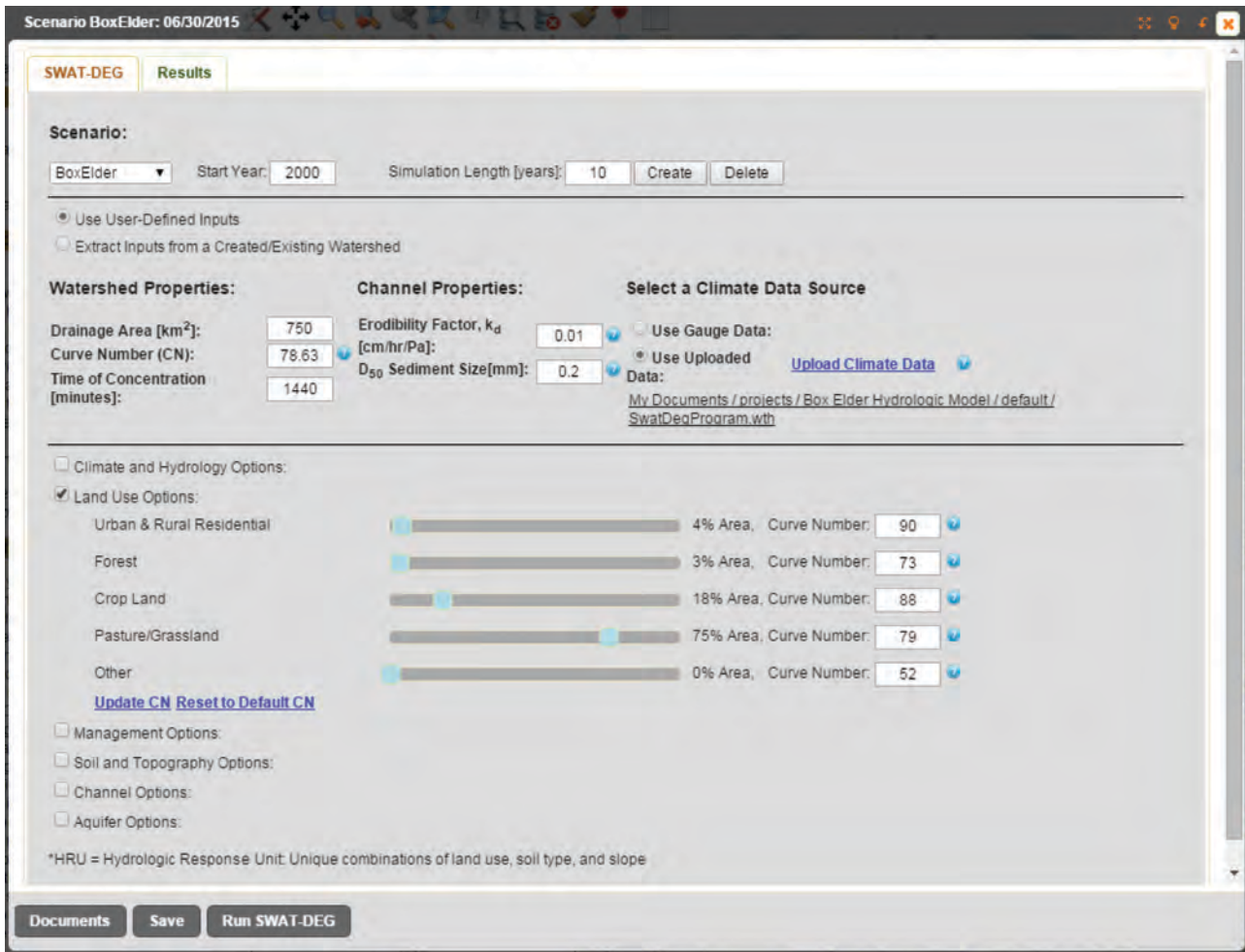


Figure 3-6. eRAMS SWAT-DEG inputs for Box Elder Creek, Colorado.

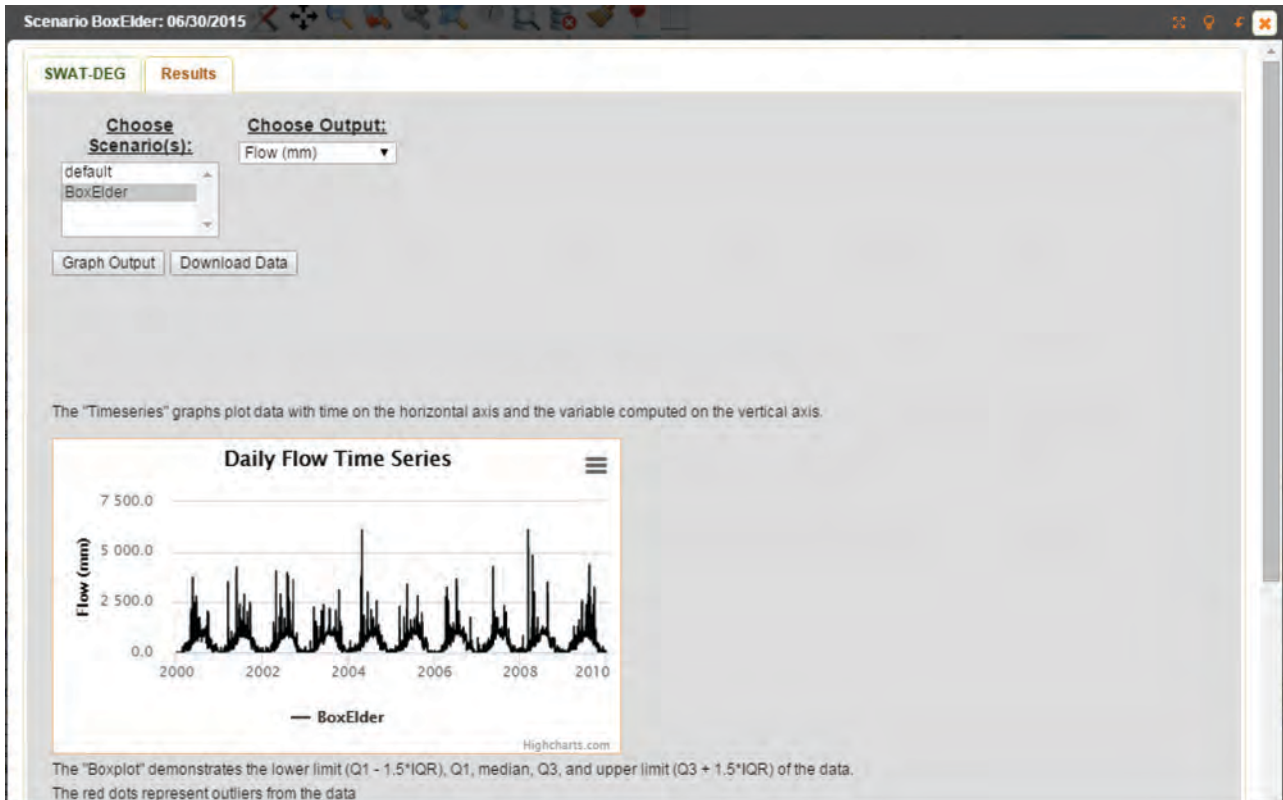


Figure 3-7. Daily series of streamflow for Box Elder Creek.

3.3.3 Example 3: Using eRAMS to Calculate the Richards-Baker Flashiness Index of the Iowa River near Iowa City, Iowa (Step 5)

After signing into eRAMS.com and starting a new “Flow Analysis” project, the user can select a streamflow gage of interest. This can be accomplished by searching for a USGS station by name or keyword, or by drawing a rectangle or polygon on the map. Once the gage has been selected, the user clicks the “Flow Analysis Model” link to launch the application (Figure 3-8).

The user then proceeds to the “Data” tab and specifies the preferred time series, analysis period, and parameter (Figure 3-9). Finally, the user clicks “Run Model” to obtain the output.

Clicking “Run Model” launches the output screen (Figure 3-10). From here, a variety of streamflow statistics can be downloaded, including the R-B Index, by clicking “Download Add'l Stats.” The statistics are made available on an annual basis as well as for the entire period selected.

3.3.4 Example 4: Using the Q_{s50} Decision Tree for Determining Q_{s50} for the Iowa River near Iowa City, Iowa (Steps 1 Through 5)

The Iowa River near Iowa City, is a sand-bed river that drains over 8,400 km² of land in northern Iowa (Figure 3-11). Land use in the basin is predominantly agricultural. Because of the basin’s large size and agricultural setting, land use is not expected to change significantly in the future.

The screenshot shows the eRAMS web application interface. The top navigation bar includes "Home", "My Account", "My Groups", "Resource Center", and user information "tyler.rosburg | RB Flashiness Example | Help | Sign Out". The main interface is divided into a left sidebar and a central map area.

Left Sidebar:

- Map Flow Analysis**
- Buttons: Reset Search, Help, Add Station, Quick Start
- Search: Find station by name or keyword: [input field] Submit
- Add map region to search:
 - Point Buffer
 - Line Buffer
 - Polygon
 - Rectangle
 - Within Layer Extent
 - Known Boundary
- Add attributes to search:
 - Data_Flood
 - hucnumber
 - database
 - state
 - Data_Instantaneous_Discharge
 - Data_Water_Quality
 - Data_Flow
- Station Search Results:
 - Buffalo Creek at 270N
 - Clear Creek (down)
 - Clear Creek (down)
 - Clear Creek (up)
 - Clear Creek (up)
 - Clear Creek near Coralville, IA
 - Confluence
 - Dirty Face Creek
 - Dirty Face Creek

Central Map: Shows a map of the Iowa River near Iowa City, Iowa. A red rectangle highlights the gage location. The map includes labels for Coralville, University of Iowa, University Heights, Iowa City, and Hickory Hill Park. Major roads like US 6 and I 80 are visible.

Pop-up Window: Displays details for the selected gage:

- Database: USGS
- Station ID: 05454900
- Station Name: Iowa River at Iowa City, IA
- Supervising Agency: USGS
- Latitude: 41.050653
- Longitude: -91.541002
- County: Johnson County
- State: IOWA
- Hydrologic Unit Code: 7080209
- Drainage Area: 3271 sq. mi
- Elevation: n/a

Data Table:

Data Type	Begin Date	End Date	Count
Discharge	1903-06-01	--	40617+
Water Quality	1901	2012-06-23	11453
Flood	1851	--	113+
15-Minute	2007-10-01	--	158262+

Figure 3-8. Selecting a streamflow gage with eRAMS.

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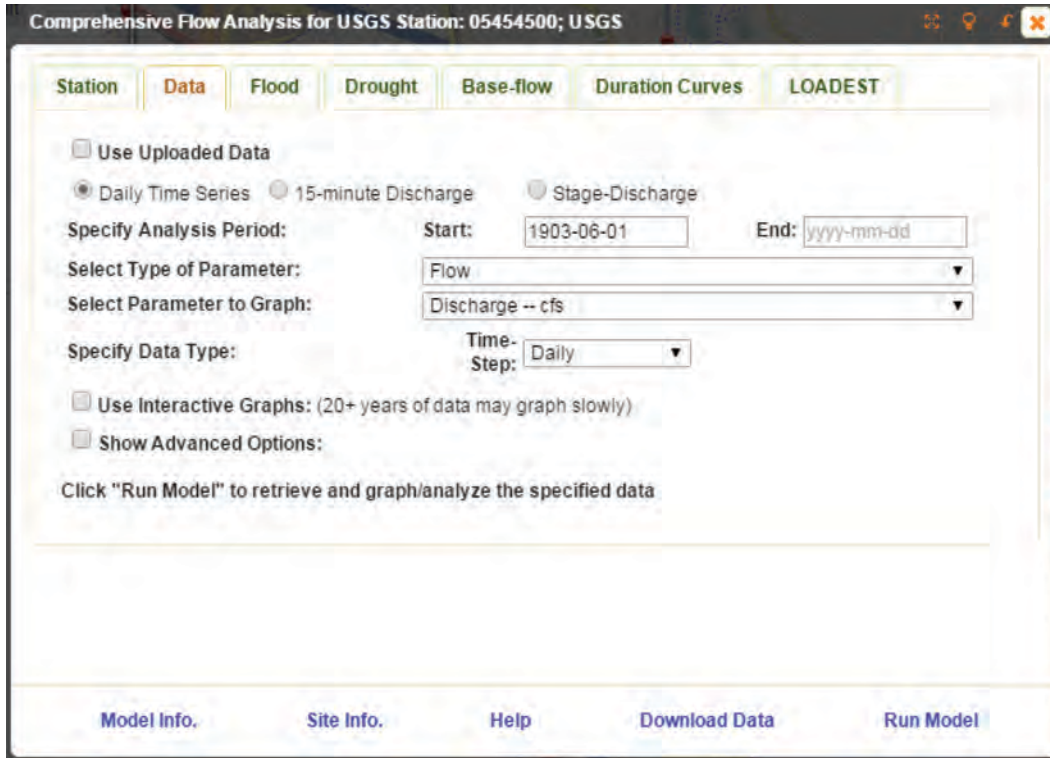


Figure 3-9. eRAMS Flow Analysis Tool input.

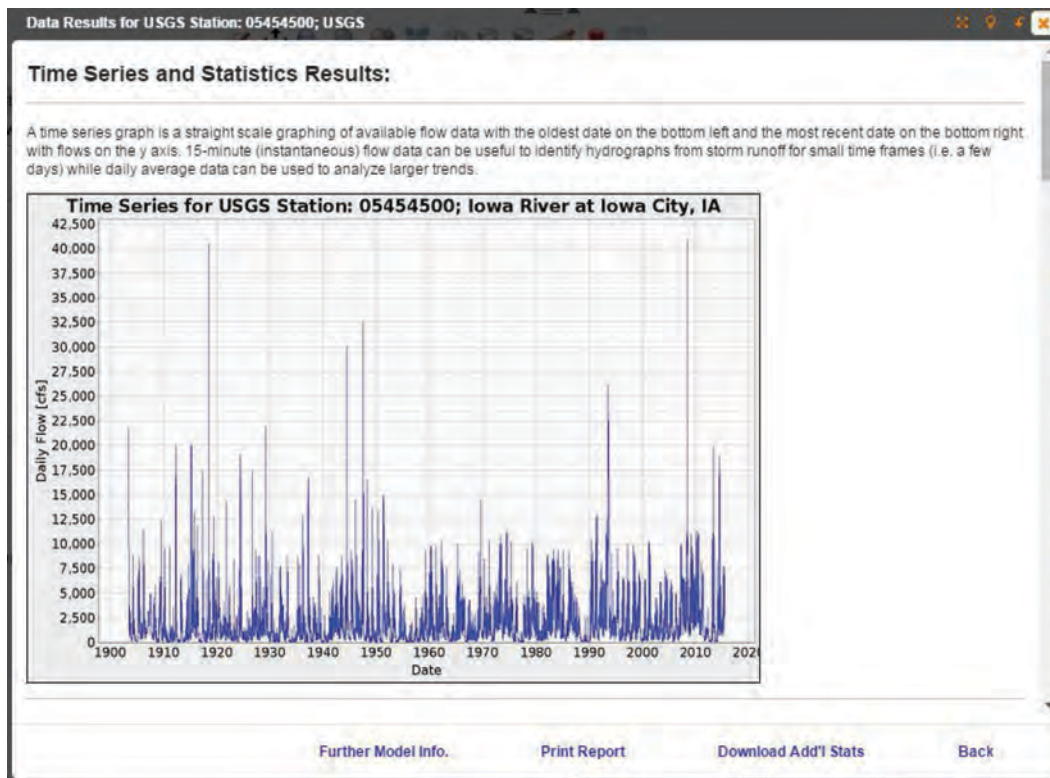


Figure 3-10. eRAMS Flow Analysis Tool output screen.

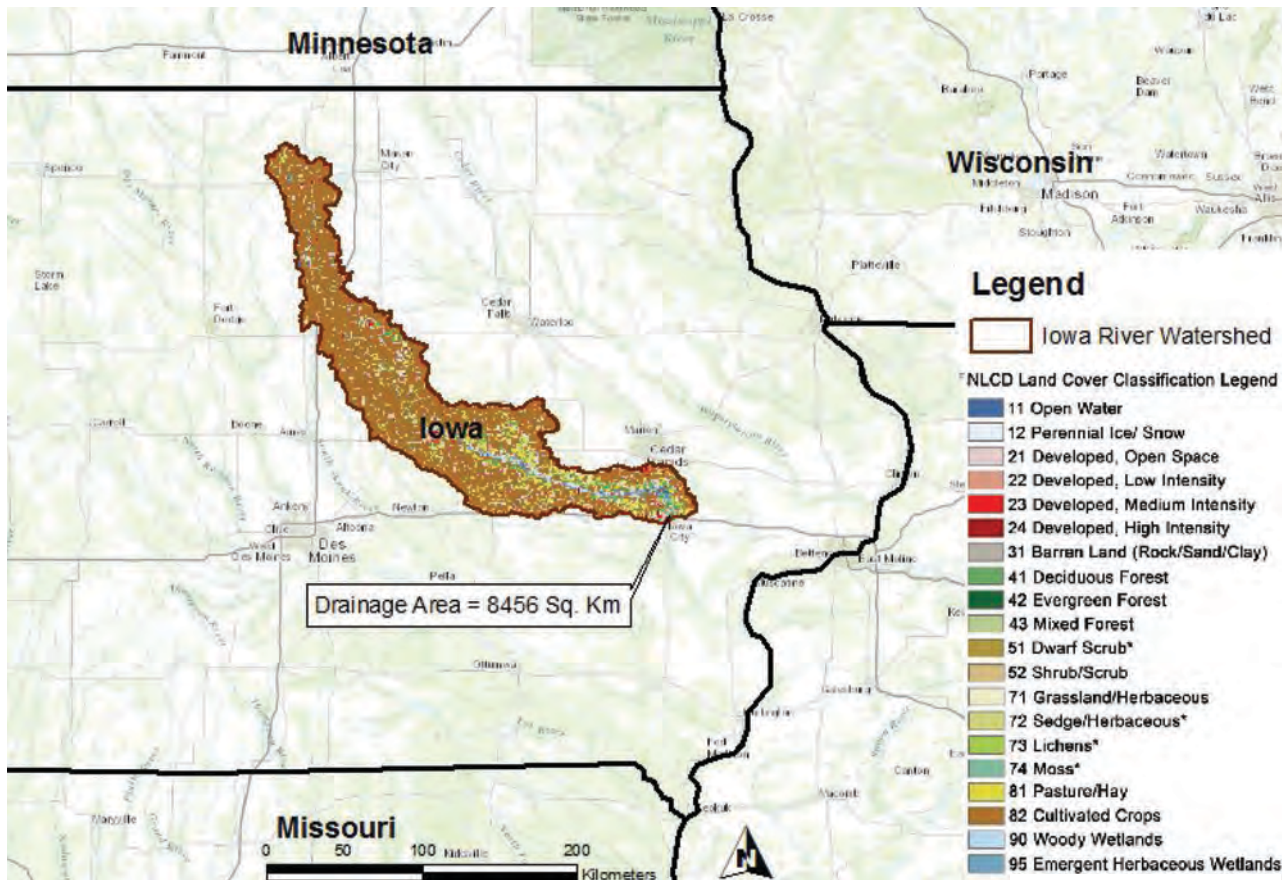


Figure 3-11. Iowa River watershed with 2011 land cover.

Hydrologic Data

Daily-averaged streamflow measurements are available from the USGS beginning in 1903. Because the site is gaged, on-site historical streamflow data should be the first choice source for hydrologic data. However, before these data can be used in the calculation of Q_{s50} , they must be checked for trends.

Stationarity Check

To check for trends in the gaged streamflow record caused by either changes in land use or climate, the user can use the Mann-Kendall test (Mann 1945; Kendall 1975) on the annual maximum flow series. The Mann-Kendall test is designed to detect increasing or decreasing trends in data. The test is particularly useful as missing values are allowed and the data do not need to conform to any particular distribution (Gilbert 1987). The Mann-Kendall test statistic (τ) is calculated as shown in Equation 3-2, where n is the total number of data points:

$$\tau = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sign}(x_j - x_k) \tag{3-2}$$

where:

- $\text{sign}(x_j - x_k) = 1$ if $(x_j - x_k) > 0$;
- $\text{sign}(x_j - x_k) = 0$ if $(x_j - x_k) = 0$; and
- $\text{sign}(x_j - x_k) = -1$ if $(x_j - x_k) < 0$.

In this example, a p-value of 0.05 was used to identify significant trends. Performing the Mann-Kendall test on the annual maximum flow series yields a Mann-Kendall τ value of 0.108 and a p-value of 0.244. Because τ is greater than 0, there is an upward trend in the flow data. However, because the p-value is greater than 0.05, the trend is not statistically significant. For this reason, the user classifies the flow data as stationary and proceeds to calculating the R-B Index (Baker et al. 2004).

Richards-Baker Flashiness Index

The user calculates the R-B Index using daily streamflow data in Equation 3-1, which results in an R-B Index of 0.089 for Iowa River at Iowa City. This indicates that the Iowa River is not very flashy, likely a result of the large drainage area.

Sediment Data

Suspended sediment transport measurements are available from the USGS for the Iowa River near Iowa City. These measurements taken at discrete points in time can be paired with streamflow data to create a sediment rating curve. The sediment rating curve for the Iowa River is shown in Figure 3-12.

Streamflow Data Resolution

The percent error in half-load discharge (Q_{50}) calculated with daily-averaged flow data at bedload sites and suspended-load sites is shown in Figure 3-13.

Calculation of Q_{50}

- Step 1: Order the streamflow data from smallest to largest.
- Step 2: Calculate the sediment transport rate for each flow value using the sediment rating curve.
- Step 3: Cumulatively sum the sediment transport rates calculated in Step 2 to calculate a cumulative sediment transport rate column.

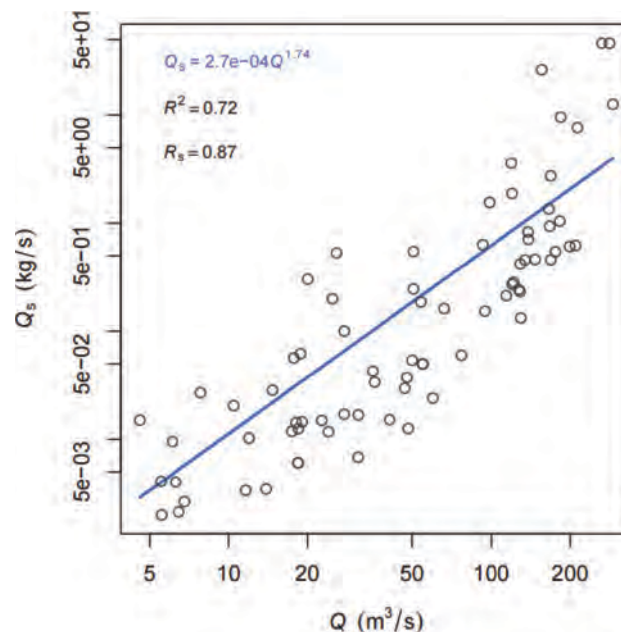


Figure 3-12. Sediment rating curve for Iowa River at Iowa City, Iowa.

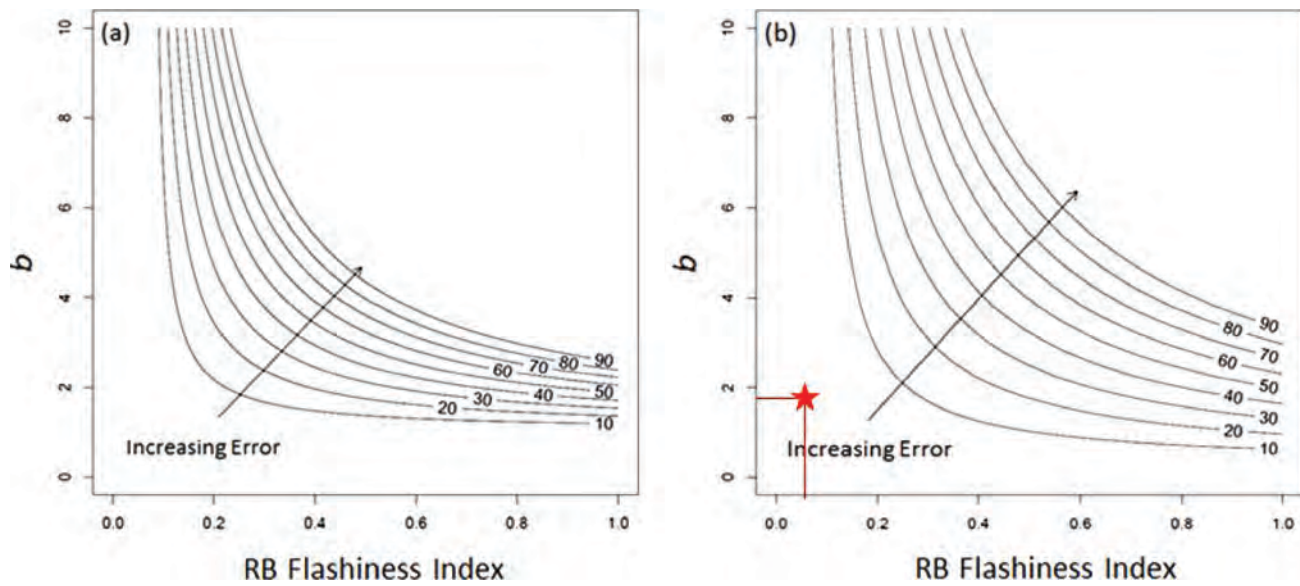


Figure 3-13. Percent error in half-load discharge (Q_{50}) calculated with daily-averaged flow data for (a) bedload sites and (b) suspended-load sites. For the Iowa River, use of daily-averaged flow data is estimated to cause no more than 10% error (red star).

Step 4: Divide each value in the cumulative sediment transport rate column by the total cumulative sediment transport (the sum of the rates calculated in Step 2) to calculate the percentage of cumulative sediment transport associated with each flow.

Step 5: Identify the streamflow associated with 50% of cumulative sediment transport, using linear interpolation if necessary. This is Q_{50} , the half-load discharge.

As shown in Table 3-2, this sample calculation of the half-load discharge (Q_{50}) was found to be 5.9 m³/s.

Table 3-2. Sample calculation of Q_{50} .

Date	Vector 1	Vector 2	Vector 3	Vector 4	
	Flow [m ³ /s]	Sediment Transport [kg/s]	Cumulative Sediment Transport	% of Cumulative Sediment Transport	
5/3/2015	3.0	5.48E-05	5.48E-05	0.05	
5/6/2015	3.3	6.47E-05	1.20E-04	0.11	
5/1/2015	4.0	9.04E-05	2.10E-04	0.19	
5/7/2015	5.5	1.57E-04	3.67E-04	0.34	
5/2/2015	5.9	1.78E-04	5.45E-04	0.50	Q_{50}
5/4/2015	6.3	1.99E-04	7.45E-04	0.68	
5/5/2015	8.6	3.43E-04	1.09E-03	1.00	
Sum		1.09E-03			



CHAPTER 4

User Guidance for the CSR Tool

This chapter provides step-by-step guidance for each tab in the CSR Tool workbook. Chapter 5 provides two examples of 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 D of the final report for NCHRP 24-40, downloadable from the NCHRP Research Report 853 summary page on the TRB website (www.trb.org)].

The numbered steps in this chapter correlate to the numbers overlaid onto referenced screenshots of the CSR Tool tabs.

Figure 4-1 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” tab that refer to the type of river and hydrologic information.

4.1 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 4-2 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.

Step 1. Enter Project Info Summary (Optional)

The first step is to enter the project information summary in the area provided (Figure 4-2). This is optional and solely for the user’s reference and will not be used to run the program.

Step 2. Define 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 4-3 to run the program and view the results. The variables selected will be displayed underneath the “Select” button for reference.

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

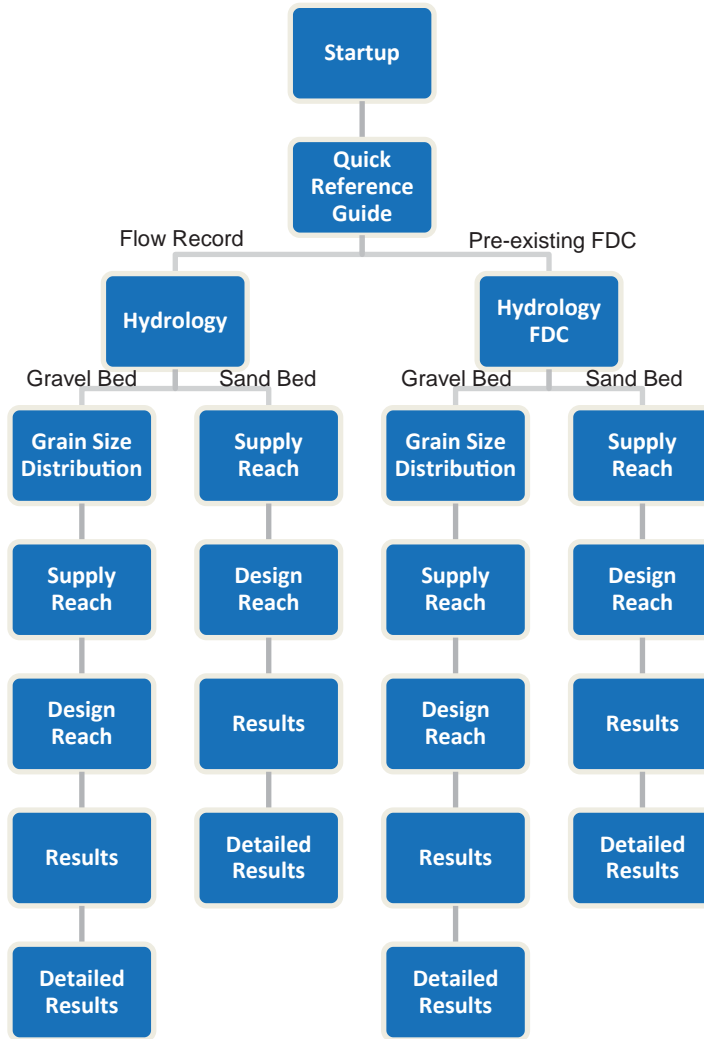


Figure 4-1. Decision tree for the tab order and usage in the CSR Tool.

“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, Table 4-1 lists the delineation of all grain size groups. 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, you can compare your stream’s sediment distribution to the sediment distributions used to derive the sediment transport equations that are available in the tool. These values are listed in the first row for each equation in Table 4-2. Comparing sediment distribution to Table 4-2 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.****

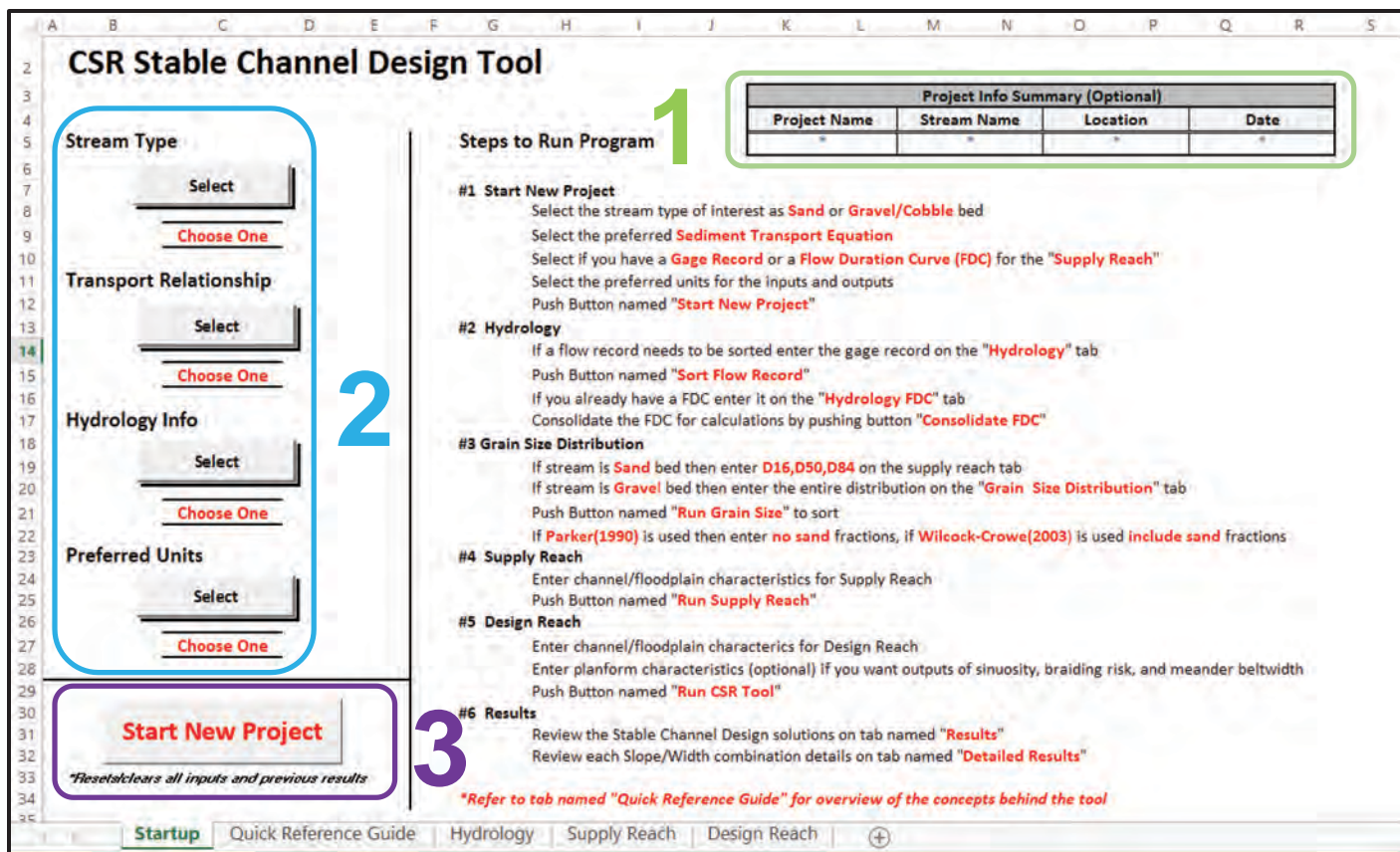


Figure 4-2. Screenshot of “Startup” tab with areas delineated for Steps 1 through 3.

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 4-2).

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 4-2 for the boundaries Brownlie (1981) listed in his publication for developing this equation. This is the same equation that is

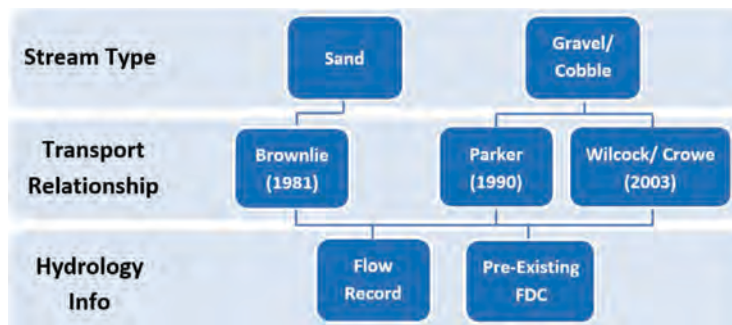


Figure 4-3. Decision tree for Step 2 (define project type) of the “Startup” tab.

Table 4-1. Grain size class delineations.

Bed Material	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

used for the Copeland method of stable channel design in the Hydrologic Engineering Center's 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 4-2 to review the boundaries listed by the authors in developing these transport relationships. The

Table 4-2. 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	40.0
	Discharge [m^3/s]	0.0032	22,000.0
	Slope	0.000003	0.037
	Hydraulic radius [m]	0.025	17.0
	Temperature [$^{\circ}C$]	0	63.0
	Width/depth ratio	≥ 4.0	≥ 4.0
	Geometric standard deviation of particles sizes, σ_g	≤ 5.0	≤ 5.0
Parker (1990)	Gravel-sized particles [mm]	2.0	203.0
	Sand-sized particles [mm]	sand removed	sand removed
	Sand in mixture [%]	3.3 (surface)	13 (subsurface)
Wilcock-Crowe (2003)	Gravel-sized particles [mm]	2.0	64.0
	Sand-sized particles [mm]	0.5	2.0
	Sand in mixture [%]	6.2	34.3
	Depth [m]	0.09	0.12

Parker (1990) equation is a well-respected bedload equation for streams that is recommended when the grain size distribution consists of primarily gravel/cobble particles and less than 3% to 5% sand. This equation will eliminate all sand (<2 mm) fractions in the distribution prior to calculating the bedload. The Wilcock-Crowe (2003) bedload equation is similar to the Parker (1990) equation, but it considers sand fractions in the calculations. This equation is recommended if there is a significant amount of sand (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 4-2). As stated in the CSR Tool Reference Manual (Appendix D of the final report for NCHRP 24-40), the tool requires a sequence of flows over time for the channel reach of interest in order to perform a magnitude-frequency analysis 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 who 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 (more than 10 to 15 years) 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 who have a pre-derived FDC to enter rather than a flow record. This feature was added to the program mainly to help with the great limitation of needing an extended flow record for the supply reach, which is often absent. 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 an 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 must be entered in millimeters and the flow record must be entered in cubic feet per second because 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 and 2 complete, press the “Start New Project” button as seen in Figure 4-2. 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.

4.2 Quick Reference Guide Tab

The “Quick Reference Guide” tab (Figure 4-4) can be viewed at any time to obtain a visual representation of the main concepts behind the CSR Tool analysis as presented in the CSR Tool Reference Manual (Appendix D of the final report for NCHRP 24-40). There are no required inputs on this tab.

4.3 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 4-5 shows a screenshot of the “Hydrology” tab pointing out the areas on the sheet that are needed for each step.

Step 1. Enter Flow Record Information/Tab Guidance

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 4-5). This is optional and solely for the user’s reference and will not be used to run the program.

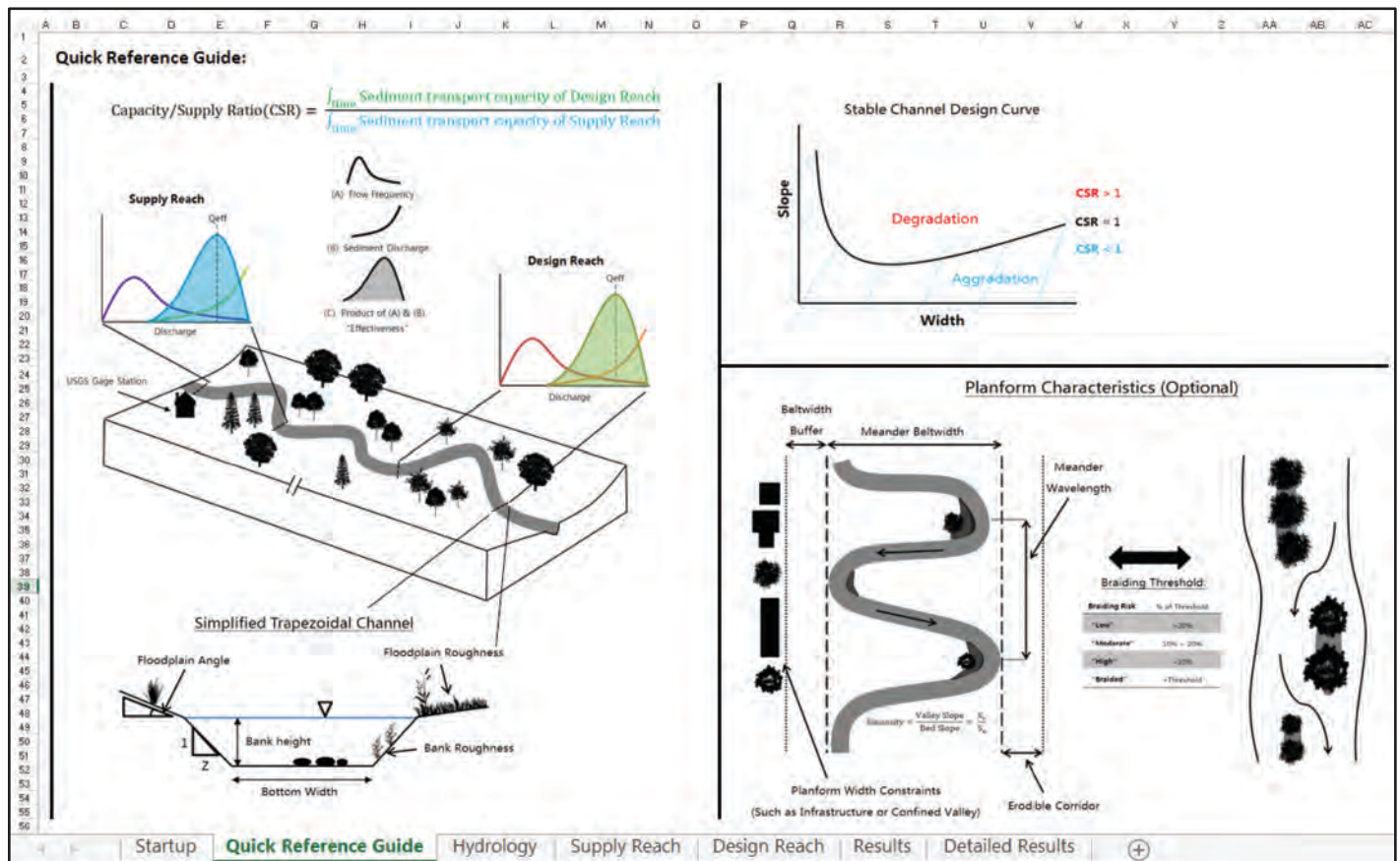


Figure 4-4. “Quick Reference Guide” tab of CSR Tool.

4.4 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 steps guide you in running this tab. Figure 4-6 shows a screenshot of the “Hydrology FDC” tab pointing out the areas on the sheet that are needed for each step.

Step 1. Enter FDC Information/Tab Guidance

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 4-6). This is optional and solely for the user’s reference and will not be used to run the program.

Step 2. Enter Flow Duration Curve

This tab is optimized to import FDCs generated by the SWAT-DEG Tool in eRAMS. Other sources of FDCs are compatible as well. Enter the FDC of exceedance probability in percentage (%) versus discharge (cfs) under the corresponding labels in Columns B and 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

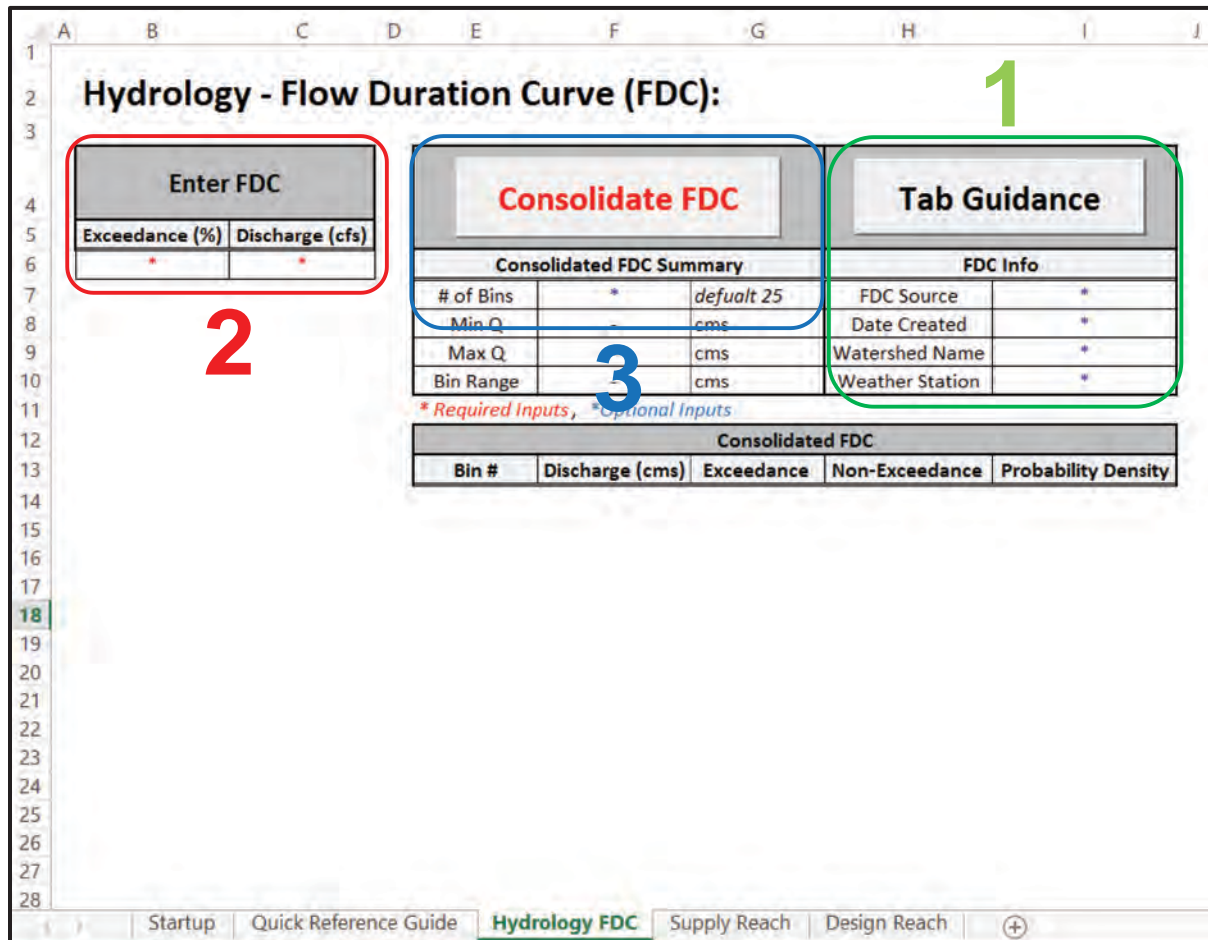


Figure 4-6. Screenshot of “Hydrology FDC” tab with areas delineated for Steps 1 through 3.

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.)

4.5 Grain Size Distribution Tab

This tab was created to sort grain size distributions 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. Figure 4-7 shows a screenshot of the “Grain Size Distribution” tab pointing out the areas on the sheet that are needed for each of the following steps.

Step 1. Grain Size Sample Information/Tab Guidance

You can enter a summary of the “Grain Size Sample Info” in the area provided and/or press the “Tab Guidance” button to access a quick reference on how to run the tab (Figure 4-7). This is optional and solely for the user’s reference and will not be used to run the program.

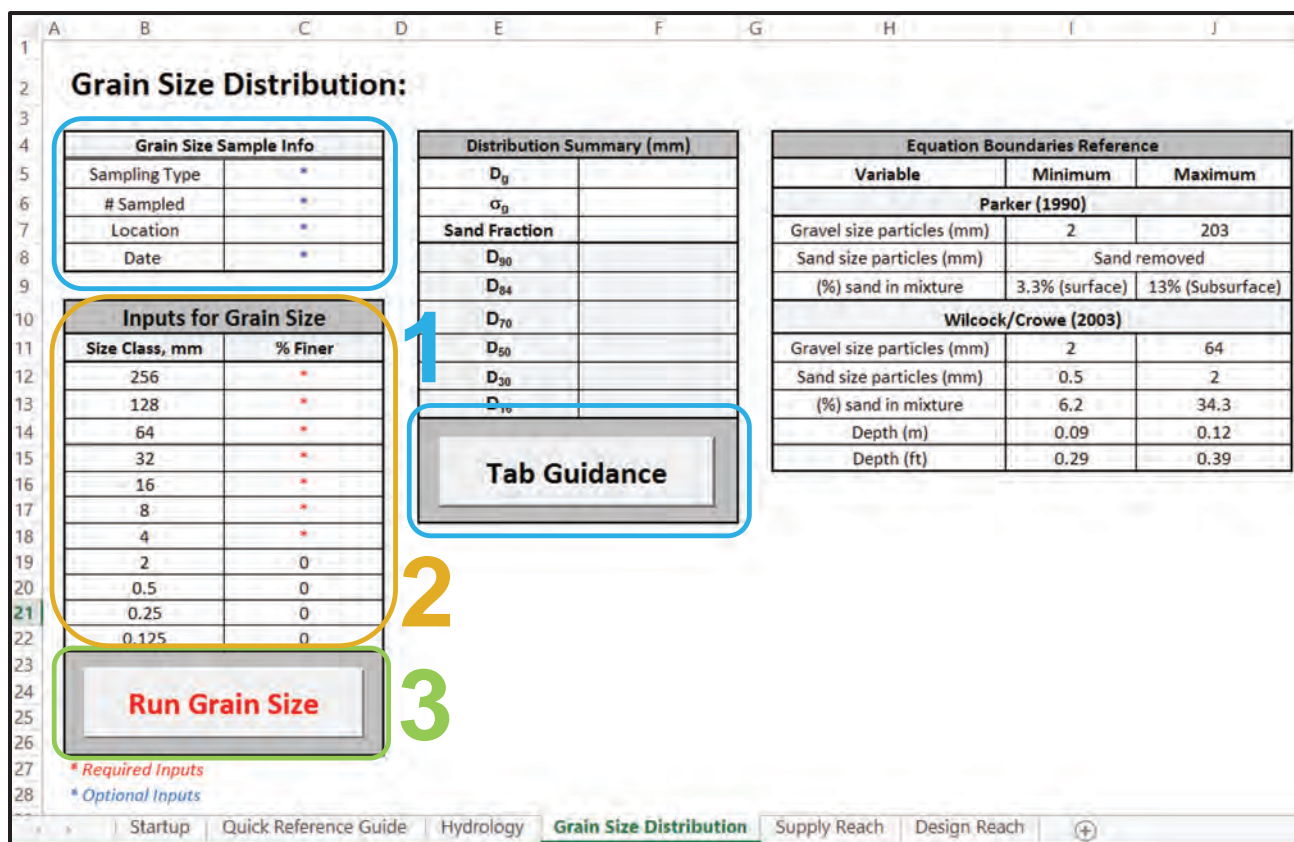


Figure 4-7. Screenshot of “Grain Size Distribution” tab with areas delineated for Steps 1 through 3.

Step 2. Inputs for Grain Size

In Column C of the tab, enter the percentage of bed material that is finer than the grain size class in Column B. If you selected the Parker (1990) transport equation, then no sand size classes (<2 mm) will 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.)

4.6 Supply Reach Tab

The main purpose of the “Supply Reach” 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 steps provide guidance on running this tab. Figure 4-8 shows a screenshot of the “Supply Reach” tab pointing out the areas on the sheet that are needed for each step.

Step 1. Tab Guidance

You can press the “Tab Guidance” button to access a quick reference on how to run the tab (Figure 4-8). This is optional, 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 and 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 5-9 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 you need to specify for the sediment calculations. If the channel type is gravel/cobble, then D_{16} , D_{50} , and D_{84} are auto-updated 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.)

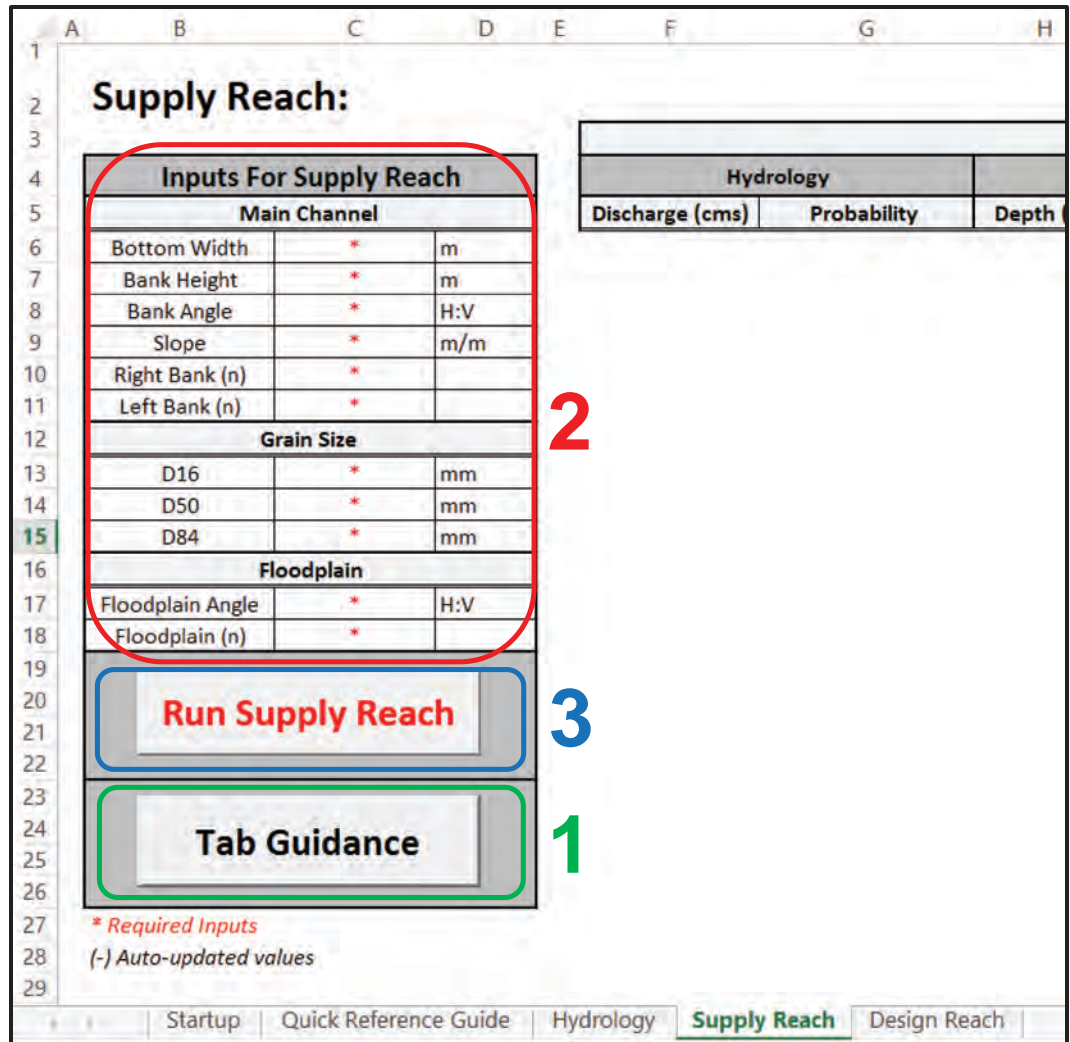


Figure 4-8. Screenshot of “Supply Reach” tab with areas delineated for Steps 1 through 3.

Floodplain

Enter the floodplain angle and roughness characteristics of the supply reach in Cells C17 and 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 and G. Review the hydraulic output for each bin discharge in Columns H and N and the sediment transport outputs in Columns O and Q. The “effectiveness,” or total sediment transported on average in a given year, for each bin discharge will be plotted in the bottom left, and a diagram of the supply reach channel geometry will be shown in the bottom right. The channel geometry diagram is on a generic scale, but all lengths and angles are proportional to each other.

4.7 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 steps provide guidance on running this tab. Figure 4-9 shows a screenshot of the “Design Reach” tab pointing out the areas on the sheet that are needed for each step.

Step 1. Tab Guidance

You can press the “Tab Guidance” button to access a quick reference on how to run the tab (Figure 4-9). This is optional, 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 and C9. The bank height is a bankfull depth that the program needs in order to know when the flow

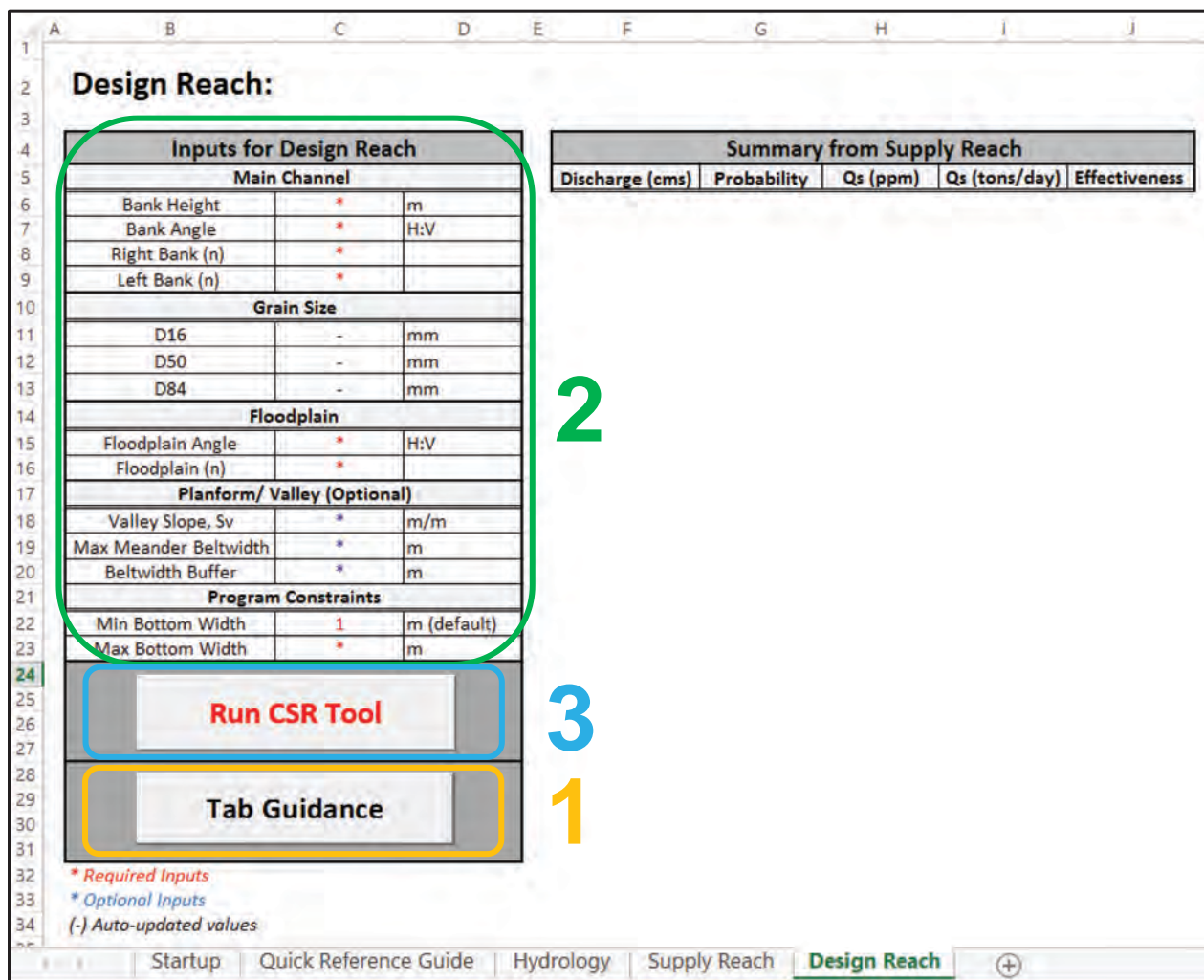


Figure 4-9. Screenshot of “Design Reach” tab with areas delineated for Steps 1 through 3.

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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 5-9 for a 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 values for the supply reach.

Floodplain

Enter the floodplain angle and roughness characteristics of the design reach in Cells C15 and 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” subsection of the CSR Tool Reference Manual (Appendix D of the final report for NCHRP 24-40) for a detailed overview of these concepts and Figure 5-9 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 the supply reach bottom width) to produce a full family of solutions. The program will loop this width range in conjunction with an automated range of slope guesses to find design channels with $CSR = 1$.

Step 3. Run Design Reach

Press the “Run CSR Tool” button to produce a family of stable channel width and slope combinations (Figure 4-9) 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 width/slope 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.

4.8 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 4-10. A shape similar to this should be expected for sand-bed channel types and, for gravel/cobble-bed channel types, less curl up at lower widths and a generally flatter curve should be expected.



Figure 4-10. Family of width and slope combinations which provide continuity of water and sediment.

4.9 Detailed Results Tab

The “Detailed Results” tab will display more specific results for each slope and 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 and width combination is displayed below each effectiveness table. For more information on sediment percentiles, refer to the CSR Tool Reference Manual (Appendix D of the final report for NCHRP 24-40).



CHAPTER 5

CSR Tool Examples

This chapter presents two examples of using the CSR Tool. One example is a sand-bed river using U.S. customary units and the other is a gravel/cobble-bed river using metric units. Chapter 4 focused on explaining the inputs and functions required by the user to run the CSR Tool. This chapter will provide visuals and explanations on each tab for the output of the tool.

5.1 Sand Bed

This example is for a reach on Big Raccoon Creek, Indiana (Figure 5-1). The data used for this example are from Soar and Thorne (2001; Appendix B: U.S. sand-bed river data).

5.1.1 Startup Tab

The CSR Tool initial screen is shown in Figure 5-2. The project information summary is optionally entered in the top right of the tab.

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 4-2 for the Brownlie (1981) sand-bed transport equation. This range is also provided in the selection guidance window as shown in Figure 5-3. The selection for each field will display for reference below the “Select” buttons.

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. You can also select the equation manually as shown in Figure 5-4.

This example reach has USGS gage data of significant length (26 years) available to represent the hydrology of the channel for calculations, so the “Flow Record” option was selected for “Hydrology Info” (Figure 5-5).

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 5-6).

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 5-7.

5.1.2 Hydrology Tab

To follow the steps provided in Section 4.3, 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.

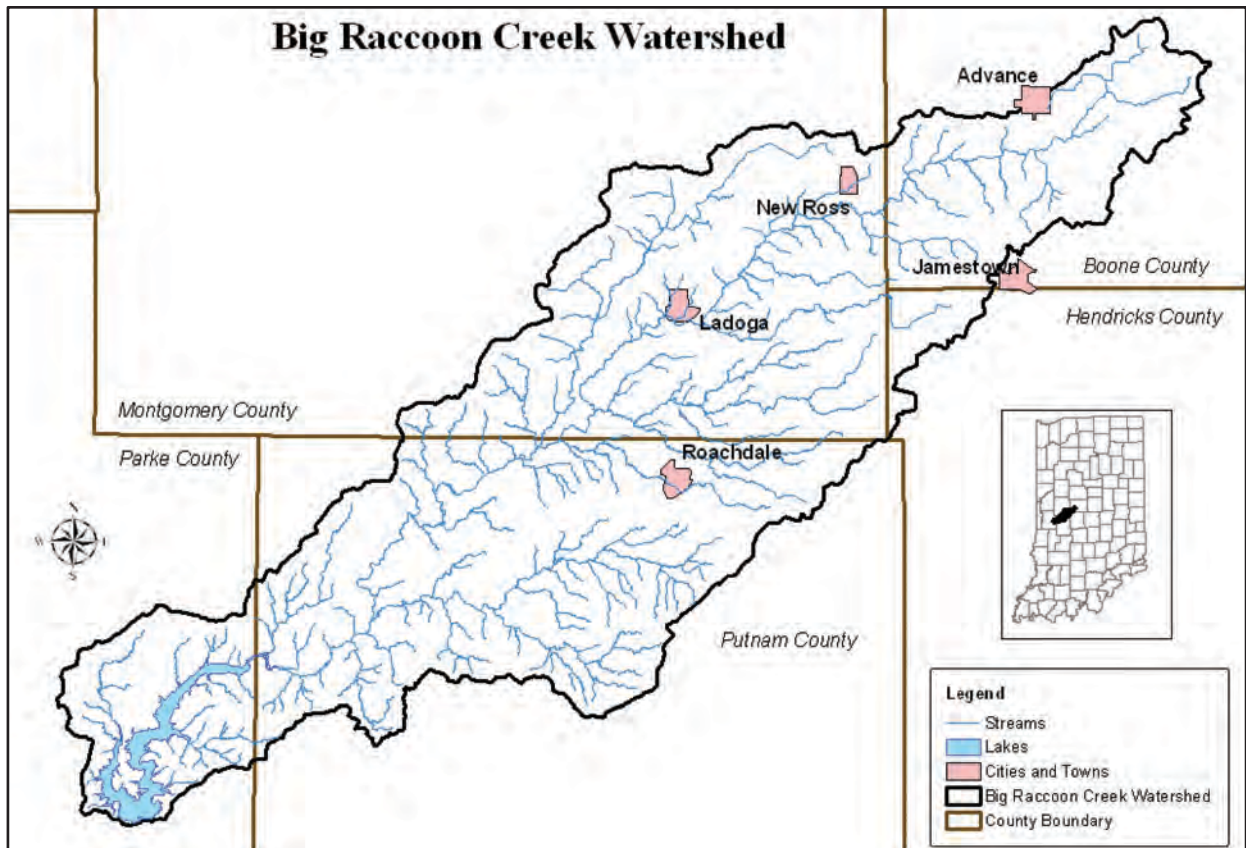


Figure 5-1. Map of Big Raccoon Creek watershed in Indiana (Indiana Department of Environmental Management 2013).

CSR Stable Channel Design Tool

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

Stream Type
Select
Choose One

Transport Relationship
Select
Choose One

Hydrology Info
Select
Choose One

Preferred Units
Select
Choose One

Start New Project
*Resets/clears all inputs and previous results

Startup Quick Reference Guide

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 characteristics 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 5-2. "Startup" tab of the CSR Tool.

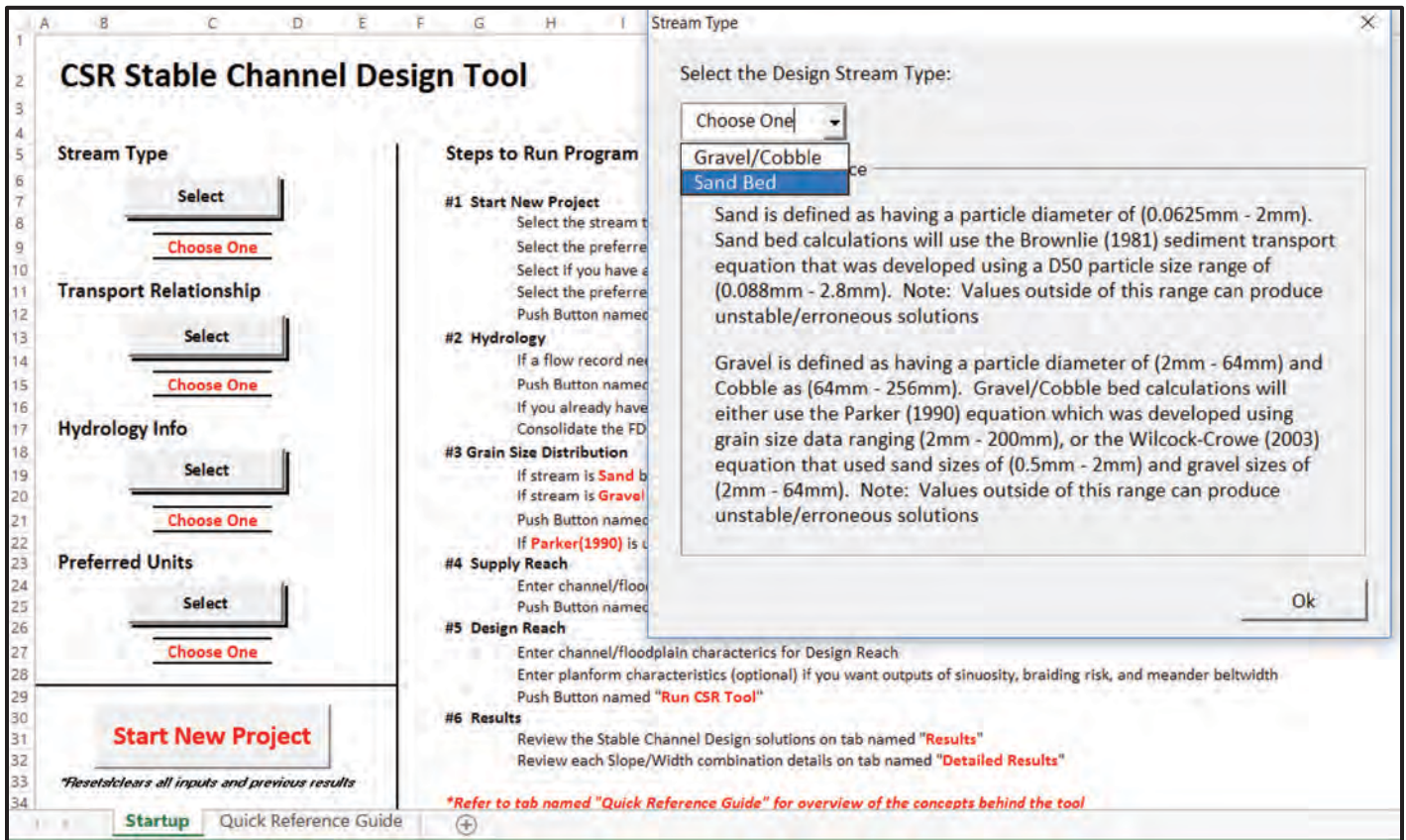


Figure 5-3. Selecting "Stream Type" on "Startup" tab.

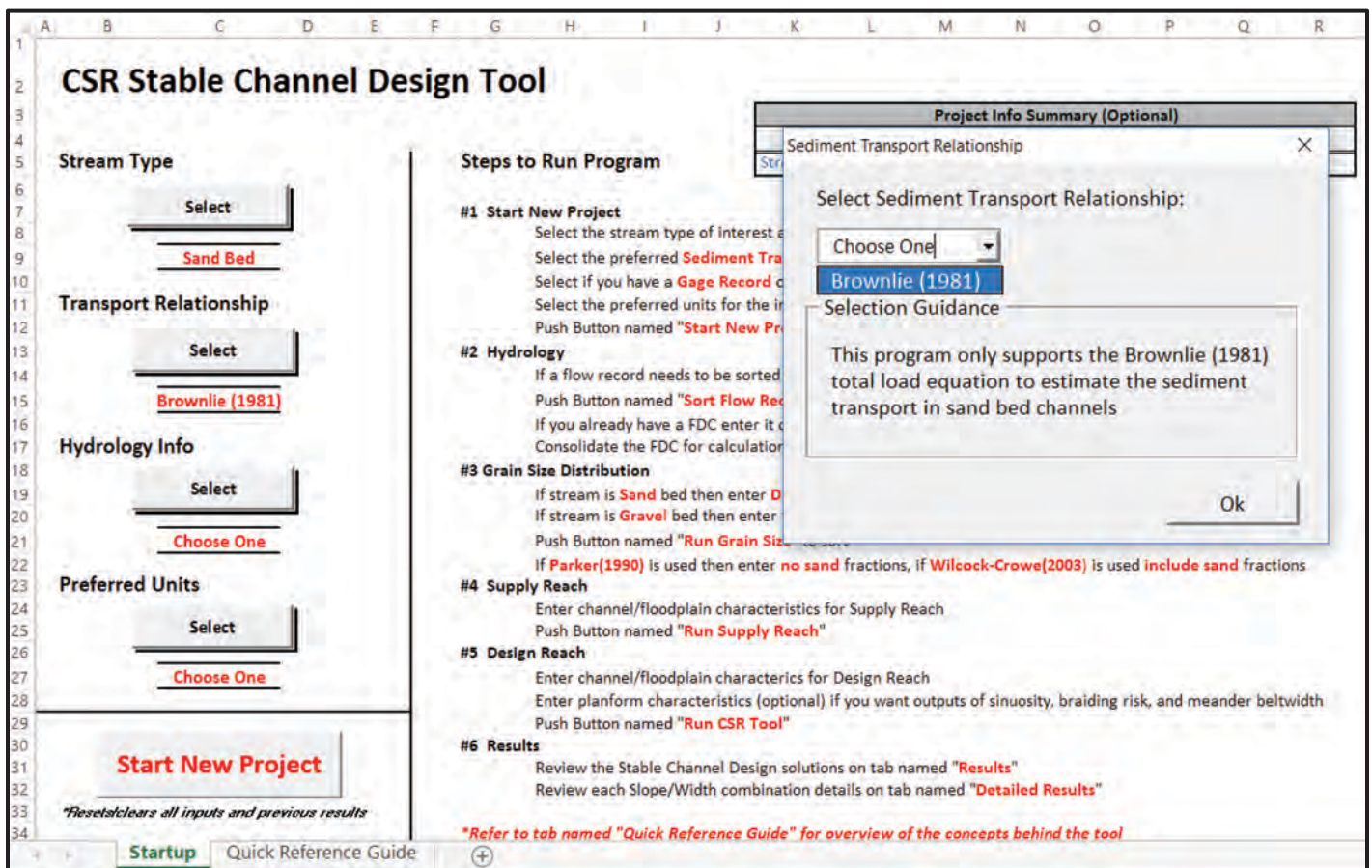


Figure 5-4. Selecting "Transport Relationship" on "Startup" tab.

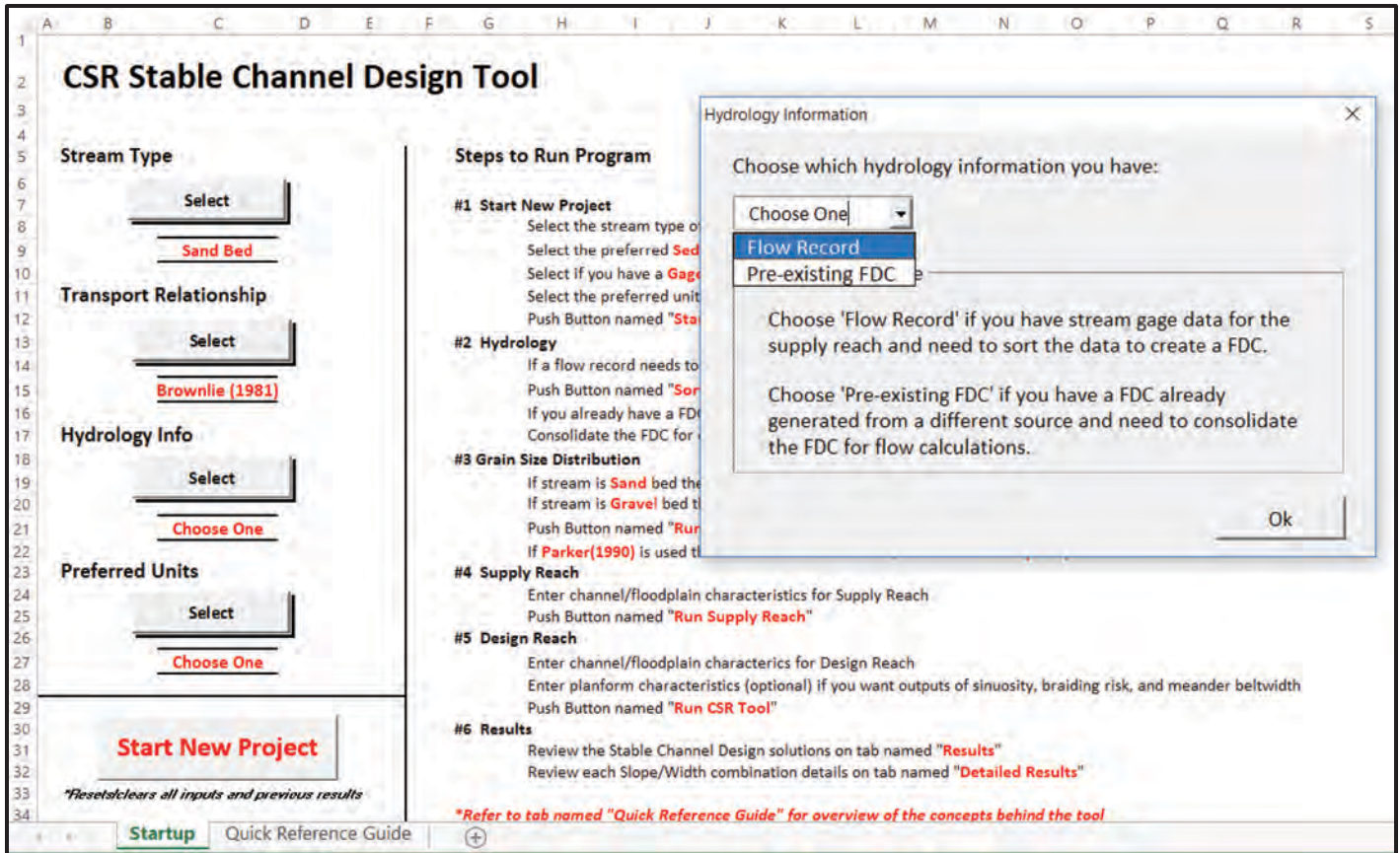


Figure 5-5. Selecting "Hydrology Info" on "Startup" tab.

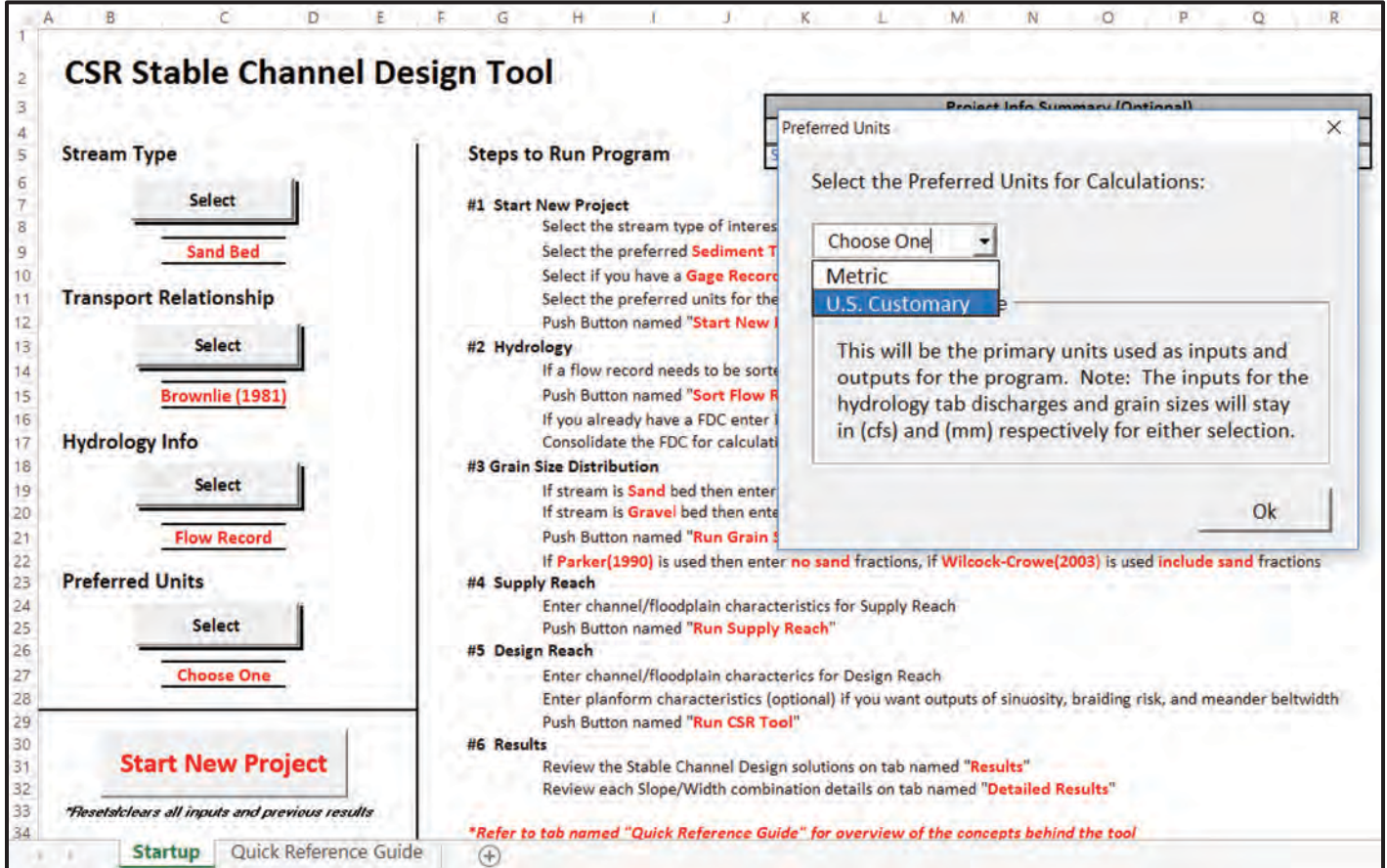


Figure 5-6. Selecting "Preferred Units" on "Startup" tab.

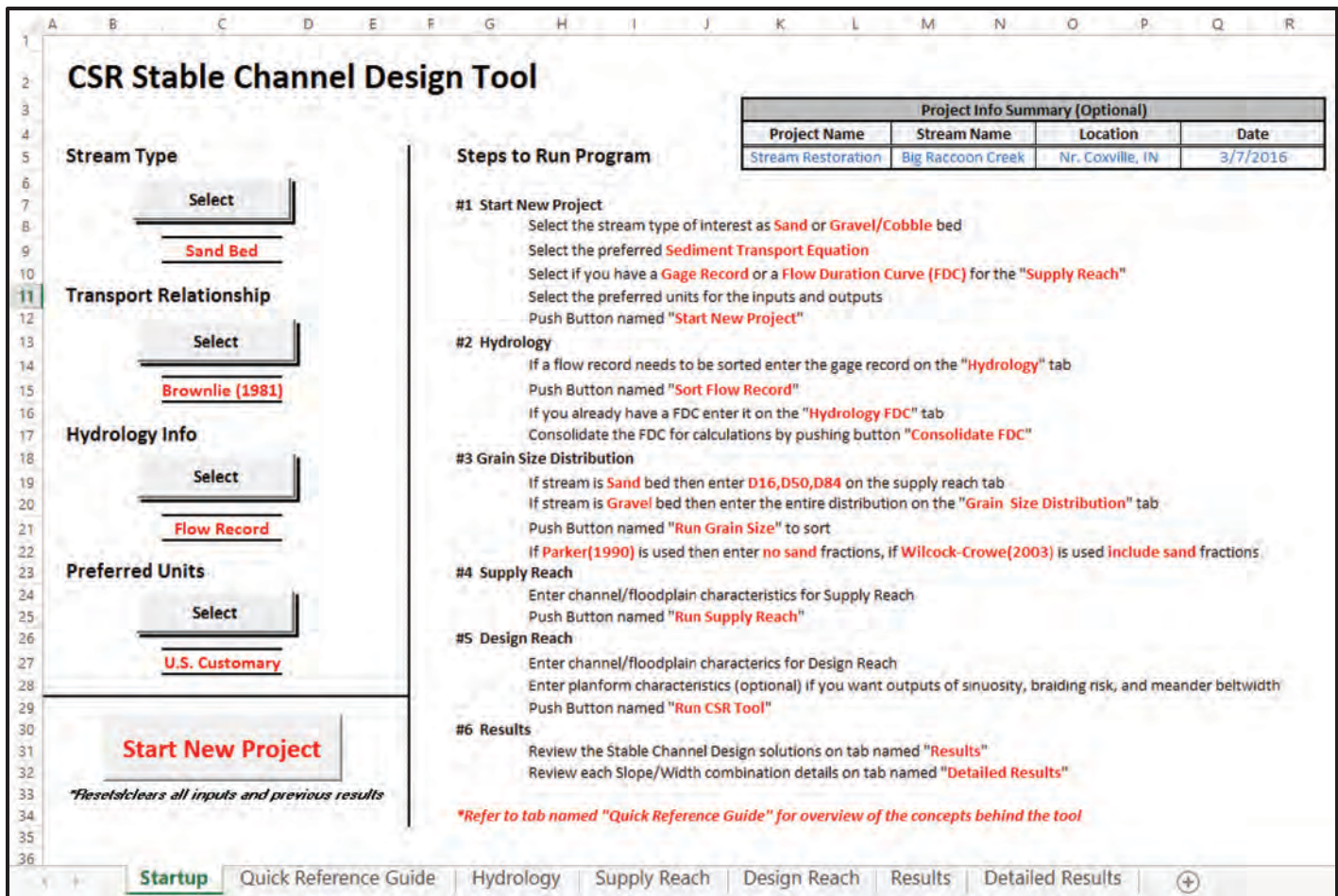


Figure 5-7. "Startup" tab with "Start New Project" defined.

Hydrology Results

This example uses the default 25 bins to sort the data, which are displayed in Column D under "Bin #" (Figure 5-8). 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 through 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.

5.1.3 Supply Reach Tab

The inputs required for the supply reach are entered in the cells that contain red asterisks (see Figure 4-8 for location of asterisks and Figure 5-9 for entered input). 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.

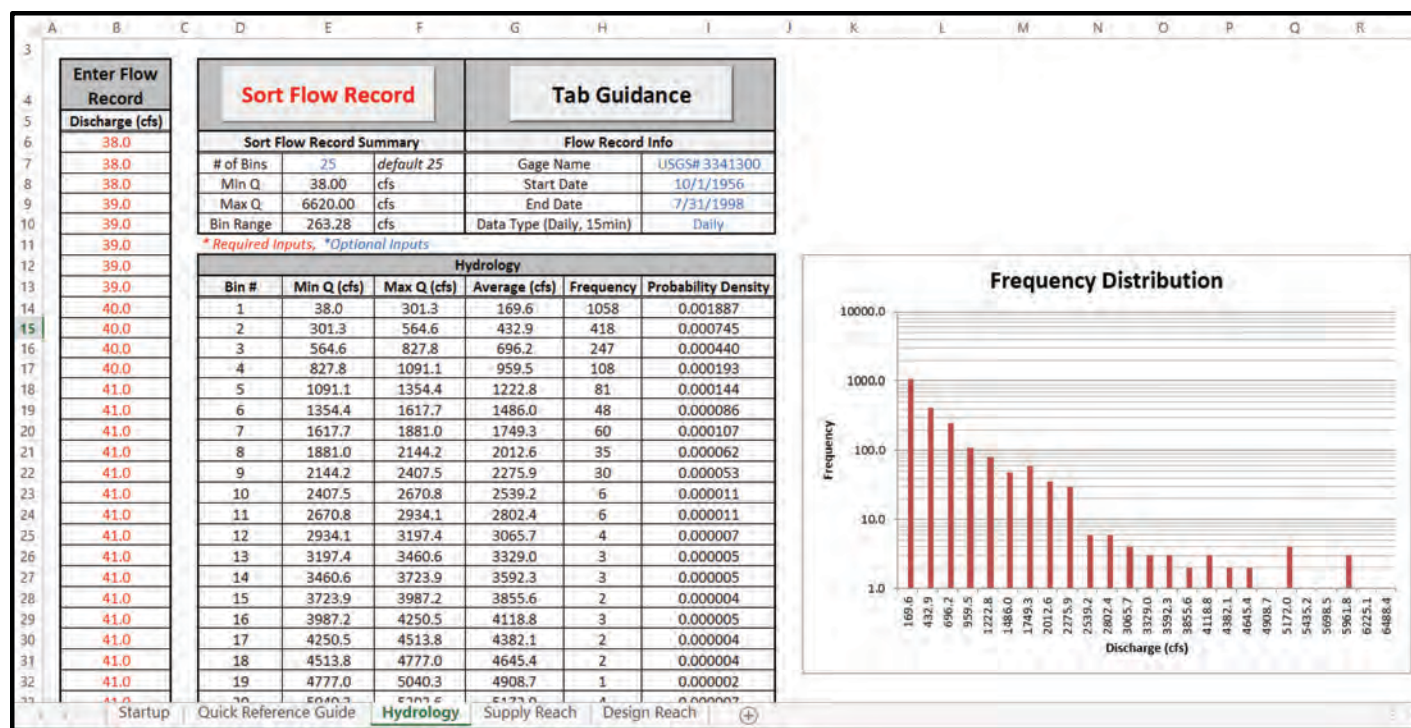


Figure 5-8. "Hydrology" tab, Big Raccoon Creek example results.

Hydrology

Columns F and G of Figure 5-9 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 through N in Figure 5-9 display the hydraulic characteristics calculated by the program for the associated bin discharge and 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 the bank height, 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 through Q in Figure 5-9 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 per day. Columns O and 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 the estimated sediment transported per day by each bin discharge on average in a given year based on the probability of daily flows in the

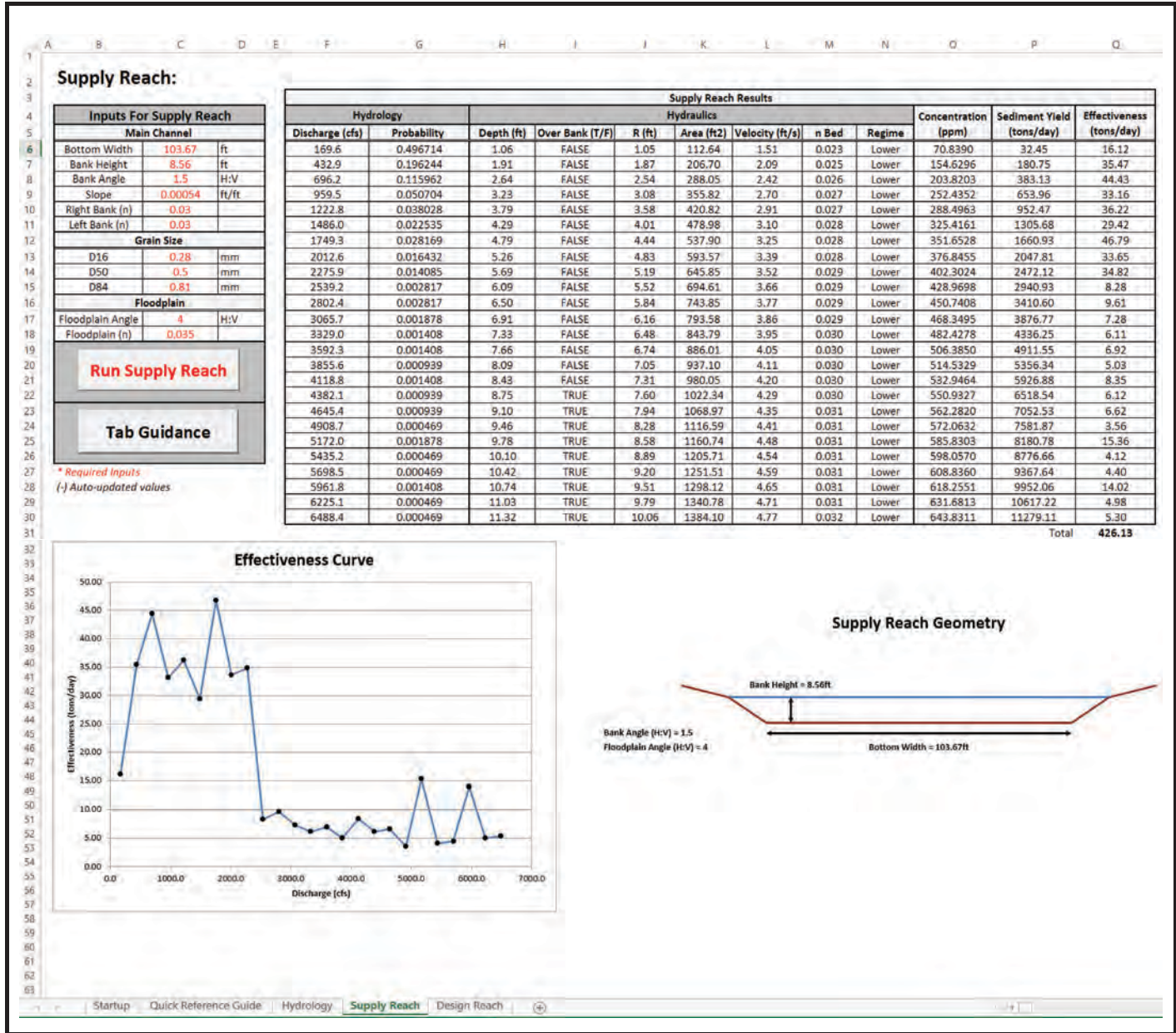


Figure 5-9. "Supply Reach" tab, Big Raccoon Creek example results.

flow record. The total effectiveness or total sediment transported per day on average in a given year 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.

5.1.4 Design Reach Tab

The required inputs, denoted by red asterisks, are entered for the design reach (Figure 5-10). For this example, the channel dimensions and grain size are assumed to be the same as those of 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 to attempt

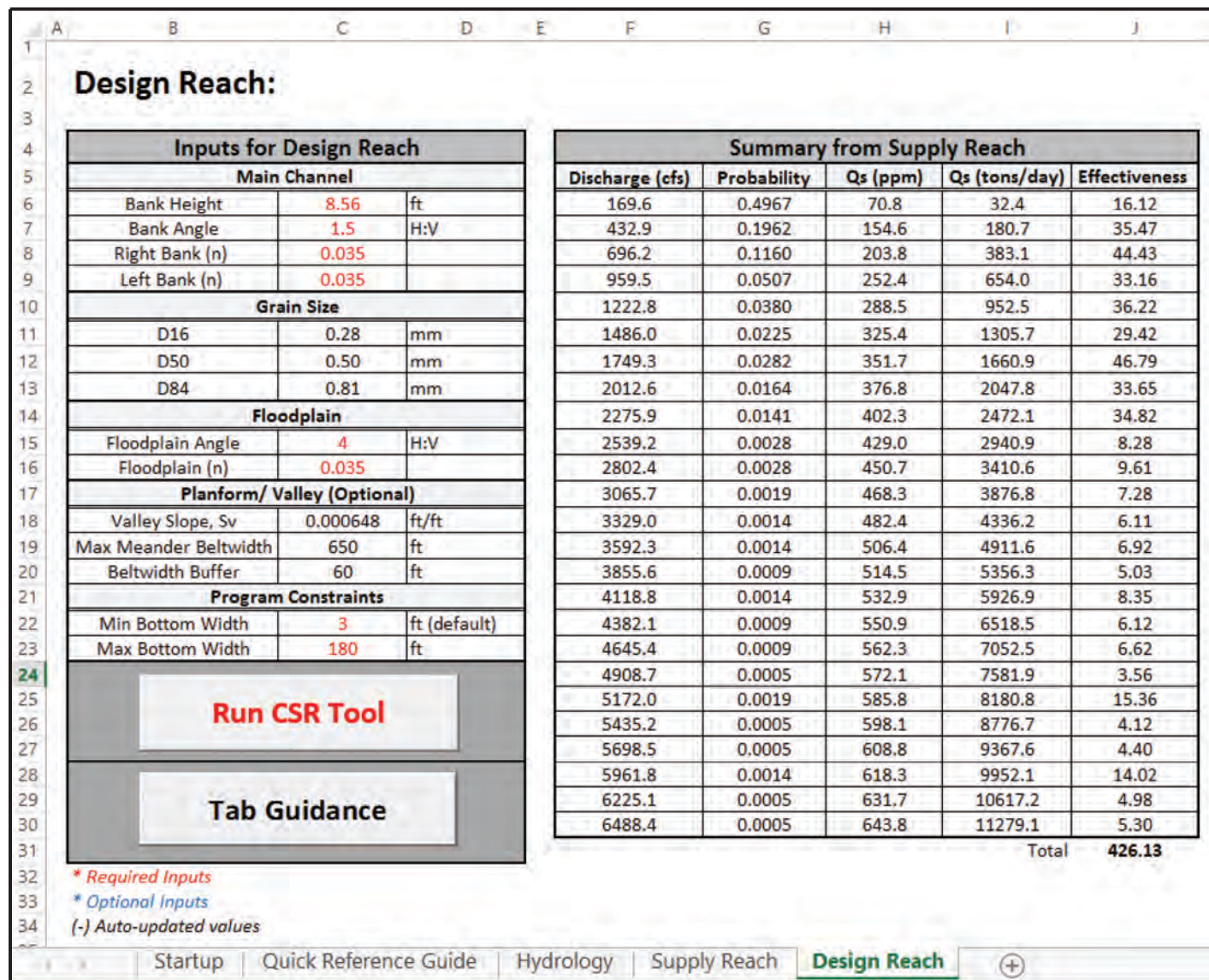


Figure 5-10. “Design Reach” tab, Big Raccoon Creek example inputs.

to find associated slopes that will produce $CSR = 1$. 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 and width combinations that balance the sediment capacity of the supply and design reach and produce $CSR = 1$. This will create a “Results” tab and a “Detailed Results” tab.

5.1.5 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 design solutions found by the program with $CSR = 1$ is graphed at the top left of the tab (Figure 5-11). This is analogous to the output of Copeland’s stable channel design tool in HEC-RAS.

Stable Geometries

To the right of the plot, the individual stable width and slope combinations are listed in Columns N through P of Figure 5-11. Column Q shows the associated CSR for each solution. The solutions are selected because they are within 0.025 of $CSR = 1$, 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 5-11. The bottom width for the supply reach is 103.67 ft and the slope is 0.00054. This solution lies between Rows 19 and 20 for the solutions in Columns N through P.

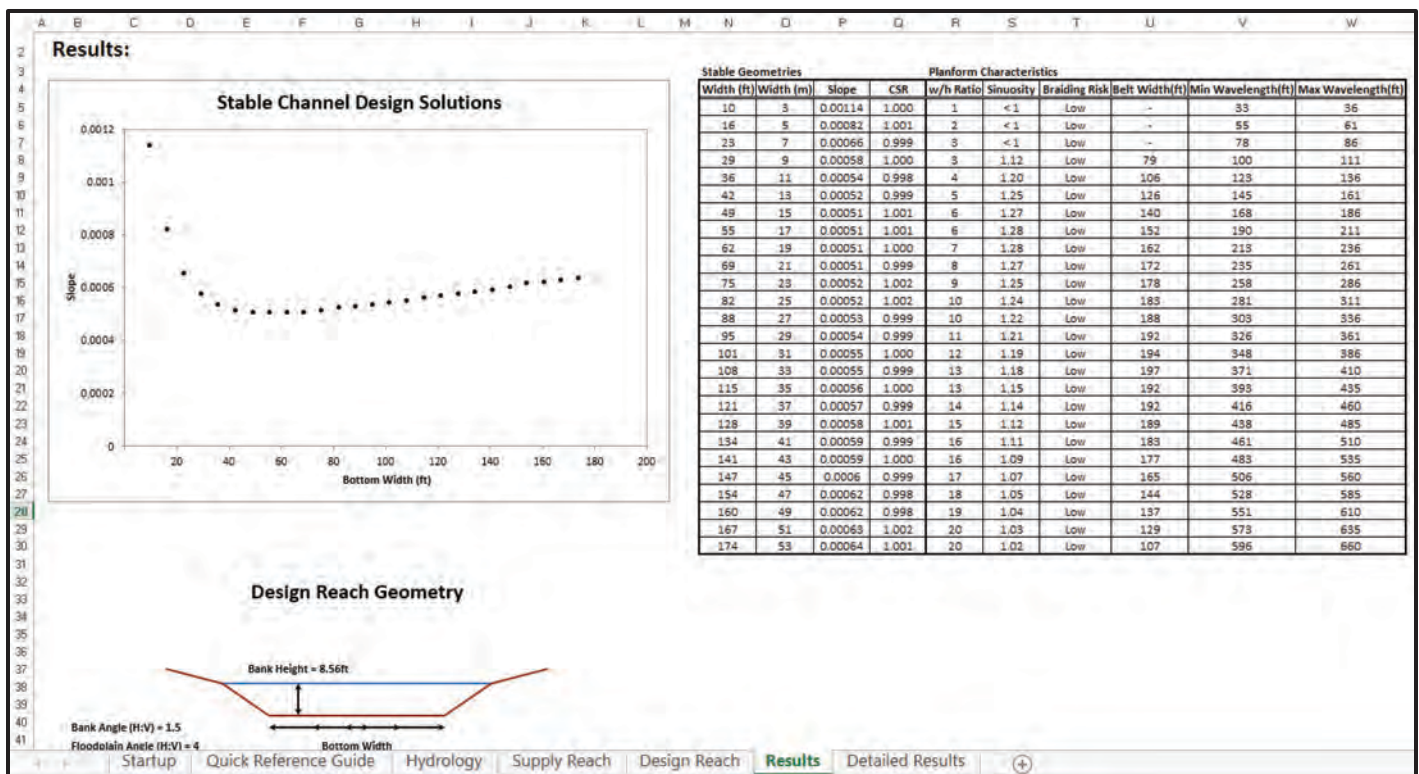


Figure 5-11. “Results” tab, Big Raccoon Creek example.

Planform Characteristics

The outputs for planform calculations are displayed in Columns R through W in Figure 5-11. 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. The estimate for the wavelength based on the 95% confidence interval presented by Soar and Thorne (2001) is displayed in Columns V and W. See “Planform Characteristics” in the CSR Tool Reference Manual (Appendix D of the final report for NCHRP 24-40) and the “Quick Reference Guide” tab for more information on the planform concepts.

Design Reach Geometry

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.

5.1.6 Detailed Results Tab

In addition to the “Results” tab, a “Detailed Results” tab is also created when the CSR analysis is run (Figure 5-12). This tab exhibits more detailed outputs of the analysis per discharge bin

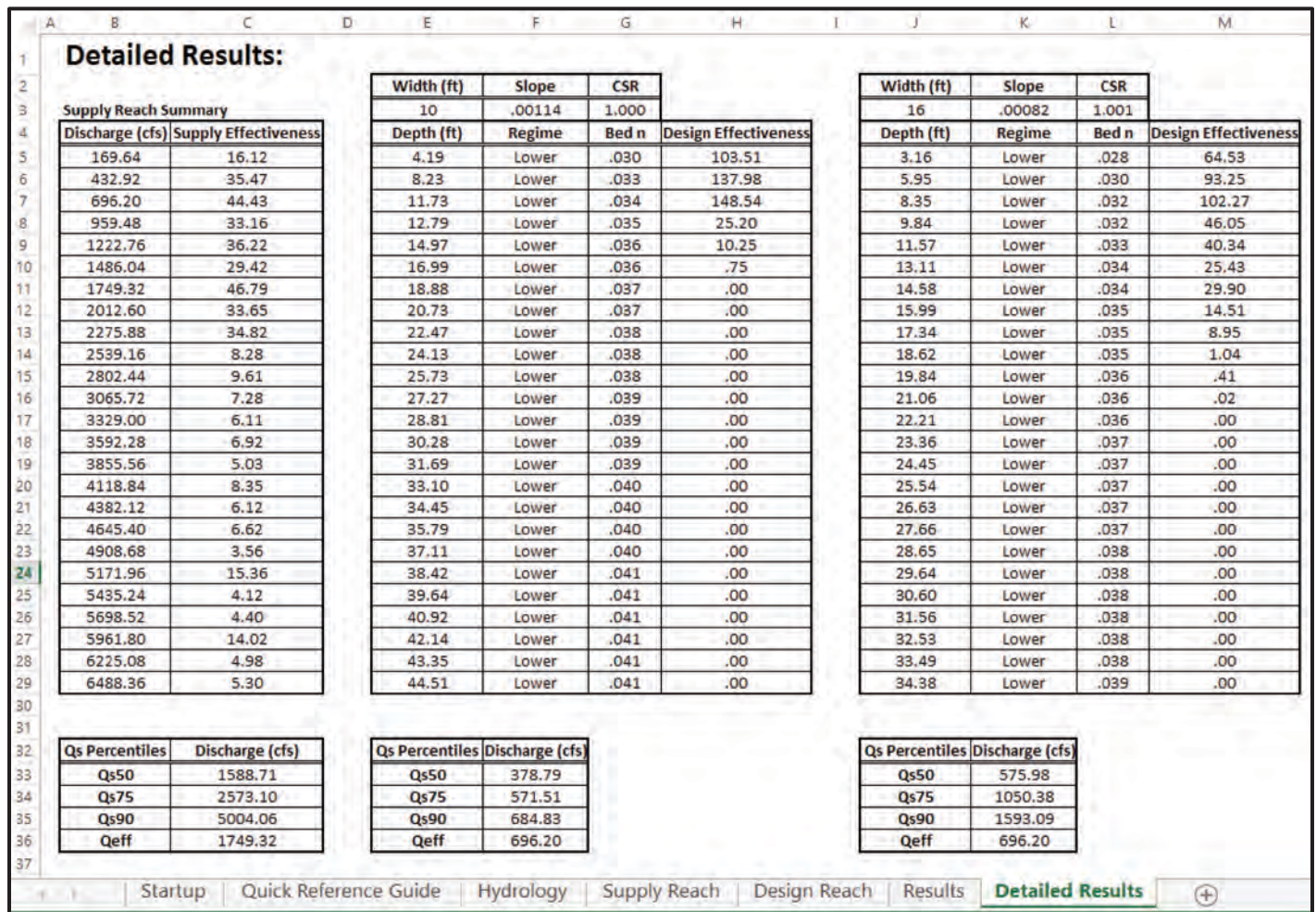


Figure 5-12. “Detailed Results” tab, Big Raccoon Creek example.

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for each stable channel solution. Columns B and 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 width, slope, and CSR are 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 is very high for the smallest widths.

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 D of the final report for NCHRP 24-40)]. The effective discharge (Q_{eff}) or the discharge bin that moves the most sediment is presented. Also, the discharges corresponding to the percentiles Q_{50} , Q_{75} , and Q_{90} 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.

5.2 Gravel/Cobble Bed

This example is for a reach on the Main Fork Red River, Idaho (Figure 5-13). 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).

5.2.1 Startup Tab

Figure 5-14 shows the Startup tab that appears when the CSR Tool is first opened. The project information summary is optionally entered in the top right of the tab.



Figure 5-13. *Main Fork Red River looking downstream from upper end of study reach (King et al. 2004).*

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

Stream Type
Select
Choose One

Transport Relationship
Select
Choose One

Hydrology Info
Select
Choose One

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 **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 characteristics 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*

Startup Quick Reference Guide

Figure 5-14. "Startup" tab 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 4-1. 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 4-2). These ranges are also summarized in the selection guidance window as shown in Figure 5-15. The selection for each field will display the answer chosen below the "Select" button.

Unlike the "Sand Bed" stream type, there is more than one "Transport Relationship" option for the "Gravel/Cobble" stream type. For this example, the Wilcock-Crowe (2003) equation was selected for the analysis because the amount of sand 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 4-2). 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 5-15 and 5-16).

This example reach has discharge data of significant length (35 years) 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 5-17).

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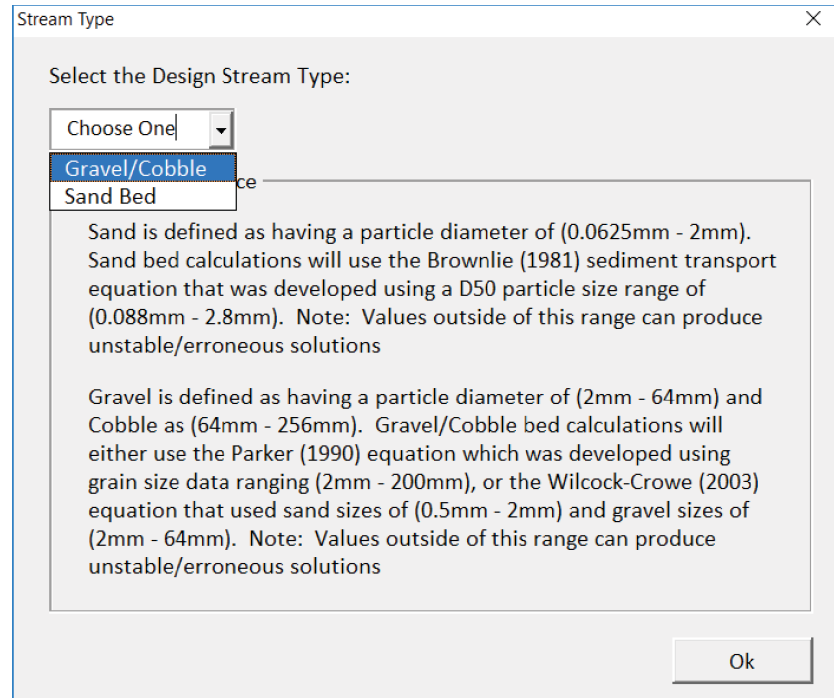


Figure 5-15. Selecting “Stream Type” on “Startup” tab.

Lastly, “Metric” is selected as the preferred units for this example (Figure 5-18). This selection will update and format the tabs to accept inputs and produce outputs in this unit of choice.

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 5-19.

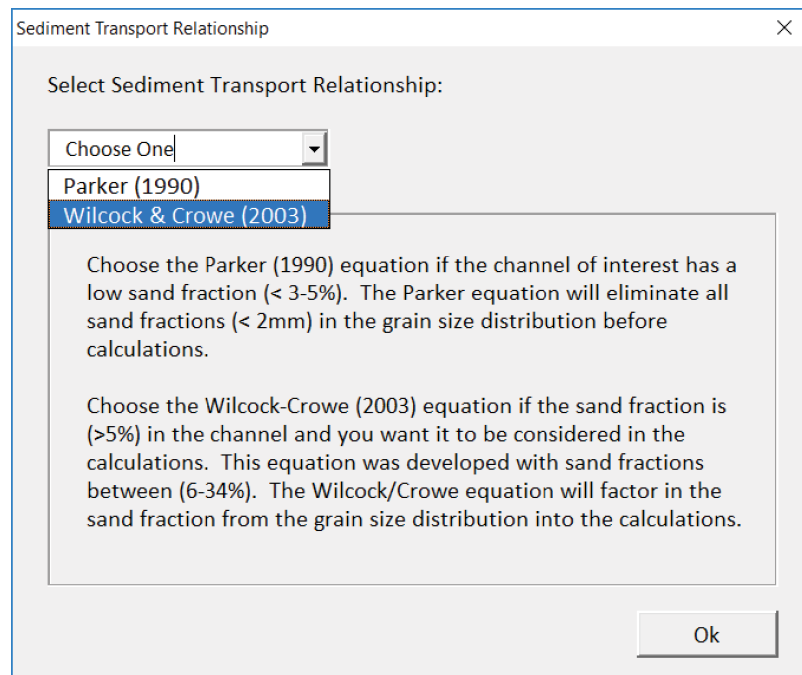


Figure 5-16. Selecting “Transport Relationship” on “Startup” tab.

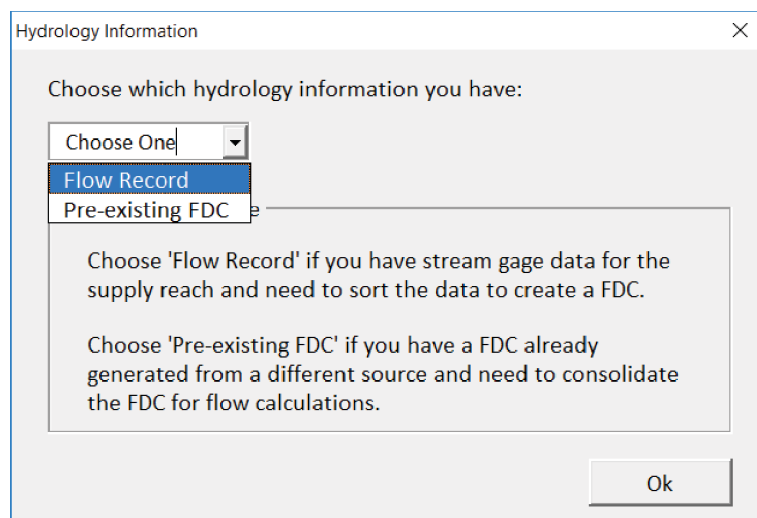


Figure 5-17. Selecting “Hydrology Info” on “Startup” tab.

5.2.2 Hydrology Tab

To follow the steps provided in Section 4.3, 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 5-20). Subsequently, the “Sort Flow Record” button is pressed to produce results.

Hydrology Results

This example uses the default 25 bins to sort the data displayed in Column D of Figure 5-20 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 through 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.

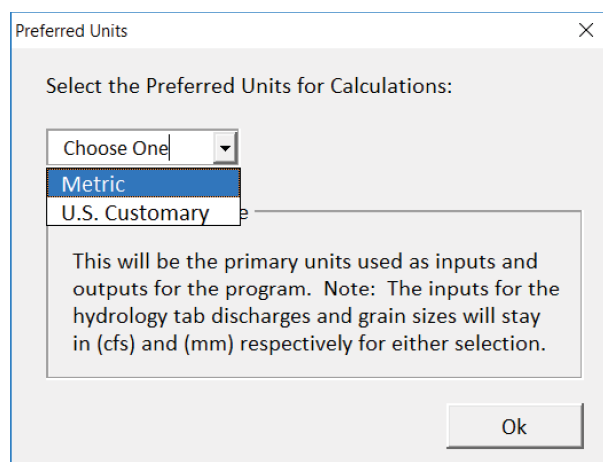


Figure 5-18. Selecting “Preferred Units” on “Startup” tab.

5.2.3 Grain Size Distribution Tab

The “Grain Size Distribution” tab (Figure 5-21) is displayed and required for this example because it is a “Gravel/Cobble” bed stream type. The “Grain Size Sample Info” is entered at the top left of the tab, if desired. Then, the percentage of bed material that is finer than the grain size class in Column B is entered into Column C of “Inputs for Grain Size” for each required field (denoted by red 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 “% Finer” versus grain size class is plotted in the graph in the lower right corner.

Distribution Summary

The results of the analysis are presented in “Distribution Summary (mm)” of the “Grain Size Distribution” tab (Figure 5-21). Rows 5 and 6 show the geometric mean grain diameter (D_g) and

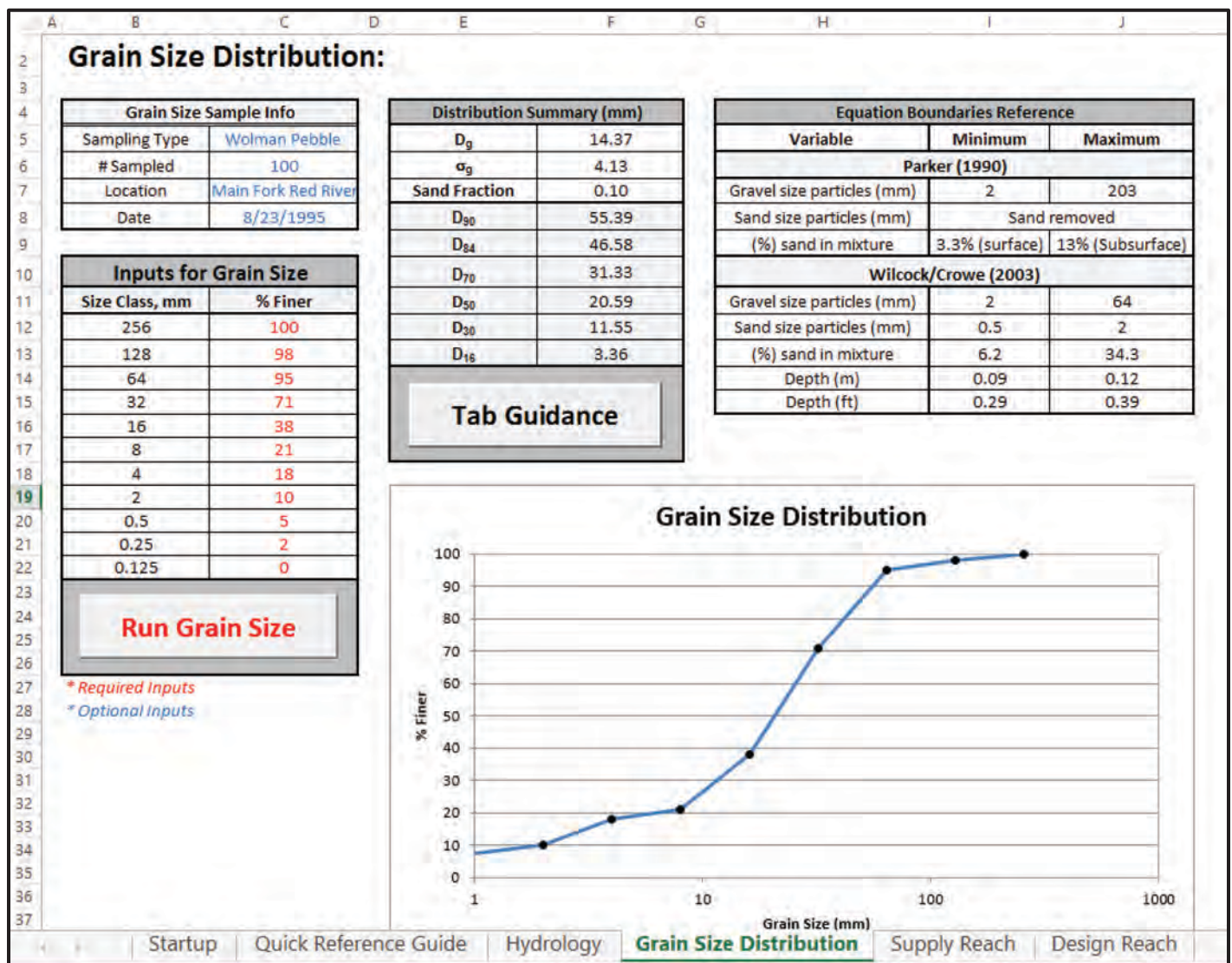


Figure 5-21. “Grain Size Distribution” tab, Red River example results.

the geometric standard deviation (σ_g); Row 7 shows the sand fraction, which in this example is 0.1 or 10%. Rows 8 through 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 4-2 of this document, 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.

5.2.4 Supply Reach Tab

The inputs required for the supply reach are entered in the cells that contain red asterisks (inputs for the example are in red in Figure 5-22). 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 the “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 5-22).

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 5-23. 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 5-24.

Hydrology

Columns F and G in Figure 5-22 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 through N display the hydraulic characteristics calculated by the program for the associated bin discharge and 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 through Q in Figure 5-22 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 per day, which represents the potential sediment yield produced 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

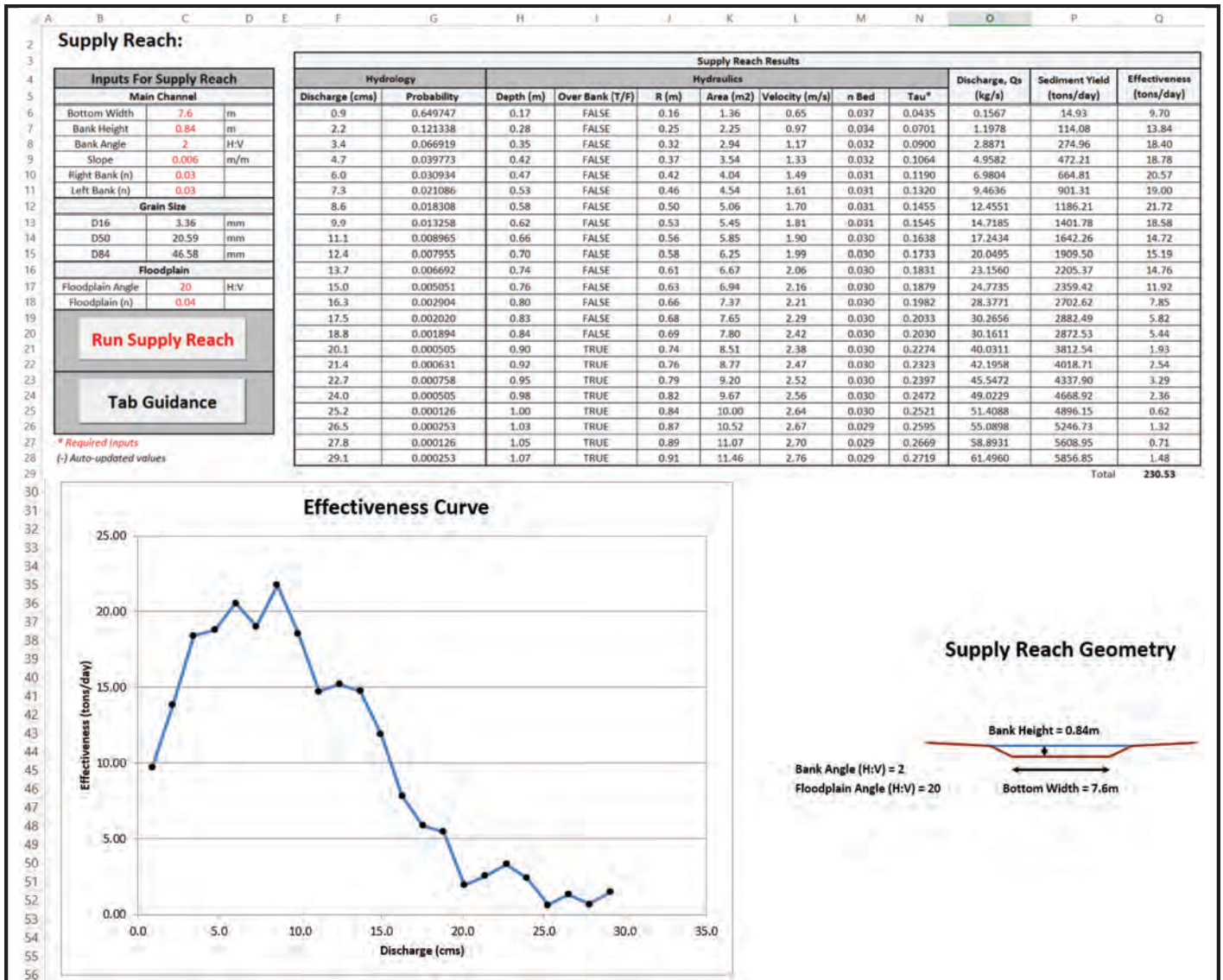


Figure 5-22. "Supply Reach" tab, Red River example results.

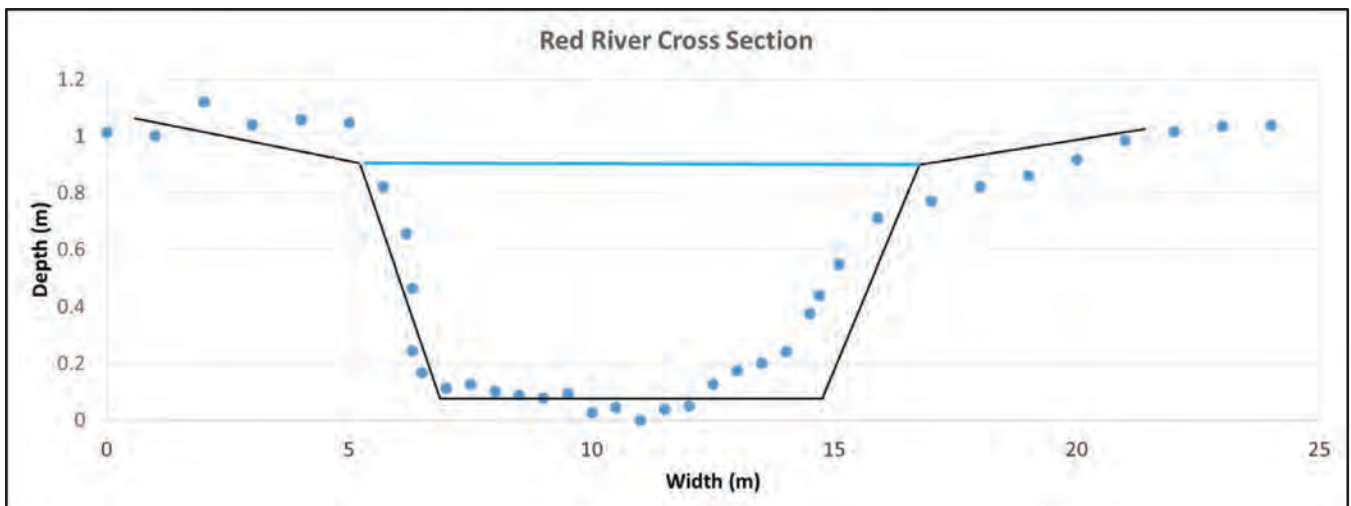


Figure 5-23. Fitted trapezoid cross section for supply reach of Red River from actual survey (King et al. 2004).

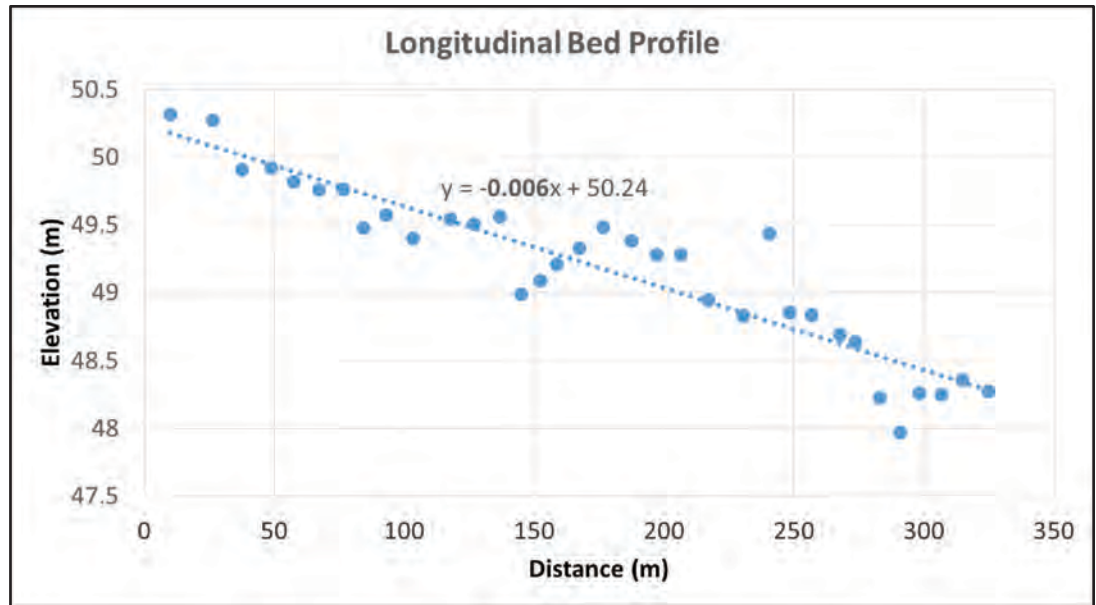


Figure 5-24. Red River longitudinal bed profile with fitted trend line to find bed slope (King et al. 2004).

the “effectiveness” or the estimated sediment transported per day by each bin discharge on average in a given year based on the probability of daily flows in the flow record. The total effectiveness or total sediment transported per day on average in a given year 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 of Figure 5-22, 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.

5.2.5 Design Reach Tab

Figure 5-25 shows the entered inputs required for the design reach (in red). 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 to attempt to find associated slopes that will produce $CSR = 1$. 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

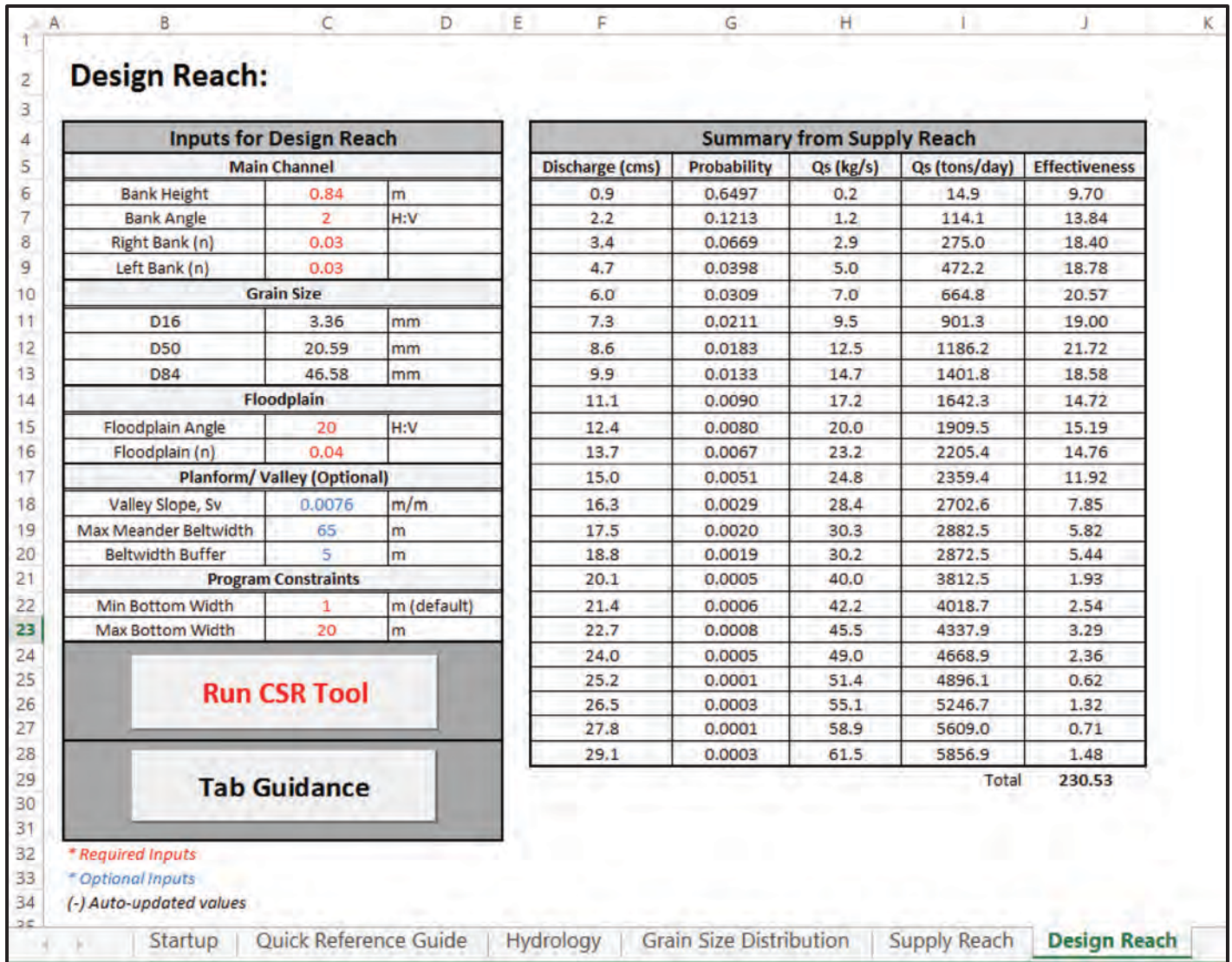


Figure 5-25. "Design Reach" tab, Red River example inputs.

to find slope and width combinations that balance the sediment capacity of the supply and design reach and produce CSR = 1. This will create a "Results" tab and a "Detailed Results" tab.

5.2.6 Results Tab

The "Results" tab (Figure 5-26) 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 design solutions found by the program with CSR = 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

To the right of the plot in Figure 5-26, the individual stable width and slope combinations are listed in Columns N through P. Column Q shows the associated CSR for each solution. The solutions are selected because they are within 0.025 of CSR = 1, which will pass the incoming sediment load from the supply reach with minimal degradation or aggradation. In this example,

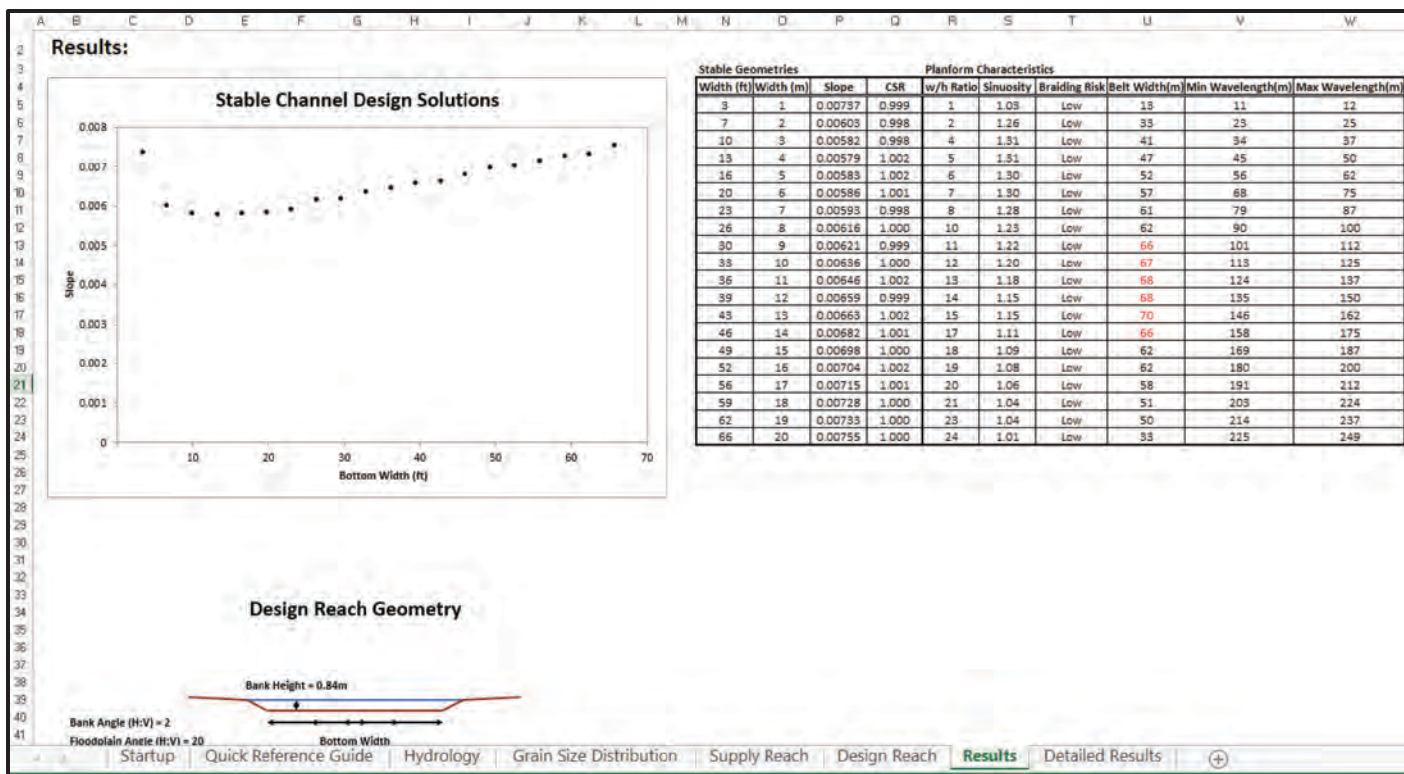


Figure 5-26. "Results" tab, Red River example.

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 because the same channel could pass the same sediment yield. This can be seen for this example in Figure 5-26. The bottom width for the supply reach is 7.6 m and the slope is 0.006. This solution lies between Rows 11 and 12 for the solutions in Columns N through P.

Planform Characteristics

The outputs for planform calculations are displayed in Columns R through W in Figure 5-26. 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. The calculated belt widths in Rows 13 through 18 are in red because the estimated belt width plus buffer is larger than the maximum meander belt width that was specified in 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 and W. See "Planform Characteristics" in the CSR Tool Reference Manual (Appendix D of the final report on NCHRP 24-40) 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.

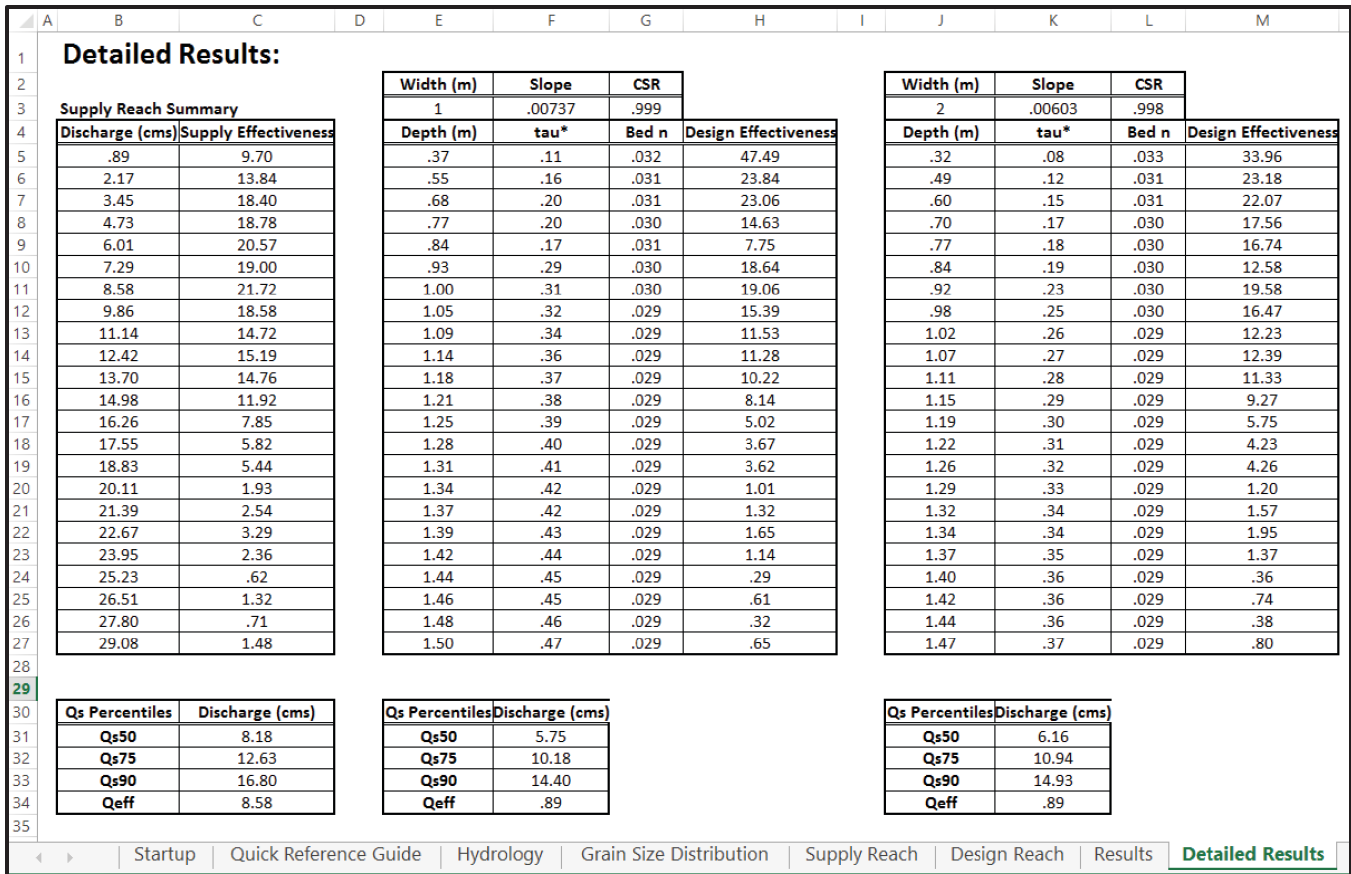


Figure 5-27. "Detailed Results" tab, Red River example.

5.2.7 Detailed Results Tab

In addition to the "Results" tab, a "Detailed Results" tab (Figure 5-27) is created when the CSR analysis is run. This tab exhibits more detailed outputs of the analysis per discharge bin for each stable channel solution. Columns B and 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 width, slope, and CSR are 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 D of the final report on NCHRP 24-40)]. 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.



References

- Ågren, A., I. Buffam, M. Jansson, and H. Laudon. 2007. "Importance of Seasonality and Small Streams for the Landscape Regulation of Dissolved Organic Carbon Export." *Journal of Geophysical Research: Biogeosciences*, Vol. 112, No. G3, DOI: 10.1029/2006JG000381.
- Asselman, N.E.M. 2000. "Fitting and Interpretation of Sediment Rating Curves." *Journal of Hydrology (Amsterdam)*, Vol. 234, Nos. 3–4, pp. 228–248, DOI: 10.1016/S0022-1694(00)00253-5.
- Bagnold, R.A. 1980. "An Empirical Correlation of Bedload Transport Rates in Flumes and Natural Rivers." *Proceedings of the Royal Society A*, Vol. A372, No. 1751, pp. 453–473, DOI: 10.1098/rspa.1980.0122.
- 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.
- Beven, K. J. 2011. *Rainfall-Runoff Modelling: The Primer* (Second Edition). John Wiley & Sons, West Sussex, UK, 488 p.
- Biedenbarn, D.S., C.M. Elliott, and C.C. Watson. 1997. *The WES Stream Investigation and Streambank Stabilization Handbook*. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. 460 p.
- Biedenbarn, 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, Nos. 3–4, pp. 281–300, DOI: 10.1016/S0169-555X(00)00099-4.
- Booth, D. B., S. R. Dusterhoff, E. D. Stein, and B. P. Bledsoe. 2010. "Hydromodification Screening Tools: GIS-Based Catchment Analyses of Potential Changes in Runoff and Sediment Discharge." Technical Report 605, Southern California Coastal Water Research Project, Costa Mesa, CA, 35 p. http://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/605_HydromodScreeningTools_GIS.pdf.
- 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).
- Bunte, K., and S. R. Abt. 2001. "Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring." General Technical Report RMRS-GTR-74, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 428 p. https://www.fs.fed.us/rm/pubs/rmrs_gtr074.pdf.
- Burt, T.P., and W.T. Swank. 1992. "Flow Frequency Responses to Hardwood-to-Grass Conversion and Subsequent Succession." *Hydrological Processes*, Vol. 6, No. 2, pp. 179–188, DOI: 10.1002/hyp.3360060206.
- Caltrans. 2015. "Caltrans Hydromodification Requirements Guidance: Storm Water Best Management Practices, Rapid Assessment of Stream Crossings, Higher Level Stream Stability Analysis." Report CTSW-OT-14-314.05, California Department of Transportation, Division of Environmental Analysis, Storm Water Liaison Program, Sacramento, CA, February, 156 p. <http://www.dot.ca.gov/hq/oppd/stormwtr/guidance/CT-Hydromodification-Requirements-Guidance.pdf>.
- Castellarin, A., G. Botter, D.A. Hughes, S. Liu, T.B.M.J. Ouarda, J. Parajka, D. Post, M. Sivapalan, C. Spence, A. Viglione, and R.M. Vogel. 2012. "Chapter 7: Prediction of Flow Duration Curves in Ungauged Basins" in G. Blöschl, M. Sivapalan, T. Wagener, A. Viglione, and H. Savenije (Eds.): *Runoff Prediction in Ungauged Basins: Synthesis Across Processes, Places and Scales*, pp. 135–162, Cambridge University Press, New York, NY.
- Cheng, L., M. Yaeger, A. Viglione, E. Coopersmith, S. Ye, and M. Sivapalan. 2012. "Exploring the Physical Controls of Regional Patterns of Flow Duration Curves—Part 1: Insights from Statistical Analyses." *Hydrology and Earth System Sciences*, Vol. 16, No. 11, pp. 4435–4446, DOI: 10.5194/hess-16-4435-2012.

- Church, M. 2006. "Bed Material Transport and the Morphology of Alluvial River Channels." *Annual Review of Earth and Planetary Sciences*, Vol. 34, No. 1, pp. 325–354, DOI: 10.1146/annurev.earth.33.092203.122721.
- Copeland, R.R., P.J. Soar, and C.R. Thorne. 2005. "Channel-forming Discharge and Hydraulic Geometry Width Predictors in Meandering Sand-Bed Rivers" in R. Walton (Ed.), *Impacts of Global Climate Change*, pp. 1–12, World Water and Environmental Resources Congress 2005, Anchorage, AL, May 15–19, DOI: 10.1061/40792(173)568.
- Dietrich, W.E., J.W. Kirchner, H. Ikeda, and F. Iseya. 1989. "Sediment Supply and the Development of the Coarse Surface Layer in Gravel-bedded Rivers." *Nature*, Vol. 340, pp. 215–217, DOI: 10.1038/340215a0.
- 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).
- Fennessey, N., and R.M. Vogel. 1990. "Regional Flow-Duration Curves for Ungauged Sites in Massachusetts." *Journal of Water Resources Planning and Management*, Vol. 116, No. 4, pp. 530–549, DOI: 10.1061/(ASCE)0733-9496(1990)116:4(530).
- Ganora, D., P. Claps, F. Laio, and A. Viglione. 2009. "An Approach to Estimate Nonparametric Flow Duration Curves in Ungauged Basins." *Water Resources Research*, Vol. 45, No. 10, pp. 1–10, DOI: 10.1029/2008WR007472.
- Gilbert, R. O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. John Wiley & Sons, New York, NY.
- Graf, W.L. 1977. "Network Characteristics in Suburbanizing Streams." *Water Resources Research*, Vol. 13, No. 2, pp. 459–463, DOI: 10.1029/WR013i002p00459.
- Hamed, K. H. 2008. "Trend Detection in Hydrologic Data: The Mann-Kendall Trend Test Under the Scaling Hypothesis." *Journal of Hydrology (Amsterdam)*, Vol. 349, Nos. 3–4, pp. 350–363, DOI: 10.1016/j.jhydrol.2007.11.009.
- 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.
- Hotchkiss, R. H., and C. M. Frei. 2007. "Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report." Publication No. FHWA-HIF-07-033, U.S. Department of Transportation, Federal Highway Administration, McLean, VA, 280 p. <http://www.fhwa.dot.gov/engineering/hydraulics/pubs/07033/07033.pdf>.
- Indiana Department of Environmental Management. 2013. "Escherichia Coli and Impaired Biotic Community Total Maximum Daily Load Report for the Big Raccoon Creek Watershed." Draft report prepared for the U.S. Environmental Protection Agency Region 5, 148 p. http://www.in.gov/idem/nps/files/tmdl_big_raccoon_report.pdf.
- Kahya, E., and S. Kalayci. 2004. "Trend Analysis of Streamflow in Turkey." *Journal of Hydrology (Amsterdam)*, Vol. 289, Nos. 1–4, pp. 128–144, DOI: 10.1016/j.jhydrol.2003.11.006.
- Kendall, M. G. 1975. *Rank Correlation Methods* (Fourth Edition). Charles Griffin, London, UK.
- 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. <https://www.treesearch.fs.fed.us/pubs/6704>.
- Kumar, S., V. Merwade, J. Kam, and K. Thurner. 2009. "Streamflow Trends in Indiana: Effects of Long-Term Persistence, Precipitation, and Subsurface Drains." *Journal of Hydrology (Amsterdam)*, Vol. 374, Nos. 1–2, pp. 171–183, DOI: 10.1016/j.jhydrol.2009.06.012.
- Lagasse, P.F., L. W. Zevenbergen, W. J. Spitz, and L. A. Arneson. 2012. *Hydraulic Engineering Circular No. 20: Stream Stability at Highway Structures* (Fourth Edition). Publication No. FHWA-HIF-12-004. Department of Transportation, Federal Highway Administration, April, 328 p. <http://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif12004.pdf>.
- Ley, R., M. C. Casper, H. Hellebrand, and R. Merz. 2011. "Catchment Classification by Runoff Behavior with Self-Organizing Maps (SOM)." *Hydrology and Earth System Sciences*, Vol. 15, No. 9, pp. 2947–2962, DOI: 10.5194/hess-15-2947-2011.
- 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. <http://pubs.usgs.gov/wsp/1898b/report.pdf>.
- Mann, H. B. 1945. "Non-parametric Tests Against Trend." *Econometrica*, Vol. 13, No. 3, pp. 245–259, DOI: 10.2307/1907187.
- Milly, P. C. D. 2007. "Stationarity is Dead." *Ground Water News & Views*, Vol. 4, No. 1, pp. 6–8.
- 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.
- Musiak, K., S. Inokuti, and Y. Takahasi. 1975. "Dependence of Low Flow Characteristics on Basin Geology in Mountainous Areas of Japan" in *The Hydrological Characteristics of River Basins*, Symposium of Tokyo,

- December. IAHS Publication No. 117. International Association of Hydrologic Sciences, Wallingford, Oxfordshire, UK, pp. 147–156.
- Nanson, G. C., and J. C. Croke. 1992. “A Genetic Classification of Floodplains.” *Geomorphology*, Vol. 4, No. 6, pp. 459–486, DOI: 10.1016/0169-555X(92)90039-Q.
- Natural Resources Conservation Service (NRCS). 1986. “Urban Hydrology for Small Watersheds.” Technical Release 55, U.S. Department of Agriculture, 164 p. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf.
- NRCS. 2007. “Chapter 4: Stream Restoration Design Process.” In: *Part 654 National Engineering Handbook*, U.S. Department of Agriculture, Washington, DC.
- Niraula, R., T. Meixner, and L. M. Norman. 2015. “Determining the Importance of Model Calibration for Forecasting Absolute/Relative Changes in Streamflow from LULC and Climate Changes.” *Journal of Hydrology (Amsterdam)*, Vol. 522, pp. 439–451, DOI: 10.1016/j.jhydrol.2015.01.007.
- 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.
- Poff, N. 1996. “A Hydrogeography of Unregulated Streams in the United States and an Examination of Scale-Dependence in Some Hydrological Descriptors.” *Freshwater Biology*, Vol. 36, No. 1, pp. 71–79, DOI: 10.1046/j.1365-2427.1996.00073.x.
- Praskievicz, S., and H. Chang. 2009. “A Review of Hydrological Modelling of Basin-Scale Climate Change and Urban Development Impacts.” *Progress in Physical Geography*, Vol. 33, No. 5, pp. 650–671, DOI: 10.1177/0309133309348098.
- Reid, L. M., and T. Dunne. 1996. *Rapid Evaluation of Sediment Budgets*. Vol. 29, Geo-Ecology Texts. Catena Verlag, Reiskirchen, Germany, 164 p.
- Reidy Liermann, C. A., J. D. Olden, T. J. Beechie, M. J. Kennard, P. B. Skidmore, C. P. Konrad, and H. Imaki. 2012. “Hydrogeomorphic Classification of Washington State Rivers to Support Emerging Environmental Flow Management Strategies.” *River Research and Applications*, Vol. 28, No. 9, pp. 1340–1358, DOI: 10.1002/rra.1541.
- 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.
- Rosgen, D. L. 1994. “A Classification of Natural Rivers.” *Catena*, Vol. 22, No. 3, pp. 169–199, DOI: 10.1016/0341-8162(94)90001-9.
- Sawicz, K. A., C. Kelleher, T. Wagener, P. Troch, M. Sivapalan, and G. Carrillo. 2014. “Characterizing Hydrologic Change Through Catchment Classification.” *Hydrology and Earth System Sciences*, Vol. 18, No. 1, pp. 273–285, DOI: 10.5194/hess-18-273-2014.
- Schumm, S. A., M. D. Harvey, and C. C. Watson. 1984. *Incised Channels: Morphology, Dynamics, and Control*. Water Resources Publications LLC, Littleton, CO.
- Searcy, J. K. 1959. “Flow-Duration Curves, Manual of Hydrology: Part 2. Low-Flow Techniques.” *Geological Survey Water-Supply Paper 1542-A*, Geological Survey, U.S. Government Printing Office, Washington, DC, 33 p.
- 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).
- Shields Jr., F. D., R. R. Copeland, P. C. Klingeman, M. W. Doyle, and A. Simon. 2008. “Chapter 9: Stream Restoration” in M. Garcia (Ed.): *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice*, Manual of Practice (MOP) 110, pp. 461–503. DOI: 10.1061/9780784408148.ch09.
- Smakhtin, V. Y. 1997. “Regional Low-Flow Studies in South Africa” in A. Gustard, S. Blazkova, M. Brilly, S. Demuth, J. Dixon, H. van Lanen, C. Llasat, S. Mkhanti, and E. Servat (Eds.): *Regional Hydrology: Concepts and Models for Sustainable Water Resource Management*, Third International Conference on FRIEND, IAHS Publication No. 246, pp. 125–132, International Association of Hydrologic Sciences, Wallingford, Oxfordshire, UK.
- Snyder & Associates, Inc. 2013. “Fourmile Creek Watershed Study.” Final Report. Ankeny, IA. www.fourmilecreekwatershed.org/FourmileCreek/FMCW_1_Report_Final-Web.pdf, accessed June 30, 2015.
- 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. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1043218.pdf.
- Soar, P. J., and C. R. Thorne. 2011. “Design Discharge for River Restoration” 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, pp. 123–150, American Geophysical Union, Geopress, Washington, DC.
- Strahler, A. N. 1952. “Hypsometric (area-altitude) Analysis of Erosional Topography.” *Bulletin of the Geological Society of America*, Vol. 63, No. 11, pp. 1117–1142, DOI: 10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2.
- Syvitski, J. P., M. D. Morehead, D. B. Bahr, and T. Mulder. 2000. “Estimating Fluvial Sediment Transport: The Rating Parameters.” *Water Resources Research*, Vol. 36, No. 9, pp. 2747–2760, DOI: 10.1029/2000WR900133.

- U.S. Forest Service. 2008. *Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings*. Report 0877 1801—SDTDC (San Dimas Technology and Development Center), U.S. Department of Agriculture, Forest Service, National Technology and Development Program, San Dimas, CA, May, 646 p. http://www.stream.fs.fed.us/fishxing/aop_pdfs.html.
- U.S. Geological Survey. 2012. "The StreamStats Program." Website. <http://streamstats.usgs.gov>.
- 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.
- Vigil, J.F., R.J. Pike, and D.G. Howell. 2000. "A Tapestry of Time and Terrain." *Geologic Investigations Series 2720*, U.S. Geological Survey, 1 plate scale 1:2,500,000, 1 pamphlet. <http://pubs.usgs.gov/imap/i2720/>.
- Villarini, G., F. Serinaldi, J.A. Smith, and W.F. Krajewski. 2009. "On the Stationarity of Annual Flood Peaks in the Continental United States During the 20th Century." *Water Resources Research*, Vol. 45, No. 8, DOI: 10.1029/2008WR007645.
- Walsh, C.J., A.H. Roy, J.W. Feminella, P.D. Cottingham, P.M. Groffman, and R.P. Morgan. 2005. "The Urban Stream Syndrome: Current Knowledge and the Search for a Cure." *Journal of the North American Benthological Society*, Vol. 24, No. 3, pp. 706–723, DOI: 10.1899/04-028.1.
- Watson, C.C., D. Dubler, and S.R. Abt. 1997. "Design Hydrology Investigations." Demonstration Erosion Control Project Report, Colorado State University, Fort Collins, CO, submitted to the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, 72 p.
- Whiting, P.J., and J.B. Bradley. 1993. "A Process-Based Classification System for Headwater Streams." *Earth Surface Processes and Landforms*, Vol. 18, No. 7, pp. 603–612, DOI: 10.1002/esp.3290180704.
- Wilcock, P.R., and S.T. Kenworthy. 2002. "A Two-Fraction Model for the Transport of Sand/Gravel Mixtures." *Water Resources Research*, Vol. 38, No. 10, pp. 12-1–12-12, DOI: 10.1029/2001WR000684.
- 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.



Abbreviations, Acronyms, Initialisms, and Symbols

Units of Measure

°C	degree(s) Celsius
cfs	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
H:V	horizontal:vertical
in.	inch(es)
kg/m ³	kilogram(s) per cubic meter
kg/s	kilogram(s) per second
km ²	square kilometer(s)
m	meter(s)
m/m	meter(s) per meter
m/s	meter(s) per second
m/s ²	meter(s) per second squared
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)
ppm	parts per million
W/m ²	Watt(s) per square meter

Statistical Terms

a	best-fit regression parameter
b	best-fit regression parameter; sediment rating curve parameter
p-value	probability
τ	Mann-Kendall test statistic

Acronyms and Initialisms

CEM	Channel Evolution Model
CN	curve number
CSR	capacity-supply ratio
CSR Tool	CSR Stable Channel Design Tool

DOT	Department of Transportation
eRAMS	Environmental Resource Assessment & Management System
FDC	flow duration curve
GHCND	Global Historical Climatology Network – Daily
HEC-20	<i>Hydraulic Engineering Circular No. 20</i>
HEC-RAS	Hydrologic Engineering Center River Analysis System
NCHRP	National Cooperative Highway Research Program
NRCS	Natural Resources Conservation Service
O	on the order of
PDF	probability density function
R-B	Richards-Baker Flashiness Index
RGA	rapid geomorphic assessment
SRP	stream response potential
SWAT-DEG	Soil and Water Assessment Tool – channel DEGradation
SWMM	Storm Water Management Model
USGS	U.S. Geological Survey

Symbols

$D_{16}, D_{75}, D_{84}, D_{90}$	particle size for which 16%, 75%, 84%, and 90% of all sediments is smaller [m], respectively
D_{50}	median grain diameter of the bed material [m]
D_g	geometric mean grain diameter [m]
F_s	approximate fraction of sand in bed sediments
g	gravitational acceleration [m/s^2]
G	specific gravity of sediment (2.65 is typically assumed)
i	day
k_d	erodibility factor
n	Manning's roughness coefficient
n	total number of days in the flow record
n	total number of data points
q	daily-averaged discharge [m^3/s]
Q	median annual peak flow (Q_2) [m^3/s]
Q	water discharge rate [m^3/s]
$Q_{1.5}, Q_2$	1.5-year and 2-year, return interval discharges [m^3/s], respectively
Q_{eff}	effective discharge [m^3/s]
Q_s	sediment discharge rate [kg/s]
$Q_{s50}, Q_{s75}, Q_{s90}$	discharge associated with 50%, 75%, and 90% of cumulative sediment transport over the sorted flow record [m^3/s], respectively
RB	Richards-Baker Flashiness Index
S	channel slope [m/m]
S_v	valley slope [m/m]
w	channel top width at bankfull [m]
w/h	width/depth ratio
ρ	density of the fluid mixture [kg/m^3]
σ_g	geometric standard deviation of particles sizes
τ^*	dimensionless shear stress
ω	specific stream power [W/m^2] ($\omega = \rho g Q S / w$)
ω^*	dimensionless specific stream power

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI-NA	Airports Council International-North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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