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Rapid Hydraulic Assessment for Stream Restoration

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OVERVIEW: The planning, design, and installation of a stream restoration project must take into account the hydraulic conditions of the stream being restored. This is true whether the project involves a few feet of bank stabilization or several miles of habitat restoration. Without a thorough review and understanding of hydraulics, any adjustment to a stream could affect flood risk, induce erosion, adversely impact biota, or create other problems. Even a cursory review of channel hydraulics can increase the probability of achieving successful restoration outcomes.

Hydraulic analysis links watershed hydrology to the channel environment and serves as a critical step toward assessment of sediment transport and channel stability. An associated technical note (Fischenich and McKay 2011) provides guidance for basic hydrologic analyses to estimate streamflow discharge. Accurate estimates of discharge are necessary and have serious design implications; however, until they are transformed to relevant hydraulic metrics, the hydrologic analyses often provide only limited insight with little design significance (e.g., Is 500 cubic feet per second a small or large amount of water for a given channel?). Hydraulic analyses vary from the simple to the complex and costs can vary from a few hundred to a few hundred thousand dollars, depending on the complexity, length, and size of the stream as well as the complexity, level of analysis, and importance of the associated project. The importance of the surrounding landscape may play an important role in determining the risk associated with a project and an appropriate level of analysis.

The goals of this technical note are to briefly review key issues in hydraulic classification, present preliminary hydraulic analyses common to most stream restoration projects, and discuss a set of simple tools for first-order, rapid hydraulic analyses. The authors do not intend to provide a comprehensive review or engineering guide for restoration (See Copeland et al. 2001, Garcia 2007, and Simon et al. 2011), and the primary audience for this document is biologists, planners, economists, and other nonengineers involved in restoration design. This technical note and associated tools are intended to facilitate discussion among members of the restoration team and help nonengineers understand the nature and application of common hydraulic analyses.

FLOW CLASSIFICATION: Hydraulic analysis of a stream may require varying levels of complexity. The first, and perhaps most critical, of these is a basic characterization of flow properties with respect to space, time, and key forces acting on the system (Chow 1959).

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Time and Space. Channel hydraulics are spatially and temporally variable. However, this variability may be small over relevant periods of time or specific spatial conditions. Flow can be temporally divided into *steady* flow, which implies flow depth and velocity do not change in time, or *unsteady* flow, in which flow depth and velocity do vary in time (French 1985). All streams are under unsteady flow conditions from an instantaneous perspective; however, in the context of restoration project design, most streams can be considered quasi-steady. Unsteady flow analysis is often unnecessary for the resolution of methods examined here, but unsteady flow may be a crucial variable where tidal influence exists, water surface elevations change rapidly (e.g., a dam break), or watersheds are susceptible to flash flooding.

If depth and velocity of flow are constant at every channel cross-section, the flow is termed *uniform*; however, the flow is classified as nonuniform or *varied* if flow depth and velocity vary spatially. Unsteady, uniform flow is extremely rare; therefore, if flow is identified as uniform, it is generally considered steady. This flow condition is often termed the *normal* flow and is the focus of this document. Varied flow can be further divided into *rapidly varied* or *gradually varied flow*. Rapidly varied flow implies flow depth and velocity vary over short spatial scales (e.g., hydraulic jump, sharp flow contraction at a culvert). Gradually varied flow implies flow depth and velocity change slowly over long spatial scales (e.g., upstream flow impoundment and backwater effects of a reservoir).

Dimensionless Ratios. The relative effect of competing hydraulic forces also provides an important means for characterizing and classifying flow conditions. The relative influence of the fluid viscosity is characterized by examining the ratio of inertial to viscous forces, known as the Reynolds number (Equation 1). A flow may be classified from this ratio as *laminar* (R_e <500), *transitional* (500< R_e <12,500), or *turbulent* (12,500<R_e) (French 1985). Almost all stream restoration projects will be in the turbulent regime, so only turbulent flows will be considered throughout this paper, but if flows are moving extremely slowly in defined, smooth paths (e.g., wetland flows with little velocity), calculation of the Reynolds number is recommended because hydraulic analyses and designs differ for laminar flows.

$$R_e = \frac{VR}{\nu} \tag{1}$$

Where R_e is Reynolds number, V is cross-section mean velocity, R is hydraulic radius (ratio of the cross-section area, A, to the wetted perimeter, P), and ν is kinematic viscosity of the fluid.

The ratio of inertial to gravitational forces, the Froude number (Equation 2), is significantly more relevant in stream restoration hydraulics. Tranquil flows are said to be *subcritical* (F_r <1), while rapid flows are said to be *supercritical* (F_r >1).

$$F_r = \frac{V}{\sqrt{gD}} \tag{2}$$

Where F_r is the Froude Number, g is gravitational acceleration, and D is the hydraulic depth ($D = A / T$ is the ratio of the cross-sectional area, A, to the width of the free surface, T)

Tranquil flows exist in most streams and rivers; however, numerous streams, especially high gradient streams, may exhibit rapid flow conditions. Streams with rapid flow conditions have an enormous erosive capacity and the identification of supercritical flow can be critical to the success of a restoration project. One simple field assessment to determine whether the flow is rapid or tranquil is to drop a stone or other object into the water. If the waves caused by the impact move upstream from the point of impact, the flow is tranquil. If all the waves are carried downstream, the flow is rapid. When flows approach the transition between rapid and tranquil, it is sometimes hard to identify the flow regime using this method. Gravel and cobble streams usually exhibit a riffle-pool sequence, where flow conditions are often transitional or supercritical in the riffles and subcritical in the pools. Because of high erosive capacity, designers should carefully analyze projects on streams with supercritical or transitional flow.

What do flow classes provide? Basic characterization of flow properties is important to hydraulic analysis of a stream restoration project. Although extraneous circumstances have been highlighted, most analyses can be approached assuming the flow is steady, uniform, turbulent, and subcritical; analyses with these assumptions will be the focus of this document. However, restoration designers should be aware of the influence of other flow types and consider their inclusion in analyses, particularly in the exceptions identified.

PRELIMINARY HYDRAULIC ANALYSES: Most hydraulic analyses involve the same steps regardless of the resolution of output desired: (1) characterize the site; (2) examine and simplify the governing equations as necessary; (3) estimate channel resistance; (4) use the governing equations and channel resistance estimates to compute channel hydraulics for a representative range of flows; and (5) apply the resulting relations for hydraulic design. This set of steps is applicable and scalable from complex three-dimensional analyses required for a high-risk project to simple analyses conducted on the banks of a river during a preliminary site visit. Although project needs may dictate use of two- and three-dimensional analyses, preliminary restoration analyses are almost always accomplished with the one-dimensional assumptions and methods; preliminary restoration analyses of this type are the focus of this section.

Site Characterization. Even the most cursory stream restoration analyses require a basic knowledge of the project site and familiarity with system characteristics. Although the spatial and temporal resolution may differ for varying project requirements (e.g., 1D, 2D, or 3D), key data needs typically include the following.

- *Basin hydrology*: What are typical river discharges (low, median, and high) experienced by this system? What particular discharges need to be accommodated by the project (e.g., a 100-year flood)? See Fischenich and McKay (2011) for additional information.
- *Channel geometry*: What is the cross-sectional shape of the channel (depth, width, area, side slope, etc.)? What is the longitudinal slope of the channel and valley at an appropriate reach scale? Are there significant planform features (e.g., high sinuosity)?
- *Channel boundaries*: What is the composition of the bed material (e.g., sand, cobble)? What role does vegetation play in the system (e.g., riparian, macrophytes)? Are there other important controls affecting hydraulic condition (e.g., channel contractions)?
- *Local conditions*: Are there local features of particular note (e.g., bridges, pipe crossings, nearby infrastructure)? What is the flow classification through the study reach?

Data collection efforts may consist of long-term detailed field studies, a review of published material, a site visit, or simply the use of best professional judgment. The project requirements and funding will dictate the detail of data collected. Although data needs may span a variety of scales and resolutions, most restoration projects typically rely on basic cross-sectional analyses in the project reach to quantify hydraulic properties of the system. In these analyses, channel geometry can be identified by survey; bed material samples may be collected; roughness may be visually estimated; local conditions of importance may be identified; and flow characteristics may be assessed.

Governing Equations. Three governing equations serve as a basis for most hydraulic designs of stream restoration projects: conservation of mass, energy, and momentum (Richardson et al. 2001). *Conservation of mass*, often called the continuity equation (Equation 3), simply states that river discharge must be the product of average velocity and cross-sectional area.

$$Q = VA \tag{3}$$

Where Q is the volumetric rate of water flow, V is the cross-section averaged velocity, and A is the cross-sectional area of flow.

The second governing equation is the law of *conservation of energy*. This principle states that the total energy (head) of a parcel of water is the sum of the potential energies (elevation and pressure) and the kinetic energy and must be conserved along the channel (Equation 4, Figure 1). Assuming hydrostatic pressure distribution, head at a given cross-section can be expressed as:

$$H = \eta + h\cos\theta + \alpha\frac{V^2}{2g} \tag{4}$$

Where H is the total head, η is the elevation of the bed, h is the depth of flow normal to the bed, θ is the slope angle of the channel bed, V is the velocity, g is gravitational acceleration, and α is the Coriolis (or energy) coefficient.

The energy coefficient, α, expresses a correction for nonuniformity in the velocity distribution, and in most applications this value is assumed to be 1 or read from a table (e.g., Chow 1959, p.28). The depth and slope angle terms can be replaced by a vertical expression of the depth, y, because in most rivers the bed slope is sufficiently small that this assumption introduces very little error ($\cos\theta \approx 1$ for $S_0 < 0.1$).

As stated, conservation of energy states that the energy at any two points in a channel must be equal to the sum of energies at the two locations plus frictional losses due to channel resistance. This is expressed schematically in Figure 1 and computationally as Equation 5 (Chow 1959):

$$H_1 = H_2 + h_f \tag{5}$$

Where $_1$ and $_2$ denote upstream and downstream cross sections, respectively, and h_f is the head loss through the reach.

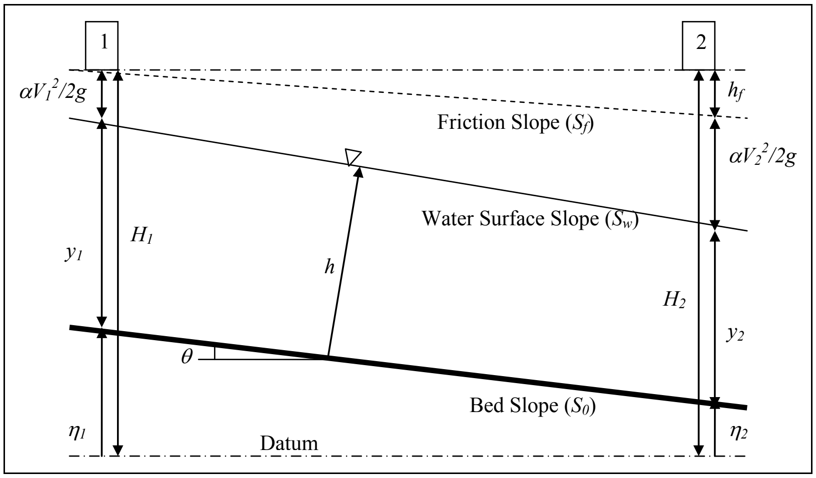


Figure 1. Conservation of energy in uniform open channel flow (after Chow 1959).

Application of Newton's second law to problems of open channel flows leads to the law of *conservation of momentum*. This law states that the sum of forces acting on a control volume is equal to the mass flow rate times the change in velocity through the control volume (Equation 6).

$$\sum F_i = \beta \rho Q \Delta V \tag{6}$$

Where F_i is force i acting on the control volume, β is the Boussinesq (or momentum) coefficient, ρ is the fluid density, Q is volumetric discharge, and ΔV is change in velocity (V_2-V_1). The momentum coefficient, β, also expresses a correction for nonuniformity in velocity distributions, and in most applications this value is assumed to be 1 or read from a table (Chow 1959).

These three governing equations are often used in conjunction with each other to define the flow characteristics of a given hydraulic phenomenon. The energy equation is often employed for use in gradually varied flow calculations (e.g., backwater profile computation upstream of a reservoir), while the momentum equation is more commonly applied to rapidly varied flow problems (e.g., hydraulic jumps). These equations, or simplifications of these equations, serve as a basis for a majority of stream restoration hydraulic calculations. Following sections will highlight practicable implementation of these equations for first-order analysis of stream restoration projects.

Channel Resistance. The laws of conservation of energy and momentum include accounting for hydraulic resistive forces, expressed either as head loss (h_f) or as a frictional force. The most frequently applied methods of relating channel resistance to flow velocity are the Manning, Chezy, and Darcy-Weisbach equations (Yen 2002, Equations 7-9, respectively).

$$V = \frac{k_n R^{1/6}}{n} \sqrt{R S_f} \qquad \text{Manning (7)}$$

$$V = C_z \sqrt{R S_f} \qquad \text{Chezy (8)}$$

$$V = \sqrt{\frac{8g}{f}}\sqrt{RS_f} \qquad \text{Darcy-Weisbach (9)}$$

Where V is the cross section averaged velocity, R is the hydraulic radius, S_f is the friction slope, k_n is a unit correctional factor (1 for SI units, 1.486 for English Units), n is Manning's coefficient, C_z is the Chezy coefficient, and f is the Darcy-Weisbach friction factor.

Rigorous application of these equations requires knowledge of the friction slope, S_f; however, accurate quantification of the friction slope relies on extensive data collection. If the channel cross section and velocity are relatively similar throughout the longitudinal domain, friction slope can be assumed to be approximately the slope of the water surface $\left(S_f \approx S_w\right)$, and if uniform flow conditions exist, then water surface slope is equal to bed slope $\left(S_w \approx S_0\right)$. Therefore, for uniform flow, friction slope is often assumed to be bed slope $\left(S_f \approx S_0 = \tan\theta\right)$.

The use of these equations requires an estimate of the resistance coefficient (n, f, C_z) for the chosen relation. Ideally, these resistance coefficients would be dimensionless and independent of hydraulic characteristics. This is the case for the Darcy-Weisbach f, but Manning and Chezy's coefficients are dimensional quantities (s/m$^{1/3}$ and m$^{1/2}$/s, respectively). For these reasons, the Darcy-Weisbach coefficient is often preferred among researchers; however, Manning's n is by far the most common resistance coefficient among practitioners. Accordingly, Manning's n will be referred to in all resistance calculations throughout this paper.

Resistance relations are valuable tools for calculating frictional losses in natural channels. The equations do, however, present two problems: lumping of all resistive forces into one parameter and accurate estimation of the resistance coefficients. Sources of resistance in rivers may include: surface roughness, form roughness due to bed irregularity, form roughness due to channel irregularities in the cross section, form roughness due to planform irregularities (e.g., meandering), obstruction of flow (e.g., debris jams), and vegetative growth. Methods exist for accounting for each of these contributions separately; however, accurate distribution of roughness to varying contributing elements is very difficult (Chow 1959). Therefore, resistance coefficients are generally estimated to account for total resistive force. McKay and Fischenich (2011) review techniques for estimating Manning's n and provide a spreadsheet tool for conducting computations, the HYDraulic ROughness CALculator (HYDROCAL).

Many channels exhibit varying roughness conditions throughout the lateral domain (e.g., vegetated floodplain of a sand bed stream). In these channels, a composite roughness must be calculated. The n value must be estimated in each of these subsections, and the overall n determined by an equation for compositing roughness. Yen (2002) provides 17 such equations based on varying assumptions. Equation 10 is commonly used for compositing roughness and assumes that subsection n values are weighted by the cross-sectional area they represent.

$$n_{composite} = \frac{A}{\sum \frac{A_i}{n_i}} \qquad (10)$$

Where $n_{composite}$ is the composite section roughness, A is the total cross-sectional area, A_i is the subsection cross-sectional area, and n_i is the subsection Manning's n value.

Computing Channel Hydraulics. From the site characterization, governing equations and channel resistance estimates, the relationship between flow depth and discharge may be determined for two important conditions, normal and critical flow. Calculation of normal and critical depth (or discharge) is a common first step in any restoration design, but the techniques presented here are only applicable to a single cross-section and may therefore be considered zero-dimensional levels of analysis. Often more sophisticated one-, two-, or three-dimensional analyses follow these predictions and are needed to address unsteady conditions, gradually or rapidly varied flow, depth and velocity distributions in a cross section, and responses to restoration designs. The following sections outline first-order analyses that are commonly applied to initially characterize hydraulic conditions, inform preliminary restoration designs, and guide the application of more sophisticated techniques and models.

Channel Geometry. River cross sections are often topographically diverse and nonuniform in shape. However, preliminary hydraulic analyses often assume geometric channel cross sections such as rectangular, trapezoidal, triangular, or parabolic forms as a general representation (Chow 1959, p. 21). These geometric forms allow for simple computation of hydraulically relevant geometric variables. For instance, if a trapezoidal cross section is assumed (Figure 2), the following equations may be used to estimate geometry for any flow depth, h.

$$T = b + 2sh \quad \text{Top Width (11)}$$

$$A = (b + sh)h \quad \text{Cross-Sectional Area (12)}$$

$$P = b + 2h\sqrt{1 + s^2} \quad \text{Wetted Perimeter (13)}$$

Where b is the width of the channel bottom, s is the channel side slope, h is flow depth, T is the top width of the free-surface, A is cross-sectional area, and P is wetted perimeter.

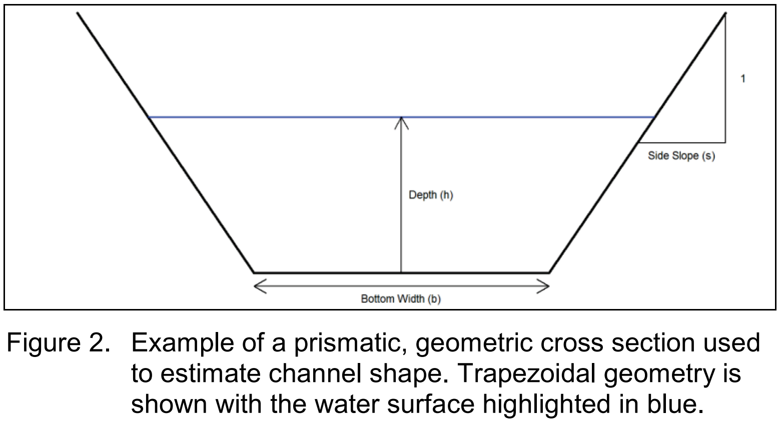


Figure 2. Example of a prismatic, geometric cross section used to estimate channel shape. Trapezoidal geometry is shown with the water surface highlighted in blue.

Normal Flow. By combining the continuity and Manning equations, a unique solution may be obtained for the normal flow approximation. The following equation provides a mechanism to compute the normal flow discharge given a value of depth, channel geometry, channel resistance, and bed slope. Alternatively, normal depth could be computed for a given discharge value using an inverse or iterative solution (Equation 14).

$$Q = \frac{k_n}{n} A R^{2/3} S_0^{1/2} \tag{14}$$

Using this approach, discharge may be predicted for a range of depth values. This "channel rating" between depth and discharge is extremely useful for translating flow duration curves into information regarding the length of time a channel is experiencing a given hydraulic force or depth (a key component of restoration design; see McKay and Fischenich 2015). Channel ratings may also be easily verified in the field using common discharge measurement techniques or nearby streamflow gages (Viessman and Lewis 2003).

Critical Flow. Computation of the critical flow allows the designer to examine what discharge corresponds to a change in flow properties to supercritical and an associated increase in erosive capacity. Critical flow conditions arise when the Froude number equals one. The equation for the Froude number may then be combined with the continuity equation and rearranged to the following form (Equation 15):

$$\frac{Q^2}{g} = \frac{A^3}{T} \tag{15}$$

As with normal flow computations, this may be solved directly for simple geometries or iteratively for more complex geometry, and solutions may be obtained by specifying depth and solving for discharge or vice versa.

Shear Stress. Stream restoration often involves assessment of sediment transport and channel stability or hydraulic structure design. In both of these analyses, forces due to shearing of the flow along the channel bed must be quantified. The cross sectional averaged shear stress (τ_0) informs these analyses and may be calculated as follows (Equation 16):

$$\tau_0 = \rho g R S_0 \tag{16}$$

Application of Hydraulic Analyses in Restoration Design. The final step in most hydraulic analyses is the application of the results to restoration design. Hydraulic design of stream restoration projects can vary from detailed three-dimensional calculation of the effects of an in-channel structure such as a W-weir to simple calculation of inundation duration for planting riparian vegetation. Therefore, a thorough review of hydraulic design for stream restoration is well beyond the scope of this paper (See EM 1110-2-1416, Watson et al. 1999, Copeland et al. 2001, and Shields et al. 2003 for detailed reviews), but the preceding analyses include the elements of a basic hydraulic analysis of a system in predesign conditions.

Often hydraulic characteristics are not the end goal of an analysis. For instance, hydraulic analysis is required for assessment of channel stability, but the geomorphic condition of the river is the desired output, not the flow characteristics themselves. The hydraulic computations presented here inform further observations of sediment transport properties and channel stability.

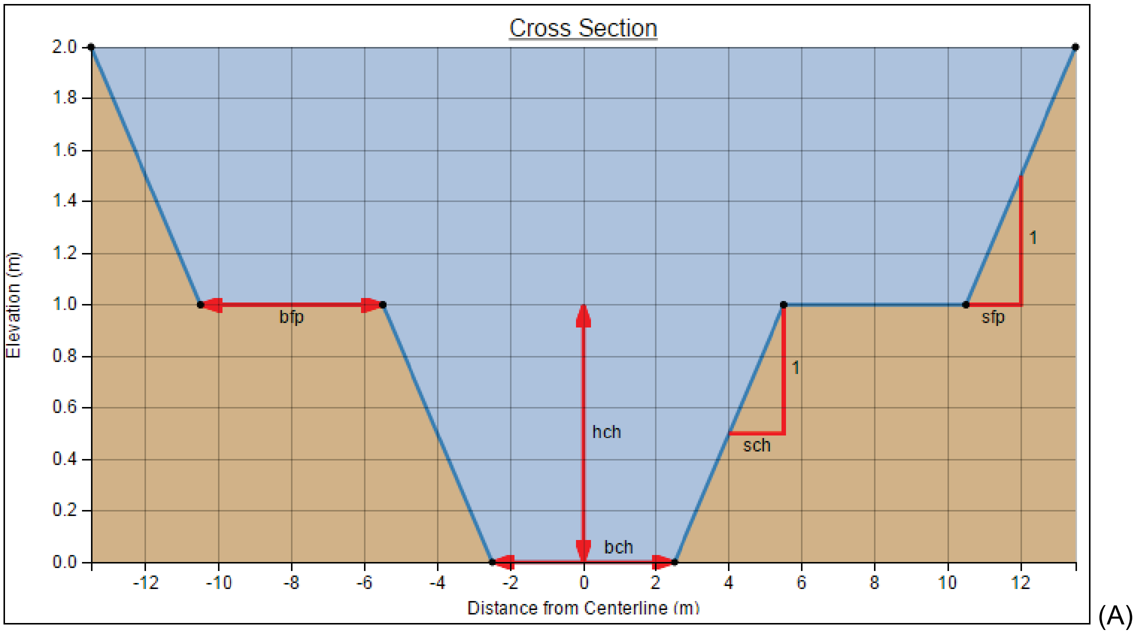
RAPID HYDRAULIC ASSESSMENT (RHA) TOOLS: As described, hydraulic analyses are scalable and must be adapted to the level of resolution required by a given project. Many hydraulic analysis tools have been developed to accommodate differing levels of complexity (Table 1). The simplest tools examine a single channel cross section and are considered a zero-dimensional analysis since the information is only calculated at one point along the stream. One-dimensional models examine longitudinal changes in hydraulics across numerous cross sections. Two-dimensional models typically examine either the lateral and longitudinal dimensions (e.g., a cross-channel velocity distribution) or the vertical and longitudinal dimensions (e.g., vertical zonation in a reservoir). The most complex tools compute three-dimensional velocity vectors in a three-dimensional domain. Clearly, all problems cannot be addressed by either the simplest or the most complex models. Thus, selection of an appropriate tool is a crucial part of any analysis.

Table 1. Select hydraulic tools commonly applied in river engineering and restoration projects.

Tool / Model	Dimensions	Development and Model Maintenance
SAM Hydraulic Design Package for Channels	0	USACE Coastal and Hydraulics Laboratory
eRAMS Channel Cross-Section Analysis	0	Colorado State University
River Analysis System (RAS)	1	USACE Hydrologic Engineering Center
Water Surface Profile (WSPRO)	1	Federal Highway Administration
SRH-1D	1	Bureau of Reclamation
MIKE 11	1	Danish Hydraulic Institute
TABS Numerical Modeling System	1, 2	USACE Coastal and Hydraulics Laboratory
SRH-2D	2	Bureau of Reclamation
CCHE2D	2	University of Mississippi
Flo2D	2	FLO-2D Software, Inc.
Adaptive Hydraulics Modeling (ADH)	2, 3	USACE Coastal and Hydraulics Laboratory
Environmental Fluid Dynamics Code (EFDC)	1, 2, 3	Environmental Protection Agency

The following section describes two extremely simple tools for conducting rapid hydraulic assessments (RHA). These models compute normal and critical flow for user-specified channel geometry, resistance coefficients, and channel slopes. These models are not intended for final restoration designs, but instead to inform preliminary thinking on hydraulics and to guide future analyses. The techniques applied here have often been implemented by hydraulic engineers in spreadsheets and through manual calculations. The models are presented to provide an error-checked, readily available tool for use by a restoration project development team including engineers, planners, biologists, and other interested parties.

Model Conceptualization. The first tool conducts a rapid hydraulic assessment for trapezoidal channel geometry (RHA-Trap). This model assumes that channel geometry may be specified as two, layered trapezoids, one each for the channel and floodplain (Figure 3A). Channel resistance (Manning's n) is specified for the channel and floodplain separately. Finally, the user must input a channel slope.



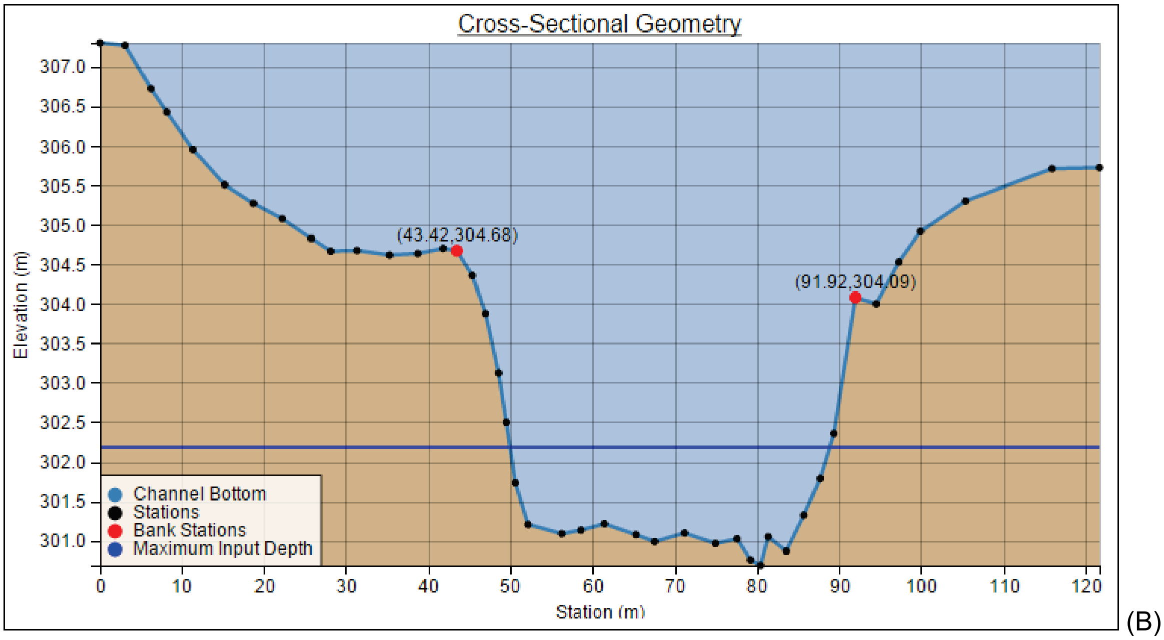


Figure 3. Channel geometry inputs for the hydraulic tools described herein. (A) In RHA-Trap the user specifies the shown geometric variables. (B) In RHA-Cross the user specifies stations, elevations, and bank stations.

The second tool conducts rapid hydraulic assessment for user-specified, irregular cross-sectional channel geometry (RHA-Cross). The user must specify the lateral station and vertical elevation for an entire cross section (Figure 3B). This information may be obtained from field surveys or extracted from a digital elevation model. The user must also assign left and right bank stations, which delineate the channel and floodplain environments. Manning's *n* may then be specified for the channel and floodplains separately.

These models compute normal and critical flow using the methods described in this document. As is the case with any numerical model, a variety of assumptions limit the use of these models. Table 2 summarizes key limitations for both RHA-Trap and RHA-Cross.

Table 2. Limitations and key assumptions of RHA-Trap and RHA-Cross.

RHA-Trap	RHA-Cross
• Depth > 0 • Metric units only • Rigid channel boundaries • Prismatic channels only	• Depth > 0 • Metric units only • Rigid channel boundaries • Single thread channels only • Stations are specified from left to right bank looking downstream • Discharge in the small areas at the edge of the water are neglected • The maximum depth that may be examined is the difference between the highest and lowest elevations specified

Using this information, both models compute normal and critical discharge for any user-specified depth. The model may be run for one value of depth or executed in batch mode by specifying a range of depths. In addition to discharge, top width, cross-sectional area, wetted perimeter, average velocity, and shear stress are computed for normal flow conditions (Figure 4).

Model Quantification. RHA-Trap and RHA-Cross have been executed and compiled as web-based models on the USACE urban stream restoration portal[1][2]. These web-based models are programmed in HTML5 and JavaScript. Tabular and graphical outputs are provided and may be easily transferred into other programs (e.g., Microsoft Excel). Cross-sectional input data for RHA-Cross may also be transferred directly from spreadsheets by importing comma delimited data (i.e., *.csv). Each model was originally programmed in the R Statistical Software, and code is available from the authors upon request.

Model Evaluation. Models were developed, programmed, and error-checked by the authors and web programmers. Three additional modelers executed the tools as web-based programs. Code was subsequently error checked by all parties. Models were tested by inputting extreme input values and verifying results (e.g., extremely large and small depth values). Bugs or issues may be reported directly to the authors. Maintenance of models in a web-based format ensures bug fixes are readily addressed and the most current versions of models are used. All model versions are documented on the associated website along with a developer version history.

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[1] RHA-Trap may be accessed directly at http://cw-environment.usace.army.mil/cwmg/rha/RHA-Trap.html.
[2] RHA-Cross may be accessed directly at http://cw-environment.usace.army.mil/cwmg/rha/RHA-Cross.html.

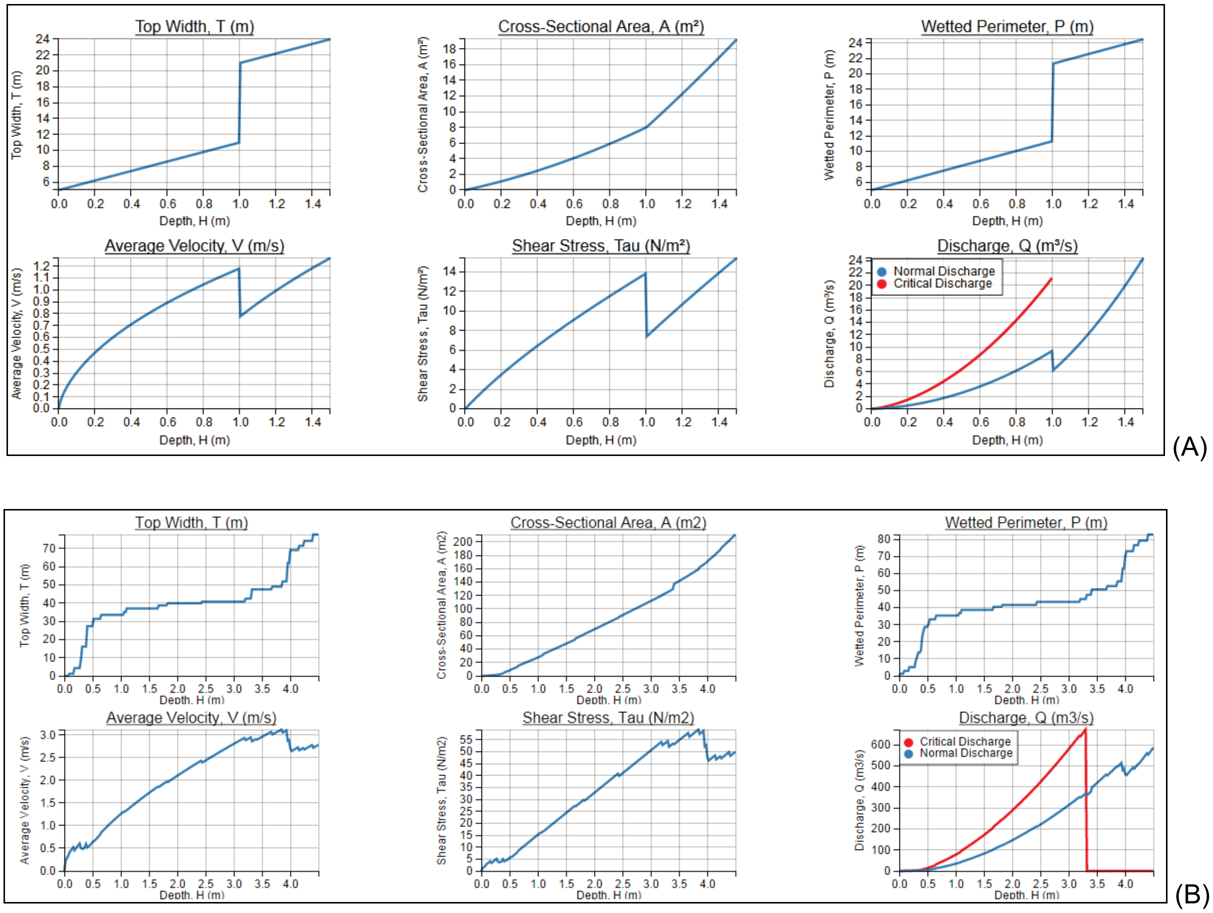

Figure 4. Model outputs for the hydraulic tools described herein run in batch mode. (A) RHA-Trap output for the geometry shown in Figure 3A with depth ranging by 200 intervals from 0.0m to 1.5m. (B) RHA-Cross output for the geometry shown in Figure 3B with depth ranging by 200 intervals from 0.0m to 4.5m. Discontinuities occur at the point of incipient flooding onto floodplain due to rapid expansion in wetted perimeter.

SUMMARY: This technical note has reviewed topics associated with first-order hydraulic analyses and presented two tools to execute such analyses, RHA-Trap and RHA-Cross. These models are not intended to be used in detailed project design, but instead to inform preliminary thinking, direct early alternative development, and guide future analyses. The SMART Planning framework encourages the use of tools that structure alternative comparison early in the planning process[1], and the tools presented here meet this objective. Furthermore, the authors hope these models may be applied by project development team members that may be less familiar with hydraulic analyses (e.g., planners, biologists) to increase communication among the team.

Hydraulic analyses can be simple or complex, but basic hydraulic information must be obtained in order to have confidence in a restoration design. The equations are often simple, and it sometimes appears that all that is required is to pick a number or two from a table and execute the hydraulic calculations. At times this may even be the case. The practitioner who understands the basic theory and the history of hydraulics knows, however, that the exceptions occur with

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[1] http://planning.usace.army.mil/toolbox/smart.cfm

regularity. Furthermore, the assumptions that accompany each type of analysis may or may not hold in the project under consideration. Experience, careful analysis, and keen observation are the keys to a successful hydraulic analysis.

NOTATION:

A	Cross-section area
b	Width of the channel bottom
C_z	Chezy roughness coefficient
D	Hydraulic depth (A/T)
f	Darcy-Weisbach friction factor
F_r	Froude number
g	Gravitational acceleration
h	Depth of flow
H	Total head
h_f	Head loss through the reach
k_n	Unit correction factor of Manning's equation (1 for SI, 1.486 for English)
n	Manning's roughness coefficient
$n_{composite}$	Composite Manning's *n*
P	Wetted perimeter
Q	Volumetric rate of water flow or discharge
R	Hydraulic radius
R_e	Reynolds number
s	Channel side slope
S_0	Channel bed slope
S_f	Friction slope
S_w	Water surface slope
T	Width of the free surface
V	Cross-section mean velocity
α	Coriolis (or energy) coefficient
β	Boussinesq (or momentum) coefficient
η	Elevation of the bed
θ	Slope angle of the channel bed
ρ	Density of the fluid
ν	Kkinematic viscosity of the fluid
τ_0	Cross-sectional averaged shear stress

ADDITIONAL INFORMATION: Research presented in this technical note was developed under the Ecosystem Management and Restoration Research Program (EMRRP). Chuck Dickerson and Ginny Dickerson (ERDC-EL) kindly developed the web interfaces for these models. The USACE Proponent for the EMRRP Program is Mindy Simmons and the Technical Director is Dr. Al Cofrancesco. Sarah Miller, Jock Conyngham, Dr. Bruce Pruitt (ERDC-EL), Dr. Dan Baker, and Tyler Wible (Colorado State University) graciously provided thorough review of this document and are gratefully acknowledged. Technical reviews and suggestions for improvement by Dr. Candice Piercy (ERDC-EL) and Chris Haring (USACE Rock Island District) are also greatly appreciated.

For additional information, contact the author, Dr. S. Kyle McKay (601-415-7160, Kyle.McKay@usace.army.mil), or the manager of the Ecosystem Management and Restoration Research Program, Glenn Rhett (601-634-3717, Glenn.G.Rhett@usace.army.mil). This technical note should be cited as follows:

> McKay, S. K., and J. C. Fischenich. 2016. *Rapid hydraulic assessment for stream restoration*. EMRRP Technical Notes Collection. ERDC TN-EMRRP-SR-48. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

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