A Use of HEC-RAS as Instructional Tool

Gregory H. Nail, PhD, PE[1]

Abstract –A Hydraulics and Hydrology elective course has been made available for Civil Engineering students at The University of Tennessee at Martin. Students are exposed to the Hydrologic Engineering Center-River Analysis System (HEC-RAS), open channel flow software, near the end of the course. This paper is a report on how HEC-RAS is introduced. Students are first required to solve an appropriately designed open channel flow problem without the aid of HEC-RAS. The way in which this problem is specified accommodates all of the basic features of HEC-RAS for subcritical flow. HEC-RAS is then applied to the same problem. If prepared correctly, identical results are obtained.

Highly advanced modern software often seems at odds with the use of pencil and paper to carry out calculations. The above scheme of introducing HEC-RAS is suggested as one approach to effectively bridge the gap from fundamental theory to technically advanced software.

Keywords: Hydraulics, Modeling, Software, Instructional, HEC-RAS.

INTRODUCTION

Clearly, software has changed the face of the engineering profession over the past few decades. The emergence of technical software as commonplace in professional practice has affected engineering education. Personal computers, widely available beginning in the early 1980's, made technical software easier to obtain and utilize. Over time computing power and storage capacity have steadily increased. During the 1990's a whole series of powerful engineering software packages appeared. This trend toward more computing power on smaller platforms seems to have no end in sight. Except for the very young, individual engineers have their own personal experiences with this history and are part of it.

BACKGROUND

The literature is replete with commentary on the antithesis between technically advanced engineering software as compared against older manual analysis techniques. Consideration of the topic takes in the whole field of computational hydraulics and, by extension, computational fluid dynamics and all other computational techniques as well.

Regarding computational hydraulics, Liggett [12] offered an extended commentary in which the above antithesis is evident. He promotes the view that the most significant development in the entire field of hydraulic engineering is that of computational hydraulics. Commenting on education, he opined that, "In spite of the importance of computation, I would like to see some of that time returned to the teaching of engineering fundamentals." These two statements touch on the antithesis mentioned above. Moreover, he warns about "artificial experience," referring to a false confidence that can arise when placing too much trust in computational results. Liggett suggests that "… the professor must take great care that the student does not consider his artificial experience real," and adds, "… this is a point that cannot be overemphasized."

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Criswell [5] stated in 2004 that "experienced engineers are extremely concerned with the increasing problem of new engineers misusing software and not understanding basic behaviors well enough to produce practical and realistic preliminary designs." He invokes the term "computer rapture," borrowed from Scott [15], "a condition where otherwise rational people show a complete and unquestioning belief in anything that emanates from a silicone brain… a complete unwillingness (or inability) to do a sanity check on a computer output."

Criswell views the history of modern civil engineering analysis as consisting of three "stages." The first encompasses the time period prior to the 1920's – 1960's era, referring to the time when engineering calculations were done essentially without computer programs or software. The second stage extends from the end of the first through the early 1990's. It is characterized by engineers often setting up engineering equations into forms that are programmed using languages such as Fortran or C. The present stage is characterized by engineers rarely doing programming themselves, but using complex technical software developed by others. From this framework he stresses that it is now more important than ever that engineers be equipped to evaluate and verify the results of computer software. He adds that, in the case of civil engineering, "…practice is no more than two centuries removed from the period when the available analysis tools were very limited…" He concludes that use of classical solutions in the classroom is one way to help developing engineers deal with this trend.

Regarding the use of computers in technical education, Obiozor [13] observed that "the tendency is to take the computer's response as true, correct and infallible. It is not directly obvious to the student that the correctness of the computer is as good as the ability of the programmer to correctly model the situation or problem and translate it to computer software." He goes on to conclude that "more must be done in the classrooms as we move into the 21st century to train future scientists and engineers on the models, assumptions, limitations and algorithms employed to develop these programs so that they are better prepared to use the software with a clearer understanding."

Huddleston [9], Rose [14], and Yousuf [17] each present suggestions on how to implement technical software into the instructional environment – while preserving basic principles or theory. This paper is a report on such an approach, with regard to the computational hydraulics software HEC-RAS. The way in which this is done takes heed to the suggestions made by Liggett, Criswell, and Obiozor. An open channel hydraulics problem will be solved using both the older hand-written method and the HEC-RAS software. In doing so, HEC-RAS becomes both a computational model and instructional tool. The author hopes to stimulate thought and discussion regarding the benefits of introducing software in parallel with older methods.

HEC-RAS

HEC-RAS is a software package capable of performing one-dimensional open channel hydraulic simulations. It can accommodate artificial as well as irregular shaped channels, steady or unsteady flow, and subcritical or supercritical flow regimes. Computational routines are equipped to handle mixed (sub- and supercritical) regimes as well. Designed for practical applications, the software has the ability to incorporate the effects of many commonly encountered artificial structures or naturally occurring geographic features. Computational routines and dialog boxes enable implementation of bridges, culverts, inline structures, pump stations, basins, levees, flood plain encroachments, and many other features into a simulation for analysis. Although designed for gradually varying flow, HEC-RAS can handle rapidly varying flow over structures and other features with appropriate coefficients. As the name implies, HEC-RAS was developed at the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers (USACE) (HEC [10] and HEC [11]). It is the direct descendent of an earlier, similar software named Hydrologic Engineering Center – 2 (HEC-2). HEC-RAS appeared in 1999, is windows-based, and continues to be as widely accepted and used as was its predecessor. Ahmed and Freeman [1], Brunner [2], Brych et. al. [3], Hicks and Peacock [7], and Horritt and Bates [8] are examples of the growing number of recent successful applications utilizing HEC-RAS.

DEMONSTRATION PROBLEM

Theoretical Background

The steady, subcritical flow of water through natural or artificial channels is described well by a steady, one-dimensional version of conservation of energy, such as Equation 1. Subscripts 1 and 2 refer to downstream and upstream locations, respectively. V, P, Z, H_L, and ρ are velocity, pressure, bed elevation, head loss, and density, respectively.

$$0=\left(\frac{V_1^2}{2g}+\frac{P_1}{\rho g}+Z_1\right)-\left(\frac{V_2^2}{2g}+\frac{P_2}{\rho g}+Z_2\right)+H_L \tag{1}$$

When applied to open channel hydraulics, Equation 1 is often modified by introducing the approximations and relationships shown in Equations 2 – 7. Equation 2 is the oft-employed hydrostatic pressure assumption, completely valid when the flow has no acceleration in the vertical direction. WS and z are water surface elevation and depth, respectively. As shown in Equation 3, depth and bed elevation are added together to equal water surface elevation.

$$\frac{P}{\rho g}=z \tag{2}$$

$$WS=z+Z \tag{3}$$

Equation 4 shows head loss broken down into contributions due to bottom friction (h_f) and due channel geometric expansion and contraction (h_{exp}). These terms are approximated as shown in Equations 5 and 6. The friction slope (S_f) of Equation 5 is approximated by using a conveyance (K) originating from Manning's Equation – as depicted in Equation 7, where Q is discharge. It is through the conveyance that the frictional coefficient, Manning's n, is incorporated. K_m is the head loss coefficient associated with channel expansion or contraction and ΔX is the length between cross-sections.

$$H_L=h_f+h_{\text{exp}} \tag{4}$$

$$h_f=S_f\Delta X \tag{5}$$

$$h_{\text{exp}}=K_m\left|\frac{V_1^2}{2}-\frac{V_2^2}{2}\right| \tag{6}$$

$$S_f=\left(\frac{Q}{K}\right)^2 \tag{7}$$

Incorporating all the approximations and relationships described in Equations 2 through 7 causes Equation 1 to appear as shown in Equation 8.

$$0=\left(\frac{V_1^2}{2g}+WS_1\right)-\left(\frac{V_2^2}{2g}+WS_2\right)+S_f\Delta X+K_m\left|\frac{V_1^2}{2g}-\frac{V_2^2}{2g}\right| \tag{8}$$

For one-dimensional flow the velocity is defined as an average velocity, depicted by an overbar. The friction slope is likewise defined as an average, based on values obtained from Equation 7 applied at locations 1 and 2, and also indicated by an overbar. Finally, a velocity coefficient is defined as shown in Equation 9, where v is the local velocity associated with the differential discharge, dQ. The purpose of Equation 9 is to obtain a coefficient by which to modify the velocity head term in Equation 8. This modification is an effort to more closely approximate the velocity head term when the velocity value varies significantly across the channel.

$$\alpha = \frac{\int v^2 dQ}{\bar{V}^2 Q} \tag{9}$$

Incorporation of the overbar averages and velocity coefficient results in Equation 10. This is the equation which was solved for subcritical water surface profile calculations before any software was available. In this sense it could be considered a classical solution of sorts. Yet it is also the equation solved by HEC-RAS for the same flows. The solution technique utilizing this equation is called the standard step method, an older technique widely used before any computational aids were available (Chow [1], Henderson [6], and Wurbs and James [16]).

$$WS_2 = WS_1 + \alpha_1 \frac{\bar{V}_1^2}{2g} - \alpha_2 \frac{\bar{V}_2^2}{2g} + \bar{S}_f \Delta X + K_m \left| \frac{\bar{V}_1^2}{2g} - \frac{\bar{V}_2^2}{2g} \right| \tag{10}$$

Problem Statement

The problem to be solved is that of computing a water surface profile for subcritical flow. The channel geometry selected is shown in Figure 1. The channel is completely described by eight stations or coordinate pairs. The objective is to compute a water surface profile, consisting of just two cross-sections, for subcritical flow in a channel like the one shown in Figure 1. In the following analysis location or subscript 1 refers to the downstream cross-section, while location or subscript 2 refers to the upstream cross-section.

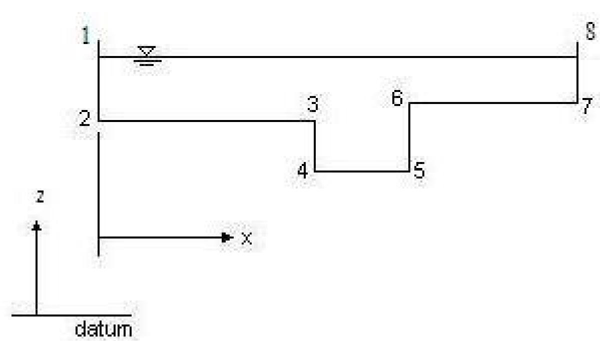


Figure 1. Channel geometry.

For this class of hydraulics problem the necessary information includes channel geometry (eight coordinate pairs), Manning's n bottom friction coefficient values, channel expansion and contraction coefficients, discharge, and downstream water surface elevation. The goal is to solve for the water surface elevation at the upstream cross-section, WS_2. To summarize, a reasonable guess for WS_2 is assumed. Based on this trial value, all quantities on the right hand side of Equation 10 can be calculated, and a new value of WS_2 can be calculated. This calculated value is then compared against the known value. Based on the result, a new guess for WS_2 is made and the process repeated. The solution is reached when the difference between the calculated and known values for WS_2 are within a specified error tolerance. The details of this algorithm are described below.

Conventional Solution

As outlined above, a reasonable initial guess is first developed for WS_2. However, before this is utilized, it is possible to complete the calculations for all terms at the downstream cross-section first. This is convenient because they will not change throughout the trial-and-error process. For purposes of calculating cross-sectional areas, wetted perimeters, hydraulic radii, and conveyances, the cross-section is subdivided into three regions. These three areas are left overbank, main channel, and right overbank, as shown in Figure 2. This scheme allows for more realistic incorporation of the frictional resistance, and allows some variation of parameters laterally across the channel.

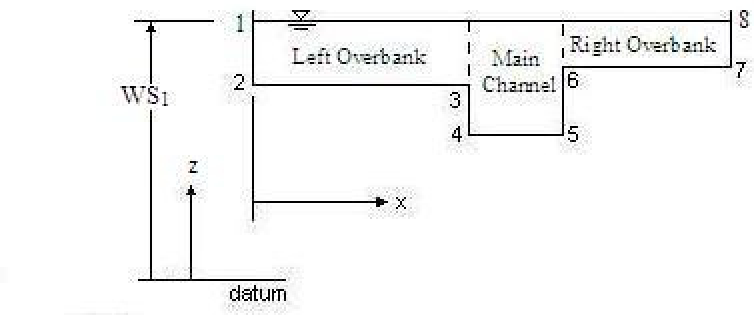


Figure 2. Cross-sectional view of channel geometry at downstream location showing division into overbanks and main channel areas.

The areas of the left and right overbanks, and main channel are calculated as shown in Equations 11 through 13.

$$A_{LOB} = (WS_1 - z_2)(x_3 - x_2) \tag{11}$$

$$A_{ROB} = (WS_1 - z_7)(x_7 - x_6) \tag{12}$$

$$A_{CHN} = (WS_1 - z_4)(x_5 - x_4) \tag{13}$$

The wetted perimeters of the left and right overbanks, and main channel are calculated as shown in Equations 14 through 16.

$$P_{LOB} = (WS_1 - z_2) + (x_3 - x_2) \tag{14}$$

$$P_{ROB} = (WS_1 - z_7) + (x_7 - x_6) \tag{15}$$

$$P_{CHN} = (z_3 - z_4) + (x_5 - x_4) + (z_6 - z_5) \tag{16}$$

The areas and wetted perimeters are then used to calculate the hydraulic radii for the overbanks and main channel, each in exactly the same way as shown in Equation 17 – by dividing the area by wetted perimeter.

$$R = \frac{A}{P} \tag{17}$$

The conveyances for the overbanks and main channel are each calculated in the same way, as shown in Equation 18 (part of Manning's equation) – using the previously calculated areas and hydraulic radii.

$$k = \frac{1.49}{n} A R^{\frac{2}{3}} \tag{18}$$

The velocity head coefficient can now be calculated as shown in Equation 19, where the total flow area and conveyance are determined by summation as shown in Equations 20 and 21, respectively.

$$\alpha_1 = \frac{\left(\frac{k_{LOB}^3}{A_{LOB}^2} + \frac{k_{CHN}^3}{A_{CHN}^2} + \frac{k_{ROB}^3}{A_{ROB}^2} \right) A_1^2}{K^3} \tag{19}$$

$$A_1 = A_{LOB} + A_{CHN} + A_{ROB} \tag{20}$$

$$K_1 = k_{LOB} + k_{CHN} + k_{ROB} \tag{21}$$

The average velocity can now be calculated as shown in Equation 22. At this point the velocity head terms in Equation 10, for the downstream location can be determined. Also, the friction slope of Equation 8 can be determined, for the downstream cross-section.

$$\overline{V}_1 = \frac{Q_1}{A_1} \tag{22}$$

The guess for WS_2 is used in repeating all calculations outlined in Equations 11 through 23, resulting in determination of the velocity head terms in Equation 10, for the upstream location. The head loss term due to channel expansion or contraction in Equation 10 (first introduced in Equation 6) can be determined by first comparing the upstream and downstream velocity head terms. A larger upstream velocity head term is understood to mean that the channel is expanding, as per Bernoulli effect. In this case the loss coefficient K_m corresponding to expansion (larger value) is selected. Otherwise, the K_m for contraction is used. With the appropriate loss coefficient selected, the head loss due to expansion or contraction is calculated for Equation 10. The friction slope of Equation 8 is determined for the upstream location. To determine an average friction slope for use in Equation 10 a simple mean, as shown in Equation 23, can be used. The frictional head loss term can now be calculated for Equation 10.

$$\overline{S}_f = \frac{S_{f1} + S_{f2}}{2} \tag{23}$$

At this point all of the terms in Equation 10 have calculated values, so that a new value for WS_2 can be computed and compared against the guess. If the difference between the two is within acceptable error then the calculations are finished and the solution is considered converged. Otherwise, a new trial value for WS_2 is obtained and the process is repeated until convergence is obtained. Note that the process outlined in Equations 11 through 23 need be repeated only for the upstream cross-section. The known value of WS_1 (and other quantities) means that none of the calculations associated with the downstream cross-section will change from one trial WS_2 to the next. The entire algorithm can be entered into a spreadsheet.

Figure 3 shows a spreadsheet display of the numerical values associated with an actual exercise. The stationing shown in Figure 3 describes a channel similar in appearance to that depicted in Figures 1 and 2. The only piece of information not shown in Figure 3 is WS_1, which is equal to 285 ft. Note that ΔX is not needed for the downstream cross-section, 1. Also note that expansion and contraction coefficients, K_m, are not specified for the downstream cross-section. Only one set of K_m are needed – and have been displayed with the upstream cross section data.

When the standard step method is applied to the channel of Figures 1 and 2, with the data of Figure 3, as outlined in Equations 11 through 23, the result is a WS_2 of 285.327 ft.

HEC-RAS

HEC-RAS employs a file management system that separates the information into *plan*, *geometry*, and (steady) *flow* data files. The same problem described above can be modeled with HEC-RAS by first entering the data of Figure 3 into the geometry data, cross-section editor. The upstream cross-section data is shown entered into HEC-RAS in Figure 4. HEC-RAS utilizes a naming convention for channels that divides the stream into *rivers* and *reaches*. A separate editor feature (not shown) allows the user to first define the stream (or stream network) in terms of rivers and reaches, identified by number or name. For this particular problem only one river with one reach, composed of

Channel Cross Section Geometry											
				Left Overbank (LOB)			Channel (CHN)		Right Overbank (ROB)		
Cross-Section	ΔX(ft)	Q(cfs)	Station	1	2	3	4	5	6	7	8
1 (downstream)	**N/A**	**2500**	z_i(ft)	300	280	280	270	270	280	280	300
			x_i(ft)	0	0	185	185	230	230	400	400
			n	0.08			0.05		0.08		
2 (upstream)	**1600**	**2300**	z_i(ft)	300.5	280.5	280.5	270.5	270.5	281	281	300.5
			x_i(ft)	0	0	200	200	230	230	390	390
			n	0.09			0.04		0.09		
			K_m	0.5				0.3			

Figure 3. Spreadsheet display of all channel cross-section geometry and associated information.

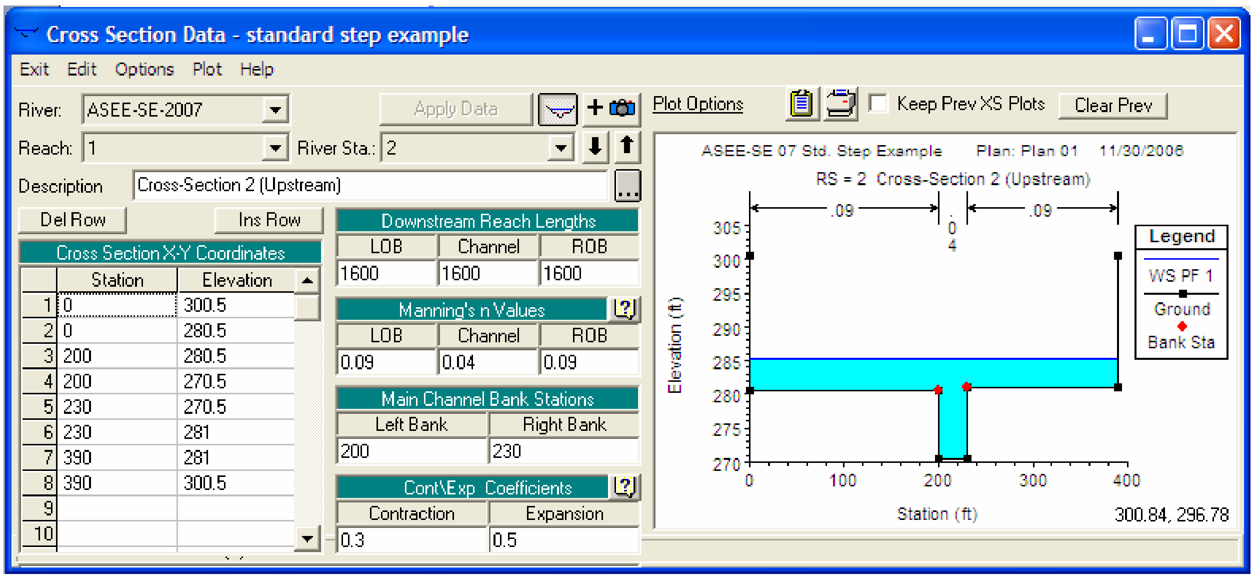


Figure 4. Geometric data editor of HEC-RAS showing upstream cross-section data input.

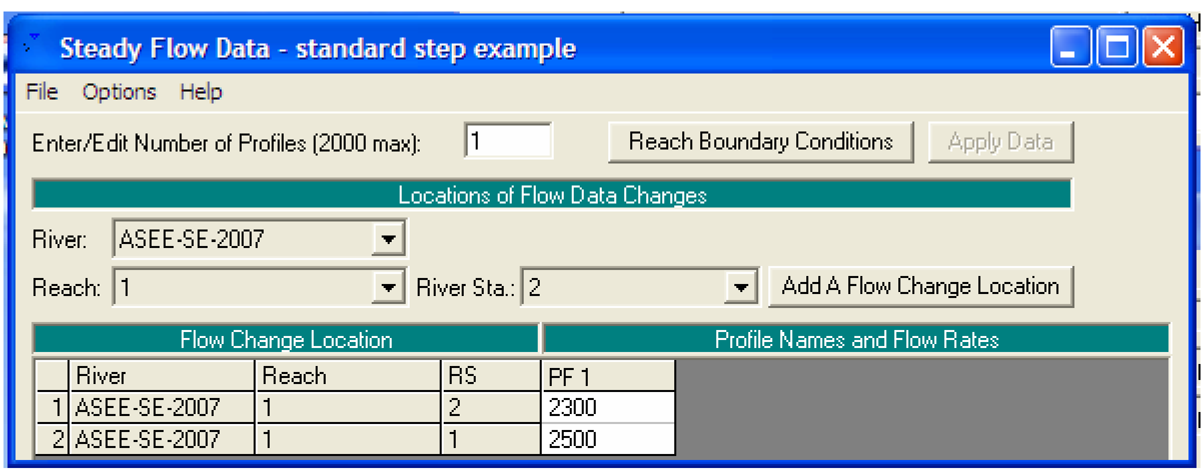


Figure 5. Steady flow data editor of HEC-RAS showing discharges.

two cross-sections, is required. Note that the data displayed in Figure 4 excludes discharges and water surface elevations. The discharges are considered part of the flow data and are entered through the steady flow data editor

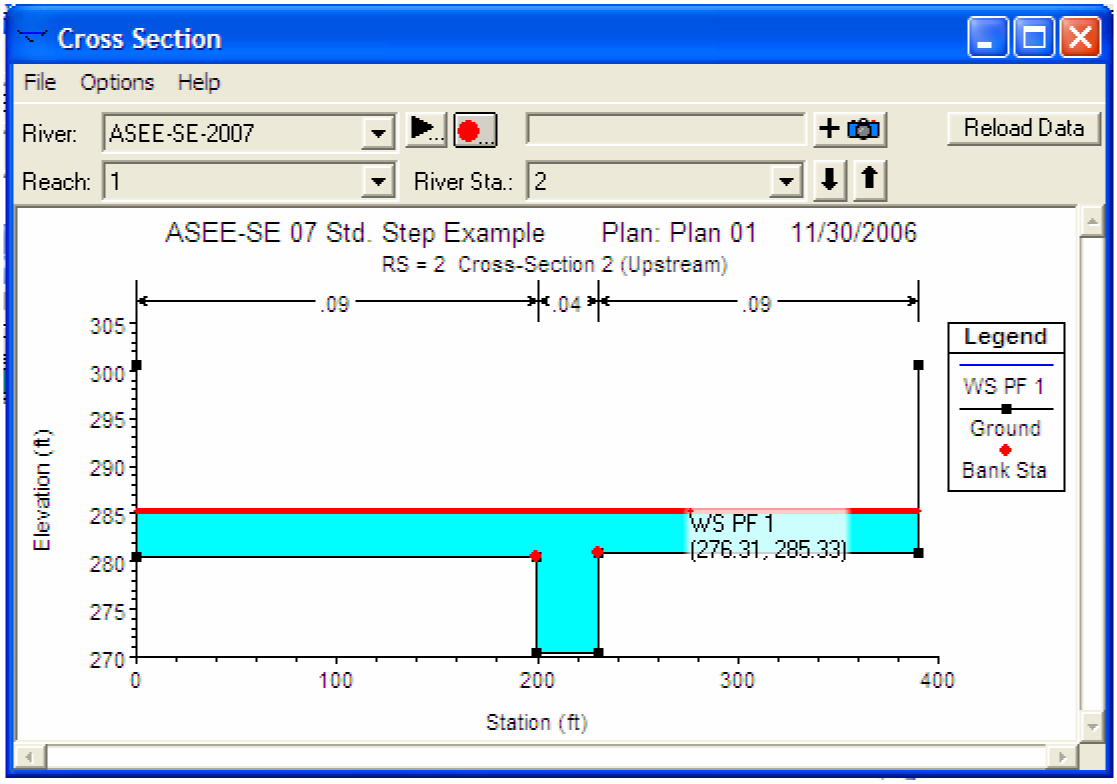
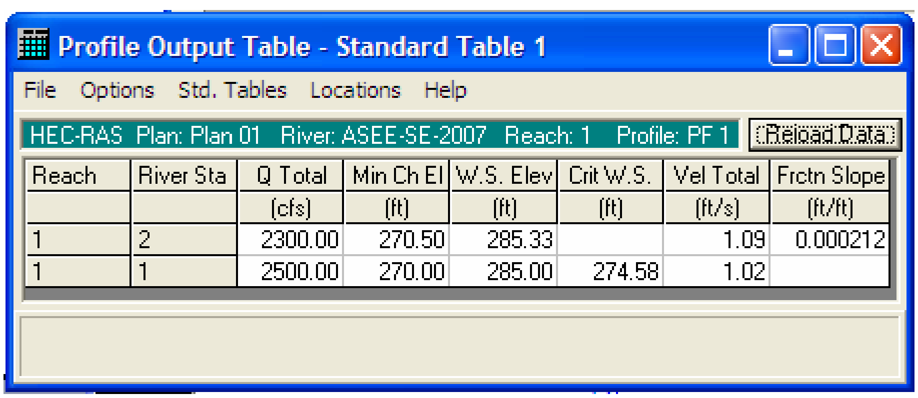


Figure 6. Graphical output from HEC-RAS showing water surface elevation computed for upstream cross-section.



Reach	River Sta	Q Total	Min Ch El	W.S. Elev	Crit W.S.	Vel Total	Frctn Slope
		(cfs)	(ft)	(ft)	(ft)	(ft/s)	(ft/ft)
1	2	2300.00	270.50	285.33		1.09	0.000212
1	1	2500.00	270.00	285.00	274.58	1.02	

Figure 7. Example of numerical output in tabular format from HEC-RAS.

as shown in Figure 5. Dialogue boxes accessible from the steady flow date editor (not shown) accommodate specification of the downstream water surface elevation of 285 ft. Computations are initiated via the *steady flow analysis* window (not shown), which also allows selection of flow regime (subcritical, supercritical, or mixed).

HEC-RAS results can be viewed both graphically and numerically. Figure 6 shows a graphical representation of the predicted water surface profile for the upstream cross-section. Note the computed value of water surface elevation, 285.33 ft in Figure 6. This value agrees with the WS_2 of 285.327 ft calculated by conventional means above. Many other graphical and numerical displays of results are available from within HEC-RAS.

DISCUSSION

Note that the computations of Equations 11 through 23 constitute a non-trivial problem. Nothing prevents the standard step method from being programmed into MATLAB or similar software. Regardless of the platform or method, execution these calculations requires focused attention to the governing equation (Equation 10), on a term by term basis. Consequently, attention is devoted to the open channel hydraulics. Despite the simplicity of the demonstration problem, the student gains insight as to how HEC-RAS is calculating results.

The output shown in Figure 7 illustrates another important point – acquiring the ability to evaluate results from software. The standard step procedure requires calculation of individual terms such as friction slope, wetted perimeter, and conveyance. The output options available in HEC-RAS, shown in Figure 7, enable these values (and more) to be displayed as tabular columns. Verifying the computed values for many quantities is possible.

Moreover, HEC-RAS is equipped to accept variations in the way in which certain parameters are entered. An example is averaging the friction slope for Equation 23. HEC-RAS can be configured to use any one of four different methods of calculating an average friction slope for Equation 10. The insight gained in using the standard step method above can be extended to usage of various features of the HEC-RAS software. In this way HEC-RAS itself becomes an instructional tool – as the student investigates alternative ways of calculating various parameters.

Note that for the demonstration problem, shown in Figures 1 and 2, the geometry causes all of the terms in Equation 10 to be included in the calculations. The boxed shape of the channel eliminates complex calculations of corners and trapezoids. However, inclusion of both channel and overbanks allows lateral variation of Manning's n – and incorporates all of the associated calculations. This is one feature that makes the standard step method, and HEC-RAS by extension, successful. Although HEC-RAS is a one-dimensional model, lateral variations in bottom friction are included in the calculations. This is clearly seen in the expression for velocity coefficient in Equation 19. Appreciation for this feature is acquired when carrying out the standard step calculations.

Due to limited numbers of students involved, a control group was not identified. Finally, the author found that assigning a unique geometry and flow condition to each student tends to reduce frequency of plagiarism.

CLOSURE

By working through the demonstration problem a student gains understanding of how HEC-RAS works. This contributes to appreciation of both how to apply the software and the results it produces. This approach is suggested as but one way to help students avoid becoming overly dependent on the software for its own sake. No test scores, or other metrics, are presented to support the assertion that this approach results in improved student understanding – due to small numbers of students involved. While limited in scope, the demonstration problem includes all the basics encountered in any simulation of subcritical open channel hydraulics. By extension, other software in other fields can be introduced to students in a manner similar to HEC-RAS.

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