

Rapid Floodplain Delineation

Presented by:
Leo R. Kreymborg[1], P.E.
David T. Williams[2], Ph.D., P.E.
Iwan H. Thomas[3], E.I.T.

[1]Project Manager, PBS&J, 9275 Sky Park Court, Suite 200, San Diego, CA 92123; PH (858) 514-1060; FAX (858) 514-1001; email: lrkreymborg@pbsj.com
[2]National Technical Director for Water Resources, PBS&J, 9275 Sky Park Court, Suite 200, San Diego, CA 92123; PH (858) 874-1810; FAX (858) 514-1001; email: dtwillaims@pbsj.com
[3]Engineer II, PBS&J, 9275 Sky Park Court, Suite 200, San Diego, CA 92123; PH (858) 514-1017; FAX (858) 514-1001; email: imthomas@pbsj.com

Abstract

A command-line program was created that enables a backwater model to be calculated directly from a set of GIS cross-sections. The program furthermore generates a GIS representation of the floodplain, a simple set of elevation plots of the cross-sections and water surface in PDF format, and a set of GIS cross-sections with the calculated hydraulic parameters attached as attributes. The program does not fully provide the functionality of a hydraulic model such as HEC-RAS. However, it can generate a reasonably accurate floodplain very quickly, typically in about ten seconds once the input files (centerline and topography) have been created. Cross-sections can be added, moved or realigned in GIS and the script will ascertain the sequence of the cross-sections and the reach lengths. The program is also robust and will almost always generate a floodplain. An optional feature also generates a shapefile of evenly spaced cross-sections based on the stream centerline using either of two algorithms, although some cross-sections may be later adjusted manually. The rapid delineation of the floodplain using this technique is useful for the approximate delineation of floodplains and fulfills all requirements for FEMA submittal as an approximate study. Although many simplifying assumptions are made, the script computes a backwater analysis (equivalent to the standard-step approach), and therefore is more accurate than any delineation based on normal depth approximations. Furthermore, the program is useful in rapidly obtaining reasonable alignments of the stream centerline and cross-sections and an accurate estimate of the floodplain limits even when a detailed hydraulic model will be created later.

Introduction

The most accurate floodplain delineations are based on standard-step hydraulic computer models; for example, HEC-RAS or other full-featured hydraulic modeling software. These models are in based on GIS topography and GIS cross-sections cut from that topography. Any movement of information between GIS and the hydraulic models and back is done through import and exports via intermediate files. The modeling and delineation process involves many steps and is very time consuming.

On the other end of the spectrum, approximate floodplain mapping is typically done using normal depth approximations. The normal depth approximations require some simple computations and estimates of the energy slope. Despite the conceptual simplicity, there are few available tools that integrate normal depth mapping with GIS. Furthermore, the normal depth approximations can lead to poor results compared to a backwater model, especially if the stream significantly deviates from prismatic shapes.

As an alternative to either of these approaches, a computer program was developed which calculates a backwater model directly from GIS inputs (primarily the cross-sections and the hydraulic baseline) and provides the delineation outputs directly without any import or export cycles. This program integrates better with GIS than any other approach, has the conceptual ease of use of normal depth calculations, but has accuracy comparable to a standard-step backwater model. The program is called Rapid Floodplain Delineation (RFD). RFD is written in Python, which is a mature, free, and widely used scripting language. Also utilized are various libraries for Python, such as the “numpy” array processing library (which is used extensively to speed up calculations), the Cairo graphics library (which is used to generate high-quality PDF plots), the Python Imaging Library (PIL), and the Geographic Data Abstraction Library (GDAL). RFD does not require any GIS license to run although a GIS package is required to develop the inputs (e.g. cross-sections, centerline, and topography) and to view the outputs.

Usage of RFD

The primary goal of RFD is to quickly perform all the steps without user intervention. For example, once the stream centerline and topography have been created, a typical reach of 10 miles with cross-sections spaced at 250 feet takes less than 10 seconds to model and delineate. Reaches of a mile or two can be done in 2 or 3 seconds. RFD’s outputs are fully georeferenced shapefiles and grids.

RFD also has a number of options to further facilitate rapid modeling. It can automatically generate cross-sections and has numerous configurable options to adjust the orientation, relative rotation, spacing, and width of the cross-sections. An important feature is that RFD can generate floodplains even when the cross-sections intersect. Although intersecting cross-sections can be avoided in most cases through proper specification of options, cross-section intersection can still occur and this feature allows a floodplain to be generated nevertheless.

Presentation quality PDF documents showing the cross-sections and profiles are generated automatically by RFD on each run. RFD does not require any GIS software or any non-free libraries to function. However, GIS software may be required to generate some of the inputs and may be needed to view the some of the results.

RFD can either be used as a stand-alone program or to assist in generating and adjusting cross-sections for use later in a detailed model.

The calculation method used by RFD is similar to the approach used in HEC-RAS, although much more simplified. A backwater calculation is performed which considers Manning roughness (using one representative Manning value per cross-section), and expansion and contractions loss coefficients. The program cannot model bridges or hydraulic structures of any kind.

Typical sequence of use

1. Develop a raster (grid) representation of the topography.
2. Draw a stream centerline in GIS or copy a centerline from a stream's shapefile.
3. Develop an options specifications file using a text editor.
4. (optional) Adjust, add, remove cross-sections in GIS to remove cross-section overlaps and correct alignment issues
5. (optional) Assign discharge and Manning-n values automatically using grids
6. (optional) Assign ineffective flow limits (using a vector shapefile).
7. Run RFD.
8. Troubleshoot any problems, make needed adjustments, and re-run.

RFD generates the following outputs:

1. A new set of cross-sections if automatic cross-section generation has been requested.
2. A georeferenced image representation of the floodplain (as a GeoTIFF).
3. A set of elevation plots of the cross-sections showing water depth, critical depth, and ineffective flow limits in PDF format
4. Profile plots in PDF format
5. A shapefile of GIS cross-sections with the calculated hydraulic parameters attached as attributes.

RFD can also optionally generate a grid of water depths.

Training in the use of RFD and development of inputs can be done within a few hours.

Computational algorithm for backwater calculation

Compared to a detailed hydraulic model such as HEC-RAS, RFD has some simplifying assumptions. For example, a single n-value is assigned for each cross-section, a single reach length is assigned between any two cross sections, and some other assumptions are made to speed the computation. Despite these simplifications, it is conceptually and computationally superior to any estimates of water surface elevations using normal depth approximations.

RFD solves the 1-D energy equation to arrive at water surface elevations. It does not use an iterative approach, but instead solves the equation using intersecting curves of conveyance. The following discussion illustrates the procedure.

The energy loss between upstream and downstream sections may be expressed as:

$$h_e = L\,S_f + h_{ec}$$

where h_{ec} is the expansion or contraction loss, S_f is the friction slope, and L is distance between the cross sections.

$$h_{ec} = C\left|\frac{V_{upstream}^2}{2g} - \frac{V_{downstream}^2}{2g}\right|$$

Where C = expansion or contraction loss coefficient. C is taken to be 0.1 if $V_{upstream} < V_{downstream}$ (contraction) and 0.3 if $V_{upstream} > V_{downstream}$ (expansion).

Dividing both sides of the equation by the reach length L and rearranging terms yields

$$S_f = \frac{he}{L} - \frac{hec}{L}$$

But from the Manning equation, we also know that

$$Q = \frac{1.486}{n} AR^{2/3} = KS_f^{1/2}$$

or

$$S_f = \frac{Q^2}{K^2}$$

Equating the two equations for S_f:

$$\frac{Q^2}{K^2} = \frac{h_e}{L} - \frac{h_{ec}}{L}$$

Solving for K, and labeling it as $K_{required}$:

$$K_{required} = \frac{Q^2}{(h_e - h_{ec})/L}$$

The discharge Q is the average of the discharge of the upstream and downstream cross-sections:

$$Q = \frac{Q_{us} + Q_{ds}}{2}$$

The component h_e is the different between the energy grade lines at the two cross-sections.

$$h_e = WSE_{upstream} + \frac{V_{upstream}^2}{2g} - WSE_{ds} - \frac{V_{downstream}^2}{2g}$$

Since the downstream velocity, $V_{downstream}$, is known, the upstream velocity, $V_{upstream}$, is a function only of the water surface elevation at the upstream section.

Therefore, $K_{required}$ is a function of the upstream water surface elevation since each of the components is a function of the upstream water surface elevation.

However, for each water surface elevation at the upstream section, there is also a conveyance that can be calculated from the Manning equation:

$$K_{upstream} = \frac{1.486}{n} AR^{2/3}$$

This is a function only of upstream water surface elevation.

Since the downstream water surface is known already, the conveyance for the downstream water surface is also known and the average conveyance between the upstream and downstream conveyance can be calculated:

$$K_{average} = \frac{K_{upstream} + K_{downstream}}{2}$$

Where $K_{average}$ is a function of the upstream water surface elevation.

Finding the K which satisfied both the $K_{average}$ and the $K_{required}$ equations is a matter of setting $K_{average} = K_{required}$ and finding the upstream water surface elevation which satisfies the equation. Traditionally, this, or an equivalent calculation, is done using an iterative approach because there is no closed-form solution which can solve the equation. Furthermore, it is possible that the equation may have multiple solutions or no solutions (when one of the Ks is discontinuous).

However, RFD is able to solve the equation without iteration by making the following assumptions:

(1) Only sub-critical solutions are allowed.
(2) Curves of elevation versus conveyance are calculated for $K_{average}$ and $K_{required}$ by calculating the values of each K at finely-spaced discrete elevations and any values between these elevations are interpolated. Currently, these curves are being calculated at 0.1-foot intervals.
(3) $K_{upstream}$ and $K_{downstream}$ are each forced to be a non-decreasing function of water surface elevation. This is enforced by calculating the discrete Ks from the highest elevation to the lowest and not allowing the K at any lower elevation to be higher than at a higher elevation.

This results in a monotonically non-decreasing curve for $K_{average}$ and a monotonically decreasing curve for $K_{required}$. If the initial discrete elevation is high enough, then the curves are guaranteed to cross each other, or at critical depth, $K_{average}$ is greater than $K_{required}$. If the curves cross, then the elevation at which they cross is the solution to the energy equation. If the $K_{average}$ is greater than $K_{required}$ at critical depth, the program defaults to critical depth and proceeds upstream. Although the calculation of the two curves may seem more computationally demanding than an iterative approach, in practice it is quite fast, and has the significant advantage of guaranteeing that a solution to the energy equation will be found (or default to critical depth). Figure 1 shows graphically the solution for sample curves.

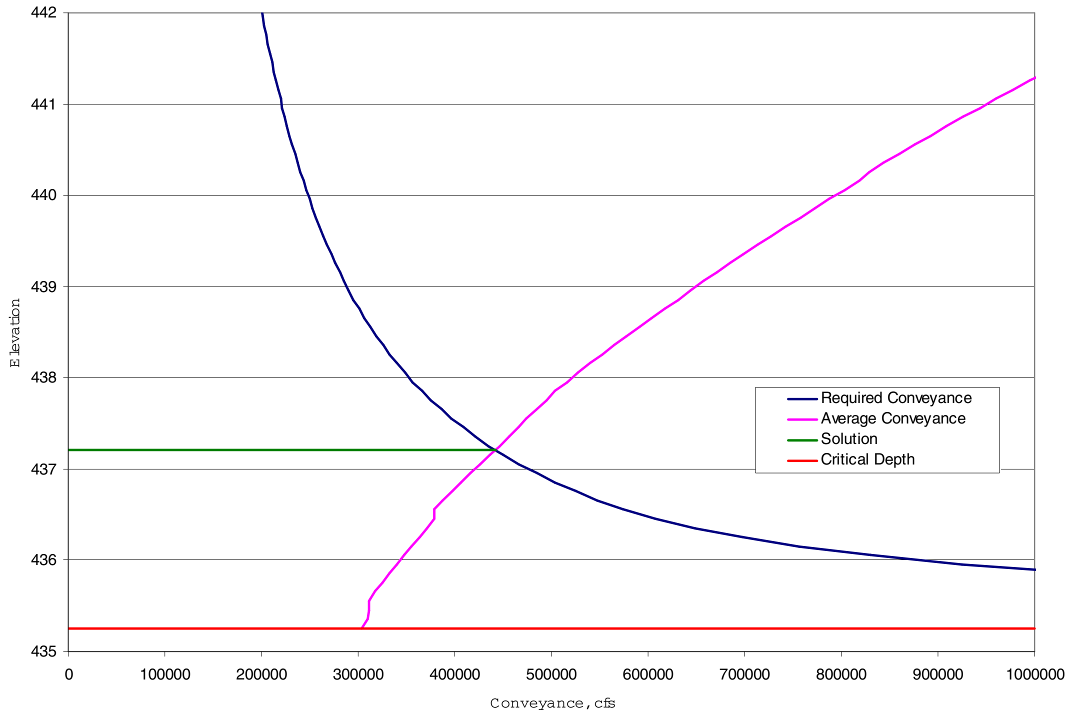

Figure 1. Energy Equation Sample Solution

Sample Floodplain

The water surface elevations from RFD are comparable to HEC-RAS results. Comparison of water surface profiles for analogous models shows that the models are generally within 0.1 feet, and usually much closer. Figure 2 shows are comparison of a HEC-RAS + Hec-GeoRAS floodplain versus the floodplain generated by RFD.

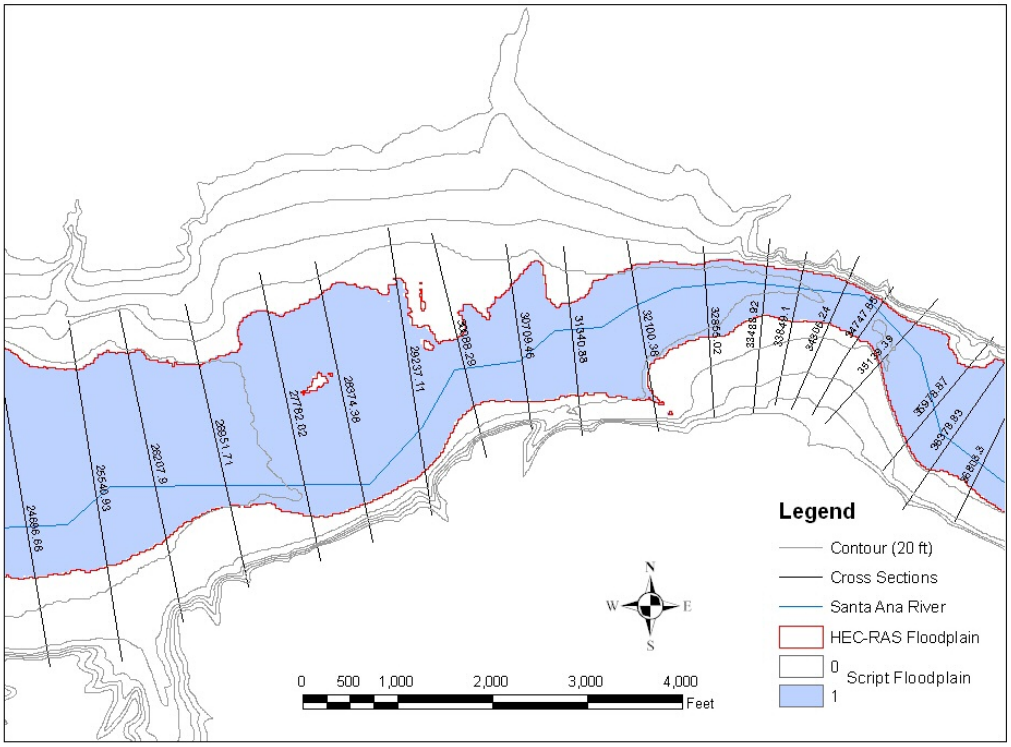

Figure 2. RFD floodplain in blue compared to HEC-RAS floodplain in red

Figure 3 and Figure 4 show screenshots from the PDF files generated by RFD providing the cross-sections and profiles. Note the flat regions in the cross-section and the profile thalweg – these are due to terracing artifacts in the source topography.

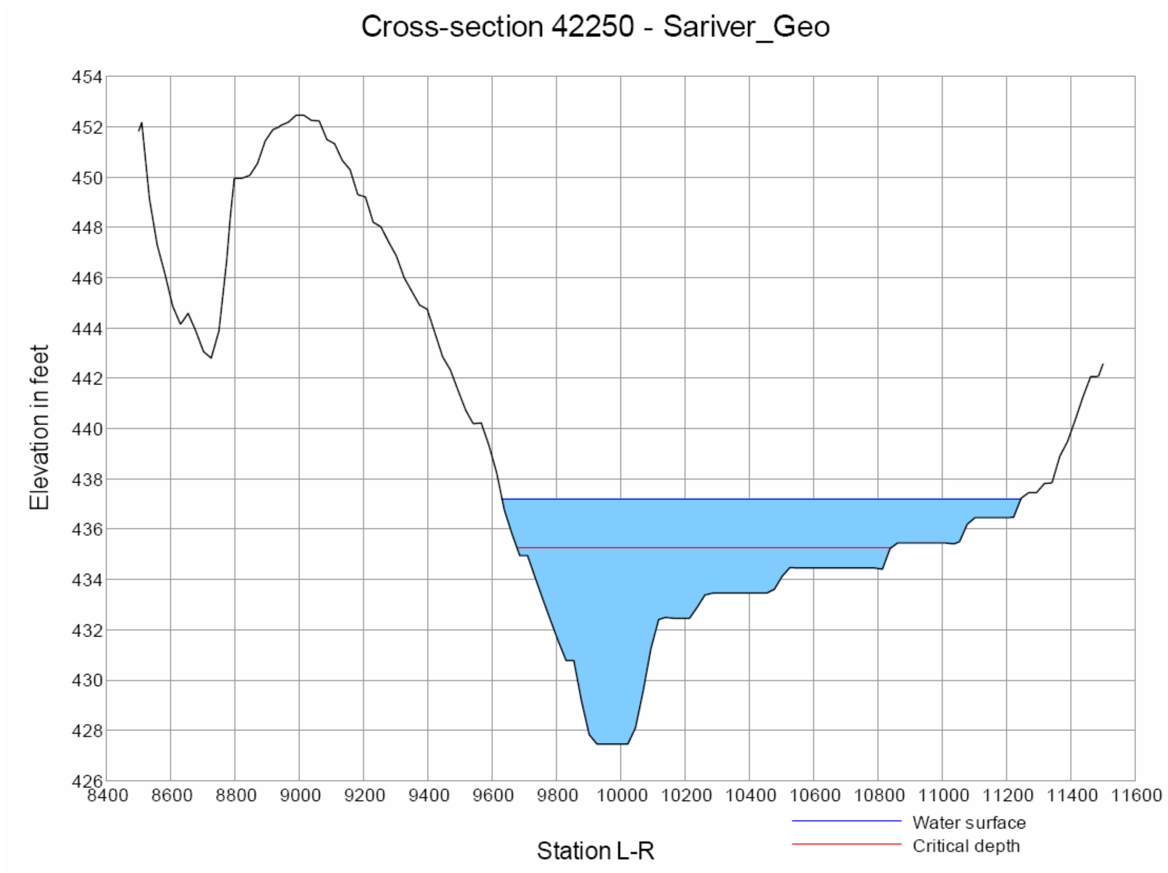

Figure 3. Sample cross-section plot.

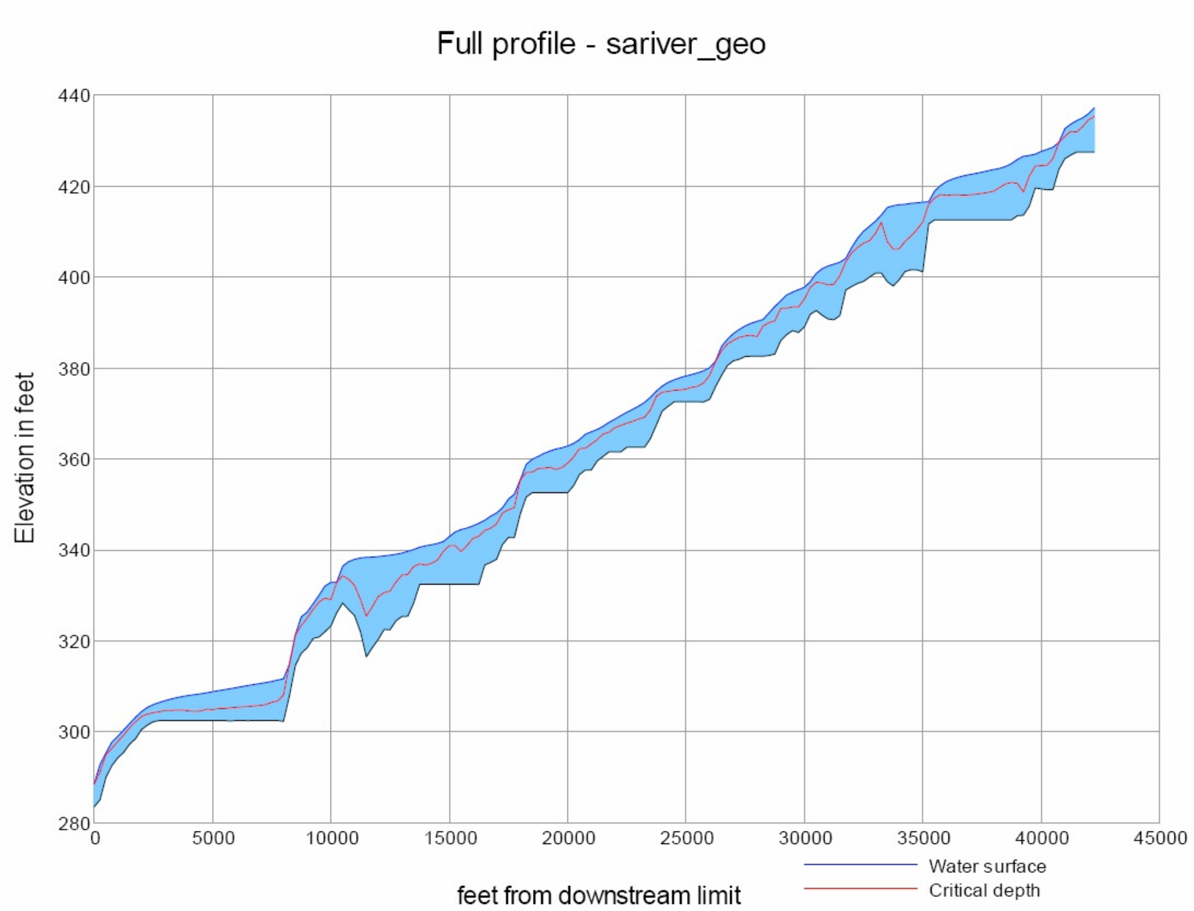

Figure 4. Sample profile plot.

Additional Features

RFD has additional features, such as the ability to disallow split flow areas from contributing to conveyance (through automatic assignment of ineffective flow limits), the ability to mosaic source topography on the fly, the ability to use National Elevation Dataset topography in geographic coordinates directly without reprojecting it, the ability to composite n-values, and the ability to resample source topography on the fly to higher or lower resolutions.

Summary

Rapid Floodplain Delineation (RFD) provides an extremely fast way of generating accurate floodplains. RFD has already been used to assist in generating hundreds of miles of approximate floodplains in California. Sample applications where RFD has been used in batch mode to delineate hundreds of miles of multiple streams at once have also been implemented.