Work-flow and Data Acquisition Analysis of Micro/Local Hydrology Analysis of Wupatki and Tuzigoot

Before starting the project of conducting hydrology analysis of Wupatki and Tuzigoot, I planned to adopt the methodology I used in another course project, in which I generated a list of historic buildings in Philadelphia that are most susceptible to flood using the ArcHydro tools[1] in ArcGIS pro. However, after diving into the site-specific problems of Wupatki and Tuzigoot, I found it is not feasible to use the same methodology.

The essential difference between the two projects is ***scale***. When ***downscaling*** from city-size analysis to single-catchment/single-basin-size analysis, it is required that we have[2]:

- More data input (e.g. weather data, land-use data, soil data ...)
- Data with higher resolution
- More complex analytical system[3]

More importantly, the problem falls into the category of ***hydrological modeling***, which is within the expertise of hydrologists instead of conservators and preservationists. After trying to educate myself with such knowledge and watching more than 6 hours of hydrology engineering lectures on-line, I am confident to state that cross-disciplinary collaboration is necessary for projects of this kind.

That being said, I managed to figure out a work flow for catchment-scale and site-specific micro hydrology analysis. I will list the required data and software(s) for each step and try to explain the rationale behind the engineering processes.

Step 1: Drainage and Catchment Delineation (Software: ArcHydro Tools in ArcGIS pro)

Software：

- ArcGIS Pro
- Toolboxes Folder Structure after installation of ArcHydro Tools：

  - *ArcHydro Tools Pro*
    - *Terrain Processing Workflows*
      - *Combined Terrain with Unknown Sink and Stream Location*

1 Esri's Arc Hydro consists of a data model, toolset, and workflows developed over the years to support specific GIS implementations in water resources. For more information on the installation and work flow of ArcHydro Tools, refer to the Esri website: https://www.esri.com/en-us/industries/water-resources/arc-hydro

2 The downscaling of heritage hydrology analysis is brought up in the paper Heritage Hydrology: A Conceptual Framework for Understanding Water Fluxes and Storage in Built and Rock-Hewn Heritage. (Oliver Sass and Heather Viles, "Heritage Hydrology: A Conceptual Framework for Understanding Water Fluxes and Storage in Built and Rock-Hewn Heritage," Heritage Science 10, no. 1 (December 2022): 66, https://doi.org/10.1186/s40494-022-00693-7.)

3 A more complex analytical system will conduct hydrology analysis based on all relevant parameters and the mathematical relationship among them, it will go beyond the tools in ArcGIS pro which is developed based on assumptions that can reduce the number of parameters of the system.

Data Input：
- 1m x 1m DEM
- Source: University of Arizona NAIP Imagery Collection[4]

Algorithm of ArcHydro：

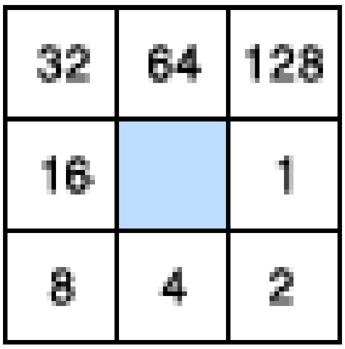


Fig-1. The values for each direction

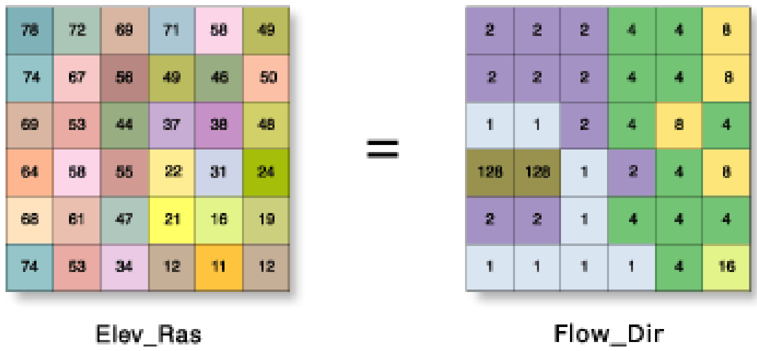


Fig-2. From DEM to flow direction

The whole process of the computation is based on the elevation data of each pixel (focal statistics):
- For each pixel, the algorithm will look at all of its neighboring pixels and find the one with the biggest slope to decide flow direction and catchment;
- Then by computing the accumulated flow direction the program is able to define streams/ drainages.

Calculating Assumptions and Limitations:

ArcHydro Tools employs DEM[5] as input. The ArcHydro algorithm generates results based on the following assumptions:

- No precipitation condition will be considered
- The surface of the ground is made of a uniform material
- The material of the ground is impervious
- No evaporation is taken into account

As a result, the best and the only way to make use of this tool is to generate the delineation of drainages and catchments. And the result will only indicate:

Areas of higher probability of surface flow if there is surface runoff of any kind.

4 "Imagery & LiDAR," Data Cooperative, July 29, 2021, https://data.library.arizona.edu/geo/find-data/imagery-lidar.
5 A DEM, or digital elevation model, is a representation of the bare ground topographic surface of the earth, presenting a uniform surface material which is free of any variation other than elevation. It presumes the absence of trees, buildings and other surface objects. (www.USGS.org)

Running the Analysis:

Using different values in the flow accumulation[6] tool when defining stream pattern, the software will be able to generate surface flow at different level of density. It is worth mentioning that the value used to define stream patterning DOES NOT carry any geospatial information, it is calculated based on an abstract numerical value in the flow direction raster (fig-1 and fig-2).

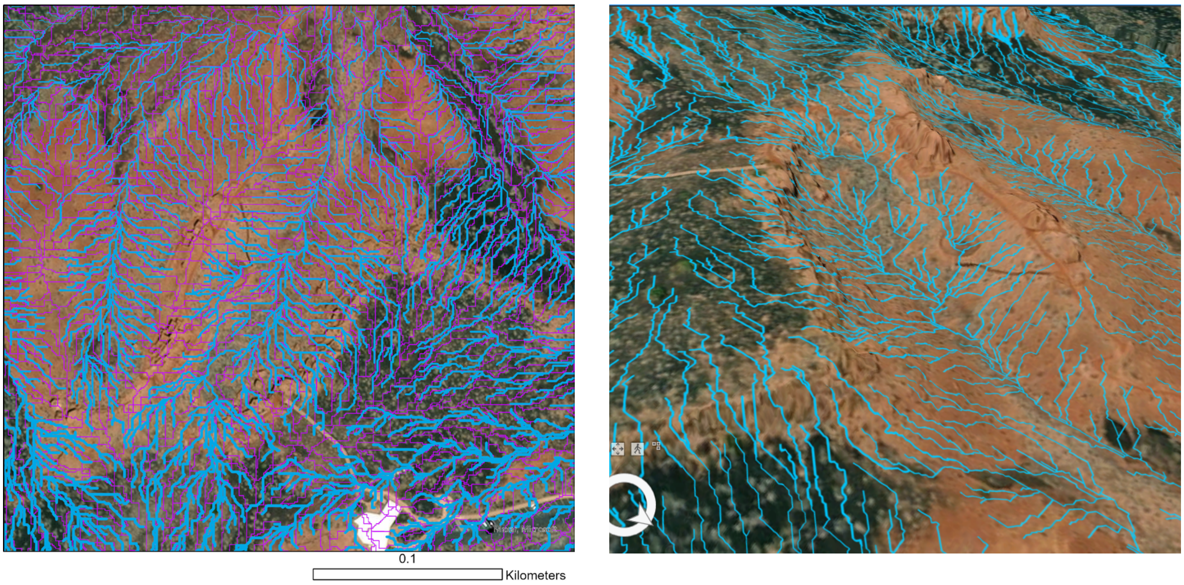


Fig-3 & Fig-4. Using smaller value to generate more dense drainage and catchments. 2D view is on the left and 3D view is on the right. The result is calculated using ArcGIS pro.

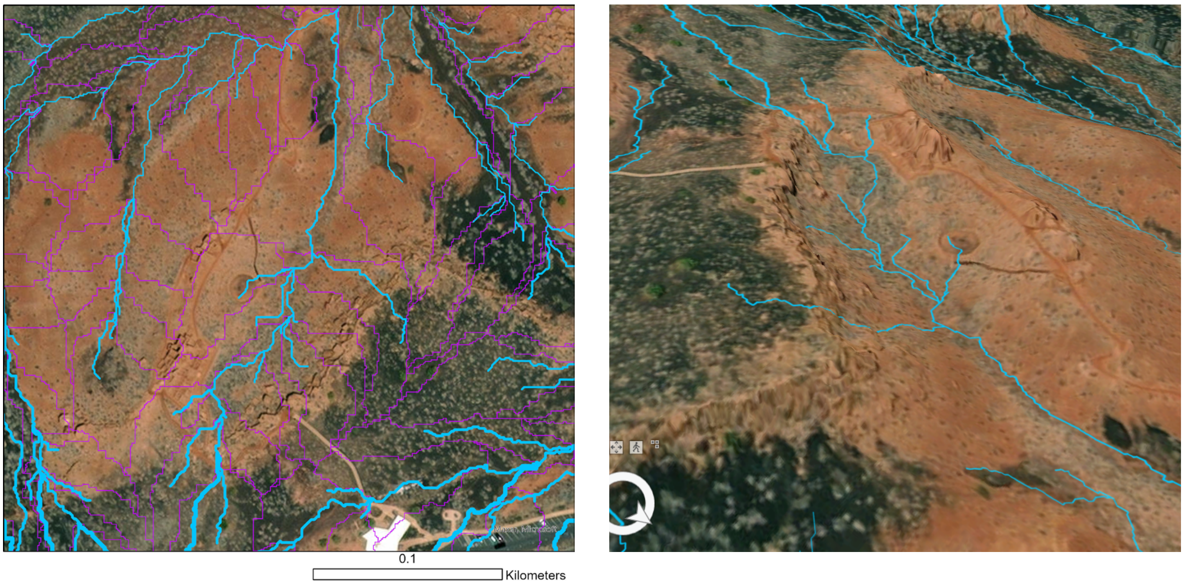


Fig-5 & Fig-6. Using bigger value to generate less dense drainage and catchments. 2D view is on the left and 3D view is on the right. The result is calculated using ArcGIS pro.

Issues with ArcGIS pro:

The data generated using ArcGIS pro is good for visualizing the geometry of all the possible drainages and catchments, however, the data can only be considered as valid for ***coarser scale[7] analysis***, if micro/local hydrology condition needs to be examined, we need more suitable tools and methodologies!

6 "Flow Accumulation (Spatial Analyst)—ArcGIS Pro | Documentation," accessed July 2, 2022, https://pro.arcgis.com/en/pro-app/2.8/tool-reference/spatial-analyst/flow-accumulation.htm.

7 A coarser scale means the area of interest in the hydrology analysis is large enough to leave out parameters like infiltration rate, evaporation, precipitation etc..

Step 2: Calculate the Peak Surface Runoff Rate Q Using the Rational Method (for Hydrological Modeling)

Hydrological Modeling:

Hydrological modeling can be defined as the characterization of real hydrologic features and system by the use of small-scale physical models, mathematical analogues, and computer simulations (Allaby and Allaby, 1999).

In heritage hydrology analysis, hydrological modeling should be developed for micro-level and site-specific problems because of the complexity and accuracy of its analytical system.

Rational Method for Hydrological Modeling:

- ***Rational Method:***
  The Rational Method expresses a relationship between rainfall intensity and catchment area as independent variables and the peak flood discharge resulting from the rainfall as the dependent variable. Although the origin of its name is unclear, it has been used for over 150 years, and known as the Rational Method for nearly 100 years. It continues to be useful in estimating runoff from simple, relatively small drainage areas. The Rational Method is most applicable to drainage areas that are 20 acres or less[8].

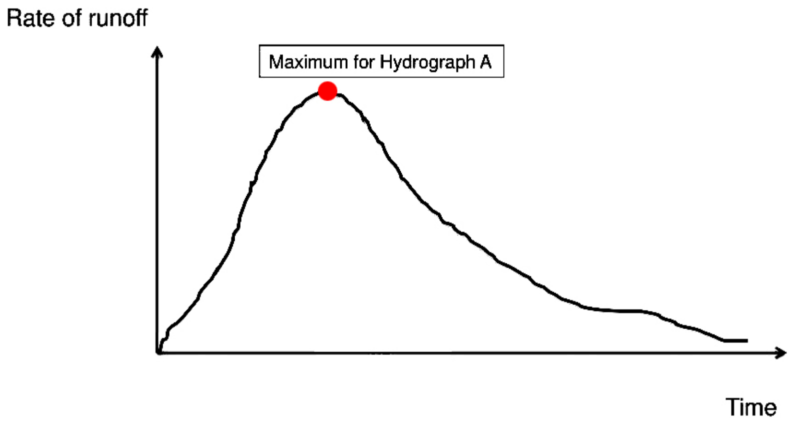


Fig-7. The peak runoff rate Q as marked red.

- ***Math Formula:***

  $Q = C * i * A$

  Q: Peak Runoff[9] Rate: ft^3/s or m^3/hr
  C: Ratio of Runoff (Depending on surface material): unitless
  i: Peak Rainfall Intensity for this watershed: in/hr or m/hr
  A: Area of the watershed: acres or m^2

8 "B. Stormwater Calculations" of "Stormwater Design Manual | NC DEQ," https://files.nc.gov/ncdeq/Energy%20Mineral%20and%20Land%20Resources/Stormwater/BMP%20Manual/B%20%20Stormwater%20Calculations.pdf. The complete Design Manual: https://deq.nc.gov/about/divisions/energy-mineral-and-land-resources/stormwater/stormwater-program/stormwater-design

9 The runoff rate and the discharge is interchangable in this formula.

- ***Calculation Process:***
  To calculate how the surface flow rate will influence the walls within a catchment defined at Wupatki as shown in the diagram below:

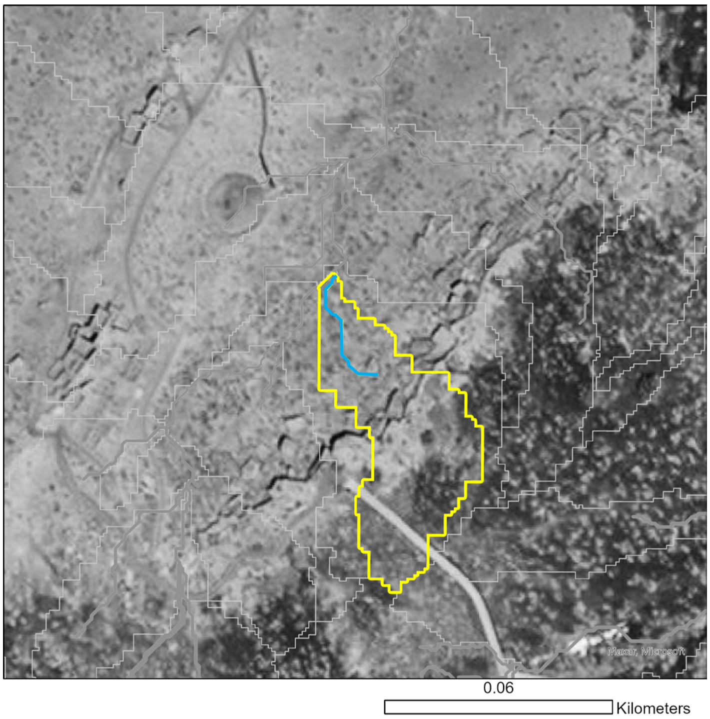


Fig-8. A catchment of Wupatki site.

A process needs to be followed as:

1. Identify and calculate the area of all the sub-areas with different surface material (this can be done by mapping out the sub-areas of each catchment on-site):
   S1, S2 ... Sn

2. Calculate the runoff-ratio(C) of each sub-area based on material and local climate (by refering to a reputable runoff-ratio sheet[10]):
   C1, C2, ... Cn

3. Calculate the time-of-concentration tc based on the longest time for a raindrop to travel from one area to the output of the catchment[11].

   $$\mathbf{t_c = t_s + t_c + t_o}$$

   t_c = time of concentration, hours
   t_s = travel time for sheet flow, hours
   t_c = travel time of shallow concentrated flow, hours
   t_o = travel time for open channel flow, hours

10 An example of a runoff-ratio sheet: https://www.waterboards.ca.gov/water_issues/programs/swamp/docs/cwt/guidance/513.pdf .
11 The NRCS Velocity Method can be used to calculate tc. The method uses a series of formula to calculate tc based on surface roughness, channel shape and slope. The process of calculation is explained in detail in "Chapter 2 - Stormwater 2B - Urban Hydrology and Runoff" of the Iowa Statewide Urban Design and Specifications: https://intrans.iastate.edu/app/uploads/sites/15/2020/03/2B-3.pdf. The complete design manual: “Iowa Statewide Urban Design and Specifications,” Iowa Statewide Urban Design and Specifications, accessed July 2, 2022, https://iowasudas.org/.

4. Determine rainfall intensity **i** corresponding to the time-of-concentration t_c using local weather data (IDF curve - the larger of tc, the lower the intensity of the rainfall):

   The IDF curve has rainfall duration as x axis and its intensity as y axis. The intensity can be read at the y value when x value is tc of the curve of a given storm's frequency.

5. Add all sub-area results up to solve for Q

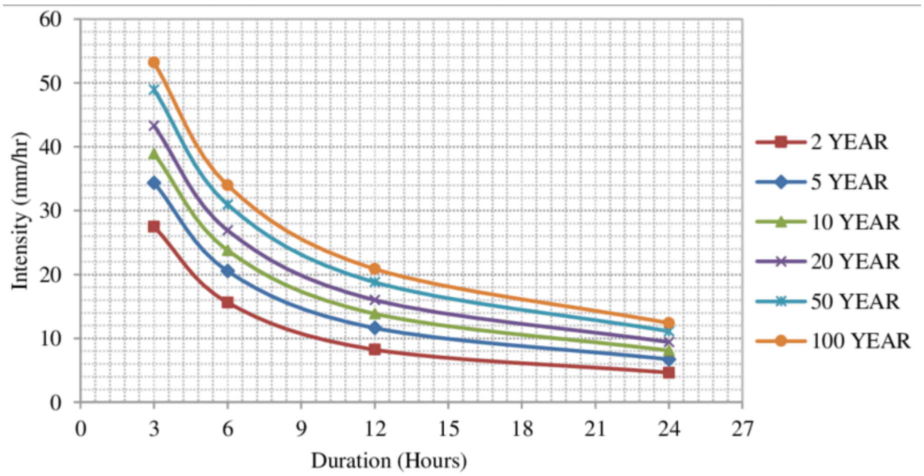


Fig-9. An example of IDF curve.

Q = i * (S1 * C1 + S2 * C2 + ... + Sn * Cn)

6. If the calculation involves multiple catchments, each downstream flow will need to take the output of each upstreams and use the longest tc to calculate the rainfall intensity (i)

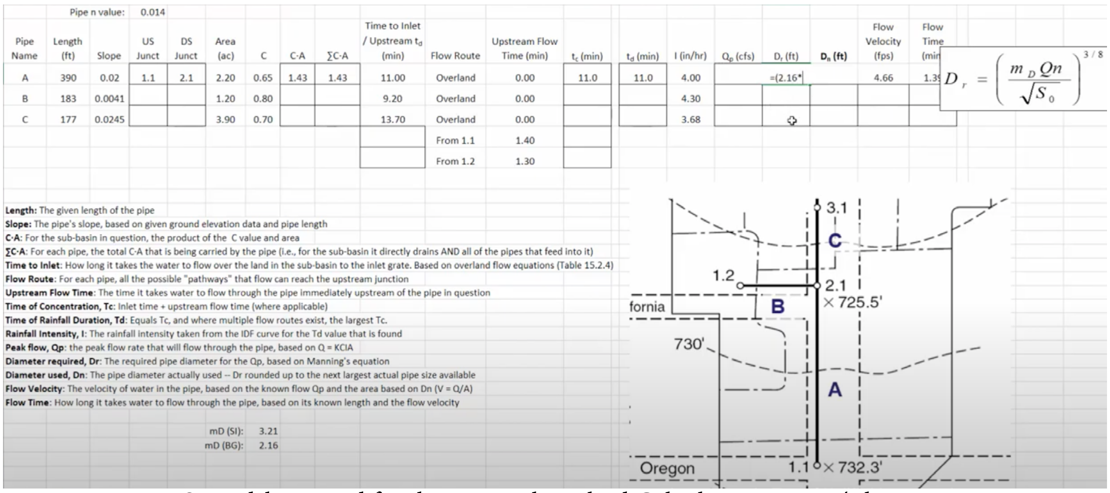
Sample Calculation:

Here is a list of data required:

- Delineation of catchment and streams
- Area of the sub-areas of different surface material for each catchment through on-site mapping
- Runoff ratio for each sub-area per catchment
- tc calculated based on surface condition and drainage channel
- Local weather data: IDF(intensity-duration-frequency) curve. (General weather data of larger area does not work for the Rational Method.)

Because most of the data is unavailable for Wupatki or Tuzigoot right now, it is difficult to run the analysis. However, a lecture on hydrology engineering by Issac Wait[12] runs a sample calculation on a multi-catchment hydrological system, which provides the necessary methodology. The interface of calculation tools is presented below:

12 Isaac Wait, CE 433- Class 5 (24 Jan 2020) Rational Method Pipe Sizing with Spreadsheets, Time of Concentration, 2020, https://www.youtube.com/watch?v=acAD7m5CMMk.



Pipe n value: 0.014

Pipe Name	Length (ft)	Slope	US Junct	DS Junct	Area (ac)	C	C·A	ΣC·A	Time to Inlet / Upstream t_d (min)	Flow Route	Upstream Flow Time (min)	t_c (min)	t_d (min)	I (in/hr)	Q_p (cfs)	D_r (ft)	D_n (ft)	Flow Velocity (fps)	Flow Time (min)
A	390	0.02	1.1	2.1	2.20	0.65	1.43	1.43	11.00	Overland	0.00	11.0	11.0	4.00		=(2.16*		4.66	1.3
B	183	0.0041			1.20	0.80			9.20	Overland	0.00			4.30					
C	177	0.0245			3.90	0.70			13.70	Overland	0.00			3.68					
										From 1.1	1.40								
										From 1.2	1.30								

$$D_r = \left(\frac{m_D Q n}{\sqrt{S_0}} \right)^{3/8}$$

Length: The given length of the pipe
Slope: The pipe's slope, based on given ground elevation data and pipe length
C·A: For the sub-basin in question, the product of the C value and area
ΣC·A: For each pipe, the total C·A that is being carried by the pipe (i.e., for the sub-basin it directly drains AND all of the pipes that feed into it)
Time to Inlet: How long it takes the water to flow over the land in the sub-basin to the inlet grate. Based on overland flow equations (Table 15.2.4)
Flow Route: For each pipe, all the possible "pathways" that flow can reach the upstream junction
Upstream Flow Time: The time it takes water to flow through the pipe immediately upstream of the pipe in question
Time of Concentration, Tc: Inlet time + upstream flow time (where applicable)
Time of Rainfall Duration, Td: Equals Tc, and where multiple flow routes exist, the largest Tc.
Rainfall Intensity, I: The rainfall intensity taken from the IDF curve for the Td value that is found
Peak flow, Qp: the peak flow rate that will flow through the pipe, based on Q = KCIA
Diameter required, Dr: The required pipe diameter for the Qp, based on Manning's equation
Diameter used, Dn: The pipe diameter actually used -- Dr rounded up to the next largest actual pipe size available
Flow Velocity: The velocity of water in the pipe, based on the known flow Qp and the area based on Dn (V = Q/A)
Flow Time: How long it takes water to flow through the pipe, based on its known length and the flow velocity

mD (SI): 3.21
mD (BG): 2.16

Fig-10. Spreadsheet used for the Rational Method Calculation in Issac's lecture series.

Fig-10 shows the types of data required for the calculation. Mapping and calculation with much higher accuracy is required for this step.

Issues with the Rational Method:

- It over-estimates the peak runoff rate because it uses a uniform peak rainfall intensity
- It does not count the evaporation of rainfall

Software using Rational Method for Hydrological Modeling:

HydroCAD[13] can be used as an substitute of the spreadsheet calculation. Besides, it has a built-in rainfall library to automatically generate IDF curves. The complete HydroCAD systems start at $295 per year. The software also offers a free sampler version that provides most of the capabilities of a full HydroCAD program, but is limited to 60-minutes of operation per session.

WMS (Watershed Modeling System)[14] can also be used to calculate runoff rate; however, without proper data for the sites in question, it is impossible to run any analysis using this software. The caculation of the Rational Method can be conducted using its free community version.

Fig-11. Logo of HydroCAD

Fig-12. Logo of WMS

13 The website for HydroCAD software: https://www.hydrocad.net/. Detailed pricing can be found at: https://www.hydrocad.net/ordering.htm. The free sampler is available for download at this address: https://www.hydrocad.net/sampler/index.htm.

14 The website for WMS (Watershed Modeling System): https://www.aquaveo.com/software/wms-watershed-modeling-system-introduction. Detailed pricing can be found at: https://www.aquaveo.com/software/wms-pricing.

Other Methods - Hydrograph Method :

While the rational method only calculates peak runoff rate and does not count in the evaporation, the ***Hydrograph Method*** represents runoff as it varies over time at a particular location within the watershed. The area integrated under the hydrograph represents the volume of runoff. It also takes evaporation, percolation, capillary rise, etc. into consideration[15].

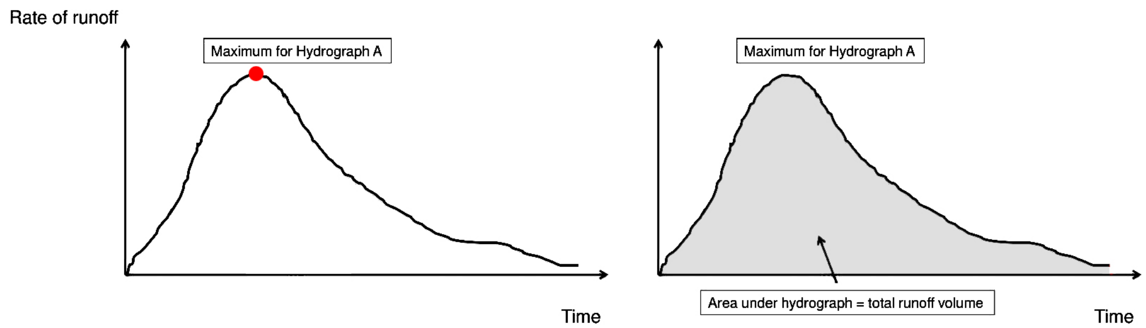


Fig-13. The hydrograph method depicts the curve as shown on the right. The rational method only calculate the peak value (on the left).

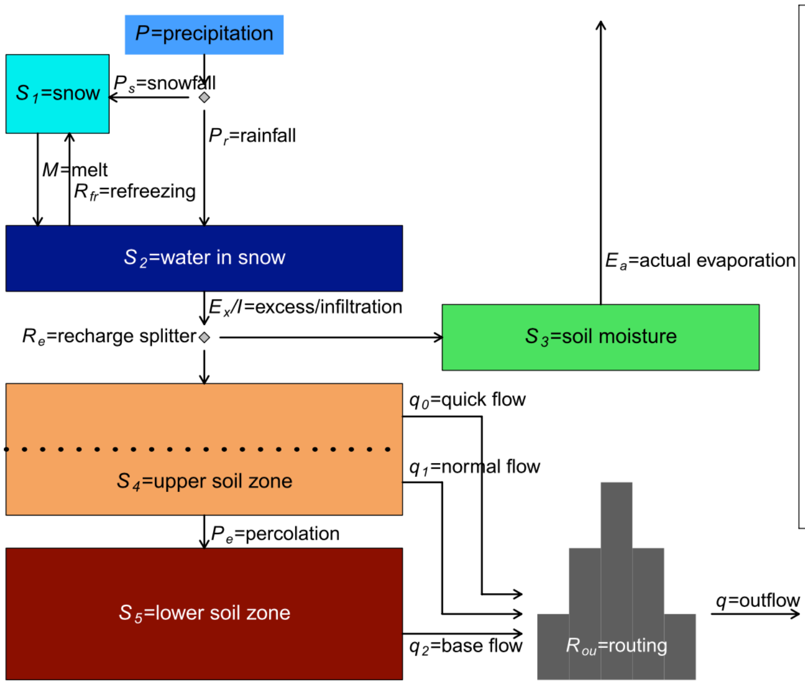
Compared to the Rational Method, the Hydrograph Method is applicable when

- The runoff rate varies in the time period considered and it is not feasible to consider it as a uniform rate over time
- The precipitation lasts for longer period (the tc value in the rational method is long)
- Storage must be evaluated (how long does it take to fill up a pond)
- There are combined rates of flow for two drainage areas which peak at different times.

*For Wupatki and Tuzigoot, it is important to figure out what is the **QUESTION** to ask when deciding which method to use. Quantifying water accumulation in a pond and the analyzing of the destructive effect of surface flow on a wall during a storm will lead to different methods and analysis process.*

HBV model(Hydrologiska Byråns Vattenbalansavdelning model) can be used for the application of the Hydrograph Method (Fig-14). It is developed originally for use in Scandinavia and has also been applied in a large number of catchments on most continents[16]. However, high computational capacity is required for using this model.

15 Detailed discussion on the Hydrograph Method can be found at 819.4 Hydrograph Methods, Chapter 810 hydrology in Highway Design Manual (HDM) of Caltrans: https://dot.ca.gov/-/media/dot-media/programs/design/documents/chp0810-a11y.pdf. The complete manual can be accessed through: https://dot.ca.gov/programs/design/manual-highway-design-manual-hdm.
16 Wikipedia for HBV model: https://en.wikipedia.org/wiki/HBV_hydrology_model



Condition	Formula
$T \le t_t$	$P_s = P s_{cf}$
$T \le t_t$	$R_{fr} = (t_t - T) c_{fmax} c_{fr}$
$T > t_t$	$P_r = P$
$T > t_t$	$M = (T - t_t) c_{fmax}$
$T > t_t$	$E_x = S_{2old} - (S_1 c_{wh})$
$S_{2old} < S_1 c_{wh}$	$I = P_r + M - \delta S_2$
$S_{2old} \ge S_1 c_{wh}$	$I = P_r + M$
	$R_e = (I + E_x)(\frac{S_3}{F_C})^{beta}$
$S_3 < F_c L_P$	$E_a = E_p \frac{S_3}{F_c L_P}$
$S_3 \ge F_c L_P$	$E_a = E_p$
	$P_e = per$
$S_4 > u_{zl}$	$q_0 = (S_4 - u_{zl}) k_0$
	$q_1 = S_4 k_1$
	$q_2 = S_5 k_2$
	$R_{ou} = \mathrm{f}(maxbas, q)$
	$q = q_1 + q_2 + q_0$

Fig-14. Mathematical model of HBV-6-model (one variant of the HBV model).

Step 3: Calculate Surface Flow Depth and Velocity Using HEC-RAS (Hydrological Engineering Center River Analysis System)

With the following data now available:

- Geometry data (from ArcGIS ArcHydro drainage and catchment delineation)
- Flow data (calculated using rational method)

The next step should be to generate

- The computation of depth and velocity of surface flow at any cross section along the stream
- The animation of how water overflow from the stream and affect the surround 2D area

This task can be done by ***1D Hydrological Modeling using*** the HEC-RAS software. 1D hydrological modeling can be used to calculate the depth and velocity of a defined stream at any cross section. The following is a sample of 1D hydrological Modeling. How certain steps should be applied to Wupatki and Tuzigoot will be specified[17].

17 HydrologyVideos, Introduction to 1D Hydraulic Modeling Using HEC-RAS (1/10), 2021, https://www.youtube.com/watch?v=LBDsJyhvspM.

HEC-RAS file structure:

- ***Project File*** *(.prj):*
  Containing basic info about the project including the name, some default options and names of relevant files

- ***Geometry File*** *(.g##):*
  Containing info on reach[18] *connectivity, cross-section profiles and hydraulic structure.*
  **The drainage .shp file (from ArcGIS pro) can be used for reach connectivity*
  **DEM can be used to generate cross-section for the reach*
  **Additional geometry data is required if any structures like bridges and boulders exist*

- ***Flow (steady/unsteady) File*** *(.f##):*
  Containing information on flow/boundary conditions
  **The Peak run off rate Q for steady flow or runoff_rate-time graph for unsteady flow should be input as the flow file.*

- ***Plan File*** *(.p##):*
  Containing info about a plan, including geometry, flow and simulation option

Step1: Create a project

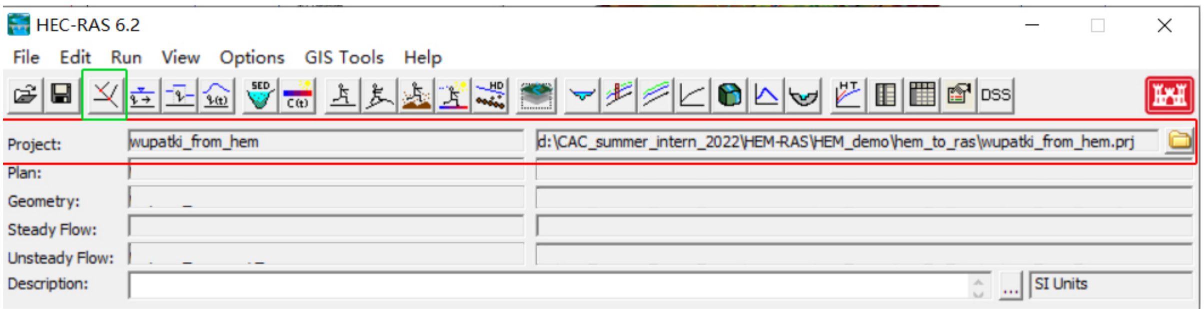


Fig-15. The new project can be seen on the main pannel of HEC-RAS. The geometry editor can be opened clicking on the icon with green outline.

18 A reach is a section of a stream or river along which similar hydrologic conditions exist, such as discharge, depth, area, and slope. It can also be the length of a stream or river (with varying conditions) between two streamgages, or a length of river for which the characteristics are well described by readings at a single streamgage. In practical use, a reach is any length of a stream or river. The term is often used by hydrologists when they're referring to a small section of a stream or river rather than its entire length. (https://www.usgs.gov/faqs/what-reach)

Step 2: Create a geometry file

To create a geometry file, open geometry editor(Fig-15) and save an empty file.

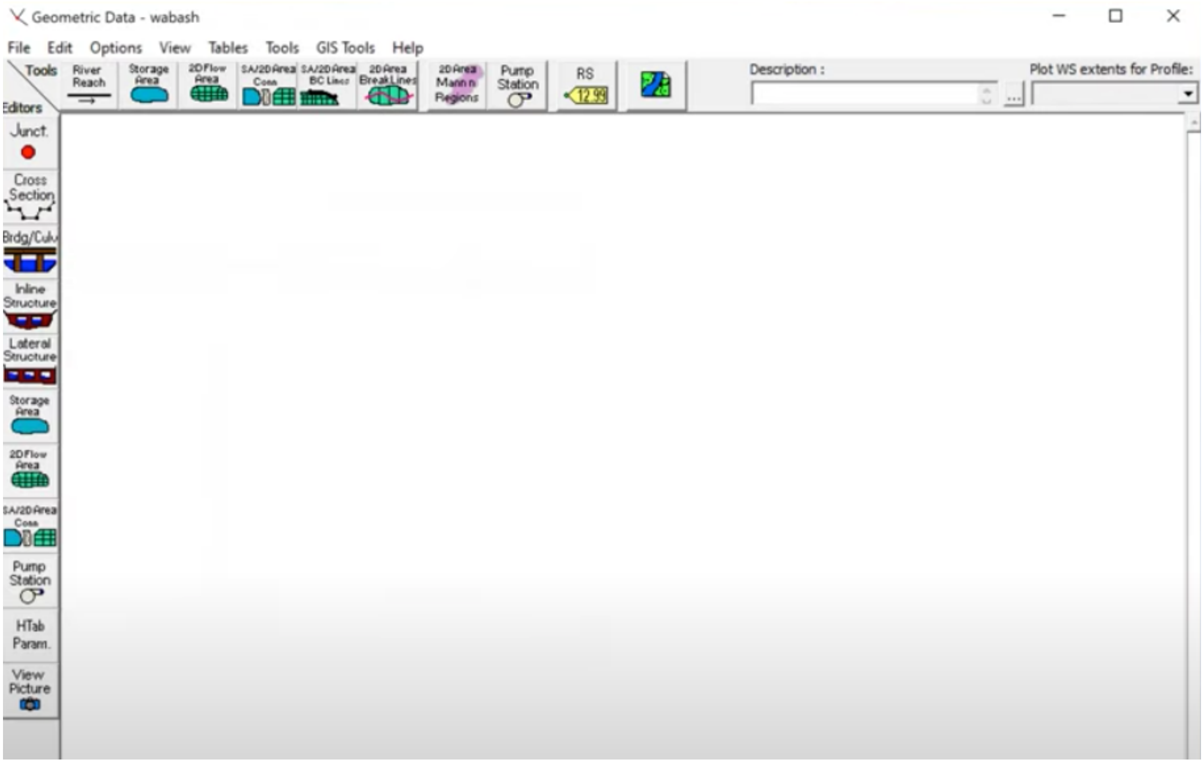


Fig-16. GUI for an empty geometry file

Step 3: Open RAS Mapper

RAS Mapper can be accessed through the main pannel of HEC-RAS (Fig-17).

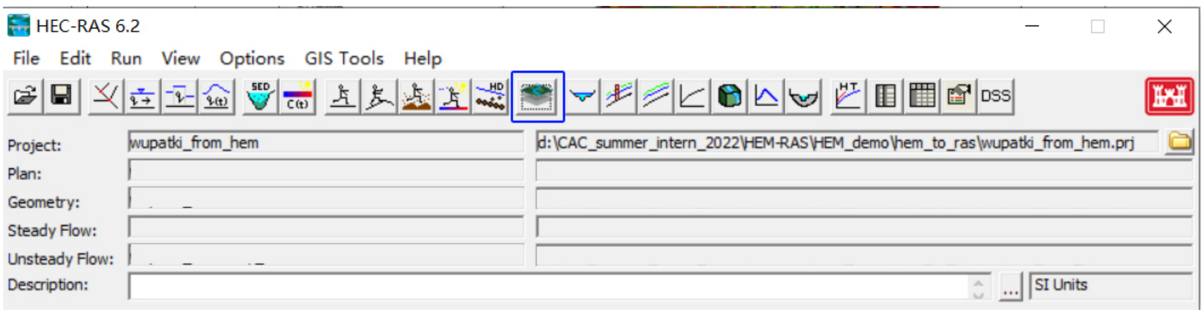


Fig-17. RAS Mapper's icon(outlined as blue)

•Set projection[19]: Import the projection file for a specified coordinate system. For example, Wupatki can use UTM 12N[20]. To set the spatial reference system for the project, from the RAS Mapper menu bar, select the Project | Set Projection menu item. When the Set Projection option is selected, the window shown below will appear:

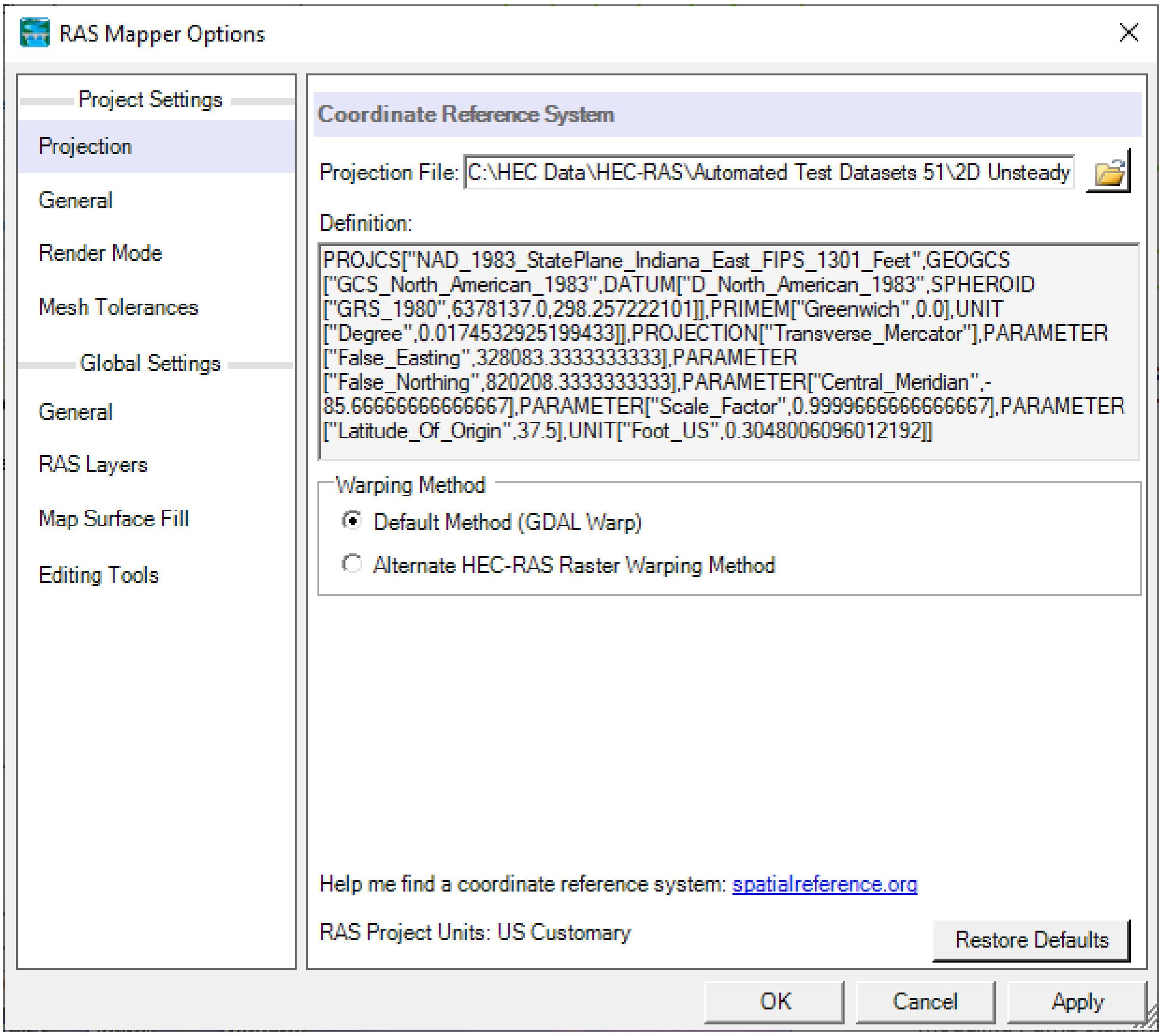


Fig-18. Set projection for the project.

To set the spatial reference system (coordinate system), browse and select an existing ".prj" file (ESRI projection file) that contains the correct coordinate system.

19 Once RAS Mapper is open, if the data is in a specific spatial coordinate projection, that projection should be set in RAS Mapper. Setting a spatial coordinate system is not required (i.e., maybe the user is just doing some testing of hypothetical data), but setting the coordinate system has many advantages in HEC-RAS and HEC-RAS Mapper (https://www.hec.usace.army.mil/confluence/rasdocs/r2dum/latest/developing-a-terrain-model-and-geospatial-layers/setting-the-spatial-reference-projection).

20 UTM is the acronym for Universal Transverse Mercator, a plane coordinate grid system named for the map projection on which it is based (Transverse Mercator). The UTM system consists of 60 zones, each 6-degrees of longitude in width. Arizona is in zone 12N (https://www.usgs.gov/faqs/what-does-term-utm-mean-utm-better-or-more-accurate-latitudelongitude#:~:text=UTM%20is%20the%20acronym%20for,degrees%20of%20longitude%20in%20width).

• Create a new terrain by importing DEM in RAS Mapper:

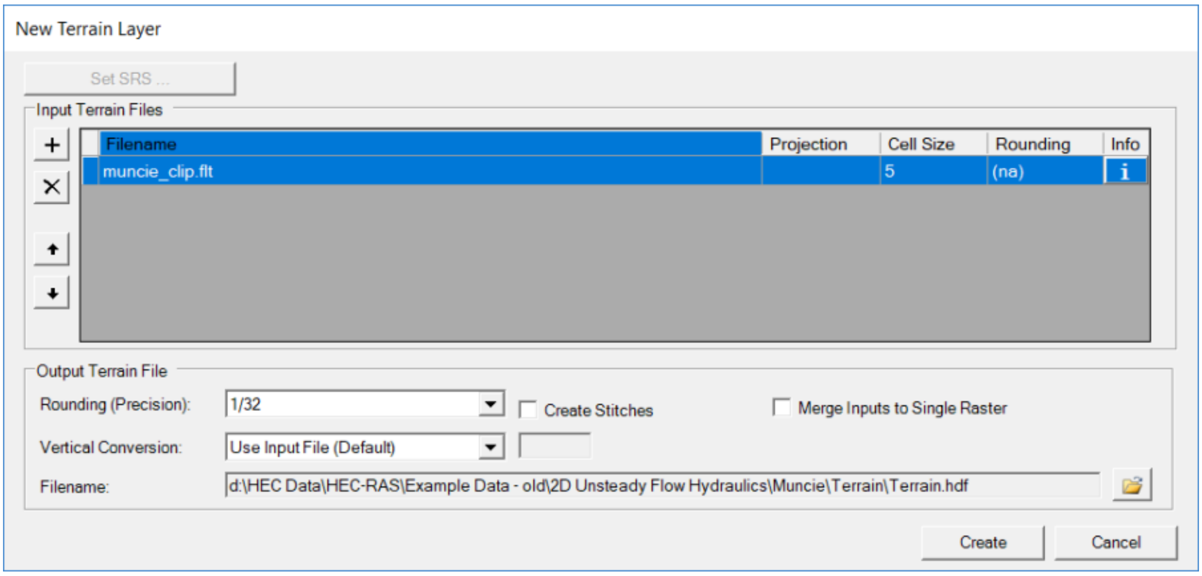


Fig-19. Create a new terrain in RAS Mapper

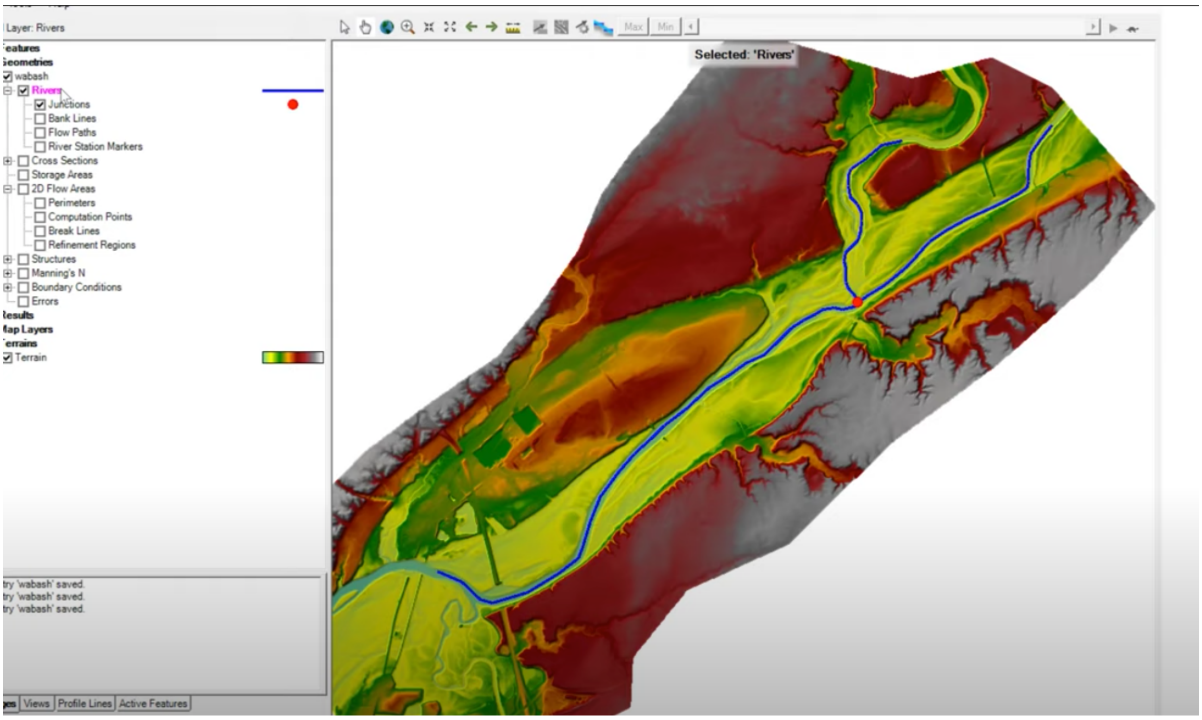


Fig-20. GUI after creating a new terrain from DEM.

Step 4: Create Channel centerlines in Ras Mapper

Centerlines represent the reaches in HEC-RAS but are not used for calculation (bank lines and flow path lines are used in the computation of lengths as explained in the next step) . Centerlines can either be drawn in Ras Mapper or imported from ArcGIS pro's drainages shapefile.

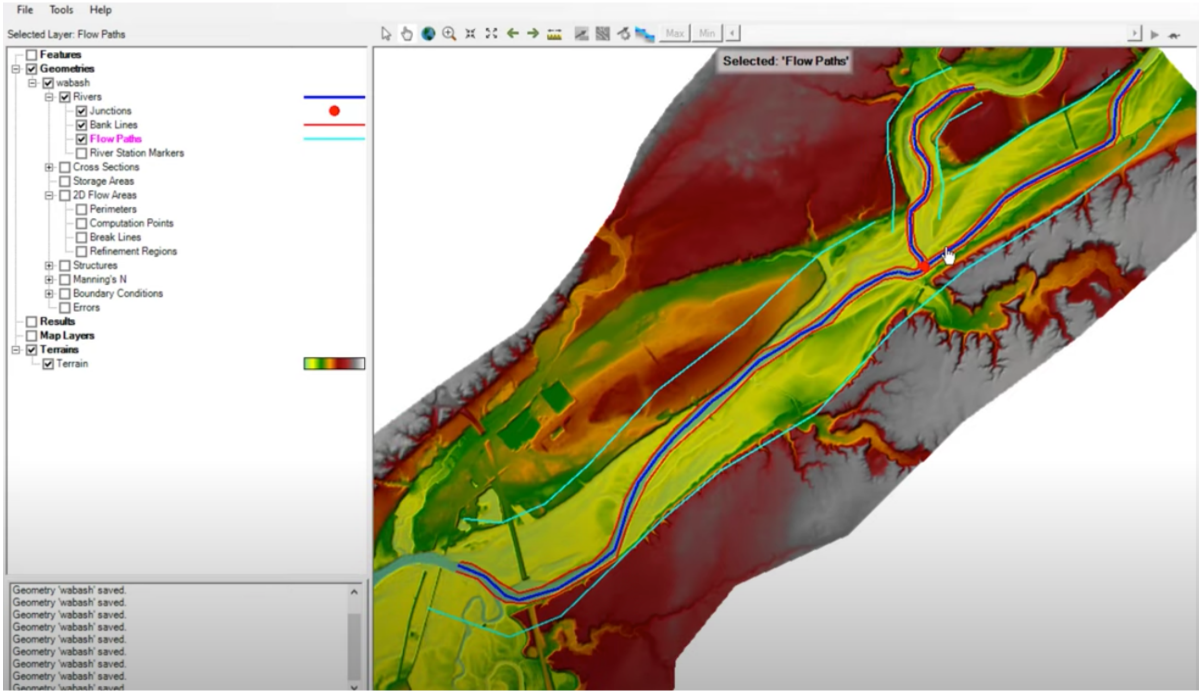


Fig-21. GUI after creating centerlines.

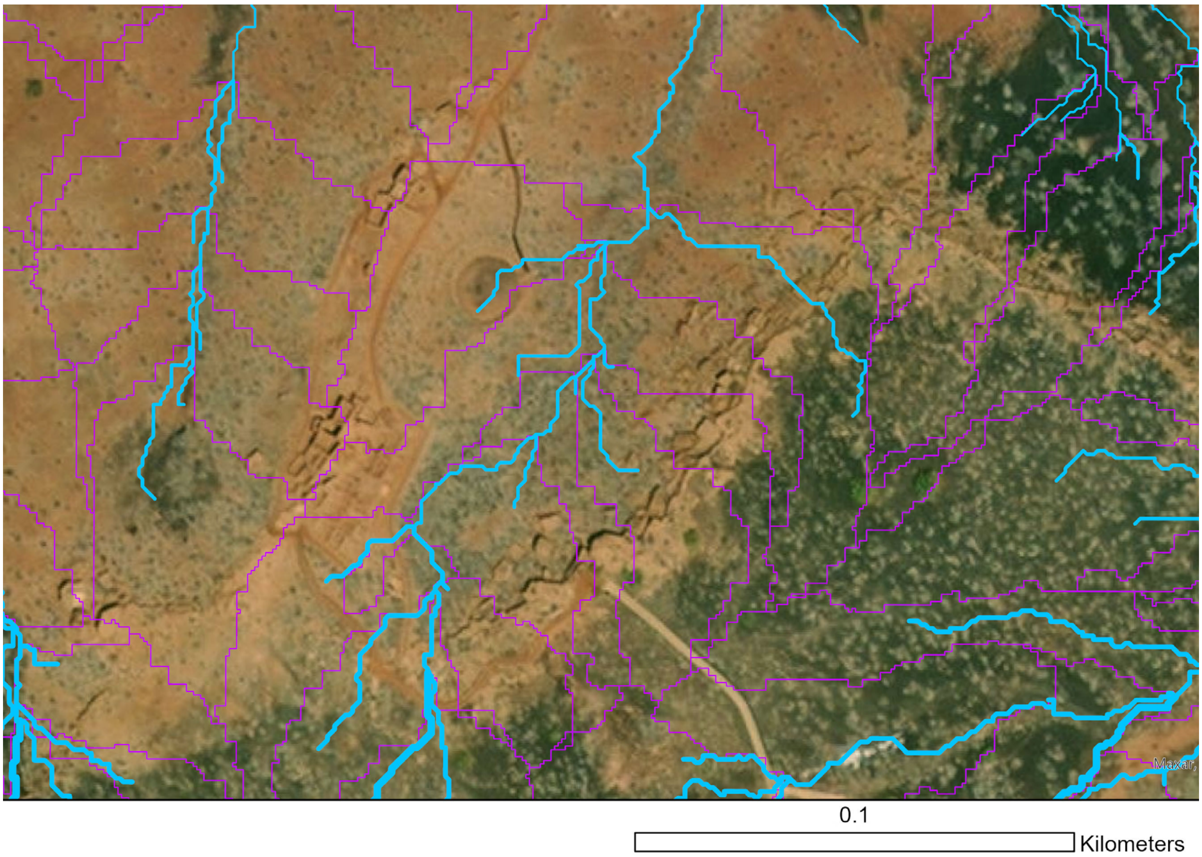


Fig-22. Input for Wupatki site for the centerlines of all drainages. I layered a Google map layer on top of the DEM so it may looks different than the example

Step 5: Create bank lines[21] and flow paths[22]

Bank lines are used to define the main channel bank for and flow path lines are used to are used to compute reach lengths between cross sections in the left and right overbank[23] (Fig-23).

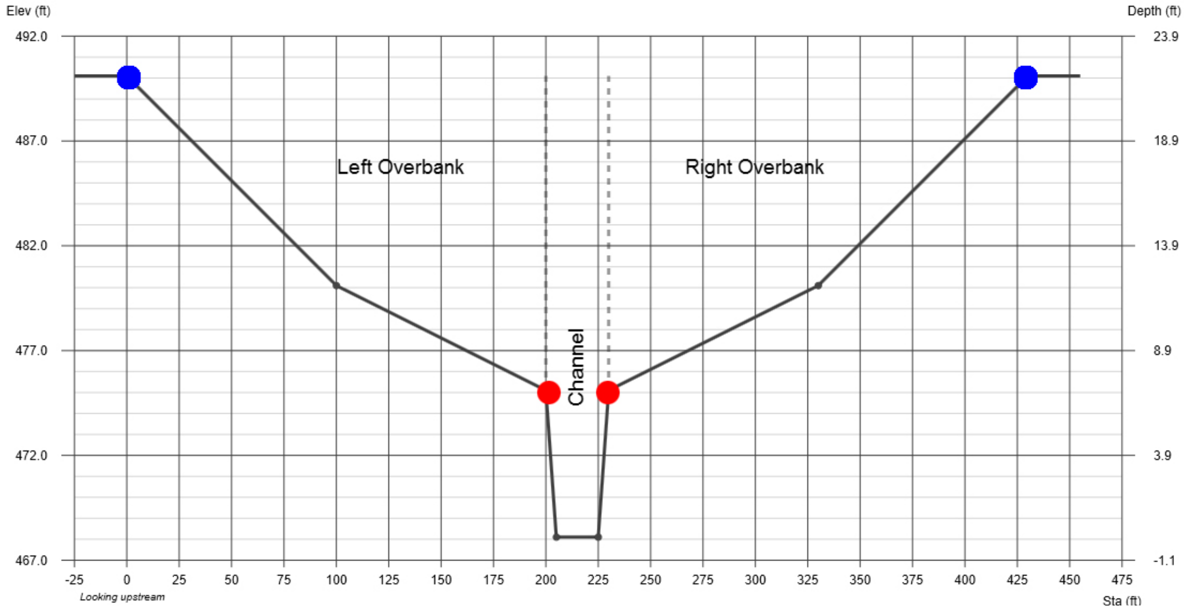


Fig-23. Bank lines (marked red) and overbank (flow path) lines (marked blue) for the main channel. (source of picture: https://learn.hydrologystudio.com/channel-studio/knowledge-base/adding-cross-section-data/.)

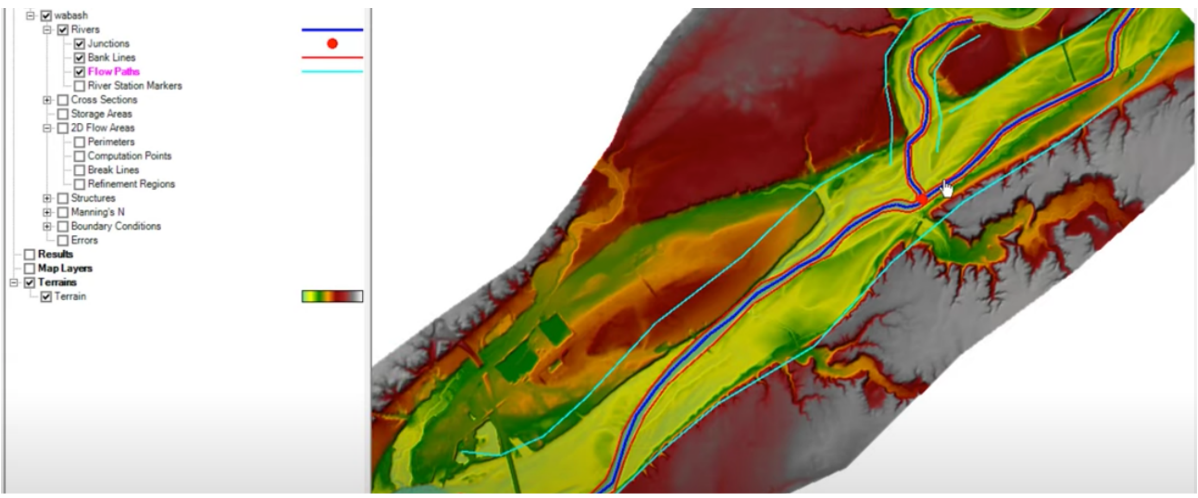


Fig-24. GUI after creating bank lines (red) and flow path lines(cyan).

21 Bank Lines are used to define the main channel banks for a cross section. If the bank lines are not defined, the bank stations will be set to the ends of the cross sections. Banks lines may be drawn continuous or discontinuous, in either the downstream or upstream direction, but it is suggest that you have a left and right bank line for each river line. Make sure the bank lines don't intersect the river lines or each other and only cross a cut line once(https://www.hec.usace.army.mil/confluence/rasdocs/rmum/latest/geometry-data/bank-lines).

22 Flow Path lines are used to compute reach lengths between cross sections in the left and right overbank. Flow path lines are created in the downstream direction following the center-of-mass of flow in the left and right overbanks (it is not necessary to create a flow path in the main channel). They should be drawn in the direction of flow, never intersect river lines and only intersect a cross section line once. Flow path lines should be constructed prior to creating Cross Section locations to assist the user in laying out cross sections perpendicular to flow(https://www.hec.usace.army.mil/confluence/rasdocs/rmum/latest/geometry-data/flow-path-lines).

23 An overbank is an alluvial geological deposit consisting of sediment that has been deposited on the floodplain of a river or stream by flood waters that have broken through or overtopped the banks. The sediment is carried in suspension, and because it is carried outside of the main channel, away from faster flow, the sediment is typically fine-grained. An overbank deposit usually consists primarily of fine sand, silt and clay. Overbank deposits can be beneficial because they refresh valley soils (https://en.wikipedia.org/wiki/Overbank).

ArcGIS pro does not appear to have the tools necessary to generate bank lines and flow path lines that RAS Mapper does.

Step 6: Create cross sections for each reach:

The cross sections should be the location where you want to compute the velocity and depth of the surface flow.

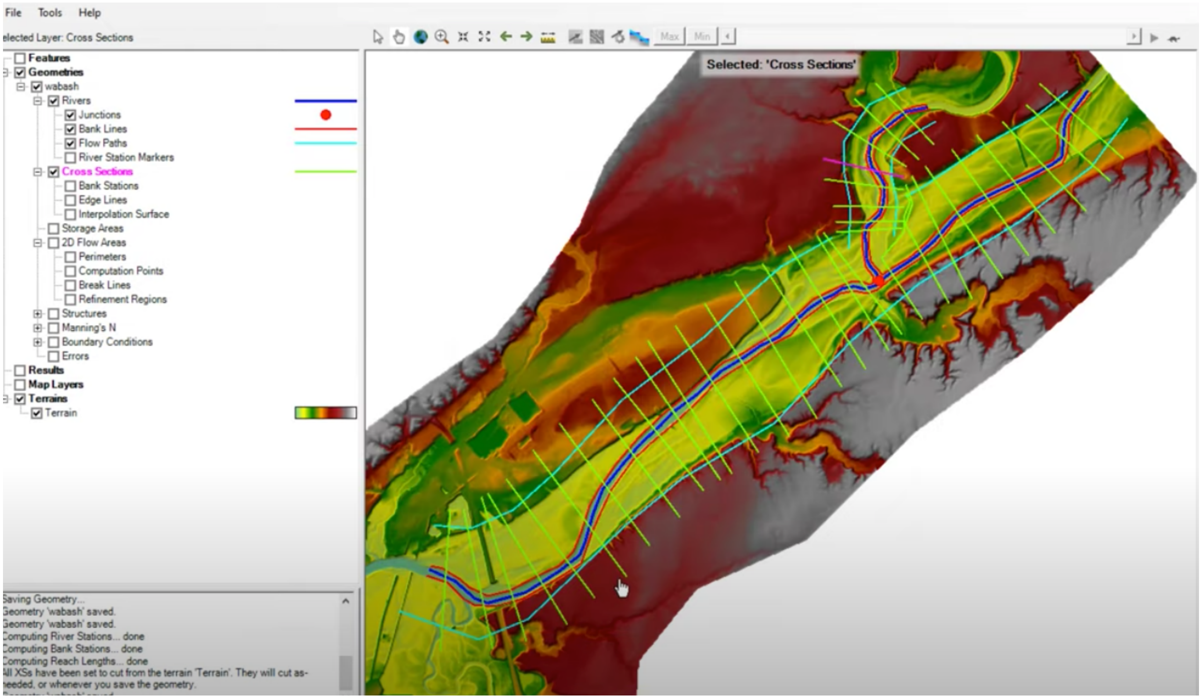


Fig-25. GUI after creating the cross sections.

Now save the geometry to the main pannel (Fig-26). HEC-RAS can calculate the geometric information for each cross-section, which is ready to be viewed in the geometric editor (Fig-26 & Fig-27).

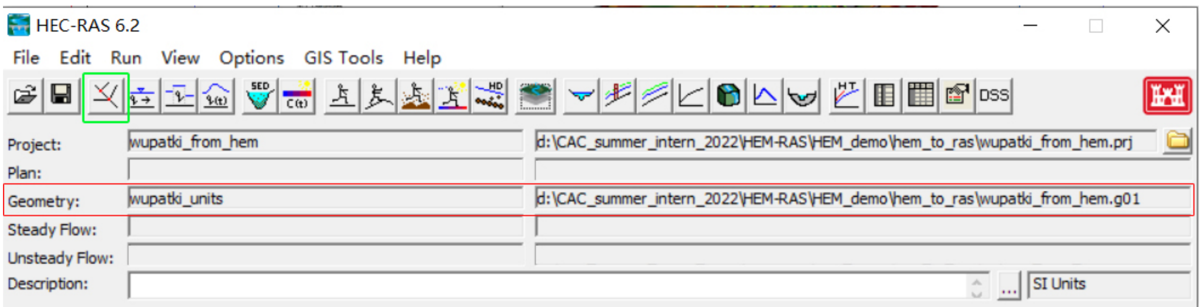


Fig-26. The Geometry file can be seen on the main pannel of HEC-RAS after saving the geometry in RAS Mapper. The geometry editor can be opened by clicking the icon outlined in green.

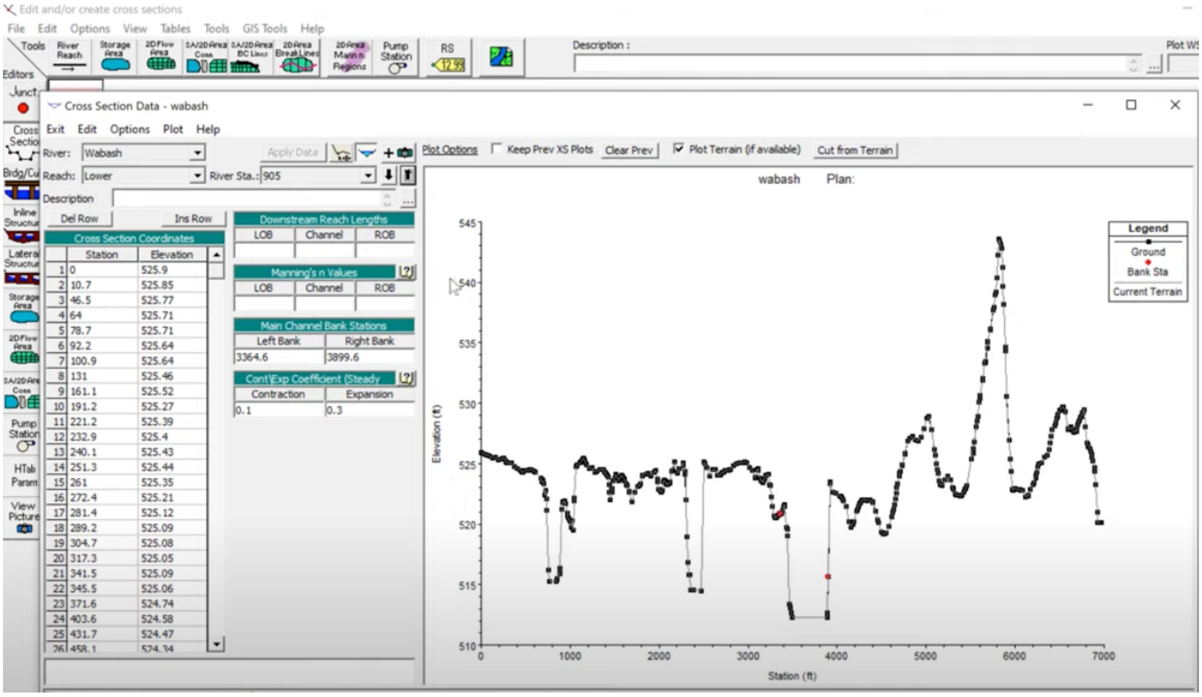


Fig-27. All cross sections can be viewed in the Geometry editor.

Step 7: Type in the Manning's Value (denoted as n) for each cross section

The Manning's n value is a unitless coefficient that represent the roughness or friction factor of the conduit. Rougher conduits with higher friction have a higher value, and smoother conduits with lower friction have a lower value.

Manning's Value for different types of channels are typically referenced in resources and can now be found on the internet[24].

Step 8: Create steady flow data for each reach

At this stage in the process it requires inputting the runoff rate calculated in the previous section.

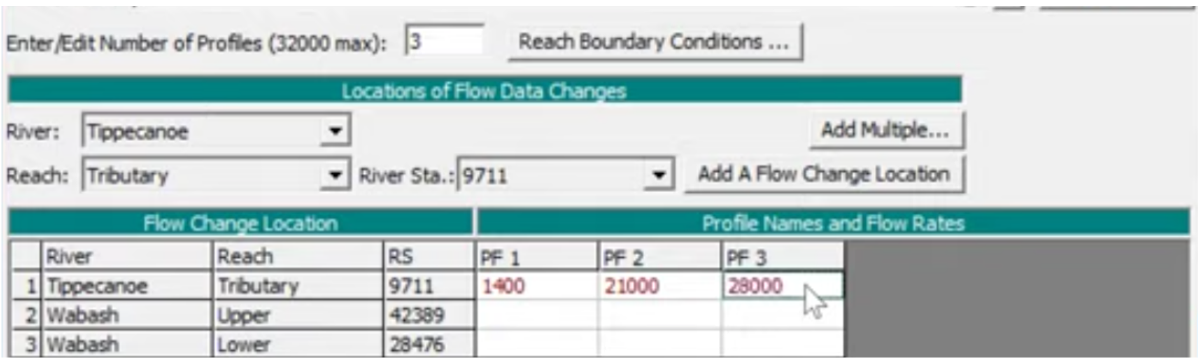


Fig-28. Place to input steady flow data.

24 Look at this as a reference for Manning's value for different channels: "Manning's n Values," accessed July 4, 2022, http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm.

Step 9: Create junction condition for the down-steam reach:

In HEC-RAS, ***stream junctions***[25] are defined as locations where two or more streams come together or split apart. The software will start the computation from the down-stream junction, so the boundary condition[26] of down-steam junction should be specified to trigger the calculation.

There are several ***boundary conditions*** acceptable for HEC-RAS, including[27]:

- **Known water surface**:
  This is the known water surface for the given profile. This option applies for cases where the water level was measured for a given discharge.
- **Critical depth**:
  With this option the program calculates the critical depth for the section and uses it as boundary condition. This option applies for cases where there is a control structure such as weir, gate or drop that controls and forces the critical depth.
- **Rating curve:**
  In this option the water level is interpolated from the given rating curve. Usually this case applies for control station where water levels and discharges are measured constantly.
- **Normal depth:**
  In this option the program uses the energy slope to calculate the normal depth with Manning's equation.

Normal depth can be used for the ***boundary conditions'*** specification in this work flow, which uses the friction slope[28]. The friction slope can be measured in the geometry editor in HEC-RAS.

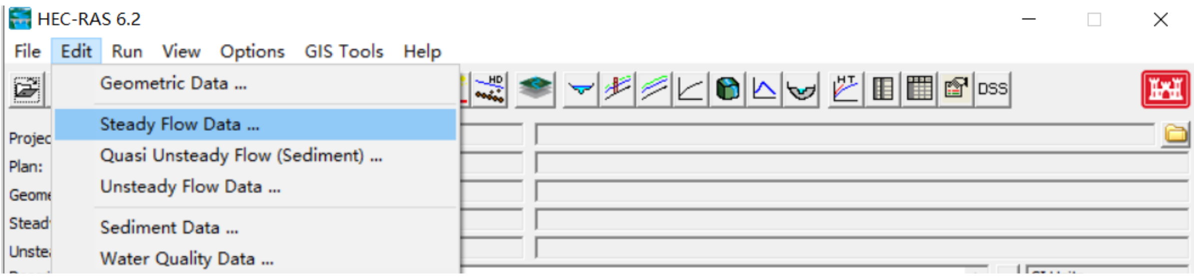


Fig-29. Create new steady flow data.

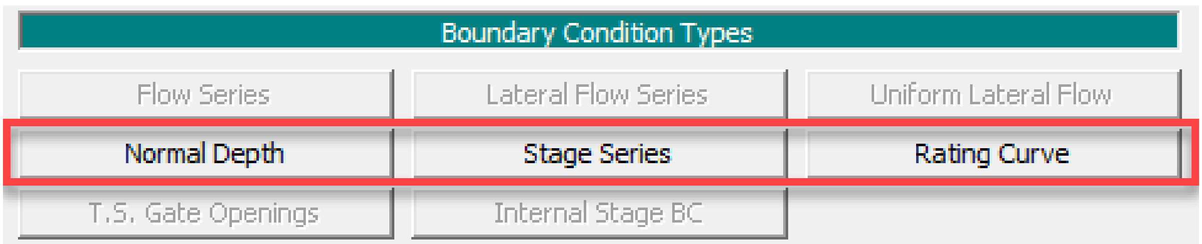


Fig-30. Choose the type of boundary condition when inputting steady flow data.

25 Junction data consist of a description; reach lengths across the junction; tributary angles; and modeling approach(https://www.hec.usace.army.mil/confluence/rasdocs/rasum/latest/entering-and-editing-geometric-data/stream-junctions#:~:text=For%20steady%20flow%20hydraulics%20in,while%20the%20momentum%20equation%20does).

26 Boundary conditions represent locations in the model where water flows into or out of the model region due to external factors. Lakes, streams, recharge, evapotranspiration and wells are all examples of boundary conditions(https://water.usgs.gov/nrp/gwsoftware/ModelMuse/Help/boundary_conditions5.htm).

27 Vadyman, "Boundary Conditions in HEC RAS," Science & Engineering (blog), accessed July 4, 2022, https://sciengsustainability.blogspot.com/2014/02/boundary-conditions-in-hec-ras.html.

28 The friction slope (S_f in Manning's equation) is the slope of the energy grade line and can be estimated a prior by measuring the slope of the bed (press the Alt key in the HEC-RAS Water Surface Profile output view to get a tool that will measure the slope) (https://www.hec.usace.army.mil/confluence/rasdocs/rassed1d/1d-sediment-transport-user-s-manual/flow-data-and-event-conditions/entering-and-editing-quasi-unsteady-flow-data/boundary-conditions/downstream-boundary-conditions).

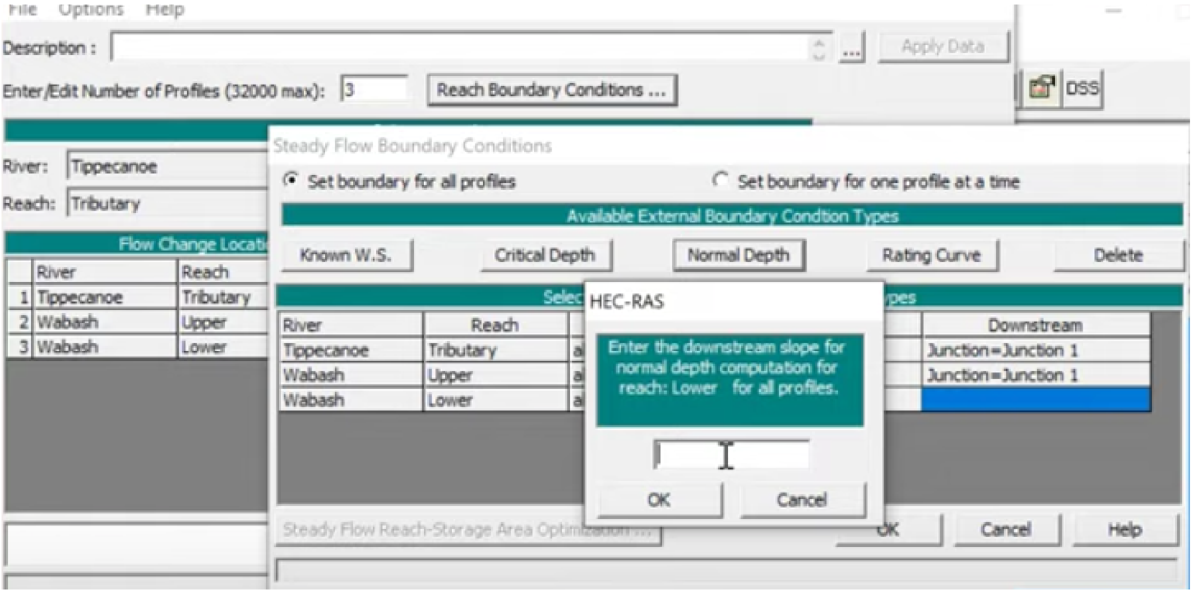


Fig-31. Inputting the friction slope for steady flow data.

Step 10: Run the simulation:

Now that all data is prepared, go to

- *Run*
    - *run steady flow simulation*

to run the analysis.

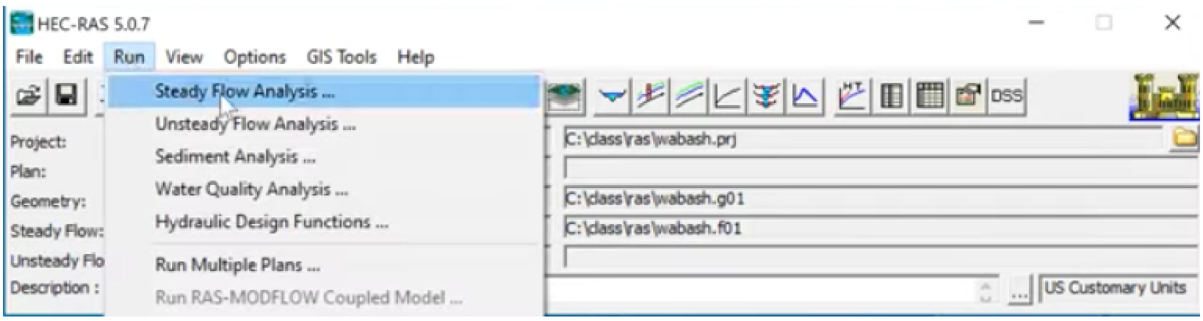


Fig-32. Run the steady flow analysis.

Step 11: Explore the result:

- The result can be viewed in HEC-RAS geometry editor.

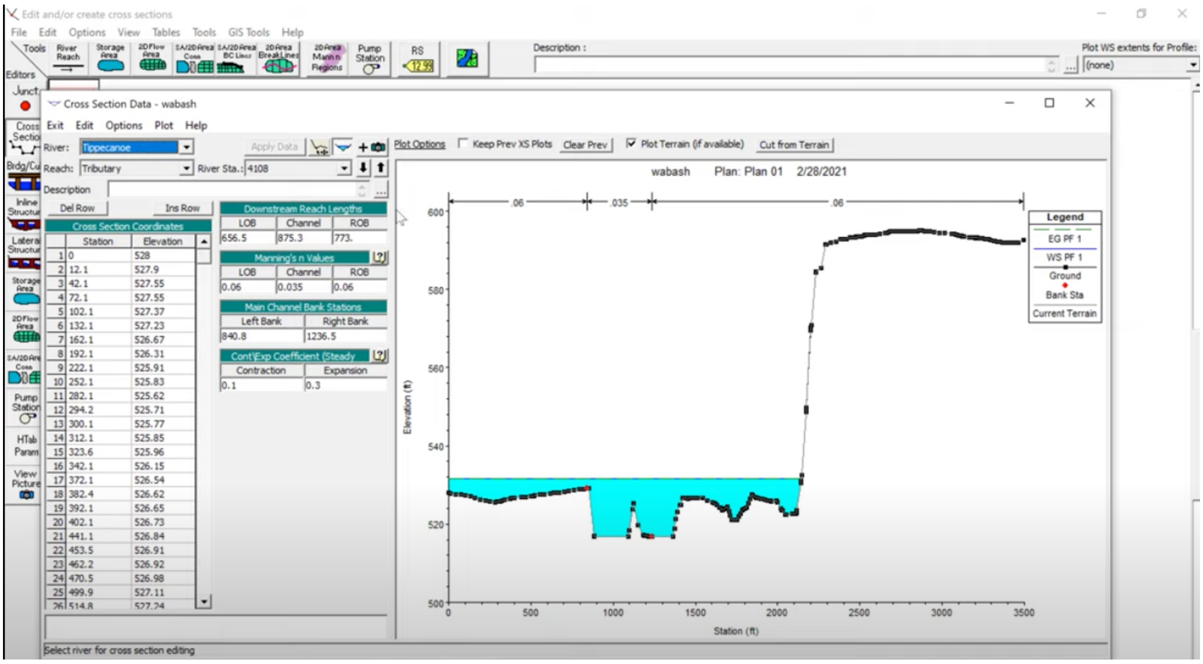


Fig-33. Specify one cross-section and the depth of surface flow is visualized in geometry editor.

- The result and a time-based animation can be viewed in RAS Mapper.

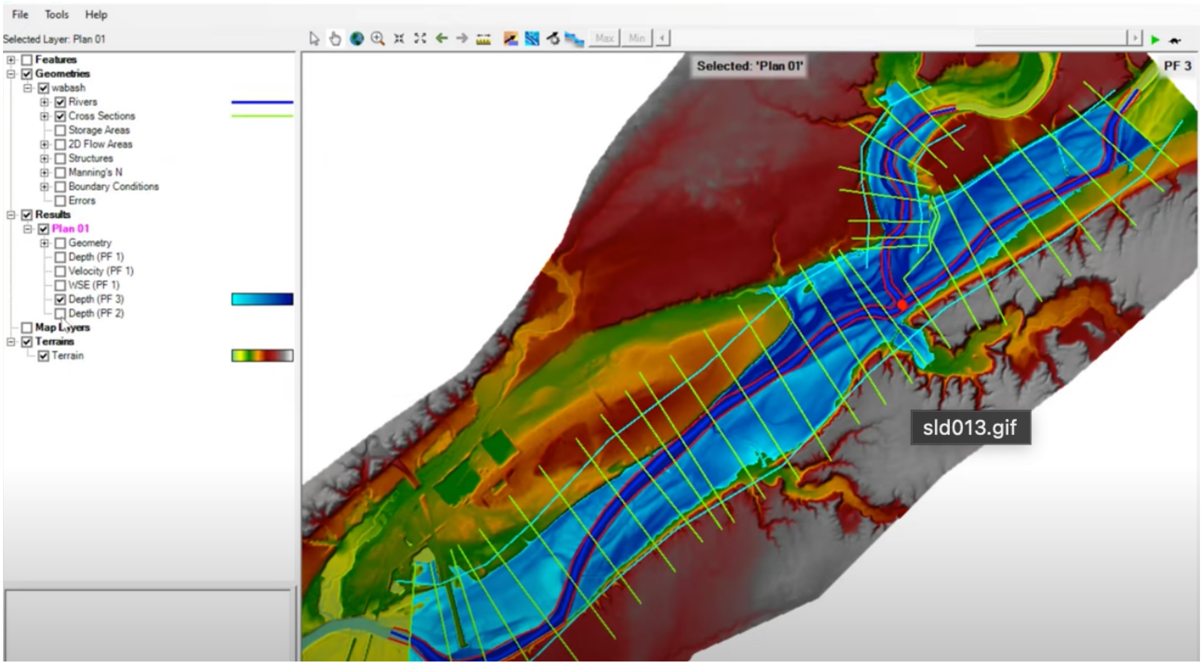


Fig-34. Time-based animation can be played in RAS Mapper.

Revisiting the Queens Valley Report[29] :

The Hydrology analysis in Queens Valley report was conducted using 1D modeling in HEC-RAS and the runoff rate data calculated using WMS(Watershed Modeling System).

It follows the following step:

1. *Rainfall analysis of the study area.*
2. *Sub-catchment delineation.*
3. *Rainfall-runoff analysis to determine the expected peak runoff rate and flow volume corresponding to a storm of 200 year return period.*
4. *Analysis of sediment yield from the catchments.*

A few things worth paying attention to:

- *The report is very clear about the potential issues with its rainfall data: it had to use the weather data collected from the station set at the nearest airport even though the rainfall can be highly localized in the area.*
- *When calculating the peak runoff rate Q, the team did* ***surface sampling*** *to determine the runoff coefficient. For Wupatki, surface sampling is also necessary for acquiring data. Hydrology analysis cannot be done just sitting in the office and clicking buttons in softwares.*
- *Because Queens Valley's hydrology analysis is aimed at modeling the risk of flash flood in the area, it adopted the unsteady flow work-flow in HEC-RAS instead of steady flow. Compared to the steady flow analysis, the unsteady flow analysis requires:*

  - *Using the* ***Hydrograph Method*** *to calculate the flow-time curve instead of using the Rational Method to calculate the peak runoff rate and use that as a uniform runoff rate for the whole period of time*
  - ***Runoff curve number[30]*** *to be calculated based on land cover characteristics, particularly soil type for the Hydrograph method.*

- *A flash flood at Queen's Valley will not only produce rainfall runoff, but a flow of water mixed with mud and rock debris, so the hydrology analysis also includes the sediment yield. How the sediment yield might be integrated into the data input of the 1D unsteady flow analysis needs to be further researched.*

Tips from the Queens Valley report:

- ***The QUESTION needs to be identified****. Analyzing flash flood requires unsteady flow data and others may only require steady flow data, the question is used to determine which work flow should be followed.*
- ***Field observation of hydrological issues is essential to identifying the Question****. In Queens Valley's report, apart from the conclusion drawn from hydrological analysis, many recommendations came from the on-site observations of cracks, dried mud and runoff.*
- ***High resolution weather data is needed****. Data of similar resolution of Fort Union is sufficient for conducting unsteady flow modeling for Wupatki.*

29 Martha Demas et al., Valley of the Queens Assessment Report, 2012, http://hdl.handle.net/10020/gci_pubs/valley_queens. The hydrology analysis result of Queen's Valley can be found on pages 169-282 in vol I of the report.
30 The runoff curve number (also called a curve number or simply CN) is an empirical parameter used in hydrology for predicting direct runoff or infiltration from rainfall excess （https://en.wikipedia.org/wiki/Runoff_curve_number）.

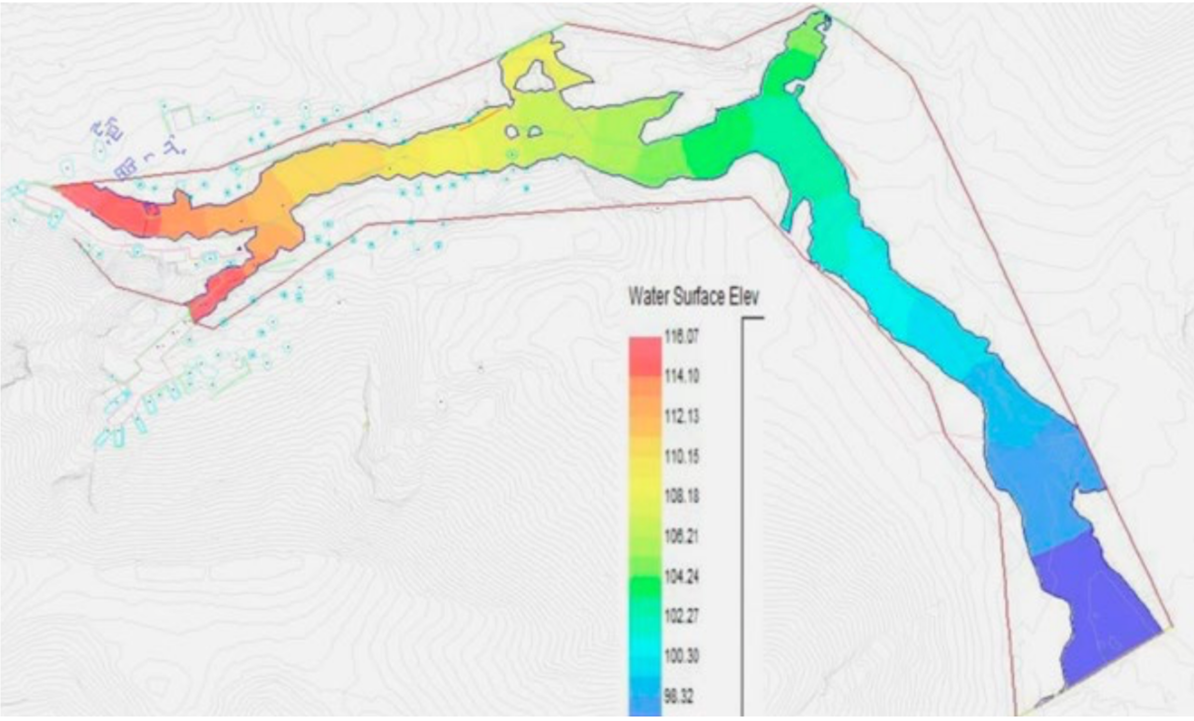


Fig-35. Result of hydrology analysis in Queens Valley's report: Water Surface Elevation, conducted using HEC-RAS.

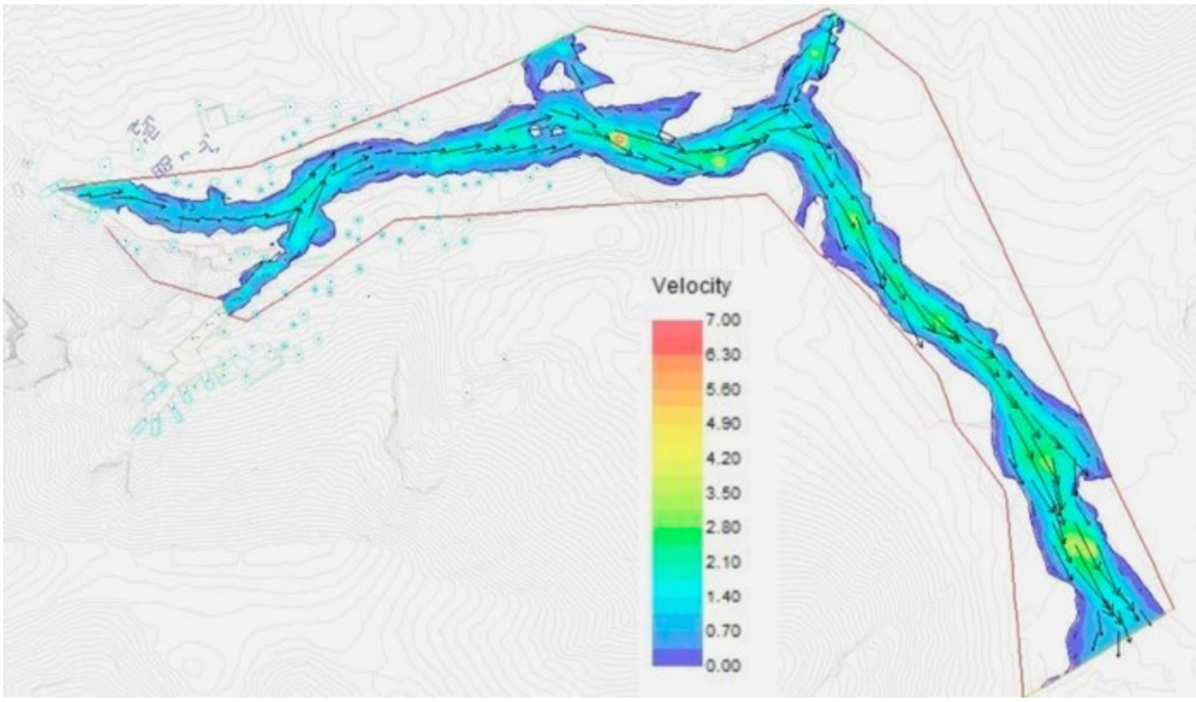


Fig-36. Result of hydrology analysis in Queens Valley's report: Velocity, conducted using HEC-RAS.

Step 4: The Integretion of the Vertical Hydrological Condition

Vertical and Horizontal Hydrological System:

When examining the hydrology of a site of a certain area with its built structure, precipitation will not only excert influence on surface flow. The vertical built structures, like walls, bridges, gates will also be exposed to direct contact with rainfalls and snowfalls. These two systems share some parameters like evaporation, infiltration etc., but also use distinct metrics. For example, for the horizontal system of surface flow, the following aspects may need to be considered:

- Driange and catchment delineation
- Cross-sections of streams
- Ground slope
- Friction of surface
- Runoff to the ground

...

While for the vertical hydrological system of built structure, a set of different parameters should be considered:

- Wind direction
- Water splash
- Callipary rise
- Runoff down the facade
- Cracks and ingress
- Micro climate of interior and exterior

...

Time-based hydrology Analysis of the Vertical System:

Paper *Heritage hydrology: a conceptual framework for understanding water fluxes and storage in built and rock-hewn heritage*[31] provides a methdology to analyze moisture in built structure from different spatial scale:

- Detail scale
- Façade scale
- Building scale

And from different temporal scale:

- Short-term (minutes to days) fuctuations
- Response to seasonal and longer-term changes

Therefore, a question should be asked based on the nature of the horizontal and vertical hydrological systems:

Both as spatial-temporal phenomenon, is there an elegant mathematical model to integret the vertical and the horizontal hydrological system? How these two systems will interact with each other and what is the range of errors that will occur if we leave out one of the systems?

31 Oliver Sass and Heather Viles, "Heritage Hydrology: A Conceptual Framework for Understanding Water Fluxes and Storage in Built and Rock-Hewn Heritage," Heritage Science 10, no. 1 (December 2022): 66, https://doi.org/10.1186/s40494-022-00693-7.

Surface flow (horizontal hydrological system) is mentioned in the hydrological system(vertical) of the stone built structures in the paper:

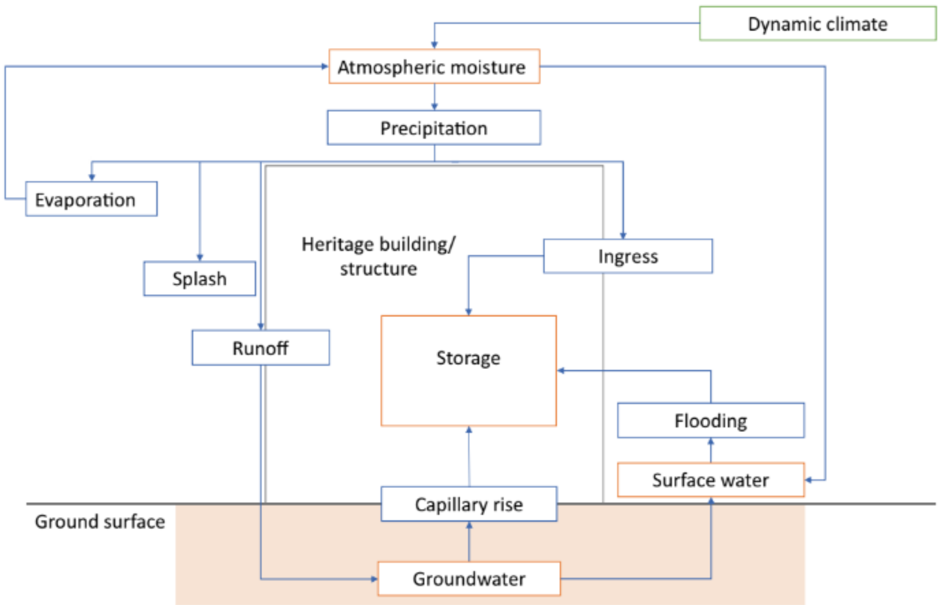


Fig-37. Diagram showing a micro-scale vertical hydrological system of the stone built structure. Surface water is counted as one of the parameters, however, the paper does not explain in depth the approach with mathematical accuracy and rationality to intergreting the horizontal and vertical hydrological system.

However, from the previous analysis on the horizontal hydrological system modeling, it is not difficult to see that the diagram(Fig-37) is an oversimplification of the surface flow analysis.

In contrast, the Queens Valley report is able to represent a rather complete picture of the area's hydrology condition without mentioning the vertical structures because most of its structures are underground. For Wupatki and Tuzigoot, both surface flow and vertically-built walls should be taken into consideration. Therefore, the hydrology analysis of these two sites will require an active and effective collaboration between hydrology engineers and conservators.

Conclusion

***ArcGIS pro's ArcHydro Tools is not sufficient for the Hydrology Analysis for Wupatki and Tuzigoot*:**

The ArcHydro Tools in ArcGIS pro is only suitable for large-scale hydrology modeling and analysis because it adopts a highly simplified hydrology model and computes the result solely based on the DEM of the site. Attempt to apply such a tool in micro-scale hydrology analysis will lead to inaccurate results.

ArcGIS pro's ArcHydro Tools can be used in one of the steps of the micro-scale hydrology analysis in the delineation of catchment and drainages. However, other tools can be used to arrive at the same results. For example, the HEC-HMS(Hydrological Engineering Center Hydrologic Modeling System)[32] can also be used to generate drainage and catchment

***A wide range of data needs to be collected on-site and online*:**

The data requirement is demanding for conducting micro-scale and site-specific hydrological modeling and analysis. For Wupatki and Tuzigoot, a wide range of data is still missing even if the high resolution point clouds had been acquired using laser scanning.

To collect sufficient data for conducting the analysis, the following aspects should be considered:

1. *Some data may take longer time to collect than others. (E.g. the rainfall data)*
2. *Some data may require intense field work to collect. (E.g. detail mapping of sub-areas within one catchment)*
3. *Lab testing and relavent equipments may be required. (E.g. surface sampling in determining the runoff coefficient for the Rational Method)*
4. *It may require people with a certain expertise to collect data (E.g. hydrology engineers)*

The process of data collection can be expensive and time-consuming. Such cost needs to be estimated for conducting hydrology analysis of such kind.

***A mathematical model to integret vertical and horizontal hydrology analysis needs to be developed*:**

All softwares run based on the mathematics used in its algorithm. However, I have not found a mathematical model to merge the vertical and horizontal hydrological system of sites like Wupatki and Tuzigoot.

In addition, when choosing which software or which model to use, understanding the math behind it is essential in making a rational and accurate decision.

***Cross-disciplinary collaboration between hydrologists and conservators is required* :**

It is evident that most parts of the micro-scale hydrology analysis are beyond the expertise of conservators and preservationists. Therefore, it is necessary to collaborate with various professional teams in the process. The Queens Valley project hired the Irrigation & Hydraulic Structures team from an Egyptian consultant company named *Hamza Associates*[33], who develops its businesses in civil engineering for the hydrology analysis of the site. Hiring professionals in hydrology can be expensive and the cost of which, along with the cost of data collection, software subscription and etc., should be taken into consideration in the finance of the project.

32 HEC-HMS is developed by the same team as HEC-RAS, the work flow using HEC-HMS can be found on its website: https://www.hec.usace.army.mil/software/hec-hms/.

33 Hamza Associates is an Egyptian engineering consultancy that offers a wide range of services including energy, transportation, and environmental. Hamza Associates's website: http://www.hamza.org/aboutus.aspx.