Python Tools to Aid and Improve Rapid Hydrologic and Hydraulic Modeling with the Automated Geospatial Watershed Assessment Tool (AGWA)

by

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Abstract

Hydrologic and hydraulic modeling are used to assess watershed function at different spatial and temporal scales. Many tools have been developed to make these types of models more accessible to use and model results easier to interpret. One tool that makes hydrologic models more accessible in a geographic information system (GIS) is the Automated Geospatial Watershed Assessment tool (AGWA); the GIS enables the development of spatially variable model inputs and model results for a variety of applications. Two major applications of AGWA are for rangeland watershed assessments and post-wildfire rapid watershed assessments. Each of these applications have primarily utilized the Kinematic Runoff and Erosion model (KINEROS2) which is accessible in AGWA. Two new tools were developed which work within the existing AGWA/KINEROS2 framework in ArcGIS to enhance rangeland and post-wildfire watershed assessments. The Storage Characterization Tool, was developed to work with high-resolution topographic data to characterize existing stock ponds so these features can easily be incorporated into AGWA/KINEROS2 for rangeland hydrologic analysis. The second tool simulates reach scale flood inundation (the Inundation Tool) utilizing AGWA/KINEROS2 outputs and local channel properties for Hydrologic Engineering Center (HEC-2) hydraulic calculations to compute flood inundation in post-wildfire environments. Both tools have been validated using multiple datasets and desired applications were outlined so that the tools are properly used.

1. INTRODUCTION

1.1 PROBLEM STATEMENT

Multiple levels of government are working with local, state and private organizations to develop high-quality and high-resolution digital elevation models (DEMs) derived from light detection and ranging (LiDAR) so that this topographic data is more readily available across the United States (National Research Council, 2007). These data can be used for many hydrologic and hydraulic tasks and can also be used to capture changes in a landscape such as development or disturbance. Changes across a landscape can have an impact on hydrologic and hydraulic processes across a watershed. Hydrologic and hydraulic modeling can incorporate the landscape details provided by high-quality, high-resolution topographic data and improve model results at a variety of spatial and temporal scales. Since these data can be large and tedious to process it is important to automate some of the procedures to use high-resolution DEMs to aid and improve aspects of hydrologic and hydraulic models. With hydrologic and hydraulic models accessible through GIS, tools that utilize scripted procedures associated with high-resolution DEMs can make these data more accessible for watershed and reach scale analysis.

One existing GIS tool which provides access to a suite of hydrologic models for watershed analysis at different spatial and temporal scales is the Automated Geospatial Watershed Assessment tool (AGWA; Miller et al., 2007; Goodrich et al., 2012; www.tucson.ars.ag.gov/agwa and www.epa.gov/water-research/automated-geospatial-watershed-assessment-agwa-tool-hydrologic-modeling-and-watershed). AGWA is an ArcGIS-based tool that makes use of nationally available datasets to parameterize, execute and display results for models like the Soil Water Assessment Tool (SWAT), the Kinematic Runoff and Erosion Model (KINEROS2), and the Rangeland Hydrology and Erosion Model (RHEM). AGWA has been developed to facilitate the use of those hydrologic models for scientists, natural resource managers, and decision makers to better understand the connection runoff and erosion has with land cover change, rangeland health, urban development, green infrastructure and wildland fires.

AGWA contains many tools for rangeland health and hydrology however KINEROS2 has the potential to model more rangeland features than AGWA is currently able to address. One common rangeland feature is the erosion control dam or stock pond. These features are very common across the western United States and can be designed to serve a variety of purposes (Young 1997). Regardless of their purpose, the ponds can have a dramatic local impact on runoff and erosion and when populous across a watershed can have an impact at the outlet of a larger watershed. However, without local knowledge of these ponds they are hard to represent in a modeling context. So, the first tool described in this thesis makes use of high-resolution digital elevation models (DEMs) to identify, characterize and plan erosion control structures (or stock ponds).

Current tools in AGWA have also been used to speed up post-wildfire hydrologic modeling for Burned Area Emergency Response (BAER) efforts (Sidman et al., 2015). While AGWA can provide estimates about changes in runoff after a wildfire, it does not contain hydraulic computations to assess flood inundation risk. In some scenarios responders need to understand flood risk and are forced to turn to complex, time-consuming hydraulic models to better understand the potential flood impact at specific values at risk. The second tool described in this thesis will provide access to the basic water surface elevation calculations employed by the Hydrologic Engineering Center (HEC-2) model (US-ACEIWR-HEC 1990). This Python tool will be utilized in combination with GIS to develop inundated boundaries along a reach of interest after a wildfire.

1.2 OBJECTIVES

The objectives of this research and development are to:

1. Develop a new tool that processes high resolution DEMs for stock pond characterization and prepare KINEROS2 input files;
2. Assess and validate the Storage Characterization tool using simplified and real world cases;
3. Develop a new tool that allows for simple hydraulic computations along a reach impacted by wildfire;
4. Assess and validate the Inundation tool using an idealized, simplified, and real world channel reach; and
5. Develop guidance on use of the tools.

1.3 APPROACH

Both tools were initiated with data collection and organization in mind. LIDAR-derived DEMs were the driver behind developing these two tools however hydraulic calculations ultimately link the tools. Hydraulic calculations of area, volume and discharge are the core computations accomplished by the stock pond tool. Hydraulic calculations of wetted perimeter, cross-sectional area, and head loss are computed from discharge and reach characteristics for the inundation tool. While both tools are distinct, it was important to follow similar coding practices in developing them and to include clear guidance on required and optional tool inputs.

In order to insure easy incorporation of these tools with geospatial data, Python was used to script the tools. The stock pond tool was built in a Python Toolbox and the inundation tool was built in an ArcToolbox that accessed Python Scripts. These toolboxes are transferable and easy to read as Python is a high level programming language. Python was also used due to the ArcPy module which provides access to all ArcGIS tools that have been previously developed by ESRI staff and users.

After developing the tools, they will be validated using idealized and realistic data sets. Idealized datasets included a perfect spherical pond (which would likely not exist in reality) and a concrete lined trapezoidal channel. Realistic datasets include the stock ponds on the Walnut Gulch Experimental Watershed (WGEW) and the Frijoles Canyon in Bandelier National Monument which was affected by wildfire in 2011.

1.4 SITE DESCRIPTIONS

The Walnut Gulch Experimental Watershed (WGEW) is located in southeastern Arizona. WGEW is heavily instrumented with data collection throughout the watershed since the 1950s (Stone et al., 2008). There are 22 stock ponds that were constructed on WGEW via excavation and construction of an earthen dam across existing channels (Nichols 2006). Eight of the stock ponds (Figure 1) located at the outlets of small watersheds (35.2ha to 159.5 ha) are instrumented for precipitation, runoff and sediment (Nichols et al., 2014). Topographic surveys are also conducted while these ponds are dry (Nichols et al., 2014). LIDAR has recently been collected twice across the entire WGEW, once in 2003 and the latest in 2015; both of the LIDAR datasets have been converted to

DEMs. Some of the surveyed stock ponds on WGEW were used along with the 2015 LIDAR to verify the Storage Characterization tool.

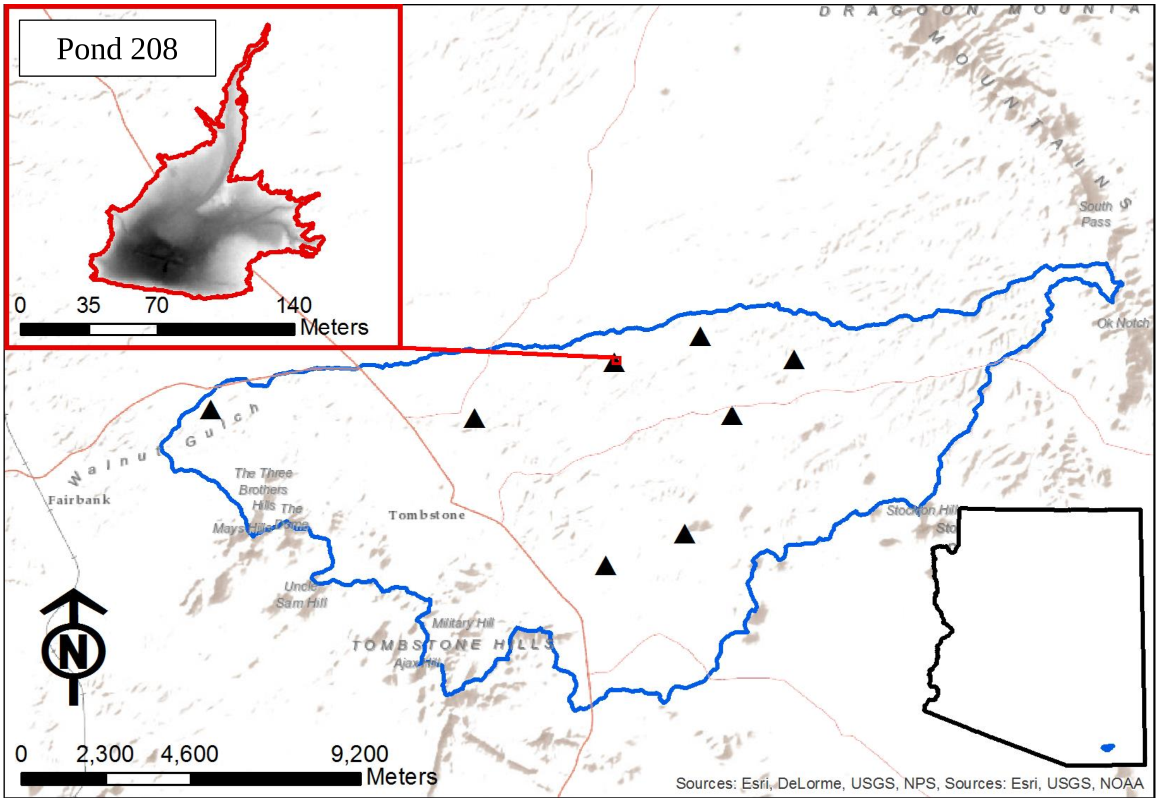

Figure 1- Stock Ponds on the Walnut Gulch Experimental Watershed in Southwestern Arizona.

Bandelier National Monument is located in the Jemez Mountains of northwestern New Mexico and protects about 13,300 ha of land (NPS 2015). Frijoles Canyon, the main canyon within the monument, contains multiple archeological sites and the park's visitor center. Fire has impacted Bandelier National Monument four times in the last four decades with the Las Conchas fire of 2011 being the largest in New Mexico's history (NPS 2015). Over 4,000 ha of the Rito de Los Frijoles watershed was burned during the Las Conchas fire (Figure 2). The Frijoles watershed has been impacted by wildfire in the past. The La Mesa and the Dome wildfires, in 1977 and 1996 respectively, lead to peak discharge about 160 times larger than that of pre-fire maximum recorded floods (Veenhuis 2002).

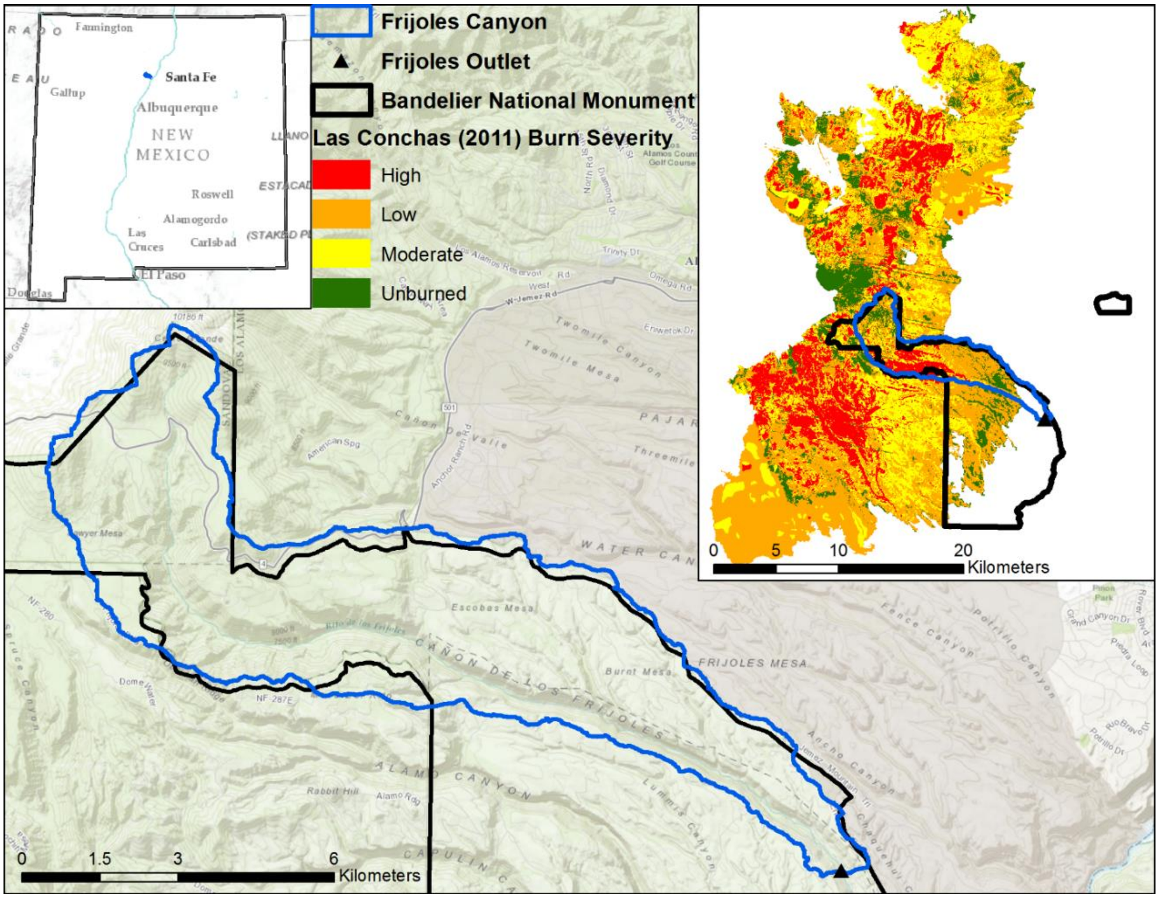

Figure 2- Las Conchas Fire of 2011 that Impacted Bandelier National Monument in New Mexico.

On August 21, 2011 the stream gage at the Frijoles watershed outlet measured over 180 cubic meters per second, which was larger than the post-fire peak discharge observed after the previous fires (USACE 2014). After this event the NPS documented high water marks and the USACE calibrated HEC-RAS in order to analyze different flood events impact on cultural sites, archaeological sites and the park's visitor center (Figure 3). The USACE and NPS data on the post-fire flood extent will be used for the more complex case study to validate the Inundation Tool.

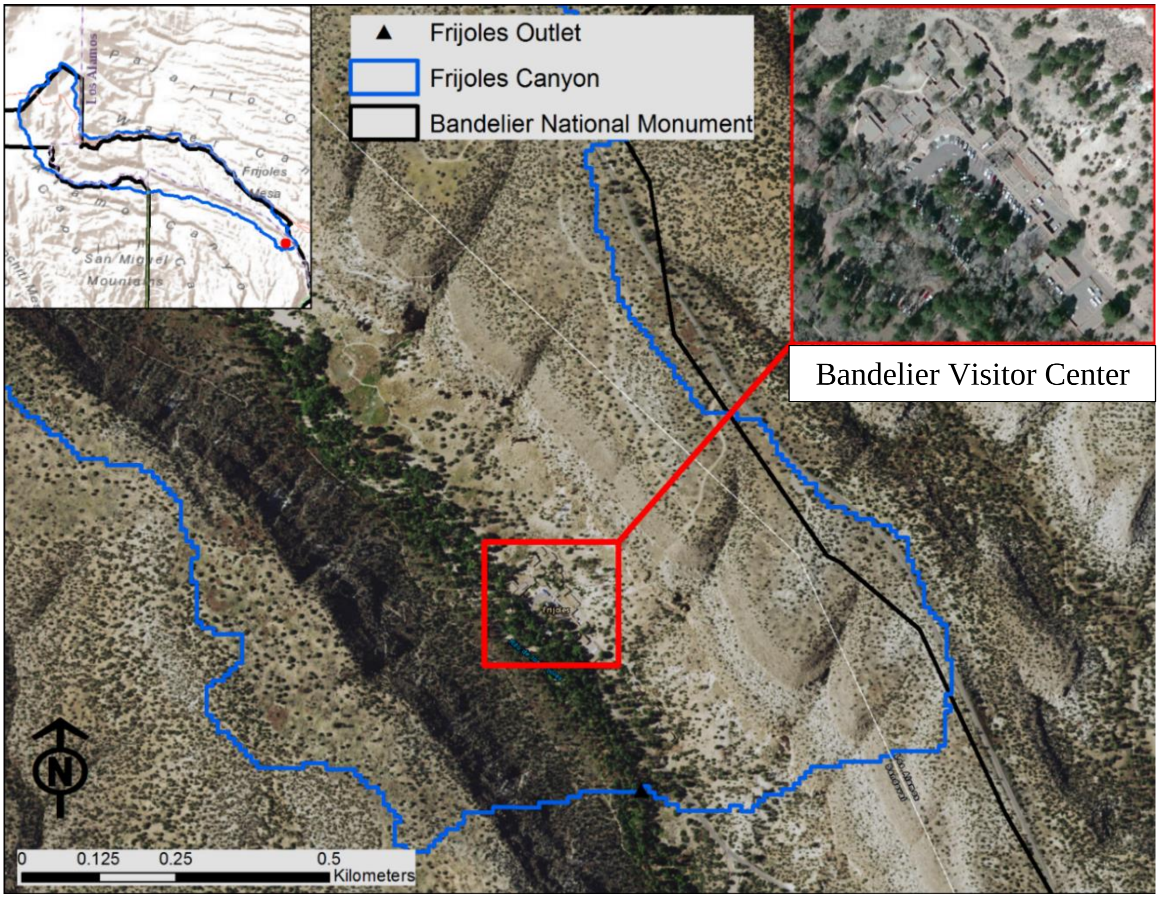

Figure 3- Visitor's Center Resides Along Frijoles Canyon in Bandelier National Monument at Risk for Flooding After the Los Conchas Fire of 2011.

1.5 THESIS ORGANIZATION

The following sections describe information that was relevant to the development, validation and incorporation of the Storage Characterization Tool and the Inundation Tool into the AGWA toolbox and/or the AGWA workflow. Description of existing models and tools is described in Section 3. The main models described here are KINEROS2 and HEC-2. The main tool detailed in Section 3 is AGWA.

Section 4 summarizes the development and application of the Storage Characterization Tool (Figure 4) and the Inundation Tool (Figure 5). The application of these tools involves a modification to the current AGWA workflow. Each tool is embedded with uncertainties; those uncertainties can be linked to the input data, the assumptions of the model or the interpretation of results.

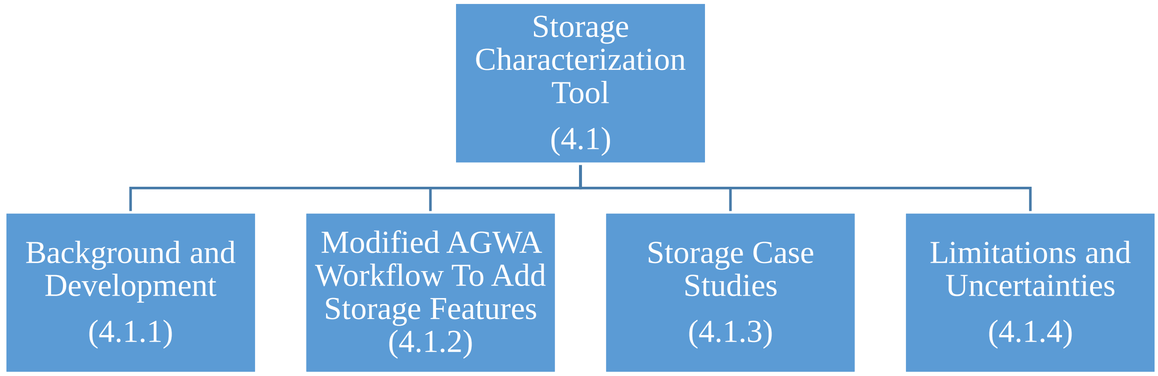

Figure 4: Storage Characterization Tool Section (4.1) Outline

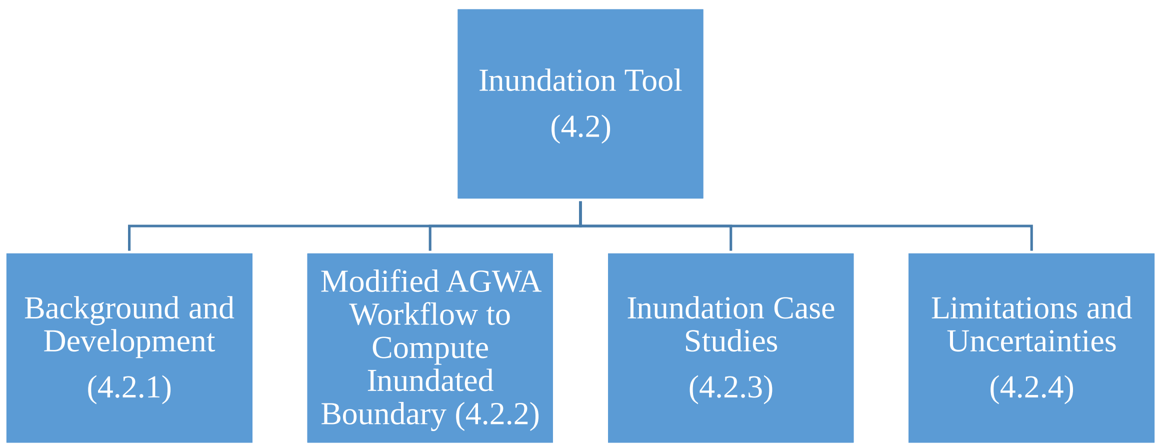

Figure 5: Inundation Tool Section (4.2) Outline

Finally, future tasks associated with the Storage Characterization Tool and the Inundation Tool will be outlined in Section 5. For guidance on how to use these tools and examples of data collection techniques consult Appendices A-C.

2. LITERATURE REVIEW

There are three sections to this literature review, each specifically outlines a subject that relates to the tools developed for this thesis. The first section describes LiDAR and its role as topographic data used to enhance hydrologic studies, hydrologic modeling and hydraulic computations. The second section describes stock ponds, their function on rangelands and how they are modeled throughout Western watersheds. The third section describes hydrologic modeling for post-wildfire runoff and erosion and hydraulic computation for flood inundation after wildfires.

2.1 LIDAR FOR HYDROLOGY

Light detection and ranging (LiDAR) is a technique which emits light pulses in order to measure the distance from the laser instrument to the earth. LiDAR is linked with a global positioning system (GPS) receiver to locate the points in space (USGS 2015). The National Research Council (2007) has declared that for better site-specific land-use decisions, we must have more precise and more detailed topographic information derived from LiDAR. In 2012, only 28% of the lower 49 United States were surveyed by LiDAR (Dewberry 2012). In order to address increase coverage, there have been interagency agreements and initiatives that have started to complete the coverage of LiDAR for high-resolution elevation data in the US. One such initiative is the 3D Elevation Program (3DEP) that aims to provide high-quality topographic data to support applications related to water supply, natural resource conservation, flood risk management, stream resource management and more (Snyder 2012). LiDAR-derived topographic data can be used to inform geomorphic, ecologic, and hydrologic research and more (Harpold et al., 2015). From such developed datasets we can come up with hydrographic derivatives that can be useful for hydrologic analysis (Anderson 2012). Hydrographic derivatives can improve general understand, developed methods and accepted calculation procedures in hydrology, watershed management and hydraulic engineering.

Topographic data in the form of digital elevation models (DEMs) are commonly used to characterize the rainfall-runoff model parameters for hydrologic analysis (Elliot et al., 2004). DEM resolution may not have a large impact on hydrologic processes when broadly characterizing watersheds, at a finer scale, higher resolution DEMs are able to capture local hydrologic parameters (Levick et al., 2006; Barber and Shortridge, 2005; Syed, 1999). Certain hydrologic parameters including stream network, drainage area, and slope can be improved through interpretation and processing of high-resolution DEMs (Zhao et al., 2010). Defined stream networks are more accurate when developed from LiDAR-derived DEMs (Murphy et al., 2008; Li and Wong, 2010). Defined stream networks and LiDAR DEMs can be used to characterize channel cross sections for hydraulic geometry (Miller et al., 2004; Shatnawi and Goodall, 2010; Passalacque et al., 2010). However, in perennial streams or streams containing water at the time of LiDAR collection stream networks and other hydrographic features can be misidentified or mischaracterized (Podhoranyi and Fedorcak, 2015). Characterization of defined streams has also improved with increased availability of LiDAR. Characters including channel geometry, sinuosity, slope and roughness can be acquired from LiDAR-derived DEMs (Yang et al., 2014; Casas et al., 2010). Hydrologic features such as flood plains, alluvial fans, berms and more have also been explored using high-resolution DEMs (Zhao et al., 2010; Persendt & Gomez 2016). These features can easily be analyzed if they have previously been identified, however processing of the DEM can sometimes obscure these features before they are recognized.

Pre-processing DEMs for watershed-scale hydrology usually involves filling which removes sinks for continuous flow through the landscape (Tarboton et al., 1991). LiDAR-derived DEMs are commonly hydro-enforced prior to use for watershed hydrologic applications to allow for continuous flow (USGS 2014). Other techniques have been developed to process high resolution DEMs using geospatial data for culverts and bridges to produce LiDAR-derived hydrologic DEMs (Li et al., 2013). Pre-processing all DEMs is required to ensure hydrologic connectivity prior to hydrologic analysis, however it can denude important hydrographic features such as braided streams, storage structures and floodplains especially in low-relief areas (Jones et al., 2008). These features can have big impacts on hydrology and should be explored in more detail for accurate watershed representation.

Detailed analysis of LiDAR can be useful for hydro-geomorphological assessments (Biron et al., 2013), aquatic habitat analysis (Faux et al., 2009), flow routing and hydraulic calculations. LiDAR-derived channel representations have been shown to improve model flow routing in the hydrologic model KINEROS2 (Hutton et al., 2012). Channel geometries extracted from LiDAR have also been used in place of field surveys to perform flood modeling and mapping using hydraulic models. Especially at large spatial scales, the incorporation of LiDAR cross sections can speed up processing for flood inundation modeling (Neal et al., 2015). In one case of flood inundation mapping, LiDAR derived channel geometry over predicted bank full top width compared to field surveyed geometries when used for flood mapping (Shatnawi and Goodall, 2010). This type of analysis sparks a need to assess the uncertainty with input datasets used for hydraulic and hydrologic applications, especially LiDAR DEMs for topography.

There is a level of uncertainty with all LiDAR datasets and these uncertainties are carried through to LiDAR-derived DEMs. The errors in the original LiDAR dataset propagate through to hydrologic parameter estimations that are influenced by topography (e.g. slope, stream length, contributing area, cross-sectional area, etc.) and these uncertainties are largely attributed to the original data collection flight (Goulden et al., 2016). Another source of error that occurs during collection, if water is present across the landscape elevation data can be inaccurate as most forms of LiDAR do not penetrate water (Podhoranyi and Fedorcak, 2015). While these errors are present, improvements in LiDAR over time have been shown to decrease the error associated with LiDAR extracted channel cross-sections (Diettereck et al., 2012). Therefore, utilizing LiDAR to identify topographic features for hydrologic and hydraulic modeling can augment or replace surveyed data.

2.2 STOCK PONDS AND RANGELAND HYDROLOGIC MODELING

There are many methods employed to control runoff and erosion, one of these methods involves structural practices and constructed features that divert, trap or limit runoff (U.S. EPA 1990). Stock ponds or stock-water reservoirs are forms of structural erosion control practices that are prevalent throughout rangelands of the western United States and also serve as watering holes for livestock, habitat for wildlife, irrigation and more (USDA SCS 1982). Stock ponds can be formed through excavation of existing soil, through formation of an embankment or dam, or a combination of the two. Ponds can have one or more outlet structures in the form of culverts and spillways. Regardless of the construction method or outlet design, most stock ponds are built along existing or defined waterways in order to maximize runoff trapping.

Stock ponds are built with the intention to trap enough runoff that can meet all consumptive demands while accounting for water loss (Duesterhaus et al., 2008). Erosion control dams are built with the intent to trap sediment; however, erosion control dams also trap runoff and stock ponds also trap sediment. The effectiveness of stock ponds is scale dependent. Based on a simple water balance approach, Milne and Young (1989) found that stock ponds in the Little Colorado and Gila River Basins only trapped 1.7-7.0% of annual water production. However, at smaller spatial scales and during single events stock ponds on the WGEW trap over 30% of runoff (Nichols et al., 2014). At the same scale, sediment trap efficiency in the ponds across WGEW ranged from 76% to 94% (Nichols 2006).

Due to the multiple functions of stock ponds, planning for construction of sediment and erosion control sites should consider regional water quality issues (U.S. EPA 1990). The placement of erosion control dams is up to the land manager/owner's discretion and lacking hydrologic or geologic information, development of these stock ponds can be unsatisfactory (Langbein et al., 1951). Existing stock ponds in the Nogales Ranger District of the Coronado National Forest were analyzed for successful traits indicating that storage capacity at the spillway, maximum pond depth and upstream drainage area are the most important traits of successful stock ponds (Imler et al., 2000). These factors should be considered along with the objective of the pond. While the objective of the pond should be considered upon site selection, the general function of the pond is to trap sediment and runoff regardless of the intent of development.

This general function is important when it comes to modeling hydrologic response in watersheds that contain stock ponds. In order to properly model stock ponds, the ponds need to be characterized. Characterization of ponds can include the storage capacity as a function of depth, outlet structure(s), and location within the watershed. Storage capacity is the volume of water that can be held behind the dam. Maximum storage capacity is the maximum volume of water that occurs at the spillway elevation on the erosion control dam. The capacity of the pond dictates how much runoff can be captured by the structure, larger capacity can retain “rarer extreme flows” (Imler et al., 2000). Pond volume can be measured using topographic surveys when ponds are dry, these measurements are also done to measure sediment accumulation over time (Nichols 2006). Outlet structures are determined during design and selection should consider topography and soil type in order to avoid erosion and downstream channel health degradation (USDA SCS 1982). The position of outlet structure(s) may be constrained due to impacts on downstream water rights and legislative restrictions on maximum permanent storage (CDWR 2016).

Previously, stock ponds were modeled as part of a complete watershed assessment for the Conservation Effects Assessment Project (CEAP), the stock ponds on the La Cienega watershed were identified as a conservation practice designed to minimize soil loss for the enhancement of natural resource conservation, water quality and wildlife habitat (Weltz et al., 2011). As part of an effort to better model rangelands and conservation practices on rangelands, tools have been developed which enable AGWA to assess different management alternatives such as land cover changes, installment of riparian buffers, fire management and soon stock ponds (Goodrich et al., 2011). In past applications, users were required to manually format stock pond inputs and insert them into the KINEROS2 watershed representation for rangeland assessments; in one case, stock ponds were modeled on a small watershed and shown to decrease runoff and peak flow by 15.9% and 9.7%, respectively (Guertin et al., 2010). Weltz et al. (2011) used KINEROS2 to demonstrate similar reductions of 10% in total runoff, 10% in peak flow and 13% in sediment yield at the outlet of WGEW with more pronounced effects close to the stock ponds. The inclusion of stock ponds and erosion control structures in hydrologic modeling of rangelands is important for accurate representation of rangeland hydrology.

2.3 HYDROLOGIC AND HYDRAULIC MODELING IN POST-WILDFIRE ENVIRONMENTS

The disturbance of wildland fire has a dramatic impact on watershed hydrologic response. Wildfires directly alter soil and vegetation processes which can indirectly cause hydrological processes such as runoff to occur at changed rates until vegetation cover, soils and environmental conditions re-establish (Shakesby and Doerr 2006). Depending on the severity of the wildfire, changes in soil and vegetation properties can occur. One potential soil impact is the induction of water repellency due to increased heat of the soil (DeBano 1981).

By directly altering the physical characteristics of a watershed, wildfires can have an indirect impact on subsequent runoff and erosion. Decreased canopy cover leads to decreased interception of rainfall and therefore increased runoff; altered soil properties typically lead to decreased infiltration rates; and decreased ground cover exposes bare soil and reduces surface roughness which leads to increased runoff and erosion (DeBano et al., 1998, Neary et al., 2005). Decreased vegetation and litter along with alteration of soil physical properties and development of water repellent soils are all factors that can lead to increased peak flow, decreased response time and therefore flashy floods following wildfires (Neary et al., 2003). In fire-affected watersheds with streamflow gages, changes in time to peak and peak flow have been observed. Following the La Mesa Fire in 1977, peak flow in the Frijoles Canyon of New Mexico was over 100 times larger than the pre-fire peak flow observations; suspended sediment samples were collected in this canyon as well and increased sediment transport to increased peak flow leading to over 200 times the amount of annual suspended sediment load compared to the recovered watershed (Veenhuis, 2002). Due to observations of increased runoff and erosion after wildfire, land managers and stakeholders have developed or modified hydrologic and hydraulic methods to better understand potential risk prior to fire and flood occurrence.

One simple method uses basic equations that relate fire severity and soil properties to potential erosion rates (Vafeidis et al., 2007). In some cases, empirical methods to predict discharge have been developed for specific environments (Reed and Schaffner, 2007; Moody and Martin, 2001). Some more complex hydrologic models and methods have been used or proposed for use for post-fire environments including the Modified Rational Method (MODRAT), the FEMA method, MIKE SHE, KINEROS2, he Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS), WILDCAT4, WinTR-55, ERMiT, and SHETRAN (Chen et al., 2013; Robichaud and Ashmun 2013). Of these models, the process- and physically-based models (KINEROS2 and HEC-HMS) can simulate fire effects on watershed hydrology and provide valuable insight into changes in pre- and post-fire hydrographs (Chen et al., 2013; Woolhiser et al., 1990; Smith et al., 1995; Scharffenberg 2016).

HEC-HMS (formerly HEC-1) has been used to model post-fire environments by altering parameters including initial abstraction, curve number (CN) and lag time (Cydzik and Hogue, 2009). The Kinematic Runoff and Erosion model (KINEROS2) has also be used to model post-fire environments through alteration to hillslope roughness and hydraulic conductivity (Canfield et al., 2005). Accurate modeling of watershed hydrologic response in post-fire environments relies on realistic representation of the landscape, the fire burn severity and most importantly rainfall (Sidman et al., 2015).

In some cases, hydrologic modeling to estimate post-fire runoff response is followed by hydraulic modeling to estimate flooded areas. Various hydraulic modeling tools can be used to translate discharge estimates or observations to inundated depth and inundated area. The Hydrologic Engineering Center River Analysis System (HEC-RAS) and WIN XS Pro are two models that perform hydraulic computations of differing complexity. HEC-RAS (formerly HEC-2) is the most commonly used hydraulic analysis tool and is presented by the Federal Emergency Management Agency (FEMA) as a tool to prepare floodplain models (Dewberry and Davis, 2002).

Often, HEC-HMS watershed analysis precedes HEC-RAS flood modeling during a pseudo-coupled approach to watershed and river analysis in many different scenarios. After the Cerro Grande wildfire during the summer of 2000 in New Mexico, HEC-1 (CN method and Muskingum routing method) was used on the Pajarito Canyon to calibrate CN and lag times prior to hydraulic analysis (McLin et al., 2001). Earles et al. (2004) performed a similar post-fire analysis in the Pajarito Canyon using GIS for HEC-1 model input and for floodplain delineation. The Las Conchas fire of 2011 impacted the same region of New Mexico, the hydrologic impacts of this fire were analyzed on Frijoles Canyon using HEC-HMS, HEC-geoHMS, HEC-RAS and HEC-geoRAS (USACE 2012).

Combining hydrologic and hydraulic models with GIS enables users to incorporate geospatial data in lieu of or in addition to field observations and allows users to present model outputs in a geospatial format so that decision makers can better understand the outputs (Correia et al., 1998). GIS was used to incorporate DEMs for HEC-1/HEC-HMS runoff generation with surveyed cross sections for FLO-2D flood-flow routing for hazard and risk mapping over a set of wildfires in Colorado (Elliot et al., 2005).

Combined hydrologic and hydraulic assessments, most frequently HEC-HMS and HEC-RAS, with GIS are also commonly performed in non-fire affected watersheds for flood mapping studies. At a regional scale, HEC-HMS and HEC-RAS can be combined with GIS to assess basic flood inundation at different scales (Kneble et al., 2005; Whiteaker et al., 2006) or more complicated flood control projects (Gul et al., 2010). Other hydrologic and hydraulic models have been coupled to represent different hydrologic systems at different spatial and temporal scales. KINEROS2 and HEC-RAS were coupled by Nguyen et al. (2015) to predict the impact of flash floods in Northern Vietnam. At a larger scale, the Soil Water Assessment Tool (SWAT) and HEC-RAS were parameterized and interpreted using aerial imagery and LiDAR data to assess impacts of different climate scenarios (Moradkhani et al., 2010).

The combined use of hydrologic and hydraulic models is not new, however new tools are being developed to more closely couple the models and enable users to more rapidly perform flood inundation studies. One example of this coupling is AutoRAPID which couples the Routing Application for Parallel computation of Discharge (RAPID) with the AutoRoute model for high-resolution (10 meter), large extent (>100,000 square-kilometers) flood inundation mapping (Follum et al., 2016); AutoRAPID was developed with emergency response in mind. Model coupling to produce flood inundation maps could prove beneficial at a smaller scale for BAER teams to assess risk after wildfires.

3. EXISTING MODELS AND TOOLS

This section will discuss previously developed tools and models that have been used in the realm of watershed scale hydrologic modeling and reach scale hydraulic modeling. These are commonly accepted and have been used in a variety of scenarios.

3.1 AGWA

The Automated Geospatial Watershed Assessment tool (AGWA) is an ArcGIS-based tool that has been developed to facilitate the parameterization, simulation and visualization of results for multiple hydrologic models (Miller et al., 2007). In its current version, AGWA provides access to three hydrologic models: The Soil Water Assessment Tool (SWAT), the Rangeland Hydrology and Erosion Model (RHEM) and the kinematic runoff and erosion model (KINEROS2). RHEM is one of the hillslope-hydrology-erosion “engines” used within KINEROS2 overland flow modeling elements. AGWA uses geospatial soil, land cover and topographic data to define and characterize watersheds and watershed elements (Guertin et al., 2015). Characterization and definition of watershed elements depends on selection of the hydrologic model. For the remainder of this section, KINEROS2 will be the selected hydrologic model for AGWA.

Throughout the development of AGWA, changes and enhancements have been made to make the tool more accessible and applicable to different audiences/users/stakeholders for a variety of purposes. Some of these developments include the green infrastructure tool, the burn severity tool, and the land cover modification tool (Korgaonkar et al., 2014; Goodrich et al., 2010). Use of these tools has enabled scenario analysis of future land cover change and land management actions across a variety of landscapes (Kepner et al., 2004; Burns et al., 2013; Barlow et al., 2014).

Two major applications of AGWA are for scenario planning in post-fire environments and in rangeland watersheds. In the case of rangeland management, scenario planning is used to assess how various management actions or climate scenarios will affect soil loss and water availability. For example, AGWA/KINEROS2 allows us to look at how different grazing patterns, water tank placement, riparian buffers and stock ponds can impact the hydrology of a watershed (Weltz et al., 2011). In the case of post-fire watershed assessments, AGWA/KINEROS2 is used to first assess the impact of the wildfire on runoff and erosion and then to assess the impact of potential mitigation actions such as mulching (Goodrich et al., 2012).

While AGWA can be used for many different there is a common workflow that is typically followed when using the tool to perform watershed assessments. Prior to using AGWA, data must be collected, organized and processed so that they are projected in the same coordinate system and clipped to the appropriate extent. After data organization, users must specify the AGWA home folder and follow the basic workflow for AGWA and KINEROS2 (Figure 6).

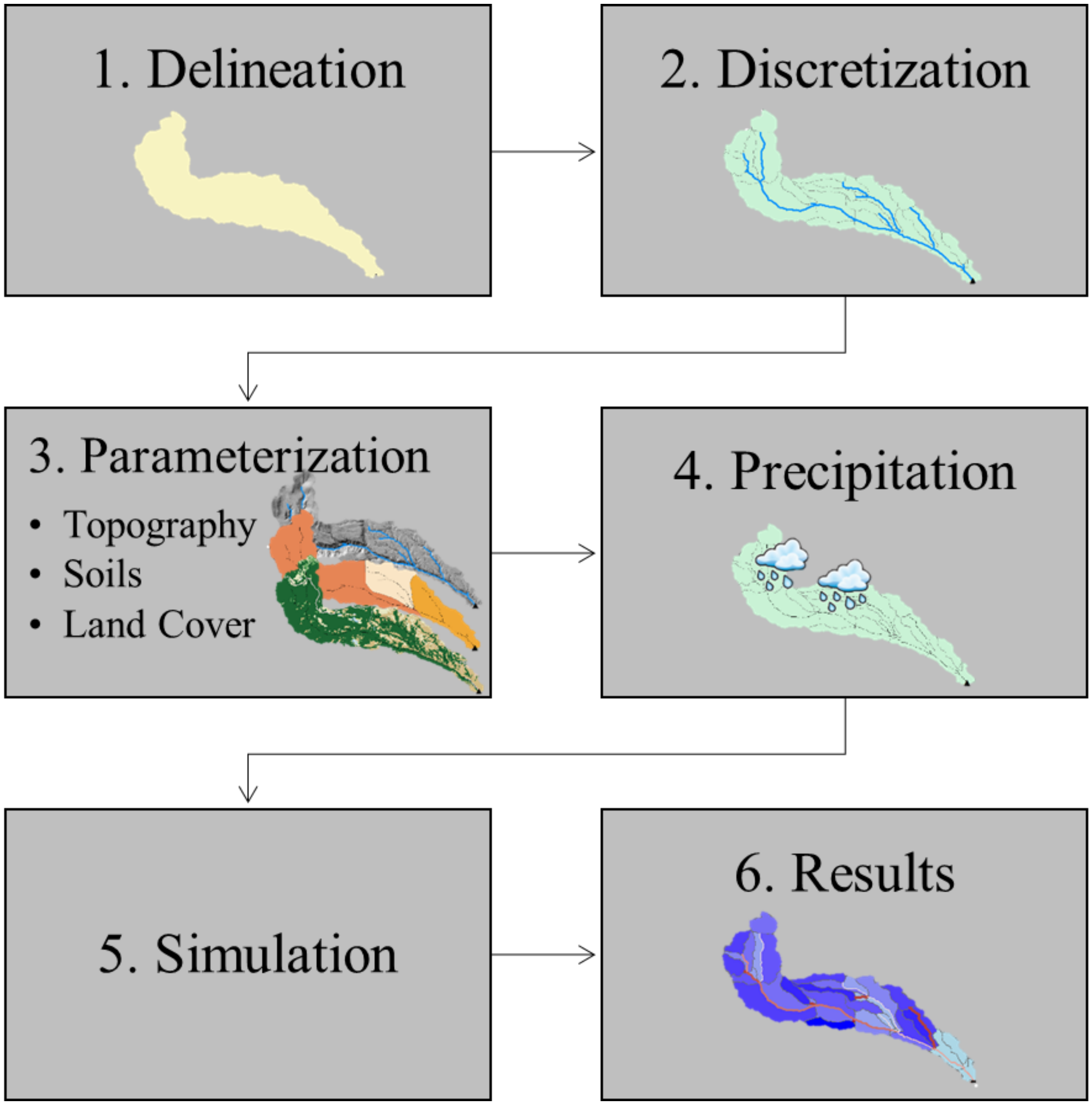

Figure 6: Basic AGWA Workflow for Watershed Assessments

3.1.1 DELINEATION

In order to begin using AGWA a watershed boundary must be delineated using a filled raster DEM, flow direction grid, flow accumulation grid and outlet point(s). AGWA can be used to facilitate the creation of the filled DEM, flow direction grid and flow accumulation grid. The watershed boundary is created as a feature class by snapping the outlet point to the highest flow accumulation grid cell within the user-specified search radius. Upon creation of a watershed boundary, a personal geodatabase is created within the user-defined AGWA workspace.

3.1.2 DISCRETIZATION

The first step in discretizing a watershed is to select the model with which simulation will proceed. Watershed discretization breaks the watershed into hillslopes (planes) and streams for KINEROS, and subwatersheds and streams for SWAT, based upon the topographic data. Users then select stream definition as threshold-based, existing stream networks or channel initiation points. Threshold-based stream definition bases the initial definition of a stream on watershed contributing source area or flow length. Existing stream networks define streams based on a previously defined stream feature class; this definition method was created to utilize the National Hydrograph Dataset (NHD) stream features. Channel initiation points are used to define the headwaters of streams. Aside from defining where streams begin, users can specify where streams and planes are subdivided by defining internal pour points. Subdivision and stream definition should be assigned based on details the user would like to capture. For example, in order to capture storage structures such as detention or retention ponds, there must be a beginning or end of a stream. Multiple discretizations can be performed for a single watershed delineation, all discretizations are stored in previously created personal geodatabase.

3.1.3 PARAMETERIZATION

Watershed elements are assigned hydrologic parameters using the DEM, soils and land cover. Tables based upon literature and experimental data relate soil texture, land cover and topography to parameters required for KINEROS2. Users may also add storage or diversions during the watershed parameterization. The current add storage tool requires user generated input files that include storage-discharge tables and the location of the storage feature. Diversions make use of the existing stream network to take a portion of the inflow from channel and direct it into a channel that is designed by the user with new length, with, slope, roughness and hydraulic conductivity. Currently the diversion tool routes water through the diversion and main channel then remaining flow re-enters the stream network at the outlet of the main channel. Parameterization, storage and diversion tables are stored in the personal geodatabase for the watershed.

3.1.4 PRECIPITATION

Precipitation can be defined by a variety of data sources. The most commonly used storm source for precipitation inputs are the user-defined hyetograph and the user-defined depth. The user-defined hyetograph option requires depth or intensity as a function of time. The user-defined depth option requires depth, duration, number of time steps and hyetograph shape. Hyetograph shape currently can be SCS Type II or temporally uniform which impacts the distribution of rainfall throughout the duration of the event. Initial soil moisture and storm location must be designated regardless of the storm source. Storm location allows users to apply rainfall across the entire watershed or across a user-defined location. Impacts of rainfall representation can alter the model outputs and application of rainfall across the watershed should be considered prior to simulation (Sidman et al., 2015). Precipitation files are stored as “*.pre” files in the watersheds workspace.

3.1.5 SIMULATION

The simulation step is comprised of writing simulation files and executing simulation files. Simulation options require watershed discretization, parameterization and precipitation. Optional simulation selections include storage configuration, diversions, and multipliers. Writing of simulations simply converts KINEROS2 parameters into simple ASCII “*.par” and precipitation into “*.pre” files that can be read by the model. These files are stored in the watersheds workspace. Simulations are not automatically executed which enables users can verify or modify any model input; after verification or modification users execute simulations to create output files that are stored as “*.out” files in the same folder as the simulation input.

3.1.6 RESULTS

Model results can be visualized and exported in a variety of formats. Results must first be imported which sorts outputs by watershed element and summarizes them into tables. Multiple simulation outputs can be viewed and compared spatially as a map, graphically as a hydrograph or sedigraph and in a tabular format.

3.2 KINEROS2

The kinematic runoff and erosion model (KINEROS2) is one of the models accessible through AGWA (http://www.tucson.ars.ag.gov/kineros/). KINEROS2 is a distributed, physically-based model that describes processes of interception, infiltration, surface runoff and erosion at a variety of spatial scales from hillslope plots (less than $10m^2$) up large watersheds (about $1,000km^2$) (Goodrich et al., 2012). Watersheds are represented as a series of cascading overland and channel elements, other possible elements that can be included in the watershed representation are urban elements, injection elements, and detention ponds. KINEROS2 simulates flow over and through elements by solving one-dimensional kinematic equations via finite difference techniques (Woolhiser et al., 1990). Runoff travels from overland flow elements into connecting channels, pipes or ponds through the watershed to its outlet.

KINEROS2 has been applied in many environments and tools have been developed to aid in those applications. For rangeland watershed assessments, the hillslope erosion methods from the Rangeland Hydrology and Erosion Model (RHEM) were incorporated into KINEROS2 (Guertin et al., 2010; Goodrich et al., 2011). Those studies highlighted a few common rangeland features such as riparian buffers, complex hillslope representations and stock ponds or erosion control structures that needed to be captured in the modeling framework. Stock ponds or erosion control structures can be modeled in KINEROS2. The most basic data inputs required to model stock ponds in KINEROS2 are storage volume, surface area and water surface elevation (Smith et al., 1995). Pond elements can represent ponds, flumes or other flow measuring structures with backwater storage as long as outflow is only a function of water surface elevation.

Due to its physical representation of hydrologic processes, KINEROS2 can also simulate hydrologic change due to land cover alterations (Goodrich et al., 2010). One major land cover alteration that KINEROS2 has been used to assess is wildland fire. The AGWA/KINEROS2 approach has been used by BAER teams in the Western U.S. to rapidly assess potential runoff, erosion and sedimentation risks after wildfire (Guertin et al., 2015). The wildfire is characterized by remotely sensed burned severity which alters land cover using the AGWA burn severity tool. Appropriate parameters are associated with the changed land cover; altered parameters represent changes in surface roughness and hydraulic conductivity (Canfield et al., 2005). Results from KINEROS2 simulations can be viewed in the form of pre- and post-fire hydrographs that reveal how physical changes within the watershed affect runoff generation mechanisms (Chen et al., 2013).

3.3 HEC-2/HEC-RAS

The most commonly used hydraulic modeling tool was created by the U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center. The hydraulic modeling software began as part of a package that included watershed hydrology (HEC-1), river hydraulics (HEC-2), reservoir analysis (HEC-3), and stochastic streamflow generation (HEC-4) (USACE 2016). Each of these programs has since evolved, with HEC-2 becoming the River Analysis System (HEC-RAS). While the capabilities and interface of HEC-2 has changed to become HEC-RAS, the basic equations for water surface elevation calculations remain the same. The basic principle of one-dimensional steady flow is governed by the energy equation:

$$Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \qquad \text{(Eq. 1)}$$

where: Z_1, Z_2 = minimum elevation of main channel (m);

Y_1, Y_2 = depth of water at cross sections (m);

V_1, V_2 = average velocities (m/s);

α_1, α_2 = velocity coefficients;

g = gravitational acceleration (9.81 m/s^2);

h_e = energy loss.

The parameters in this version of the energy equation are calculated using different user-defined methods for conveyance and starting water surface elevation. HEC-2 and HEC-RAS then solve the equation for a series of channel cross sections that make up a channel or river network. Different methods are suggested for different applications and different flow regimes (USACE 1990; Brunner, 2010). The Federal Emergency Management Agency (FEMA) previously adopted HEC-2 and HEC-RAS for preparation of Flood Insurance Studies (FIS) and refers to guidance for these tools as prepared by HEC (FEMA 2014; Brunner 2010). Basic data inputs to run HEC-RAS are channel geometry, channel roughness, and flow. Channel geometry can be collected using many different methods, recent developments to HEC-GeoRAS and RAS Mapper have enabled users to develop channel geometry datasets using DEM or terrain data (US-ACEIWR-HEC, 2009; Brunner, 2010).

Prior to HEC-GeoRAS and RAS Mapper, interpretation of HEC-RAS water surface elevation calculations for flood inundation mapping was accomplished using contour maps with some methods developed for use in Arc View (Tate and Maidment, 1999). However, through recent automation and increased availability of terrain data HEC-RAS results can be viewed in ArcGIS and RAS Mapper to understand flood boundary under many different flows or using different channel properties. Understanding potential changes to floodplains due to changes in upland cover properties or due to changes in channel properties can be done using HEC-RAS. For example, McLin et al. (2001) used HEC-HMS, HEC-RAS and HEC-GeoRAS to model changes in peak flow and thus floodplain boundary after the Cerro Grande Fire in New Mexico. HEC-RAS has been used to assess the impact on floodplain boundaries due to climate change (Moradkhani et al., 2010), wildfires (Van Eekhout, 2002) and urbanization (Suriya and Mudgal, 2012).

While HEC-RAS is a commonly accepted tool, there is a certain level of uncertainty when using the tool. Most of the uncertainty is introduced through user selected discharge input, and terrain datasets used for input channel geometry as well as output flood delineation (Merwade et al., 2008). A big source of uncertainty comes from the terrain or DEM resolution and accuracy which are related; the resolution of the DEM has a direct impact on water surface elevation calculations and subsequent floodplain delineation, the impact is more pronounced for small reaches (Saksena 2014). Therefore, in small reaches where the purpose is to investigate the impact of land cover change on floodplain extent, high resolution channel geometry should be used for hydraulic calculations and the highest resolution DEM should be used for floodplain delineation.

4. DEVELOPING AND APPLYING TOOLS

The tools developed for this research include the Storage Characterization Tool and the Inundation Tool. Both tools were developed using Python, ArcPy and existing ArcGIS Tools. Python was used due to its readability and transferability. The scripts are relatively easy to follow as they are written in a high-level programming language which means that it is further abstracted from the machine language. The tools do not need to be installed on your device but they do require basic access to ESRI ArcGIS Software and the Spatial Analyst license. ArcPy is a Python site package commonly used by GIS professionals to efficiently automate geographic data management, data analysis and even cartographic tasks in ArcGIS. ArcPy contains a suite of functions, classes and modules that provides access to most of the ArcGIS Tools that would normally be available in the ArcToolbox.

4.1 STORAGE CHARACTERIZATION TOOLBOX

The Storage Characterization Toolbox was designed to identify and characterize existing storage structures as well as to plan for the future installation of storage structures. The Storage Characterization Toolbox was developed using a Python Toolbox so that geospatial layers could be organized, used and viewed by the user throughout the process.

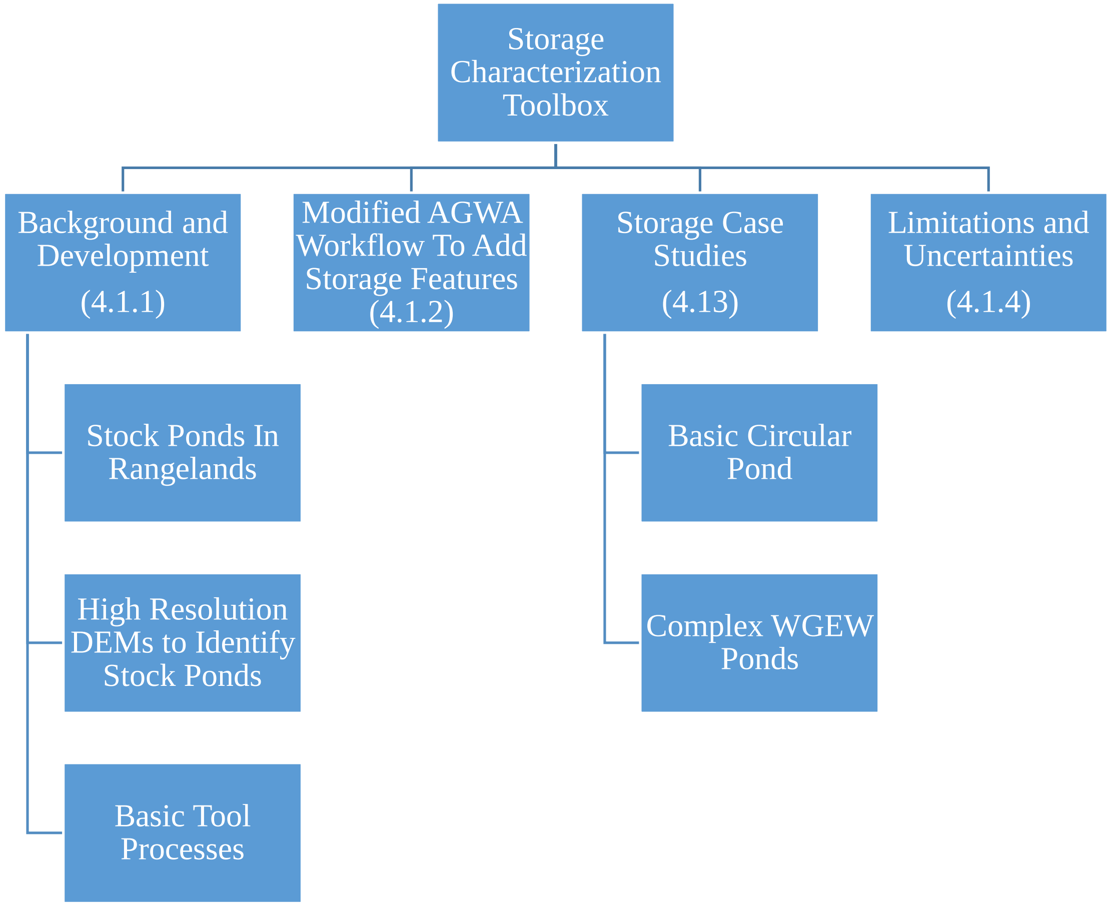

Figure 7: Storage Characterization Toolbox Section Outline

4.1.1 BACKGROUND AND DEVELOPMENT

Storage structures exist in the form of stock ponds, small reservoirs and erosion control dams among others. These structures exist mostly on rangelands throughout the Western United States and regardless of their intended purpose they trap a portion of runoff and sediment flowing through channels. Langbein et al. (1951) have indicated that in Montana there is nearly one stock pond per square mile of rangeland and a large number of them scattered throughout the Western U.S. Most hydrologic models have the capability to model ponds and reservoirs however there are two impediments to their inclusion in hydrologic models. The first issue involves the proper identification of stock pond geographic location; not all ponds are documented in publicly available geodatabases which would exclude them from hydrologic modeling if their locations are unknown. The second issue is with the characterization of existing stock ponds. Characterization of ponds can include the storage capacity as a function of depth, outlet structure(s), and location within the watershed. Observations and measurements of these characteristics can involve traditional methods of topographic field surveys that are used to develop the stage-discharge relationships required for modeling. These fields surveys and subsequent processing as well as outflow measurements can be time consuming.

Previous development of AGWA included a tool that allows users to add storage features such as stock ponds into the watershed representation and subsequent KINEROS2 simulations, however identification and characterization of these features was still the responsibility of the user. Users were required to collect data relevant to the ponds location, storage volume and outlet or discharge. This information needed to be manually formatted for use in the KINEROS2 watershed representation. In one case, this process was used for a rangeland assessment where the stock ponds were modeled on a small watershed and shown to decrease runoff and peak flow by 15.9% and 9.7%, respectively (Guertin et al., 2010). Weltz et al. (2011) used KINEROS2 to demonstrate similar reductions of 10% in total runoff, 10% in peak flow and 13% in sediment yield at the outlet of WGEW with more pronounced effects directly downstream of the stock ponds. These reductions in runoff and sediment should not be ignored simply because storage features are unidentified or uncharacterized. Therefore, the use of high resolution DEMs can be used to address both the issue of identification and characterization of storage features for more complete representation of watershed hydrology.

Stock ponds, impoundments, erosion control dams and small reservoirs can easily be spotted in high-resolution DEMs. With high-resolution topographic information becoming readily available across the country, processing these data can be an alternative to traditional field survey methods of characterizing storage structures. First, a protocol was developed for processing high-resolution topographic data to identify storage features (Figure 8). Second, the protocol was expanded to characterize stage-storage relationships for each pond (Figure 8). Automation of these two steps resulted in the Identify and Characterize Existing Storage part of the Storage Characterization Toolbox (Figure 9). Automation of this process allows a large number of ponds across a wide spatial extent to be identified and characterized in a single batch.

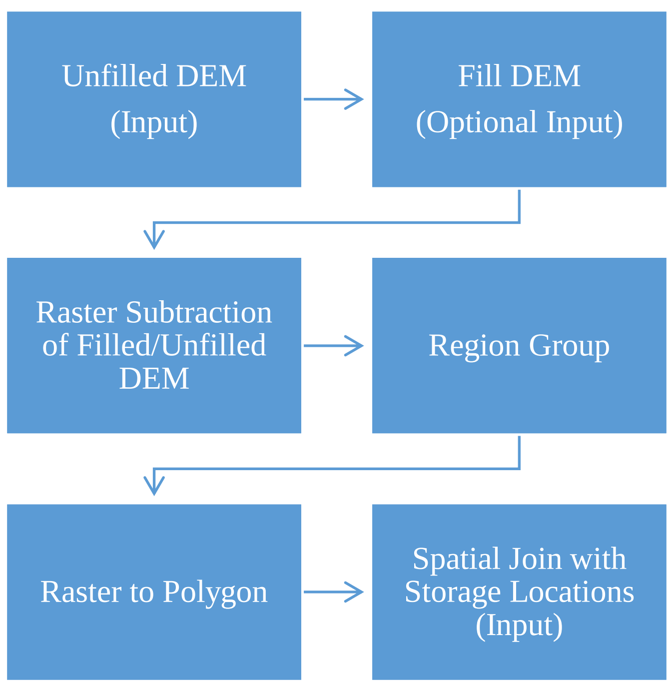

Figure 8: Storage Characterization Toolbox: Identify Storage Features using a High-Resolution DEM.

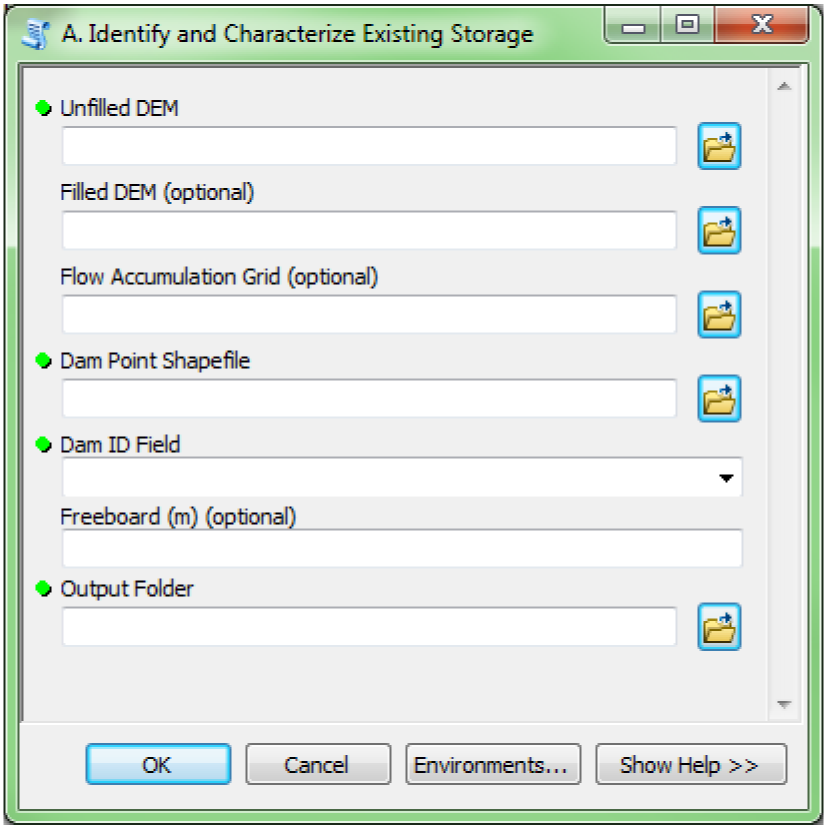

Figure 9: Part One of the Storage Characterization Toolbox.

The tool operates by first comparing a filled and unfilled DEM. The process of filling a DEM removes any sinks or peaks that would prevent flow in an otherwise hydrologically continuous surface (Tarboton et al., 1991). DEM filling is an important first step in watershed modeling to ensure proper stream and watershed delineation and is aimed at artificial sinks (e.g. errors in the DEM), however this process can remove storage features in the landscape which could impact flow (Figure 10).

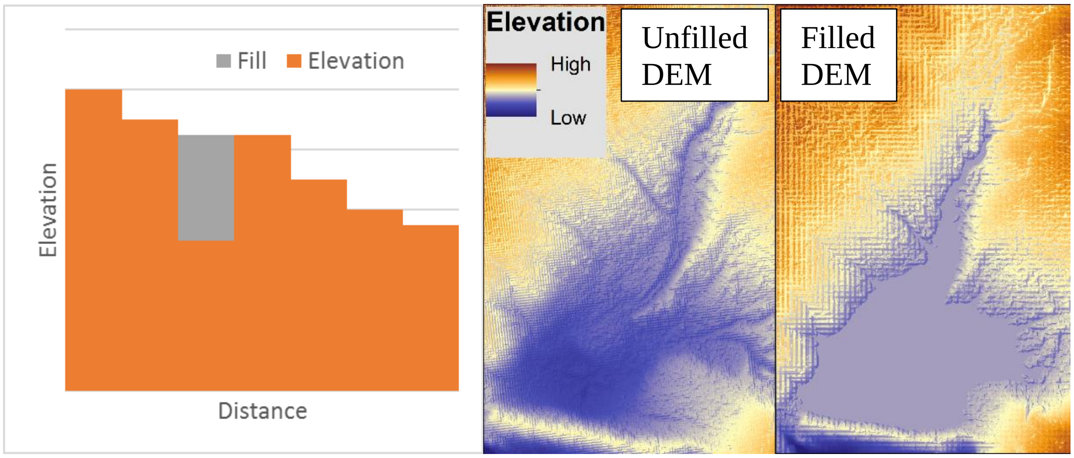

Figure 10: Fill Process as it removes sinks in theory (left) and in reality (right).

The cells that are filled are then compared to the unfilled DEM to identify large groups of cells that could be storage sinks. These sinks are then spatially compared to known storage/dam locations. Sinks closest to known storage/dam locations are associated with those points for identification purposes. At this point a storage feature has been identified and its boundary has been defined.

Next the stage-volume calculations are performed from the features minimum elevation to its maximum elevation. The Cut-Fill tool is used to automate surface area and volume calculations of the unfilled DEM and each stage raster until maximum elevation for each feature is reached (ESRI, 2016) (Figure 11).

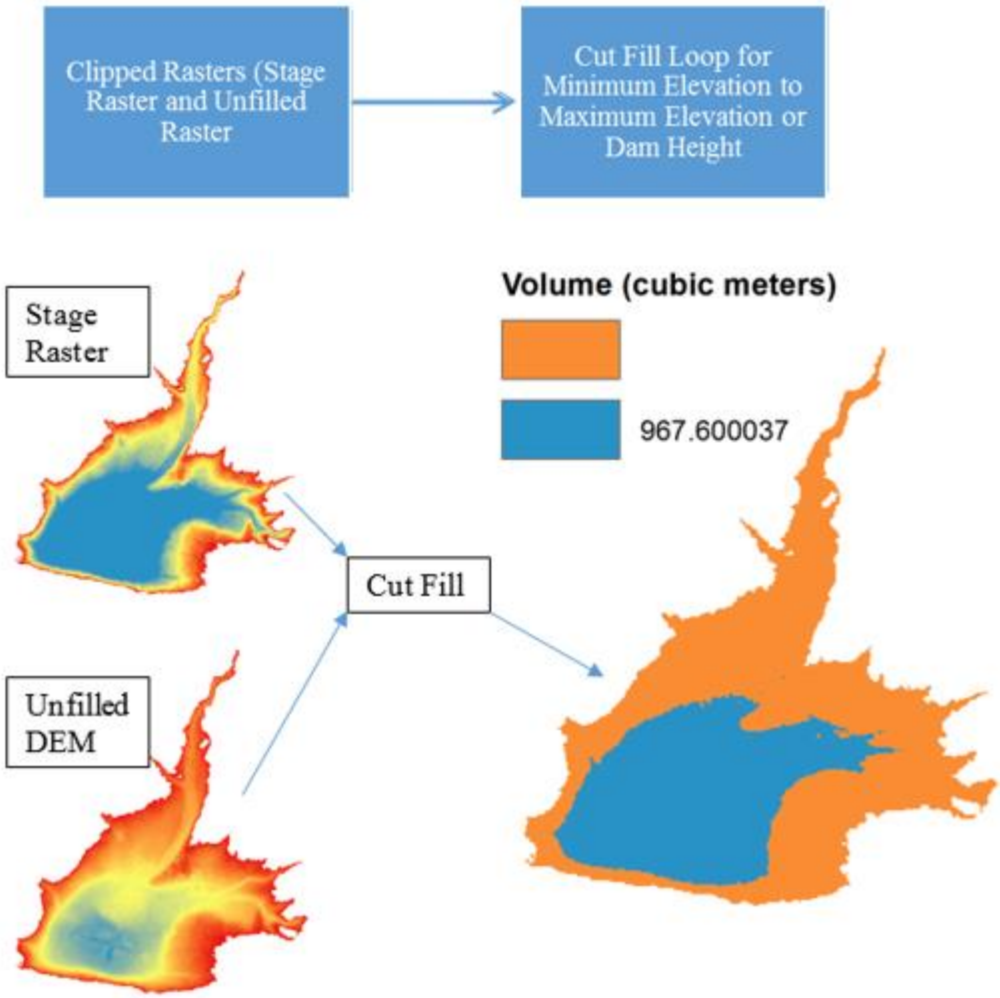

Figure 11: Cut Fill Function is Part of a Loop that Calculates Surface Area and Volume for Pond Stage from Minimum Elevation to Maximum Elevation.

After calculating the basic stage-storage relationship, for each pond the tool allows users to calculate discharge based on known information or size classifications (Figure 12). This is the second part of the Storage Characterization Toolbox known as the Calculate Storage Discharge tool (Figure 13). This step calculates discharge through a culvert and/or spillway as a function of stage and requires information about outlet types and properties.

Figure 12: Basic Input/Output of Second Tool in the Storage Characterization Toolbox: Calculate Storage Discharge.

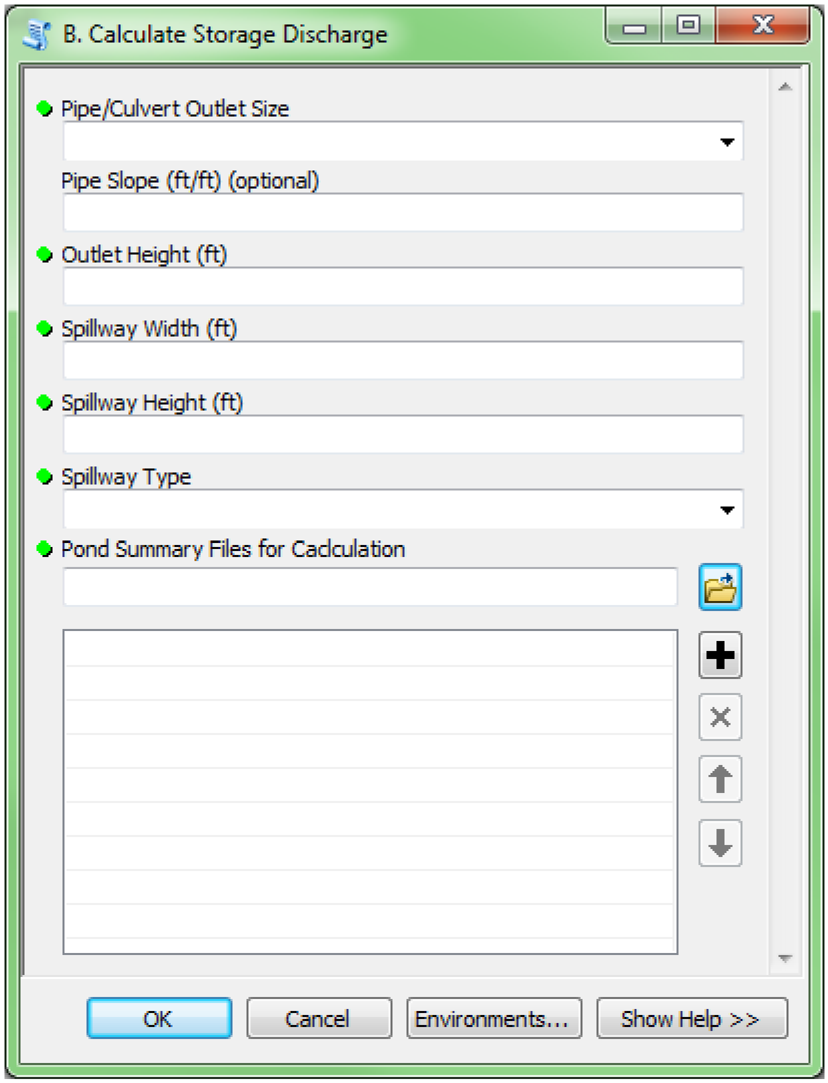

Figure 13: Part Two of the Storage Characterization Toolbox

The basic equations that calculate discharge from stage above the outlet structure are Manning's equation for pipe flow (Eq. 2), the broad-crested weir equation which accounts for discharge of earthen spillways (Eq. 3) and the sharp-crested weir equation (Eq. 4) (Crowe et al., 2001).

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S_o^{\frac{1}{2}} \qquad \text{(Eq. 2)}$$

where: n = Manning's roughness coefficient;

A = area of the pipe that is filled with water (m^2);

R = hydraulic radius of the wetted pipe (m);

S = slope of the pipe (m/m; default = 0.004).

$$Q = 0.385 L \sqrt{2g} H^{\frac{3}{2}} \qquad \text{(Eq. 3)}$$

where: L = length of the weir normal to the direction of water flow (m);

g = acceleration due to gravity (9.81 m/s^2);

H = stage of water above the spillway (m).

$$Q = \frac{2}{3} C_d \sqrt{2g} L H^{\frac{3}{2}} \qquad \text{(Eq. 4)}$$

where: Cd = coefficient of discharge;

g = acceleration due to gravity (9.81 m/s^2);

L = length of the weir normal to direction of flow (m);

H = stage of water above the spillway (m).

The final step of the tool prepares the derived input files to be used in a watershed simulation using AGWA/KINEROS2 (Figure 14). This requires user input for the soil properties of the pond (default is silty clay with hydraulic conductivity of 1.41 mm/hour) then reformats calculated storage-discharge tables and creates a link between the pond shapefile to nodes in the AGWA discretization (Figure 15). KINEROS2 models ponds using input files that can contain upstream contributing elements, lateral elements, initial storage, rating tables (volume, discharge and surface area), and saturated hydraulic conductivity (KINEROS2). The series of tools in the Storage Characterization toolbox supply KINEROS2 with the required pond inputs for AGWA to configure a simulation with storage elements.

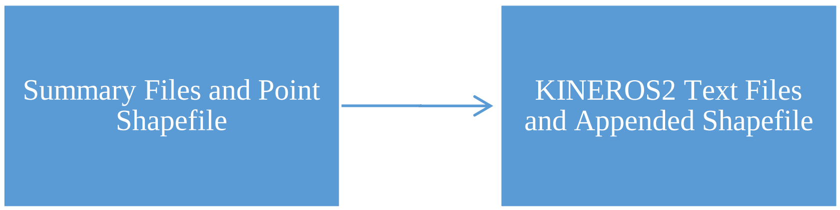

Figure 14: Final Step of Storage Characterization Tool Prepares KINEROS2 Input Files

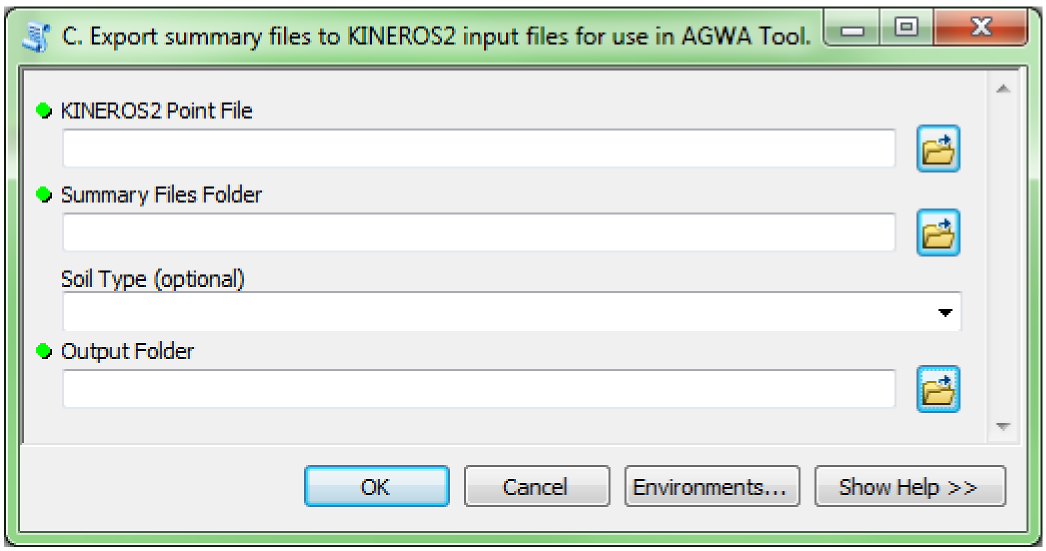

Figure 15: Part Three of the Storage Characterization Toolbox.

The best use of this tool would take the storage point file created here and use that in AGWA to discretize the watershed so that streams and hillslopes divide where a storage feature exists; the points can also be used to initiate channels in headwaters of watersheds. This tool can also be used to assess different storage construction scenarios. Users can virtually install a dam using ArcGIS tools and then use the Storage Characterization toolbox and the AGWA Add Storage tool to assess the impact of the proposed structure.

4.1.2 MODIFIED AGWA WORKFLOW TO ADD STORAGE FEATURES

The Storage Characterization Toolbox can work in tandem with AGWA/KINEROS2 to model existing or proposed storage structures. The basic AGWA workflow that was outlined in Section 3.1 can be followed with additional steps during the discretization and parameterization steps (Figure 16).

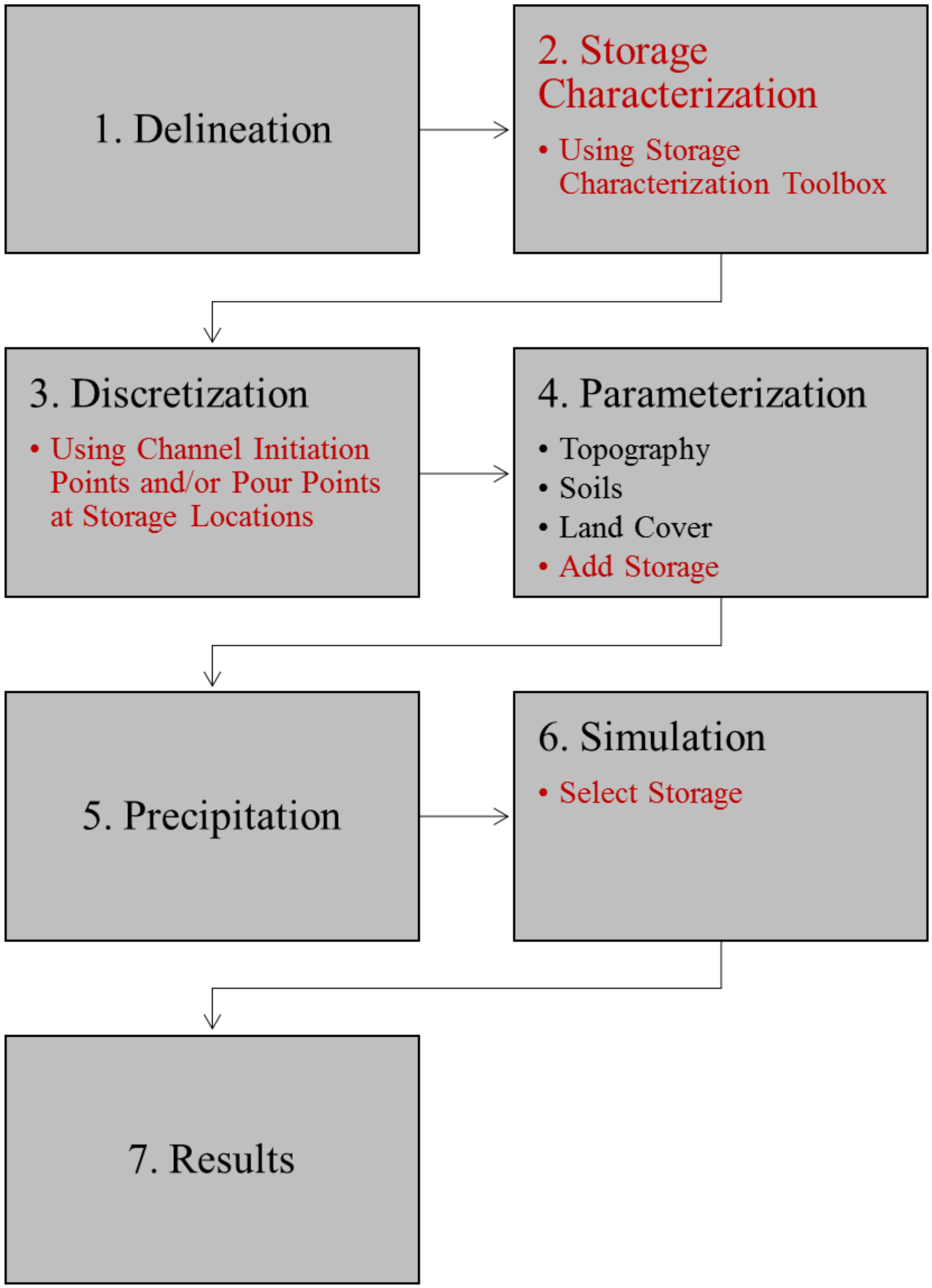

Figure 16: Modified AGWA Workflow Using the Storage Characterization Tool (Red Text are Modifications to Workflow Described in Section 3.1)

In order for KINEROS2 to capture the function of storage features within a defined watershed, the stream networks need to either break or be initiated at a pond.

Therefore, pond locations need to be documented prior to watershed discretization. Using pre-defined pond locations to initiate channels means that KINEROS2 overland flow elements would flow directly into the pond then discharge into a stream. The pre-defined pond locations can also be used as pour points so that stream and overland flow model elements would divide at the pond. By using pond locations as channel initiation or pour points, AGWA can arrange the elements for KINEROS2 modeling.

KINEROS2 simulations with and without storage can be executed so that the impacts of the pond can be hydrologically analyzed. Impacts of storage features can be visualized in a map document where the relative change due to a pond will be apparent in the stream below the structure. Another way to assess the impacts of a storage feature is to view the hydrograph (Figure 17) or sedigraph (Figure 18) downstream of the structure.

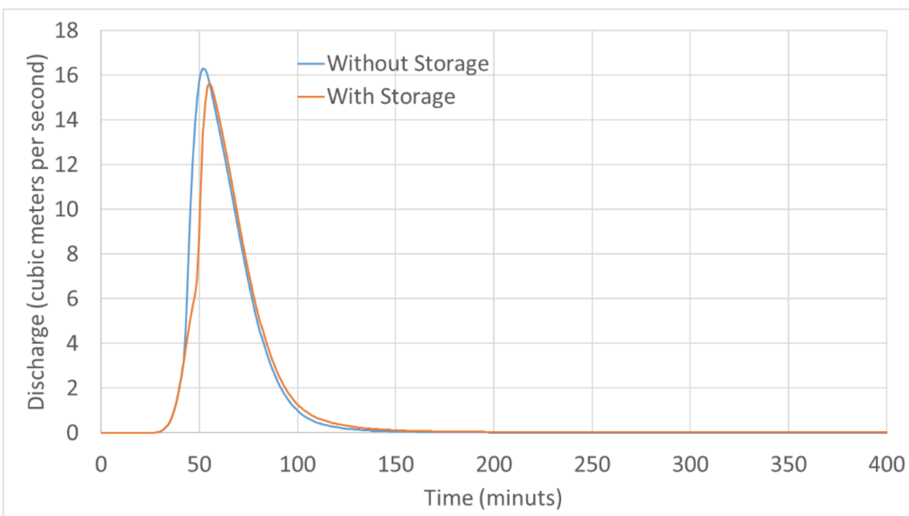

Figure 17: KINEROS2 Simulated Hydrograph Downstream of Hypothetical Storage Feature.

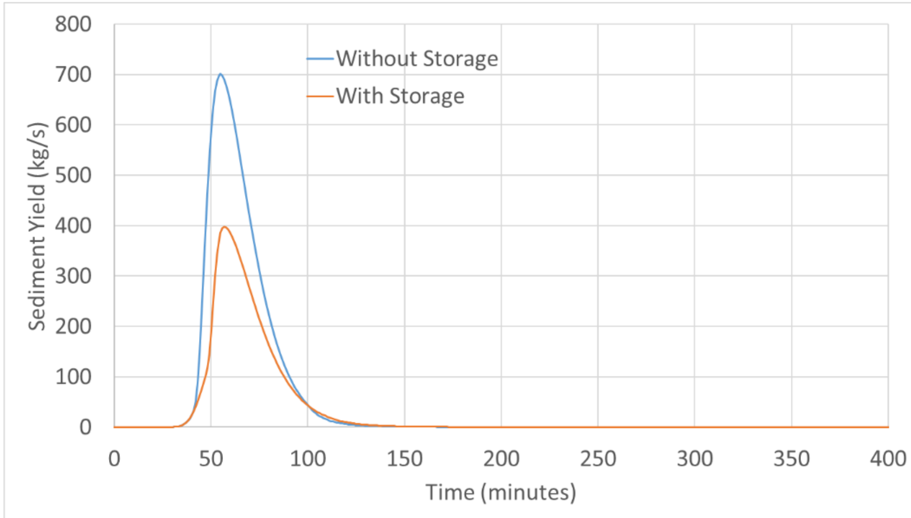

Figure 18: KINEROS2 Generated Sedigraph Downstream of Hypothetical Storage Feature

4.1.3 STORAGE CASE STUDIES

Two separate cases were used to validate the Storage Characterization Tool. The basic case is an abstraction of a pond that was made artificially in the shape of a circle. A series of nested circles, representing elevation contours, were converted to a DEM with no linear interpolation between the contours (Figure 19). The original DEM resolution was approximately 2.0 meters.

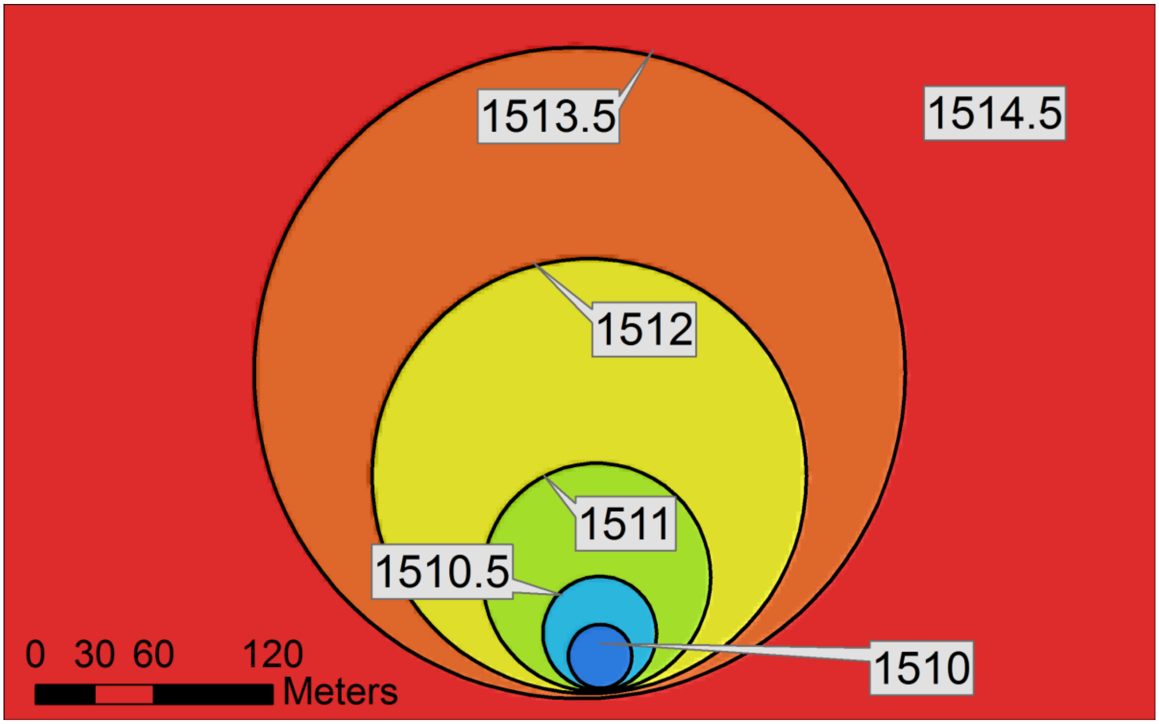

Figure 19: Circular Pond Contours (meters) and Contour-Derived DEM Used for Validation of Storage Characterization Tool

Area in square meters for each of these contours was calculated using the Calculate Geometry function in ArcGIS. Incremental volumes were then calculated using the contour area and change in elevation:

$$V = \Delta h * A \qquad \text{(Eq. 5)}$$

where: V = volume;

Δh = change in elevation;

A= Area of contour

The basic stage-storage relationship is illustrated in the form of a basic rating curve (Figure 20). The error in this analytical solution is minimal with an average error of 0.1%. As a percentage of total volume, the error diminishes as stage and volume increase (Table 1). In this idealized circumstance, the Storage Characterization toolbox captures the stage-storage rating curve (Figure 21).

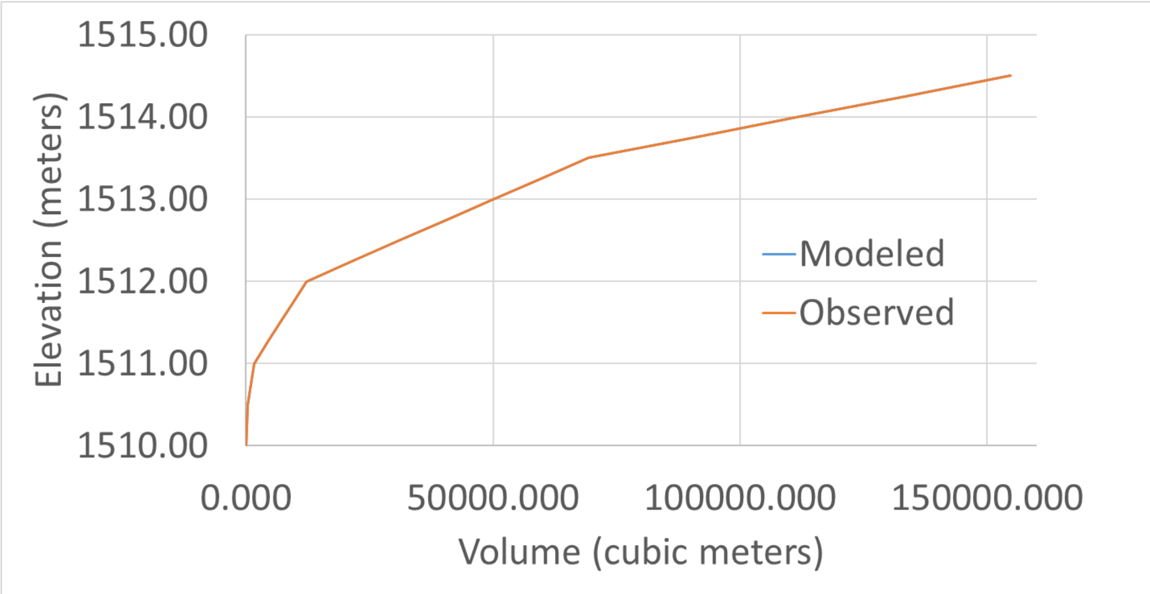

Figure 20: Stage-Storage Relationship for basic pond.

Table 1: Percent Error by Stage for Basic Pond.

Stage (m)	**Modeled Volume (m3)**	**Observed Volume (m3)**	**Percent Error**
1510	0	0	0.0
1510.25	204	204	-0.1
1510.5	408	408	-0.1
1510.75	1053	1057	0.4
1511	1698	1706	0.5
1511.25	4318	4328	0.2
1511.5	6939	6950	0.2
1511.75	9560	9572	0.1
1512	12180	12195	0.1
1512.25	21700	21712	0.1
1512.5	31219	31228	0.0
1512.75	40739	40745	0.0
1513	50258	50262	0.0
1513.25	59778	59779	0.0
1513.5	69297	69296	0.0
1513.75	90636	90660	0.0
1514	111974	112024	0.0
1514.25	133313	133388	0.1
1514.5	154652	154753	0.1

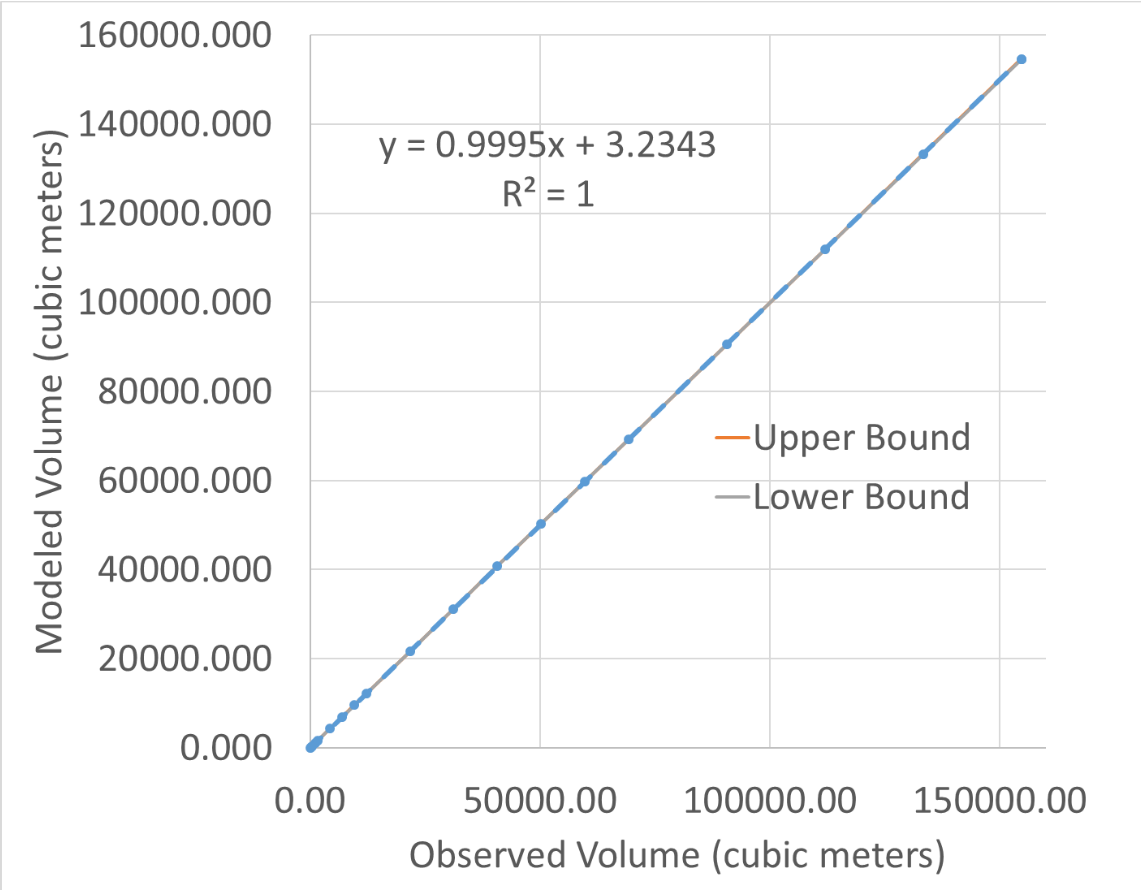

Figure 21: Modeled Volume Compared to Observed Volume for the Basic Pond.

The complex validation data includes ponds in the WGEW. The ponds in WGEW were initially instrumented to understand sediment yield and rainfall-runoff relationships at a small watershed scale (Simanton and Osborn, 1973). Some of the ponds are surveyed annually (see Nichols 2006) for runoff and sedimentation records. Surveys were shared for validation of the Storage Characterization Toolbox; however, the specific storage-discharge tables will not be shared in this document. Locations of the stock ponds on WGEW are publicly available as a vector point layer (Heilman et al., 2008; http:www.tucson.ars.ag.gov/dap/).

For validation, the Storage Characterization Toolbox was used to characterize stage-storage relationships at 0.25 meter increments for pond 208 on WGEW (Figure 1, Figure 22). For pond 208, field surveyed stage-storage relationships from February 2016 were compared to modeled relationships derived from LiDAR surveys conducted during September 2015 (M. Nichols, 2016 personal communication). The WGEW LiDAR survey was converted to a bare earth DEM with a cell resolution of 0.5 meters and a vertical accuracy of approximately 0.086 meters (USGS 2016).

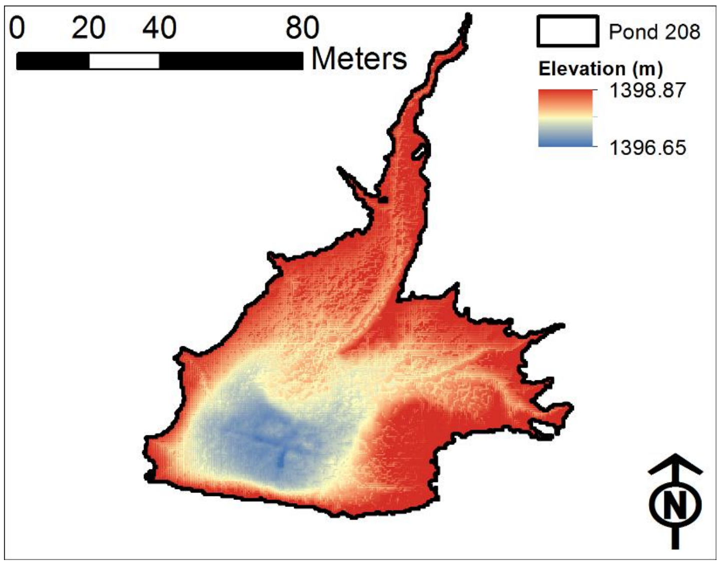

Figure 22: Pond 208 Unfilled DEM and Identified Boundary.

Due to uncertainties in absolute elevation with the DEM used for characterization, comparison of surveyed and modeled ponds was done using a relative stage. Relative stage is a measure of elevation where minimum starts at zero and every stage is in relation to that minimum value. For example, the minimum surveyed elevation was 1397.25 meters and the minimum modeled elevation was 1396.65 meters, the minimum elevation for both ponds was set to 0.0 meters. The first stage for the surveyed pond was 1397.50 meters and the first stage for the modeled pond was 1396.9 meters and the relative stage for both is calculated to be 0.25 meters. Percent error was calculated based upon relative stage for each pond 208 (Table 2). While percent error is much larger in the complex validation than the basic pond, the same pattern is observed where error diminishes as volume increases. Although error exists in the modeling of existing storage, the general shape of the stage-storage relationship is maintained (Figure 23). The complex validation series for pond 208 under predicted volume by at least 20% (Figure 24). While error exists in this validation case studies, the general stage-storage relationship is well captured.

Table 2: Percent Error by Relative Stage for Pond 208.

Relative Stage (m)	Modeled Volume (m3)	Observed Volume (m3)	Percent Error
0.00	0.0	0	0.0
0.25	0.4	2	78.5
0.50	16.9	85	80.2
0.75	133.6	276	51.6
1.00	360.7	608	40.7
1.25	754.3	1130	33.2
1.50	1345.8	1863	27.8
1.75	2169.2	2884	24.8
2.00	3284.8	4233	22.4
2.25	4686.1	5834	19.7

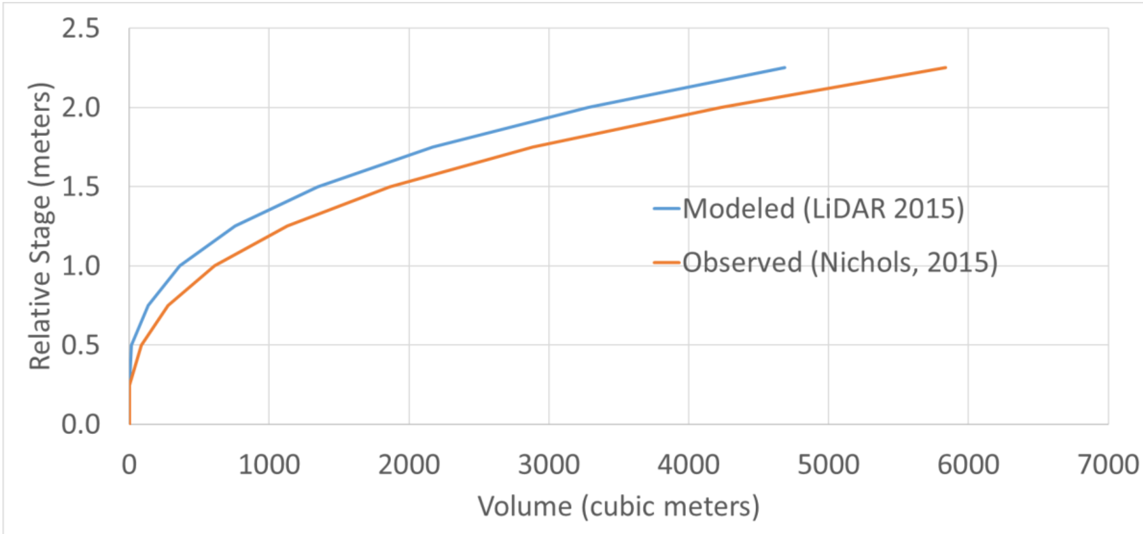

Figure 23:Stage-Storage Relationship for Pond 208

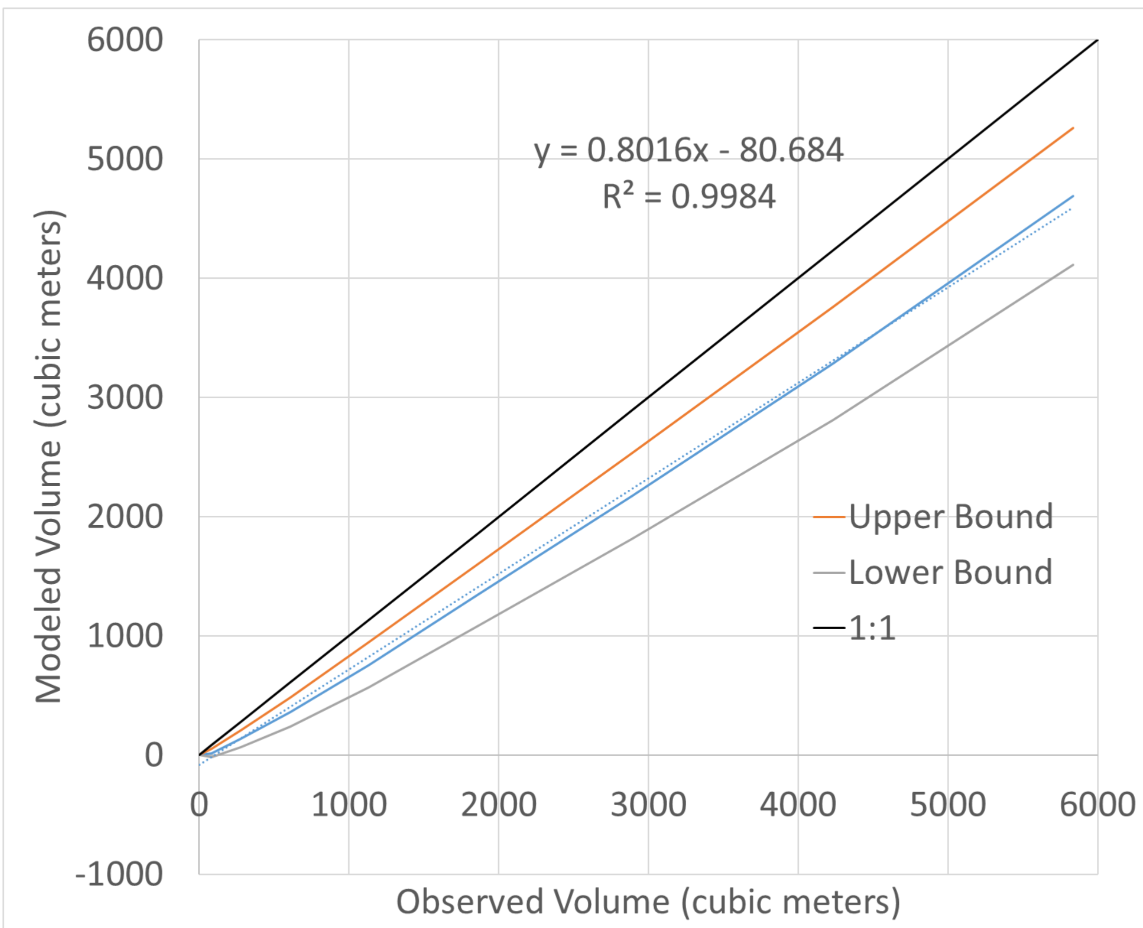

Figure 24:Modeled Volume compared to Observed Volume for Pond 208.

Another test among the complex case study was to validate identification of existing storage features. There were eight gaged stock ponds on WGEW; the location of these ponds and the 2015 LiDAR DEM were used to test if all eight ponds could be identified (Figure 25). All eight ponds were identified and maximum surface area and volume were calculated for each pond (Table 3). In this case, all ponds were correctly identified, however this test needs to be performed across a larger more variable study area to confirm correct identification.

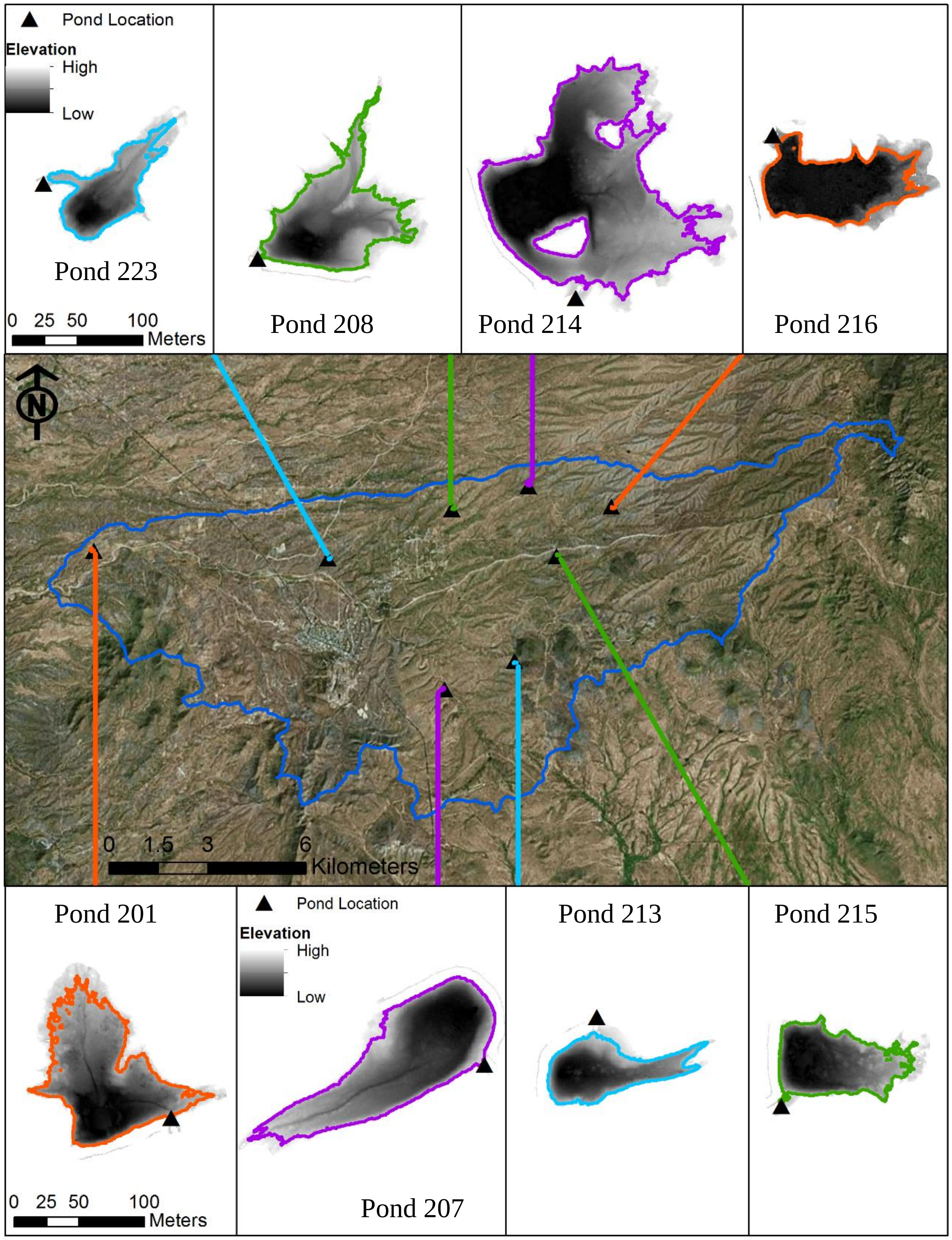

Figure 25: Storage Identification using WGEW Pond Locations and 2015 LiDAR DEM.

Table 3: WGEW Identified Storage Features and Corresponding Topographic Properties from 2015 LiDAR DEM.

Pond ID	Minimum Elevation (m)	Maximum Elevation (m)	Maximum Surface Area (m^2)	Maximum Volume (m^3)
201	1249.27	1251.26	10419.5	9398.6
207	1385.41	1388.77	10978.3	17880.8
208	1396.65	1399.38	8891.5	8312.92
213	1421.02	1423.45	4479.25	5044.09
214	1439.61	1441.91	20782	23002
215	1443.67	1445.98	5671.5	6534.74
216	1470.24	1471.35	7260.75	4870.73
223	1334.29	1336.25	4594	3694.37

To conclude, the first case study for the Storage Characterization tool, the basic pond, illustrates the validity of this tool in an idealized scenario. The second case study on WGEW shows that ponds are correctly identified but characterization of pond 208 exposes potential sources of error that could be associated with the vertical and/or horizontal accuracy of the DEM. The uncertainty in characterization highlights the need for more validation of natural storage features.

4.1.4 LIMITATIONS AND UNCERTAINTIES

The storage tool has been developed to identify and characterize existing storage as well as plan for future development but it cannot be appropriately used without understanding of the uncertainties that impact tool execution and results. These uncertainties relate to tool default parameters, the input LiDAR derived DEMs, input pond locations and location properties.

There are default parameters embedded in the Storage Characterization Tool that can introduce error into storage identification and characterization. However, these parameters can be altered to better account for different environments or user knowledge. One parameter is the minimum storage size area in square meters. This parameter is applied to designate the minimum cluster of raster cells that can be designated as a storage feature. The default is 500 square meters, which can be altered by users depending on the size of features they are interested in capturing. Another parameter is the distance between pond locations and identified storage features. This distance has a maximum default of 70 meters; that means that the closest storage feature to a pond location would be associated with that pond location up to 70 meters. This parameter was applied in a watershed with many ponds fairly close together, it became necessary to associate pond unique identifiers only with storage features within a certain distance. The final parameter that should be considered is the stage interval which has a default value of 0.15 meters. This can be altered to capture different stage-storage and stage-discharge relationships that interest the user.

Uncertainties in the input data will also impact the modeled outputs. The LiDAR-derived DEM can impact storage identification and characterization. There are general documented errors with LiDAR surfaces that include vertical and horizontal average error. These errors can be carried into storage identification and characterization. Water present across the landscape can also influence LiDAR surveys (Podhoranyi and Fedorcak, 2015). There are other errors that can be introduced during LiDAR collection that are outside of the scope of this research.

One source of identification error occurs when the date of the LiDAR survey and the date of the pond locations do not align. If the LiDAR is flown prior to location and construction of a pond, the feature will not be identified as there is not an associated location. There are three default ponds, based upon a previous characterization, that can be substituted for unidentified ponds for AGWA/KINEROS2 modeling. The date of the LiDAR survey is also important for the characterization of the ponds. LiDAR will capture the state of the pond on the date of the survey, this date could be after considerable sedimentation which will underestimate maximum storage or it could be immediately following construction (prior to any sediment accumulation) which could over estimate current storage.

Input pond locations can also introduce error into the identification, characterization and modeling of storage features. Pond locations should be analyzed prior to executing the Storage Characterization Toolbox and prior to modeling with AGWA/KINEROS2. In most scenarios, discharge out of identified storage features is based upon outlet structures that are dependent on contributing watershed area or local knowledge. Misrepresentation of outlet structures will impact the final storage-discharge relationship that is used for KINEROS2 modeling.

While uncertainties are associated with the Storage Characterization Toolbox, it provides utility in identifying and characterizing existing storage features across a large area. The tool provides estimates of storage and discharge so that the basic hydrologic function of the features can be modeled. The tool also provides utility as a planning tool, so that users can assess relative impact of storage installation prior to site visits for design.

4.3 INUNDATION TOOL

The Inundation Tool was designed to provide access to hydraulic computations at a reach scale for post wildfire response.

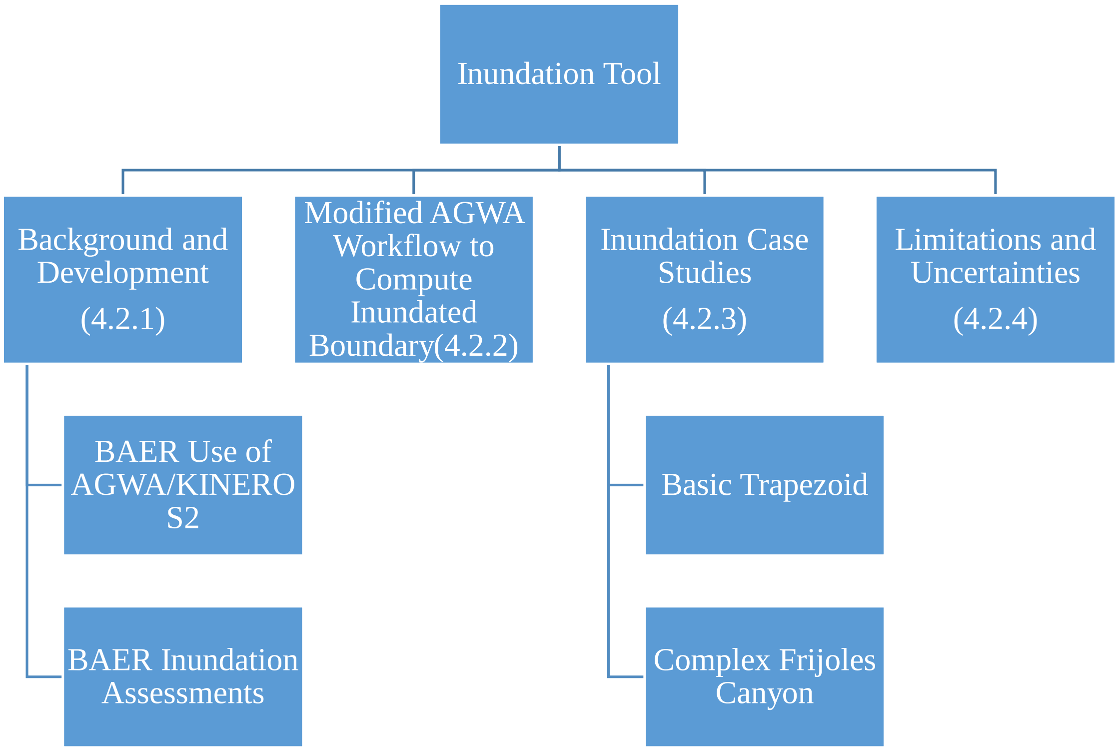

Figure 26: Inundation Tool Section Outline

4.2.1 BACKGROUND AND DEVELOPMENT

As a wildfire becomes contained, Burned Area Emergency Response (BAER) teams arrive on scene and assess risk to the areas valuable resources. These resources can be road crossings, archeological sites, fish habitat and more. While these resources can be directly affected by the wildfire, the BAER teams are largely concerned with indirect or secondary effects of the wildfire that include flooding, erosion and sediment transport.

Some BAER teams use AGWA/KINEROS2 to assess changes in watershed response after a wildfire (Figure 27). The application starts with a pre-wildfire watershed assessment. Followed by land cover modification that utilizes field verified burn area reflectance classification (BARC) maps to alter land cover and soil properties to reflect burn severity. Next the modified land cover is used as an input for the post-wildfire watershed assessment. The pre-fire and post-fire assessments are then compared so that hydrologists and decision makers can visually, graphically and numerically interpret relative changes in hydrology and sediment transport at values at risk (VARs) throughout the watershed due to wildfires. Typically, a subset of hillslopes or streams will stand out as higher relative sources of runoff or erosion.

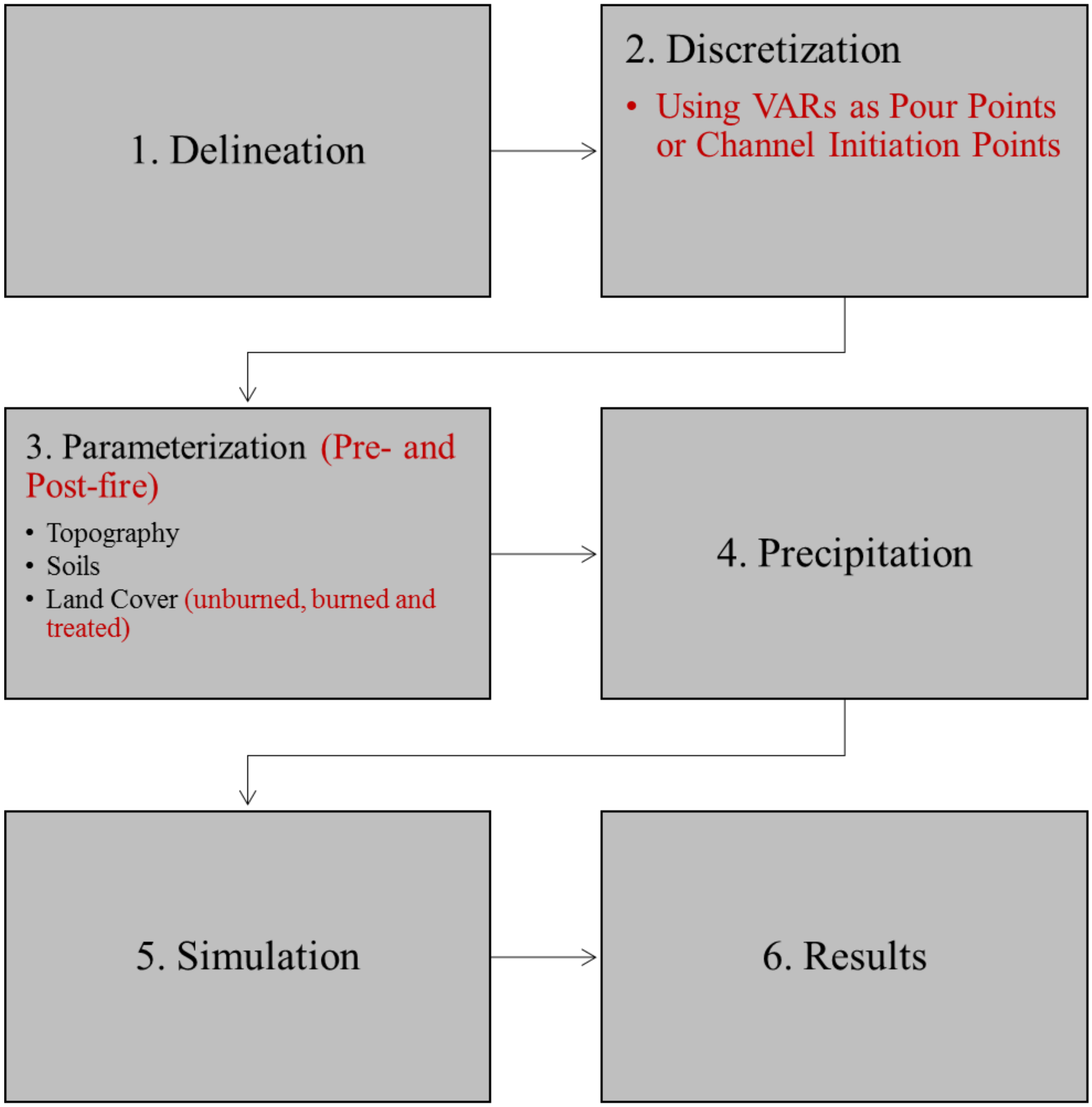

Figure 27: AGWA/KINEROS2 Workflow for Post-Fire Watershed Assessments.

If hillslopes or streams yielding relatively high sediment or runoff could impact a value at risk, BAER teams use AGWA/KINEROS to assess a variety of treatment scenarios that could mitigate those impacts. However, if a stream is predicted to have a relatively high peak discharge in the post-fire assessment compared to the pre-fire assessment, BAER teams might need to look into hydraulic models for predictions about changes in water surface elevation and thus flood extent in the post-fire environment. Hydraulic models are typically drawn on in cases where a value at risk is along the stream bank or close to the stream. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) is the most common tool used in these situations. However, HEC-RAS requires very detailed inputs which can be time consuming to collect. HEC-RAS may still be the most appropriate model to use, however in simple cases where a rapid risk assessment is required, a simpler model/computation procedure could be used.

The Inundation Tool provides a simpler procedure to assess risk at a reach scale within a fire-affected watershed. This tool works within the previously defined AGWA/KINEROS workflow for BAER watershed assessments. This tool was built as an ArcGIS Toolbox using Python scripts and modules to ingest the data and perform water surface elevation calculations (Figure 28). Basic water surface elevation calculations were copied from the HEC-2 Fortran source code and documentation. Some of the logic from the HEC-2 source code was utilized as well, however some of that logic is not as efficient as more recently developed Python conventions and was thus re-written.

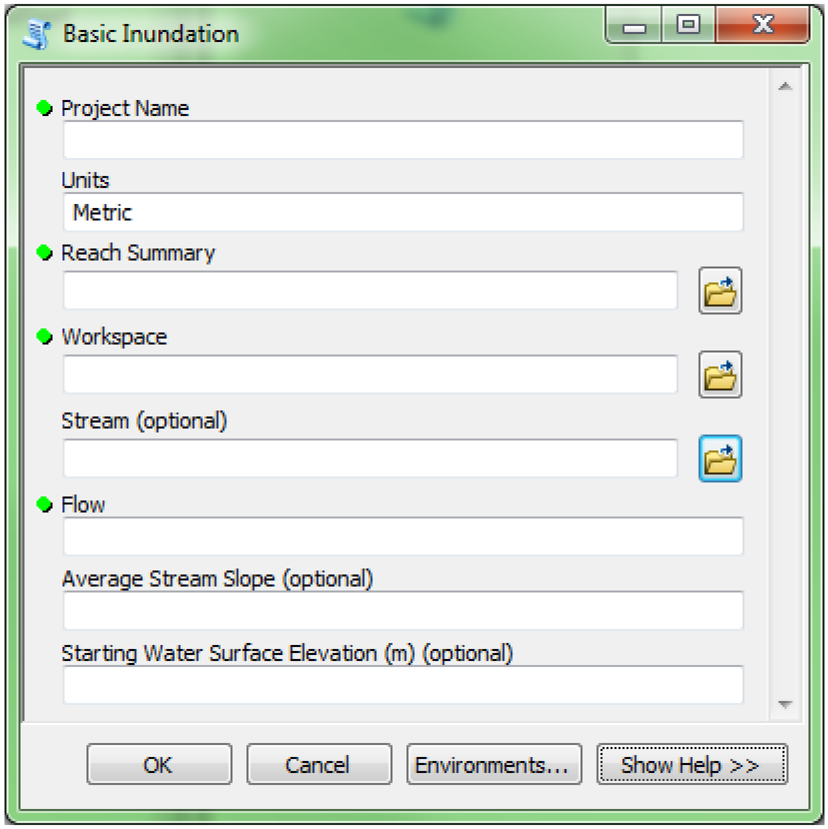

Figure 28: Inundation Tool ArcToolbox Form

The fundamental equation guiding hydraulic calculations for water surface elevation is a version of the energy equation which accounts for energy losses due to friction and expansion or contraction (Eq. 6) (Chow, 1959). A slightly modified version of this equation is used by HEC-2 and HEC-RAS (Eq. 7) (US-ACEIWR-HEC, 1990; Brunner, 2010).

$$z_1 + y_1 + \alpha_1 \frac{V_1^2}{2g} = z_2 + y_2 + \alpha_2 \frac{V_2^2}{2g} + h_f \qquad \text{(Eq. 6)}$$

where: z_1, z_2 = channel elevation above the datum plane (m);

y_1, y_2 = depth of water (m);

α_1, α_2 = velocity coefficient;

$\frac{V_1^2}{2g}$, $\frac{V_2^2}{2g}$ = velocity head (m);

h_f = energy head loss (m).

$$WS_2 + \frac{\alpha_2 V_2^2}{2g} = WS_1 + \frac{\alpha_1 V_1^2}{2g} + h_e \qquad \text{(Eq. 7)}$$

where: WS_1, WS_2 = elevation (m; the sum of z and y from the previous equation);

$\frac{\alpha_1 V_1^2}{2g}, \frac{\alpha_2 V_2^2}{2g}$ = velocity head (m);

h_e = energy head loss (m).

The velocity coefficients vary only slightly, but are a function of conveyance and channel area (Eq. 8). Energy head loss is calculated between each cross section (Eq. 9). The components of the head loss equation are discharge weighted channel length (Eq. 10) and average friction slope (Eq. 11). Average friction slope can be calculated by a variety of methods, but the average conveyance method relies on conveyance which is calculated node by node for each cross section then aggregated by main channel and overbanks (Eq. 12)

$$\alpha = \frac{(A_t)^2 \left[\frac{(K_{lob})^3}{(A_{lob})^2} + \frac{(K_{ch})^3}{(A_{ch})^2} + \frac{(K_{rob})^3}{(A_{rob})^2} \right]}{(K_t)^3} \qquad \text{(Eq. 8)}$$

where: A_t = total cross-sectional area (m^2);

A_{lob}, A_{ch}, A_{rob} = left overbank, main channel and right overbank area (m^2);

K_t = total conveyance (m^3/s);

K_{lob}, K_{ch}, K_{rob} = left overbank, main channel, and right overbank conveyance (m^3/s).

$$h_e = L\overline{S}_f + C \left| \frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g} \right| \qquad \text{(Eq. 9)}$$

where: C = contraction/expansion coefficient;

$\overline{S}_f$ = average friction slope (m/m);

L = discharge weighted channel length (m).

$$L = \frac{L_{lob}\bar{Q}_{lob} + L_{ch}\bar{Q}_{ch} + L_{rob}\bar{Q}_{rob}}{\bar{Q}_{lob} + \bar{Q}_{ch} + \bar{Q}_{rob}} \qquad \text{(Eq. 10)}$$

where: L_{lob}, L_{ch}, L_{rob} = left overbank, main channel and right overbank length;

$\bar{Q}_{lob}$, $\bar{Q}_{ch}$, $\bar{Q}_{rob}$ = left overbank, main channel and right overbank discharge.

$$\bar{S}_f = \left(\frac{Q_1 + Q_2}{K_1 + K_2}\right)^2 \qquad \text{(Eq. 11)}$$

where: Q_1, Q_2 = discharge for cross sections one and two (m^3/s);

K_1, K_2 = total conveyance for cross sections one and two (m^3/s).

$$k = \frac{1}{n} a r^{\frac{2}{3}} \qquad \text{(Eq. 12)}$$

where: n = Manning's channel roughness;

a = area (m^2);

r = hydraulic radius (m).

Starting water surface elevation can be provided by the user or calculated using a defined slope. The user-defined slope can be used to calculate critical depth as starting water surface elevation for subcritical flow profiles. In order to calculate critical depth, iterations of total energy calculations were performed until a minimum value was reached (Eq. 13).

$$H = WS + \frac{\alpha V^2}{2g} \text{(Eq. 13)}$$

where: H = total energy head (m);

WS = water surface elevation (m);

$\frac{\alpha V^2}{2g}$= velocity head (m).

Basic data requirements for use of the Inundation Tool include channel geometry and peak discharge. Channel geometry includes cross section geometry, Manning's roughness for each cross section, overbank stations, overbank and channel length, and an estimate of channel bed slope. Peak discharge should be a measured or modeled value of discharge at the outlet of the stream of interest. More details about collecting and formatting input data can be found in **Error! Reference source not found.**. The Inundation Tool was designed with the intent to be incorporated into the AGWA/KINEROS2 workflow for post-fire watershed and reach assessments.

4.1.3 MODIFIED AGWA WORKFLOW TO DEVELOP INUNDATED BOUNDARY

The workflow for AGWA/KINEROS2 is well established and use in a variety of applications including post-fire watershed assessment (Figure 27). In order to develop and inundation extent, users need to complete that workflow for peak flow estimates. A stream segment is then selected for more detailed hydraulic analysis following completion of post-fire simulations. Next, channel geometry for that stream segment or a portion of the stream segment needs to be collected. Guidance for collection and formatting of channel geometry can be found in **Error! Reference source not found.**.

Modeled peak flow from the post-fire KINEROS2 hydrologic simulation, channel geometry (reach summary), output workspace and channel slope are entered into the Basic Inundation form (Figure 29). Optional inputs allow users to use defaults that are either calculated by the Inundation Tool or derived from other inputs. The reach summary contains an attribute named “XSFile” that refers to the file location for each cross section. Station, elevation and hydraulic roughness are specified in the cross section files.

Water surface elevations are calculated for each cross section provided by the user and then converted to inundated extent using ArcGIS. Conversion from water surface elevation to inundated extent is still being developed but preliminary results are depicted in Section 4.2.3. The overall AGWA/KINEROS2 workflow including predicting possible inundation extent can be used when values at risk are on or near a channel impacted by wildfire (Figure 30).

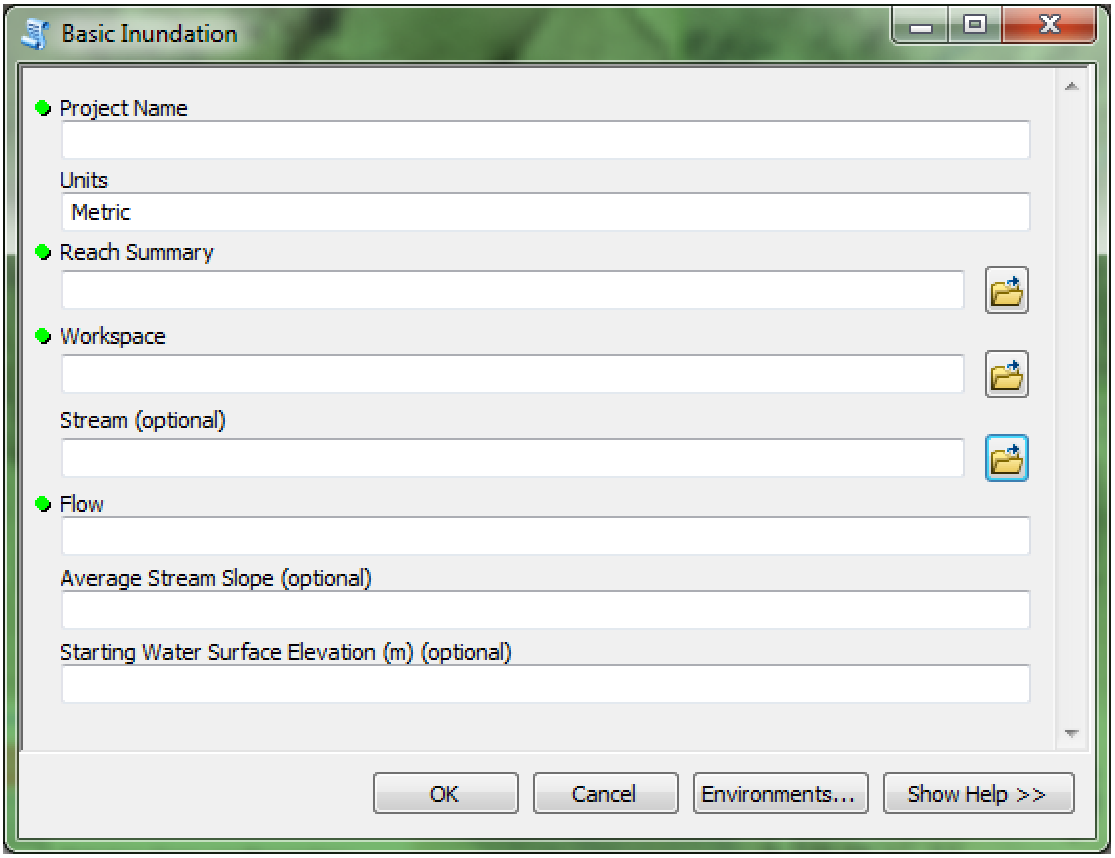

Figure 29: Basic Inundation Form for Inundation Tool Calculations.

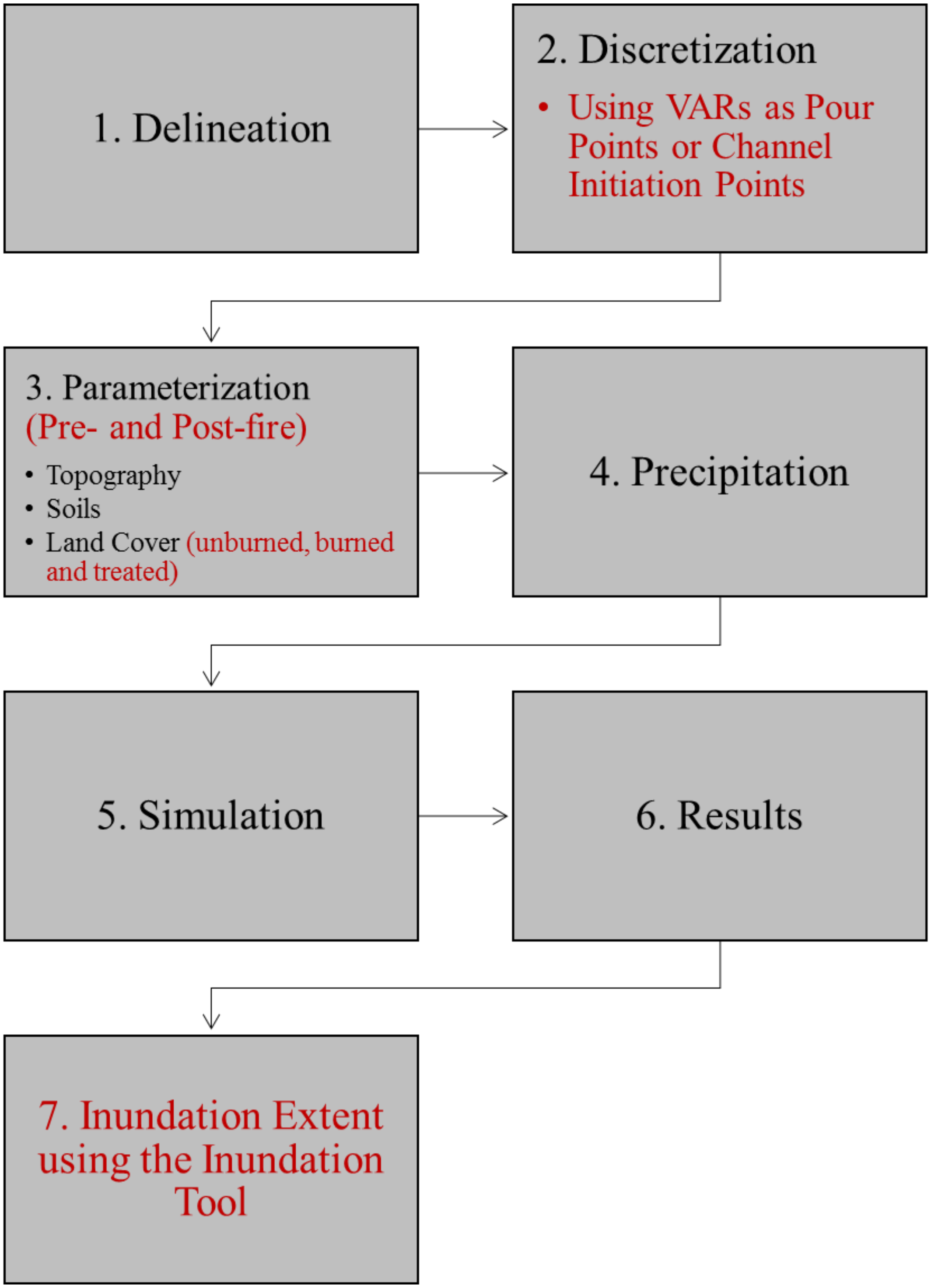

Figure 30: Modified AGWA/KINEROS2 Workflow to produce Inundated Boundary using the Inundation Tool

4.1.4 INUNDATION CASE STUDIES

Two case studies were used to validate the Inundation tool. The first is the basic case study of a concrete lined trapezoidal channel that was used to validate water surface elevation calculations. The second study was the complex case study of Frijoles Canyon where water surface elevation calculations were validated and the flood inundation boundary was delineated by an independent US Army Corps of Engineers study using HEC-RAS version 4.1 (USACE 2012).

The basic study involved a hypothetical 300-meter-long trapezoidal channel with a slope of 0.0005 m/m. Cross sections were uniform throughout the channel with bottom width of 6 meters and side slope of 0.5 (Figure 31). The three cross-sections are uniformly spaced in the channel with 100 meters between them (Figure 32). The cross sections are assumed to be constructed of a uniform concrete material with a Manning's roughness of 0.015 (Chow 1959). Multiple discharges were simulated as subcritical flow through this channel (Table 4).

Table 4: Discharge inputs for Inundation Tool Validation.

Profile	Flowrate CFS	Flowrate CMS
PF 1	3531	100
PF 2	7063	200
PF 3	8829	250

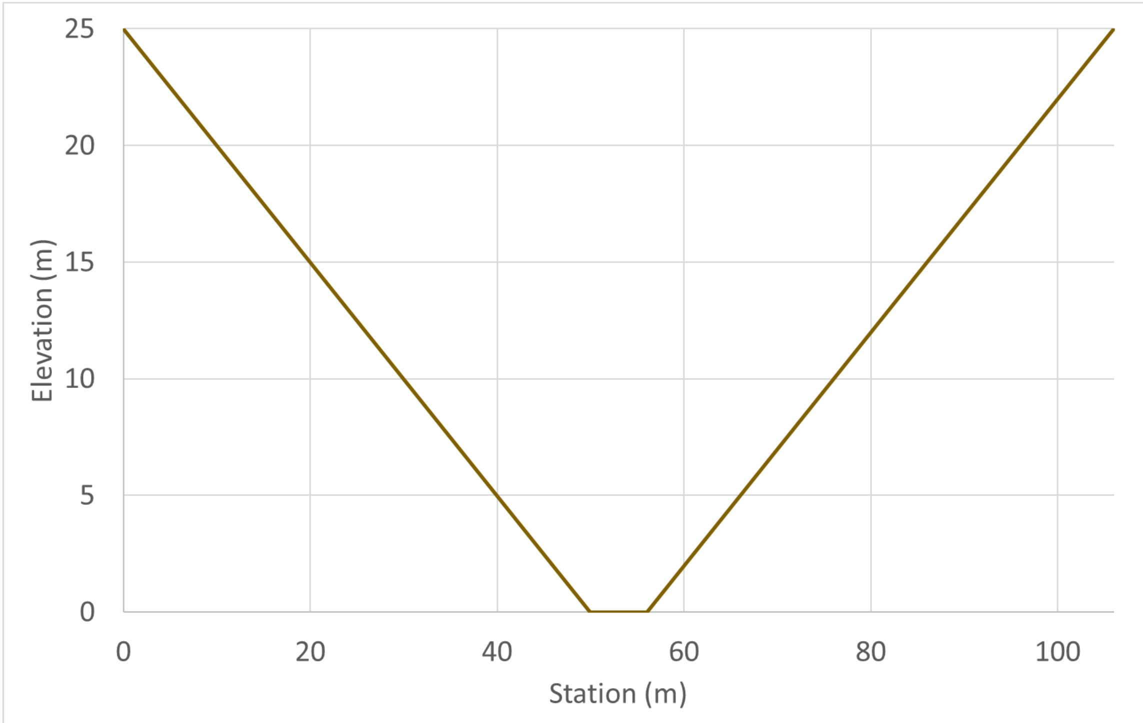

Figure 31: Basic Case Study Trapezoidal Cross Section

Table

ReachSummaryForPaper

OID	XS_ID	LOB_Length	CH_Length	ROB_Length	XSFile	LOB_Statio	ROB_Statio
0	1	0	0	0	D:\InundationFinal\Validation_Final\Basic\XS0.csv	0	106
1	2	100	100	100	D:\InundationFinal\Validation_Final\Basic\XS1.csv	0	106
2	3	100	100	100	D:\InundationFinal\Validation_Final\Basic\XS2.csv	0	106

3 (0 out of 3 Selected)

ReachSummaryForPaper

Figure 32: Reach Summary for Basic Trapezoidal Channel and Validation of Inundation Tool

After executing the Inundation Tool (Figure 33), water surface elevations were modeled using HEC-RAS 4.1.0 for comparison (Figure 34-Figure *36*). In order to more closely match HEC-2 computation methods, the method for calculating conveyance in HEC-RAS was modified to calculate between each coordinate point. Friction slope using average conveyance (Eq. 11 and 12) in the Inundation tool is calculated using the same method.

In most cases, the Inundation Tool under-predicts water surface elevation as compared to HEC-RAS water surface elevation, however critical depth elevations are nearly identical (Figure 37). The results of the basic test were intended to test water surface elevation calculations and therefore were not translated to inundated boundary.

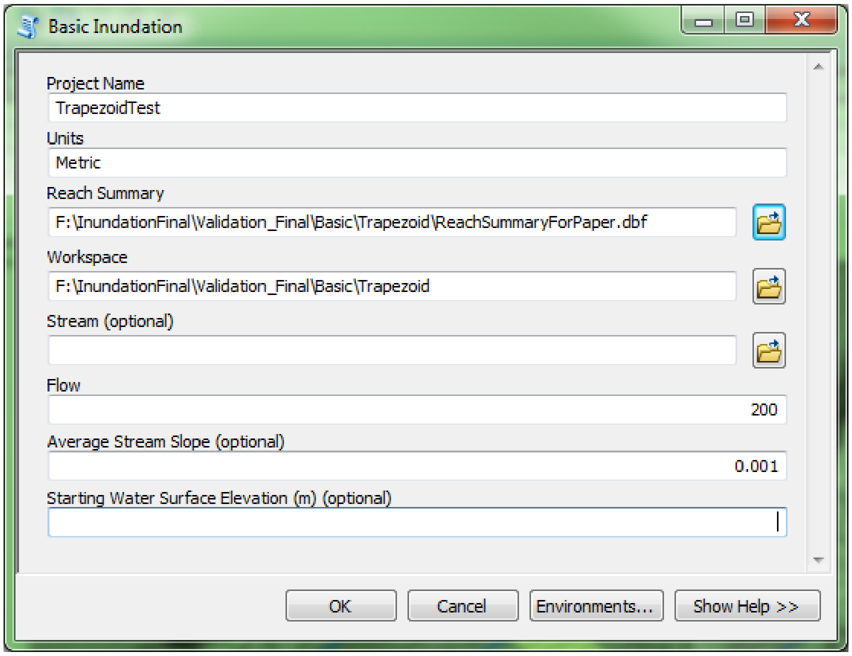

Figure 33: Example of Inundation Tool Input

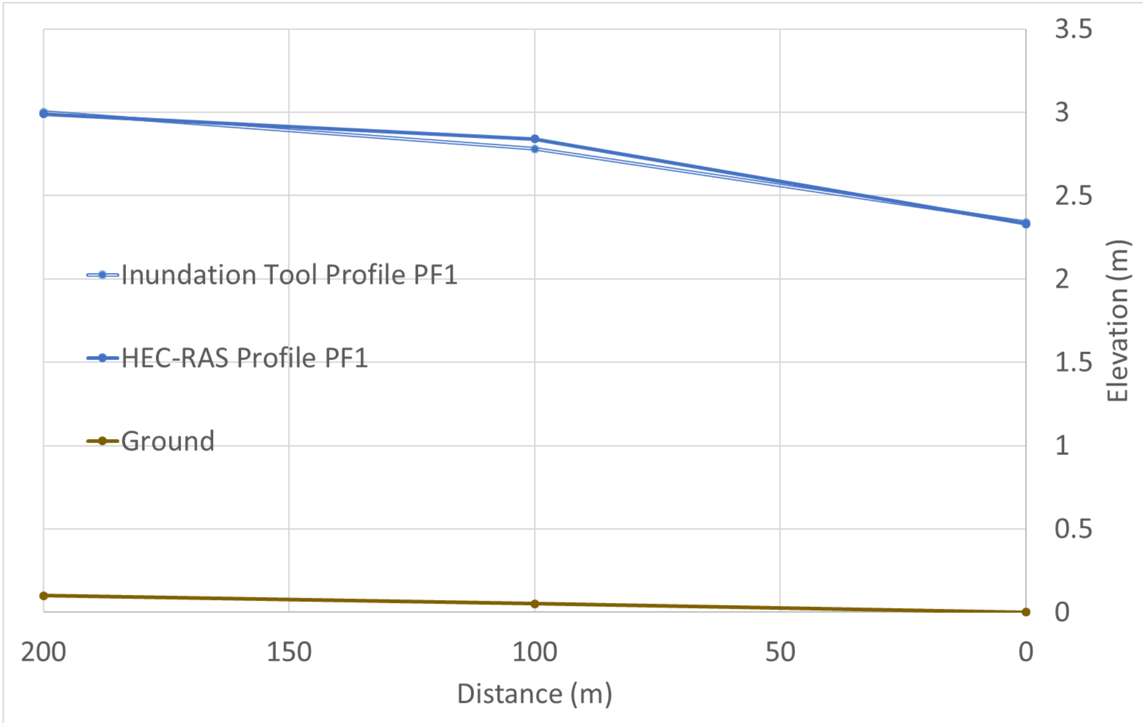

Figure 34: Water Surface Elevation for PF1 (Q = 100 cms).

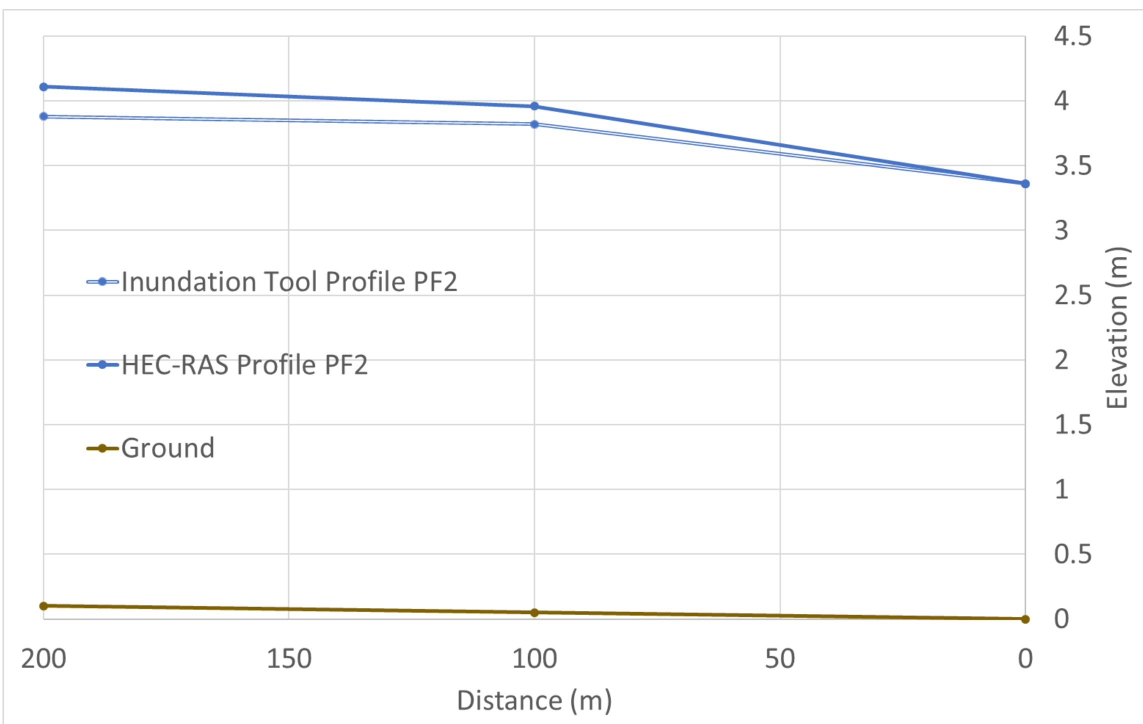

Figure 35: Water Surface Elevation for PF2 (Q = 200 cms)

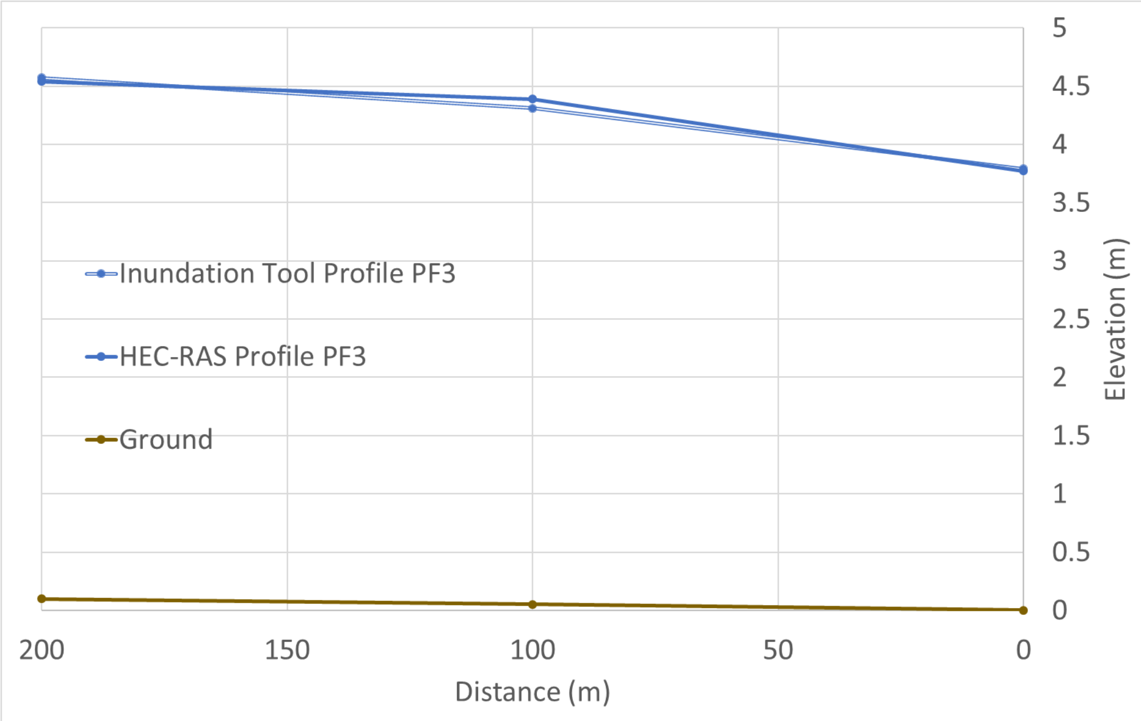

Figure 36: Water Surface Elevation for PF3 (Q = 250 cms)

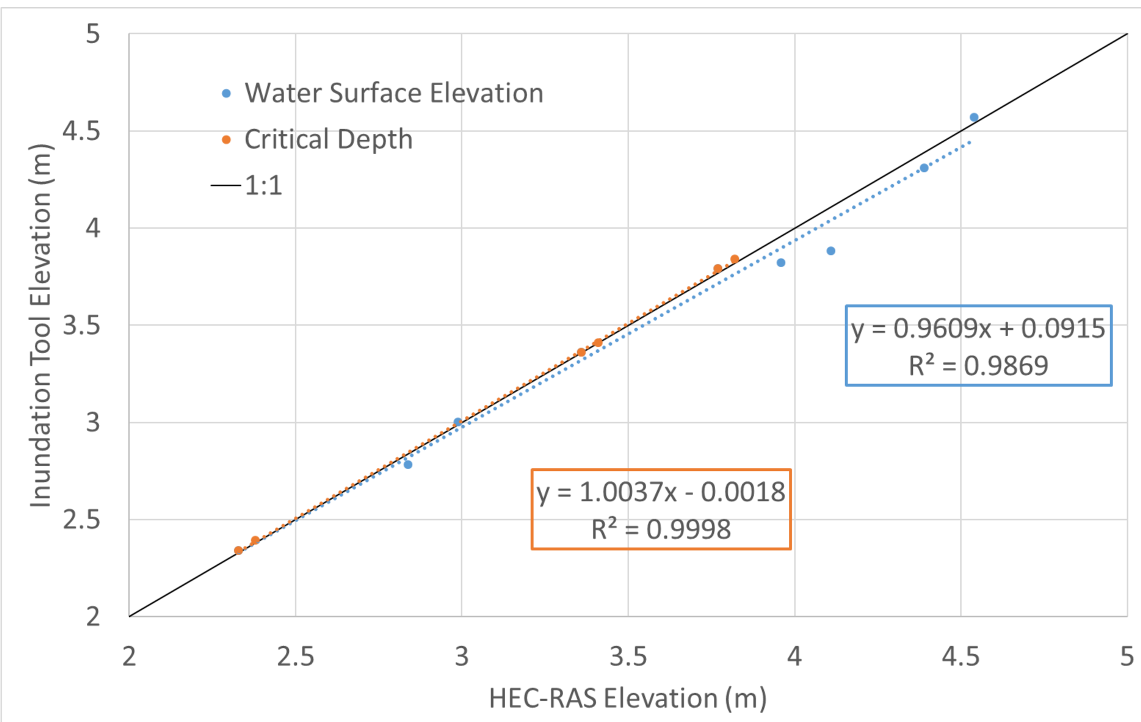

Figure 37: Comparison of Water Surface Elevation and Critical Depth from Inundation Tool and HEC-RAS Modeling.

The complex validation case study involved re-creating the USACE (2014) HEC-RAS study for Frijoles Canyon of the Bandelier National Monument in New Mexico. Frijoles Canyon was affected by the Las Conchas fire in July of 2011. A variety of modeled flow rates were based on the results of a HEC-HMS calibrated model that used measured peak discharges from the USGS stream gage downstream of the Bandelier Visitor Center (USACE 2014). HEC-HMS was used to calculate peak discharge at three points in the Frijoles Canyon watershed; point two was located just downstream of the Visitor center (USACE 2014). These peak discharges will be used as input for subcritical water surface profile calculation and the validation of the Inundation Tool (Table 5).

Table 5: HEC-HMS Modeled Peak Flow Rates used for Hydaulic Calculations in HEC-RAS and the Inundation Tool (USACE, 2014).

Profile	Event	Recurrence Interval	Flowrate CMS
PF 1	1 Inch Flood	1-year	116.8
PF 2	2 Inch Flood	< 10-year	265.9
PF 3	100-year Flood	100-year	514.5

The original HEC-RAS modeling study involved extraction of channel cross-sections from LiDAR-derived DEM; LiDAR was flown as part of the Las Conchas Post-Fire LiDAR Survey in October of 2011 (USACE 2012). Since the Bandelier Visitor Center is near the outlet of the canyon, 19 cross sections from the outlet of the canyon to just upstream of the visitor center were used as input for the Inundation Tool (Figure 38).

Basic Inundation calculations were performed for all three discharges (Table 5) along this short reach with an average slope of 0.02 m/m (Figure 39). Results from the Inundation Tool were compared to results from the USACE HEC-RAS project for each cross section (Figure 40-Figure *42*). Direct comparison of the Inundation Tool with the USACE (2014) study reveal a root mean square error of 0.17 meters (Figure 43).

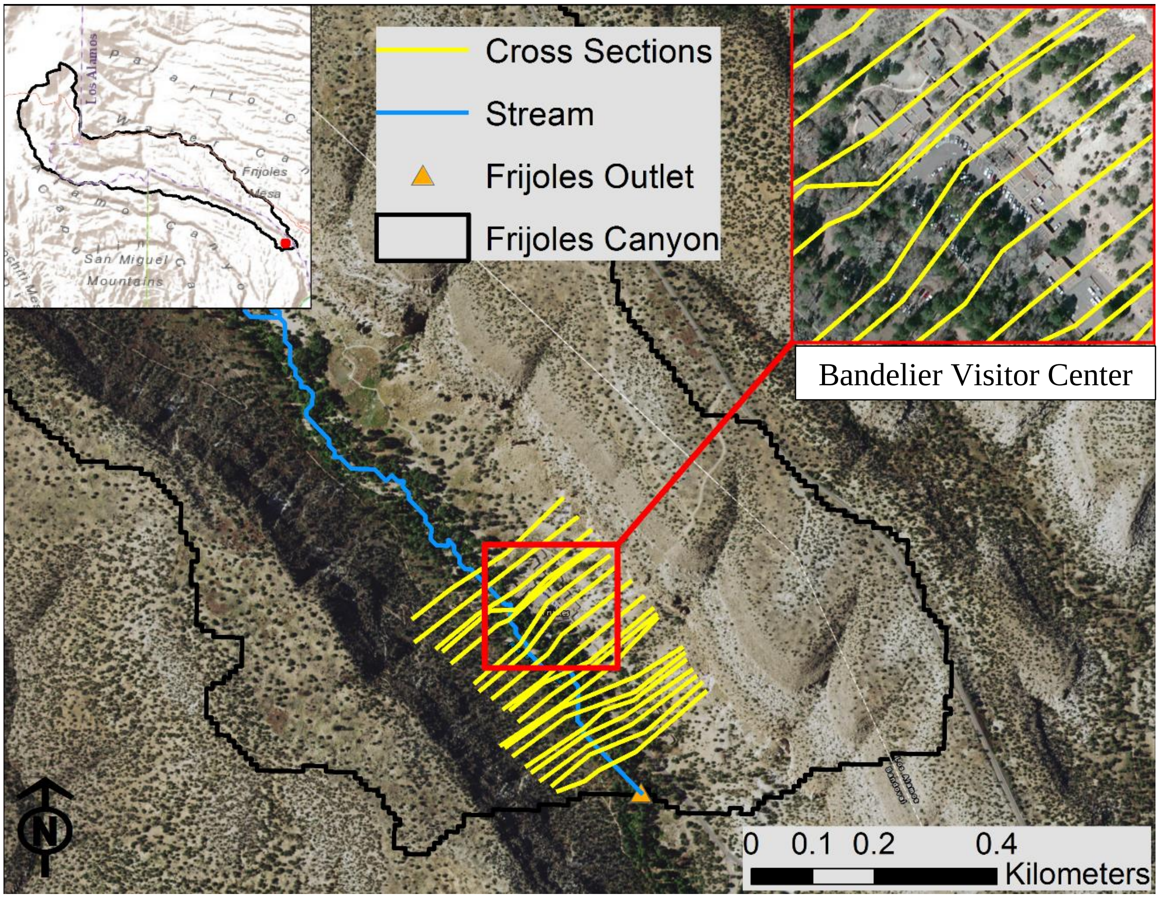

Figure 38: Cross Sections from xUSACE (2012) used for Inundation Tool; top right inset illustrates how these cross sections overlay the Bandelier Visitor Center.

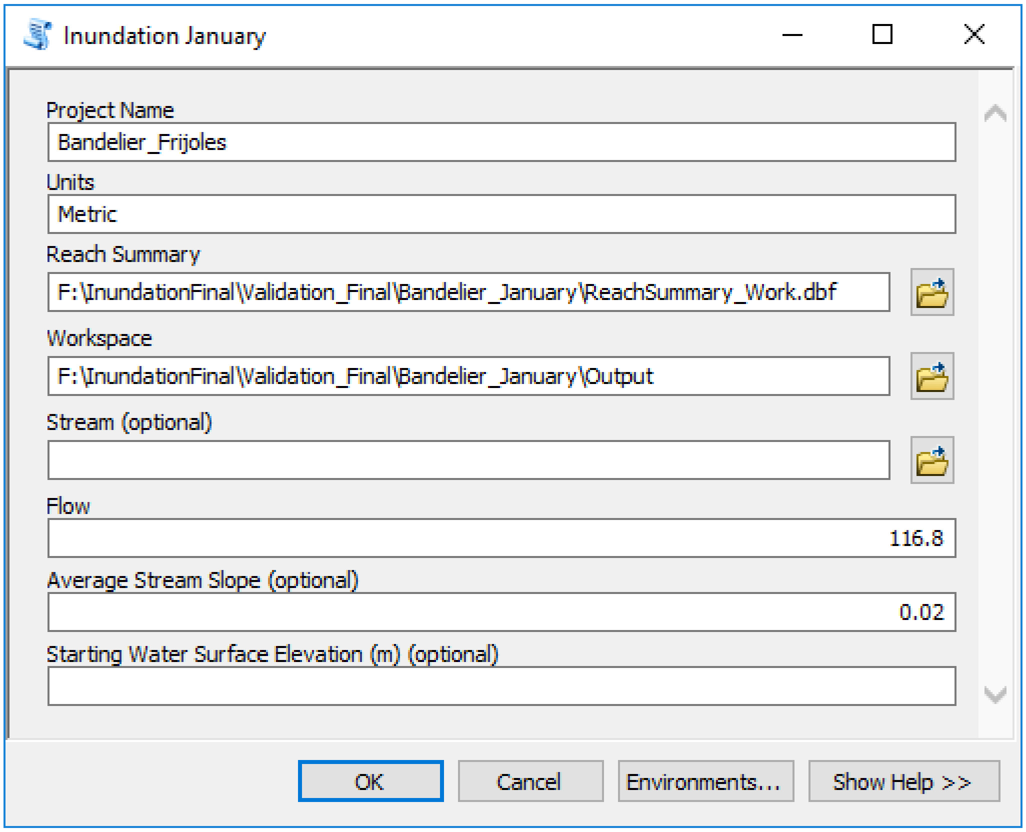

Figure 39: Basic Inundation Form Populated for Hydraulic Calculations Along Frijoles Canyon.

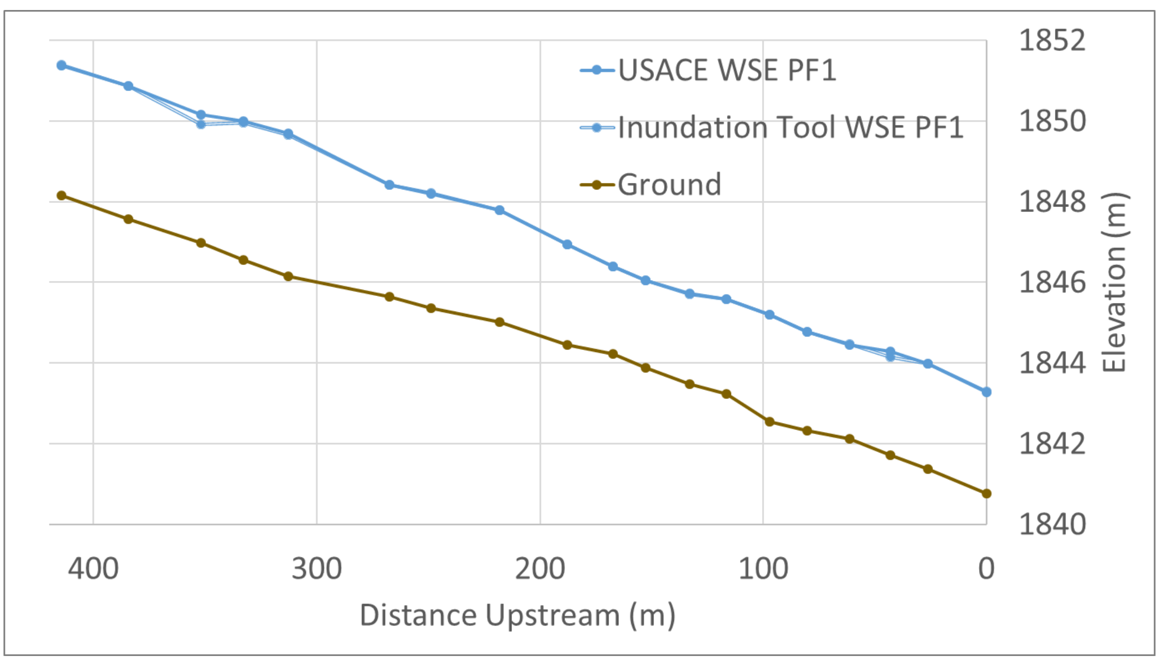

Figure 40: Water Surface Profile for 1-inch Flood (Table 3) Using HEC-RAS and the Inundation Tool.

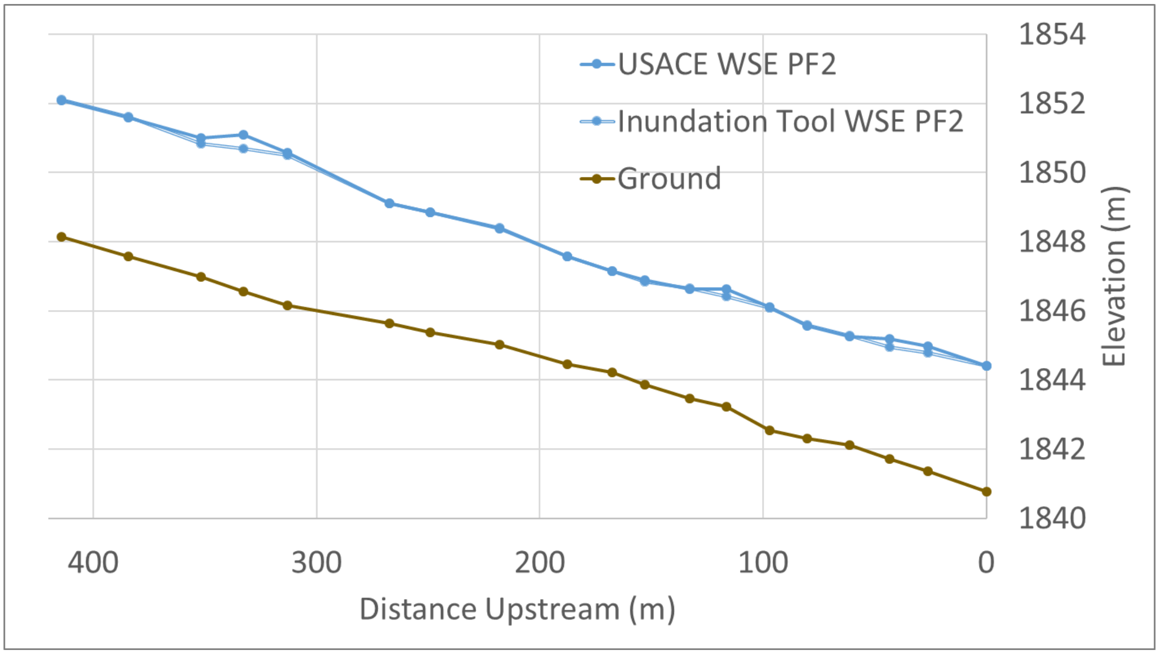

Figure 41: Water Surface Profile for 2-inch Flood (Table 3) Using HEC-RAS and the Inundation Tool.

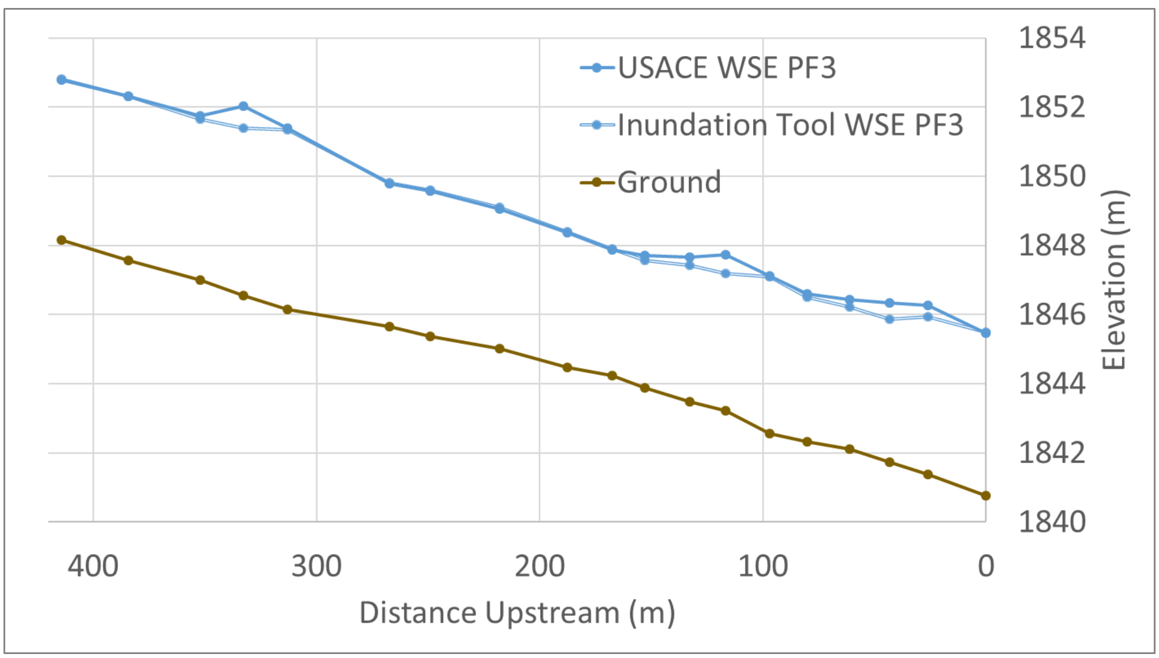

Figure 42: Water Surface Profile for 100-year Flood (Table 3) Using HEC-RAS and the Inundation Tool.

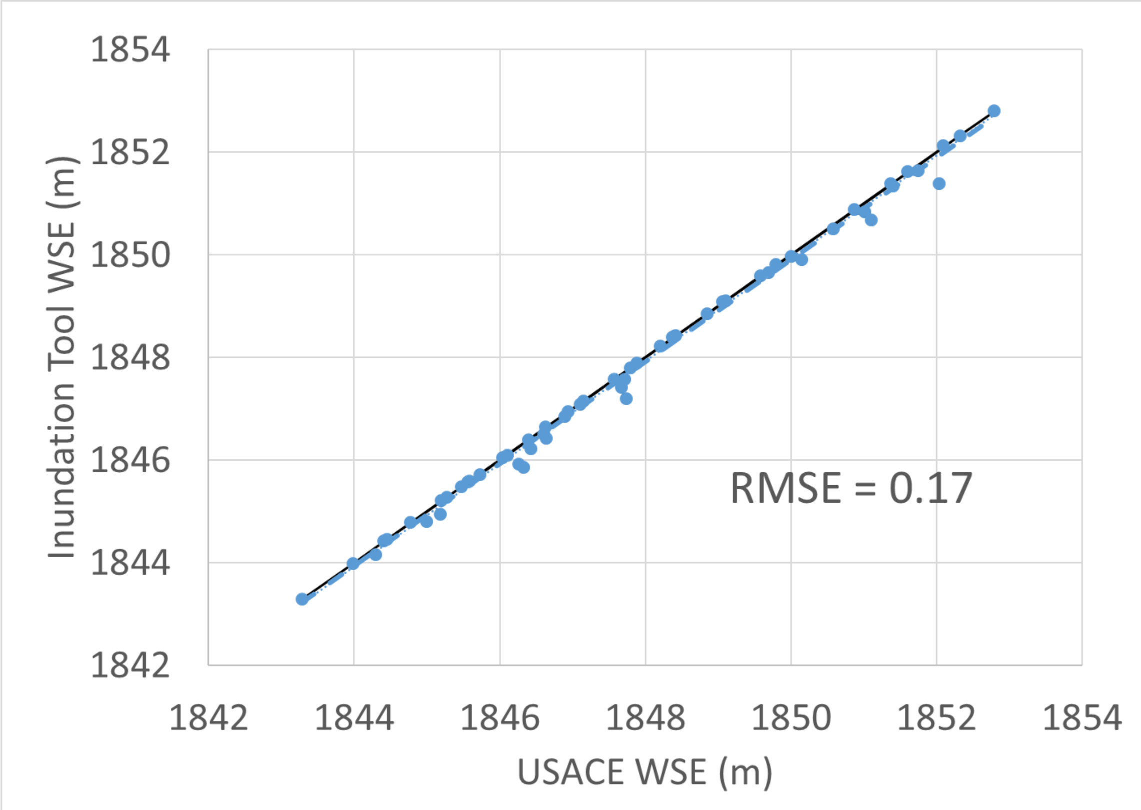

Figure 43:Comparison of Water Surface Elevation from Inundation Tool and HEC-RAS.

The final step of the Inundation Tool is to create a potentially inundated boundary. This step allows users to visually assess whether a value at risk will be affected by increased peak flow due to wildfire. In the case of Frijoles Canyon, the Bandelier National Monument Visitor Center was under potential threat of flood after the Las Conchas fire. Inundated extents were developed for each of the three flow profiles (Table 5). Water surface elevations were compared to ground profiles for each cross section, wetted areas were linearly connected between cross sections to create a polygon of inundated area (Figure 44-Figure *46*). Inundated areas created using the Inundation Tool were then compared to inundated areas created by the xUSACE (2014) to understand the effectiveness of the Inundation Tool (Table 6-8). The inundated extent created using the Inundation Tool visually compares well with the xUSACE (2014) boundary for all flow profiles; all extents show impact on the visitor's center which would provide guidance for decision makers to develop a management plan for flood mitigation. However, when comparing total inundated area, the Inundation Tool predicts 5-16% less inundation than the USACE (2014) study.

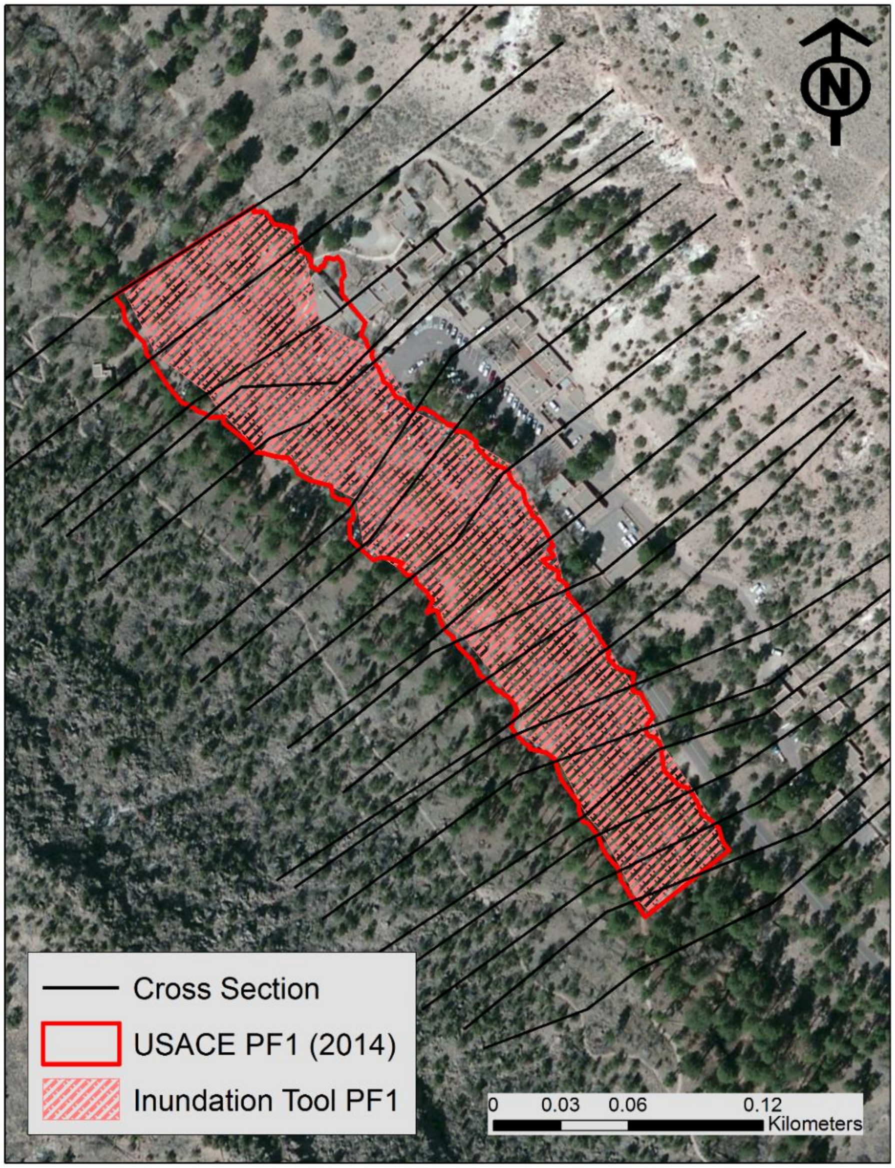

Figure 44: Inundated Extent Comparison of the USACE Report (2014) and the Inundation Tool for the 1-Inch Flow (Table 5)

Table 6: Comparison of Total Inundated Area from the USACE Report (2014) and the Inundation Tool for Flow Profile PF1 (Table 5)

PF1	Inundated Area (km2)	% Change
USACE (2014)	0.0219	0
Inundation Tool	0.0207	-5.1

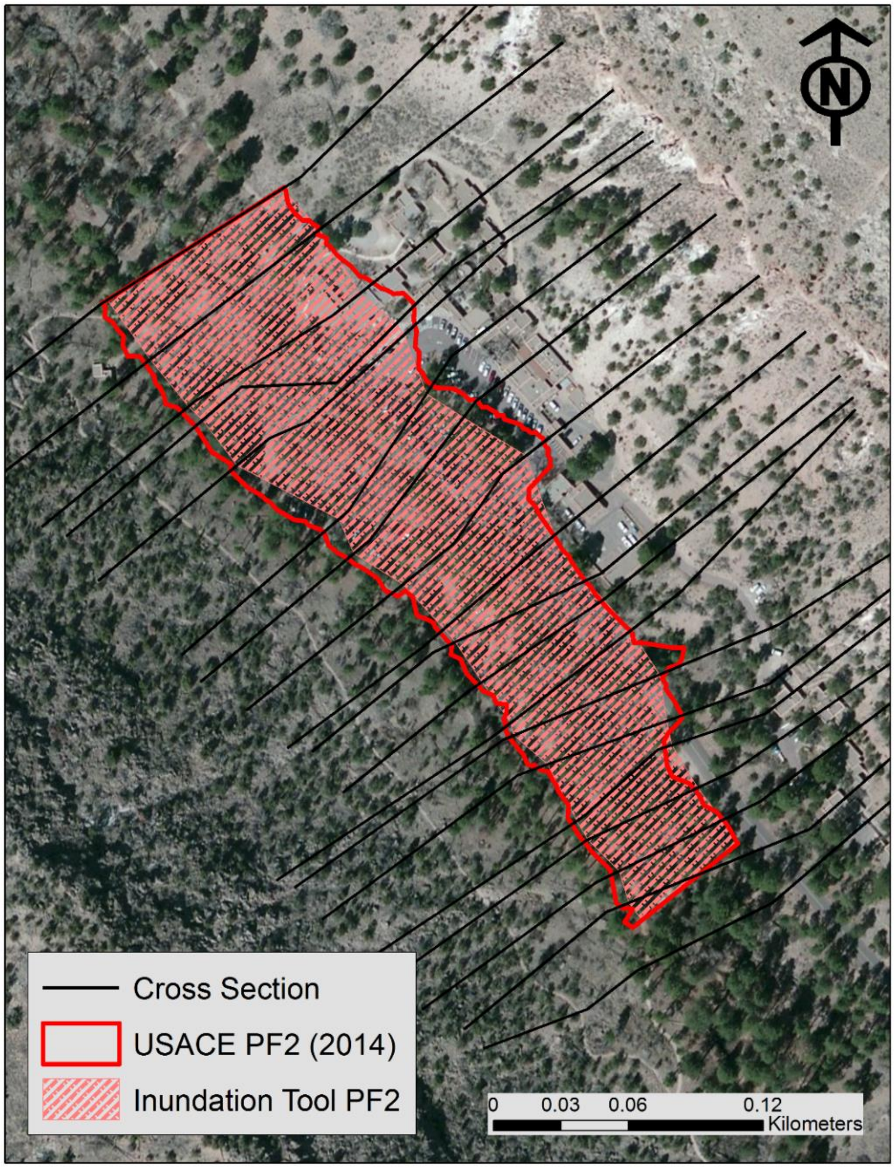

Figure 45: Inundated Extent Comparison of the USACE Report (2014) and the Inundation Tool for the 2-Inch Flow (Table 5)

Table 7: Comparison of Total Inundated Area from the USACE Report (2014) and the Inundation Tool for Flow Profile PF2 (Table 5)

PF2	Inundated Area (km2)	% Change
USACE (2014)	0.0290	0
Inundation Tool	0.0265	-8.5

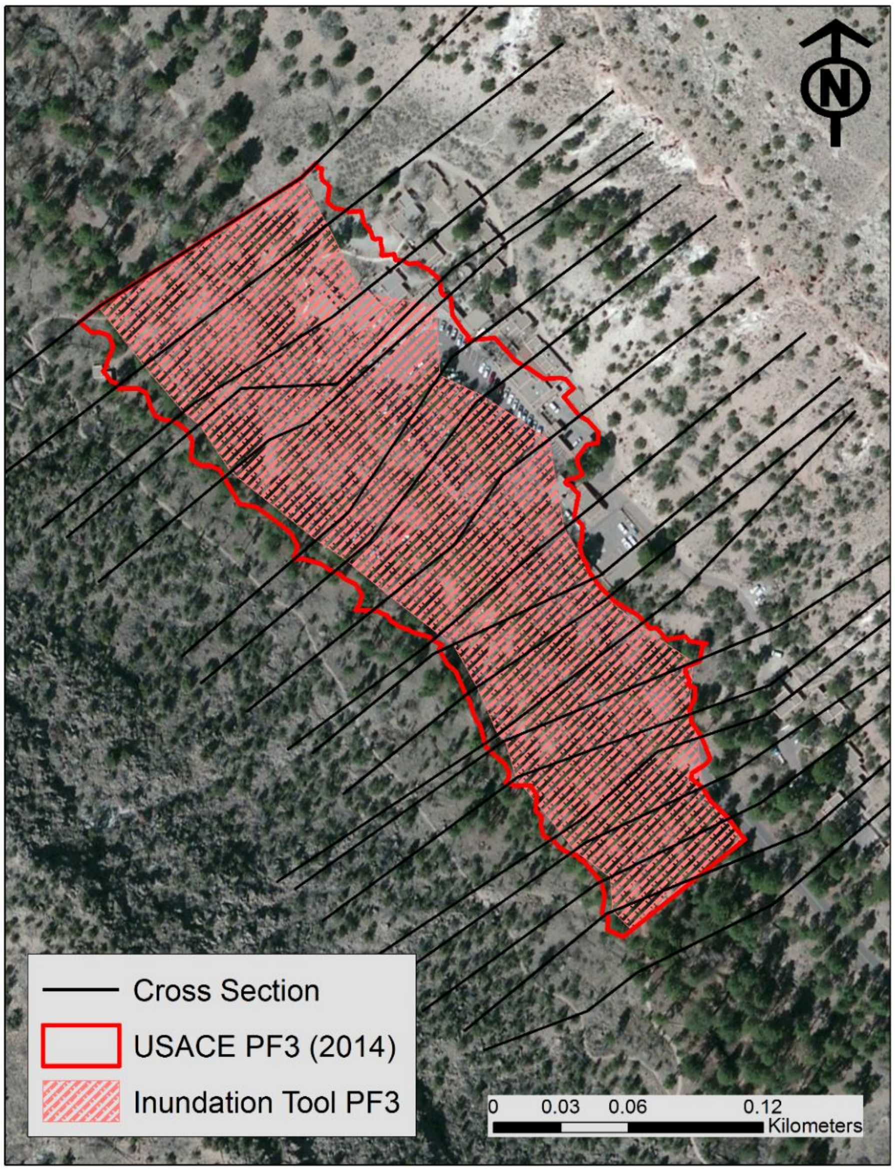

Figure 46: Inundated Extent Comparison of the USACE Report (2014) and the Inundation Tool for the 100 year Flow (Table 5)

Table 8: Comparison of Total Inundated Area from the USACE Report (2014) and the Inundation Tool for Flow Profile PF3 (Table 5)

PF3	Inundated Area (km2)	% Change
USACE (2014)	0.0375	0
Inundation Tool	0.0316	-15.7

4.1.5 LIMITATIONS AND UNCERTAINTIES

The Inundation Tool has been validated using multiple peak discharge rates under the complex and basic scenarios. Validation shows that the tool behaves well in both environments and can be used to predict simple water surface elevation in a single reach. While the tool is shown to behave expectedly, there are uncertainties and limitations of the tool that need to be considered prior to and during applications.

With regard to channel geometry, errors can be introduced during data collection and representation. In perennial streams or even ephemeral streams that happen to contain water during LiDAR survey, channel geometry can be misrepresented (Podhoranyi and Fedorcak, 2015). Even using LiDAR in dry stream beds can result in miscalculation of water surface elevation and subsequent inundated area. Cook and Merwade (2009) found that the accuracy and resolution of topographic data when used for channel geometry extraction can result in errors in the water surface elevation of up to 0.9 meters. In order to improve water surface elevation calculation, users can integrate field surveyed channel beds with DEMs (Merwade et al., 2008; Cook and Merwarde, 2009). As LiDAR technology improves these errors in hydraulic computations are shown to diminish (Dietterick et al., 2012).

Uncertainties in water surface elevation and the resolution of the topographic data will have impacts on the derived inundated boundary. The type of topographic data (raster or vector) and the resolution of the data will have direct impacts on the uncertainty of the inundated boundary (Merwade et al., 2008). Coarser vertical and horizontal resolution of a DEM will result in less accurate estimates of inundated extent. For example, a flood inundation study performed on the same region resulted in a 21% increase in inundated area when using a 30-meter DEM as compared to a 6-meter LiDAR derived DEM (Saksena, 2014).

Selecting the appropriate roughness parameters is also an important factor in hydraulic computations that can introduce error in water surface elevations. Water surface elevations can vary depending on the distribution in Manning's n between channel and over bank areas (Merwade et al., 2008); more detailed collection of Manning's n does not necessarily correspond to more accurate representation of water surface (Pappenberger et al., 2005). Guidance for selecting the appropriate roughness values can be found in many documents for different regions (Chow 1959; Barnes 1987; Phillips and Tadayon, 2006; Arcement and Schneider, 1989).

Many of these uncertainties and limitations apply to all hydraulic computation tools and the translation of their results into inundated surfaces. To minimize error with the Inundation Tool guidance on use and data collection can be found in Appendix B.

5. CONCLUSION

5.1 BENEFITS OF RESEARCH

The Storage Characterization Toolbox and the Inundation Tool were developed to make hydrologic and hydraulic modeling applications more accessible. The tools are transparent and transferable for different applications. Guidance for use of these tools should be observed as they are not applicable in all regions and there is certainly error that can be introduced when using these tools.

The Storage Characterization Toolbox has been used in Arizona and Colorado. The tool provides basic estimates of storage where structures exist so that watershed scale hydrologic models can capture their function. In one circumstance, runoff from a watershed in Colorado was observed much lower than modeled but upon inclusion of characterized erosion control structures the model was able to more closely resemble observations. Characterized storage features may not completely match real world structures, however

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Future development of the Storage Characterization Toolbox will enable users to prepare input files for AGWA/SWAT. Different formatting and parameters are required for SWAT to model ponds, therefore slight differences in the tool will be incorporated to account for those differences (Nietsch et al., 2002). The Storage Characterization Toolbox will also need to be integrated into AGWA along with a set of “generic” storage features that users can select when high-resolution DEMs are unavailable.

The Storage Characterization Toolbox will also be altered so that the tool can identify storage features on a landscape without the locations previously defined. The identification portion of the tool will prove useful for watersheds with no geospatial data regarding ponds or other storage features.

The Inundation Tool will be further developed to be more accessible to users after completing watershed simulations using AGWA. There are modules of this tool that have been used to calculated rating curves for channel cross sections as well which could be used to provide rating curves and/or estimates of channel geometry for modeling with KINEROS2. Channel geometry is an important parameter for stream channels (Leopold and Maddock, 1953). Channel geometry in AGWA/KINEROS2 are currently calculated using regression equations (Bieger et al., 2015). However, according to Miller et al. (2004) a 30% change in channel width can lead to changes in runoff ranging from 10-13%. LiDAR-derived channel geometry can improve model response especially where channel processes have a significant impact on runoff response (Hutton et al., 2012). Therefore, more accurate representations of channel geometry at a local scale could improve model results. There has been an ongoing effort to automate channel extraction and development of rating curves for improved model simulations (Semmens et al., 2006).

The inundated boundary associated with a water surface elevation has not been fully automated. The intricacy of this transformation has been addressed by others and their considerations will be incorporated into a fully automated transformation from water surface elevation to inundated boundary (Noman et al., 2001; Salimi et al., 2008).

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Appendix A: Storage Characterization Toolbox

The Storage Characterization Toolbox is composed of three separate tools. In the form of a Python Toolbox, these tools are accessible using a Python IDE or ESRI's ArcToolbox. These tools are open source and can be used and altered by others, however the previous descriptions, applications and limitations only pertain to the original code. The following tool guidelines are meant to be applied to the original code developed by the author.

Many considerations need to be taken into account when using the Storage Characterization Toolbox. Most of the considerations are relevant to the input data used for identification and characterization of existing storage features. The two main input data layers are the high-resolution DEM and the existing point features. Properties of the DEM that impact identification and characterization of existing storage features are the date of collection, the horizontal resolution and the vertical accuracy.

The date of topographic data collection will influence the identification of storage features by capturing the topography at the time of the LiDAR survey. For example, ponds will not be identified if they were not constructed at the time of the survey or historic ponds will not appear in the DEM if the condition of the features has deteriorated past recognition. The date of the DEM collection will also impact the characterization of storage features. The date of the DEM collection reflects the condition of the storage features at that point in time. For example, if the pond is newly constructed at the time of the LiDAR survey the maximum storage capacity of that pond will be at its highest while after a few large storms with sediment accumulation the storage capacity of the pond will diminish.

The horizontal resolution of the topographic data will have the largest impact on the identification of storage features. If the raster cells are coarser than small storage features the user is aiming to identify then those features will likely not be distinguishable from neighboring topography. The horizontal resolution also has an impact on the stage-storage characterization of ponds. While this impact is minor on normal polygonal ponds (e.g. circles and rectangles), in more complex ponds some detail near the boundary of the pond may be lost if the DEM resolution is too coarse. More research will be conducted to analyze the impact of DEM resolution on the identification and characterization of natural storage features.

Vertical accuracy of the DEM will impact the characterization of storage features. The vertical accuracy of LiDAR-derived DEMs is often reported with the metadata or associated documentation. This reported accuracy can vary throughout the DEM but is described as an average value across the entire generated surface. More investigation is being performed to understand the impact of that vertical accuracy as well as incorporating it into a tool that can calculate the range of potential storage capacity for a pond.

The second input of point features where known ponds exist is the second major source of error. The current version of this tool requires point locations for future modeling applications, these points are associated with identified depressions across the landscape and only those depressions associated with a point are characterized for modeling. Therefore, if the point layer available for use is outdated or does not align with the date of DEM collection the identification and characterization of storage features will be flawed. However, lacking point locations depressions can still be identified and more user involvement could enable these depressions to be modeled as storage in a watershed. The tool will therefore be developed further to work without known storage locations.

Error is inevitable when attempting to model real world processes. However, if the sources of error can be identified and understood prior to modeling then the user can translate those uncertainties into the results or discussions about the results and perform more detailed analysis when necessary. For example, a mismatch between the date of the DEM collection and the known storage locations file does not leave the user with no usable data, just a gap in data that can be filled by more detailed observations of identified features and their attributes. These identified features could then act as substitutes for unidentified features.

Appendix B: Inundation Tool

The Inundation Tool was tested using two cases and compared to known HEC-RAS outputs. During the development and testing of this tool, certain assumptions were made that can influence the outcome of model results. These details are relevant to the version of this tool that corresponds with the completion of this report. A formal guidance document will be published with the Inundation Tool that contains this information upon completion of the tool.

The most basic assumption of the tool is that flow is subcritical and therefore water surface elevation is calculated based upon user supplied discharge from the outlet to the upstream cross sections. Another assumption is uniform flow throughout the channel. Unlike HEC-RAS, the Inundation Tool does not allow users to input flow change locations so the tool should only be applied to a relatively small reach with uniform discharge. The Inundation Tool does not handle transitions between subcritical and super critical flow so if the channel has abrupt changes in properties that might cause a hydraulic jump, the user should examine those locations and the results at those locations appropriately.

Assumptions behind the Inundation Tool have directed the development of guidance for data collection and organization. The two basic inputs are discharge and channel geometry. This tool was developed with the integration of AGWA and KINEROS2 in mind so peak discharge can be extracted from KINEROS2 simulations at the downstream end of a reach. However, peak discharge can be acquired from the users preferred source.

Channel geometry is a more complex input required by the Inundation Tool. The channel geometry input is referred to as “Reach Summary” and is composed of cross section geometry files (text or comma separated value files), channel length and overbank stations (Table 9). The cross section files contain station, elevation and roughness in the form of Manning’s ‘n’ (Table 10). Manning’s ‘n’ does not need to be supplied for all station elevation pairs, if not supplied the previously designated ‘n’ will be used until a new value is supplied.

Table 9: "Reach Summary" Example for Inundation Tool

XS_ ID	LOB_ Statio	ROB_ Statio	XSFile	LOB_Length	CH_Length	ROB_Length
0	187.39	192.87	F:\InundationFinal\Validation_Final\Bandelier_January\XS24.csv	0.00	0.00	0.00
1	176.75	183.15	F:\InundationFinal\Validation_Final\Bandelier_January\XS109.csv	25.17	26.29	27.47

Table 10: Cross Section File Example Input for Reach Summary Table

XSID	Station	Elevation	MannN
18	0.00	1891.36	0.06
	0.91	1891.14	0.06
	1.83	1890.86	0.06

Channel geometry can be collected by the user from a variety of sources. The Bandelier case study made use of LIDAR DEM extracted channel cross sections with Manning’s ‘n’ calibrated to observations (USACE 2014). However, LIDAR-derived DEMs are not available across the entire United States. An alternative would be field data collection. If collecting cross sections in the field, users should focus on documenting changes in roughness within and between channel cross sections. Station-elevation pairs and changes in roughness can be collected using a method the user is comfortable with. However, one method has been employed using ESRI's ArcGIS Collector and the TruPulse 360R Laser Rangefinder.

ArcGIS Collector is an ESRI product that allows users to collect GPS data into predefined feature classes. In this case a feature class is defined that stores station, elevation pairs and roughness for each cross section. This data is then imported into ESRI's ArcMap which is important for estimating inundated extent. The laser rangefinder can be used to collect the station-elevation pairs and channel slope which can be stored into the Collector application. The method used requires two people for data collection and recording. A complete guidance document for channel geometry collection using ArcGIS Collector and a laser rangefinder will be available with the completed Inundation Tool.

While the method used for channel geometry collection is up to the user, there are many documents and reports available to guide collection. Some of these documents relate to the characterization of a stream reach and the collection of geometry and roughness data along stream reaches (Chow 1959; Barnes 1987; Hedman and Osterkamp, 1982; US-ACEIWR-HEC 1990; Harrelson et al., 1994). While collecting data relevant to channel geometry, users should be cognizant of features that may impact flow.