The Impact of Small Ponds on Streamflow Response and Sediment Yield

D. Phillip Guertin, Professor, University of Arizona, Tucson, AZ, dpg@email.arizona.edu
Jane Patel, GIS Analyst, Tucson Water, Tucson, AZ, jane.patel@tucsonaz.gov
Lainie Levick, Principal Research Specialist, University of Arizona, Tucson, AZ, llevick@email.arizona.edu
Haiyan Wei, Assistant Research Scientist, University of Arizona, Tucson, AZ, haiyan.wei@ars.usda.gov
David C. Goodrich, Research Hydraulic Engineer, USDA Agricultural Research Service, Tucson, AZ, Dave.Goodrich@ars.usda.edu
I. Shea Burns, Senior Research Specialist, University of Arizona, Tucson, AZ, shea.burns@ars.usda.gov
Carl Unkrich, Hydrologist, USDA Agricultural Research Service, Tucson, AZ, carl.unkrich@ars.usda.gov

Abstract

In the western United States the landscape is dotted with small ponds, many of them man-made (farm ponds, stock tanks, sediment basins, erosion control basins, flood control basins, etc.), which capture both streamflow and sediment. In these landscapes it is not uncommon to have over 50% of a watershed area behind storage. Although small ponds can have a significant impact on a watershed's water balance and sediment balance, they are often not included in watershed assessments because they are difficult to locate and characterize. However, new technology, in the form of high resolution imagery and LiDAR-derived products, can facilitate the tasks of locating and characterizing ponds. The Automated Geospatial Watershed Assessment Tool (AGWA) was used to model the runoff and sediment yield. AGWA (see: www.tucson.ars.ag.gov/agwa or https://www.epa.gov/water-research/automated-geospatial-watershed-assessment-agwa-tool-hydrologic-modeling-and-watershed) is a GIS interface jointly developed by the USDA-Agricultural Research Service, the U.S. Environmental Protection Agency, the University of Arizona, and the University of Wyoming to automate the parameterization and execution of a suite of hydrologic and erosion models (RHEM, KINEROS2 and SWAT). A new tool has been developed for AGWA to efficiently identify and characterize small ponds. The use of the tool is illustrated in several case studies that highlight the importance of ponds in determining water and sediment balance in western rangeland watersheds.

Introduction

The abundance of small artificial ponds (farm ponds, stock tanks, sediment basins, erosion control basins, flood control basins, etc.) constitutes a major human alteration of the hydrologic landscape. The total number of such features across the conterminous United States has been estimated to be between 2.6 and the 9 million, with densities in some areas exceeding 5 per km^2 (Renwick et al. 2006). Ponds not only capture water, but also are important sinks for sediment, carbon, and nutrients. In the western United States ponds are commonly used to water livestock. In these landscapes it is not uncommon to have over 50% of a watershed area behind storage. The influence of small ponds on water yield, peak flow and sediment yield is well documented (Berg et al. 2016, Goff and Gentry 2006, Milne and Young 1989, Nichols et al. 2013, Renwick et al. 2005, Smith et al. 2002). In general, small ponds tend to decrease water yield, peak flows and sediment yield from watersheds. The degree of change is a function of the density and size of ponds within the watershed. Although small ponds can have a significant impact on a watershed's water balance and sediment balance, they are often not included in watershed assessments because they are difficult to locate and characterize. This is especially true in the semi-arid rangelands in the western United States where the ponds are often dry for long periods of time, hence remote sensing methods used in more mesic and humid regions are ineffective because there is no water signature.

The paper will describe the use of the Automated Geospatial Watershed Assessment tool (AGWA; Goodrich et al. 2012) for watershed assessments that include evaluating the impact of ponds. The paper will review an application (Storage Characterization Toolkit) developed within AGWA to quickly identify and characterize ponds using a digital elevation model (Barlow 2017). The paper will review the results from two watershed assessments conducted in Arizona and Colorado that examined the influence of ponds.

AGWA Overview

AGWA (Goodrich et al. 2012) is a Geographic Information System (GIS) based watershed modeling tool. The guiding principles for the development of AGWA were that it: 1) provides simple, direct, transparent, and repeatable parameterization routines through an automated, intuitive interface; 2) is applicable to ungauged watersheds at multiple scales; 3) evaluates the impacts of management and is useful for scenario development; and, 4) uses free and commonly available GIS data layers.

The models currently incorporated in AGWA are KINEROS2 (K2 – KINematic runoff and EROsion model, Smith et al. 1995, Goodrich et al. 2012), RHEM (Rangeland Hydrology and Erosion Model, Hernandez et al. 2017), and SWAT (Soil and Water Assessment Tool version 2000 and version 2005, Arnold and Fohrer 2005). AGWA supports modeling along a continuum of spatial and temporal scales, ranging from hillslopes (~hectares) to large watersheds (>1000 km^2) and from individual storm events (minute time steps) to continuous simulation (daily time steps over multiple years). AGWA supports the parameterization and execution of hydrologic models for watershed modeling efforts by performing the following tasks: watershed delineation; watershed discretization into discrete model elements; watershed parameterization; precipitation definition; simulation creation; simulation execution; and simulation results visualization (). Various data are required to support this functionality, including: a raster-based DEM (digital elevation model); a polygon soil map (NRCS SSURGO, NRCS STATSGO, or FAO soil maps); and a classified, raster-based land cover (NLCD, NALC, and GAP/LANDFIRE datasets are supported via provided look-up tables; however, other datasets may also be used if accompanied with a related look-up table). AGWA does not require observed precipitation or runoff to drive the models when used for relative assessment/differencing between scenarios. For precipitation input, AGWA can use user-defined depths and durations, user-defined hyetographs, or design storms to drive the K2 model, and included weather station-based generated, daily precipitation (U.S. only) to drive the SWAT model.

AGWA is an add-in to ESRI ArcGIS 10.x and 9.x (http://www.esri.com/arcgis/about-arcgis). It is a free download from the website www.tucson.ars.ag.gov/agwa as a "package" containing all tables and models required to run AGWA. AGWA is best used as a relative change tool (i.e., preversus post-change) unless careful model calibration, supported by high quality observations, is performed.

AGWA was designed to support watershed analysis and assessment. AGWA applications include landscape change assessments (Hernandez et al. 2010, Kepner et al. 2008, Levick 2017), rangeland assessments (Goodrich et al. 2011, Weltz et al. 2011), post wildland fire assessments (Goodrich et al. 2012), sustainable urban development (Guertin et al. 2015, Korgaonkar et al. 2018), and flood risk assessment (Yatheendradas et al. 2008, Norman et al. 2010).

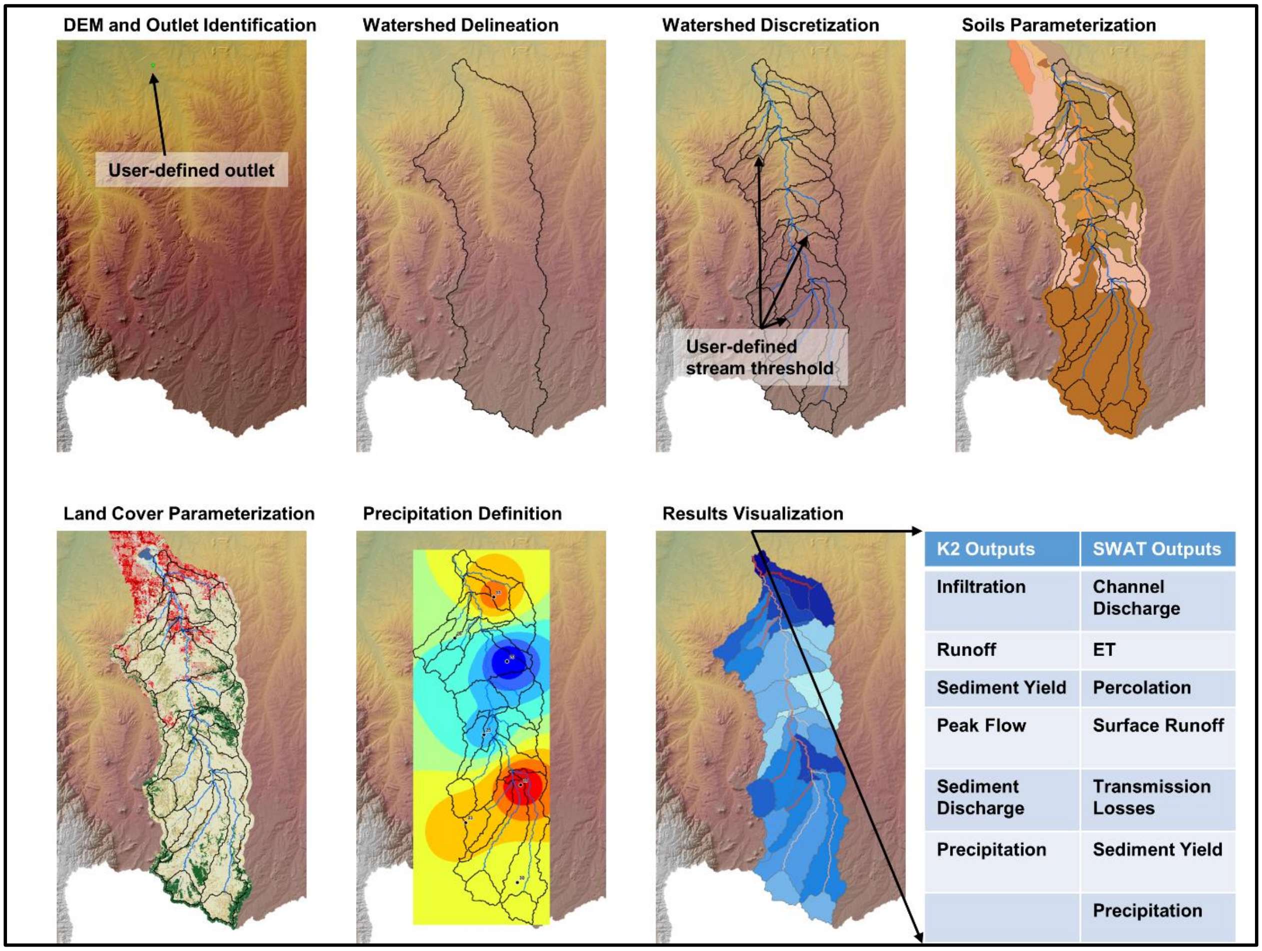

Figure 1. The required steps in AGWA to perform a watershed assessment. A DEM is used to delineate the watershed and subdivide it into model elements (i.e. hillslopes and channels for K2 and subwatersheds and channels for SWAT). The model elements are parameterized based on the DEM, soils, and land cover layers. The precipitation input is then selected from varies sources. After the model is executed, the results are imported and visualized in the GIS.

Storage Characterization Toolkit

Most landscapes will have natural or man-made ponds, lakes or reservoirs. In order to represent a watershed properly for any assessment the ponds, as well as lakes and reservoirs, must be included or the estimates for water and sediment yield will be over-estimated. The Storage Characterization Toolkit (SCT) was developed for AGWA to facilitate and automate the inclusion of pond features into the K2 and SWAT models (Barlow 2017).

The SCT was designed to identify and characterize existing water storage structures as well as to plan for the future installation of water storage structures. The SCT was developed using a Python Toolbox in ESRI ArcMap so that geospatial layers could be organized, used and viewed by the user throughout the process. The SCT has three components:

1. Identify and characterize existing storage,
2. Calculate the discharge from the structure, and
3. Export files for input to K2.

The user must first identify the location of the existing or proposed structure. Existing structures can be identified using high resolution imagery with or without additional information on structure locations. The location of ponds may also be determined using the SCT. Using a digital elevation model (DEM) and the ESRI ArcMap Sink Tool areas of potential ponds can be identified as the low points in the terrain with no drainage. A user set threshold can be used to remove sinks that are too small to be ponds. The software will identify the terrain sinks, but the user must still review identified sinks to confirm they are ponds (Figure 2).

For an existing structure, the dam location (visually identified as a linear feature in the imagery) and the height of the dam at its lowest point must be determined using a digital elevation model (DEM). For a proposed structure the dam locations can be drawn perpendicular to the channel and the dam height determined based on site conditions and objectives.

A protocol was then developed to characterize stage-storage relationships for each water storage feature. Automation of these two steps resulted in the Identify and Characterize Existing Storage tool in the SCT. Automation of this process allows a large number of ponds, across a wide spatial extent, to be identified and characterized in a single batch job.

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 2).

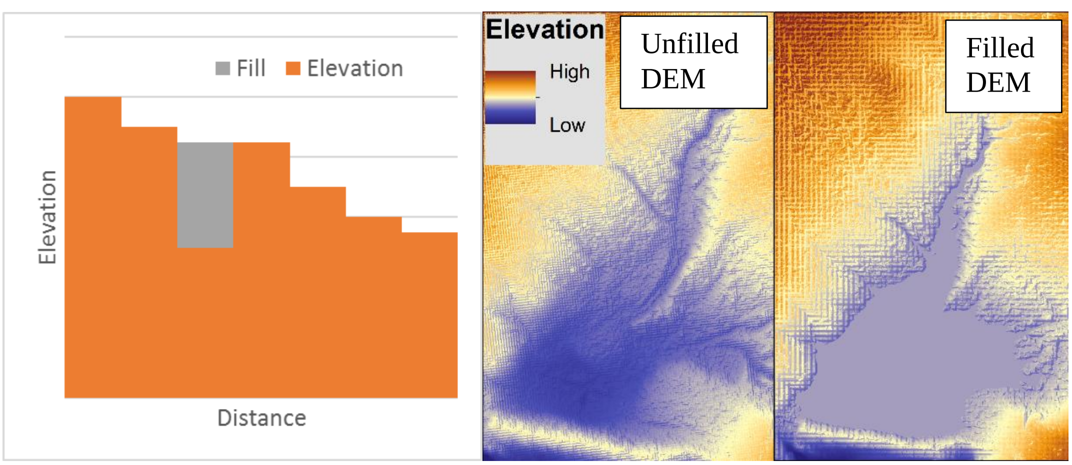

Figure2. Fill Process as it removes sinks in theory (left) and in reality (right).

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 ESRI ArcMap 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 (Figure 3). The final product is a stage-volume curve for the pond.

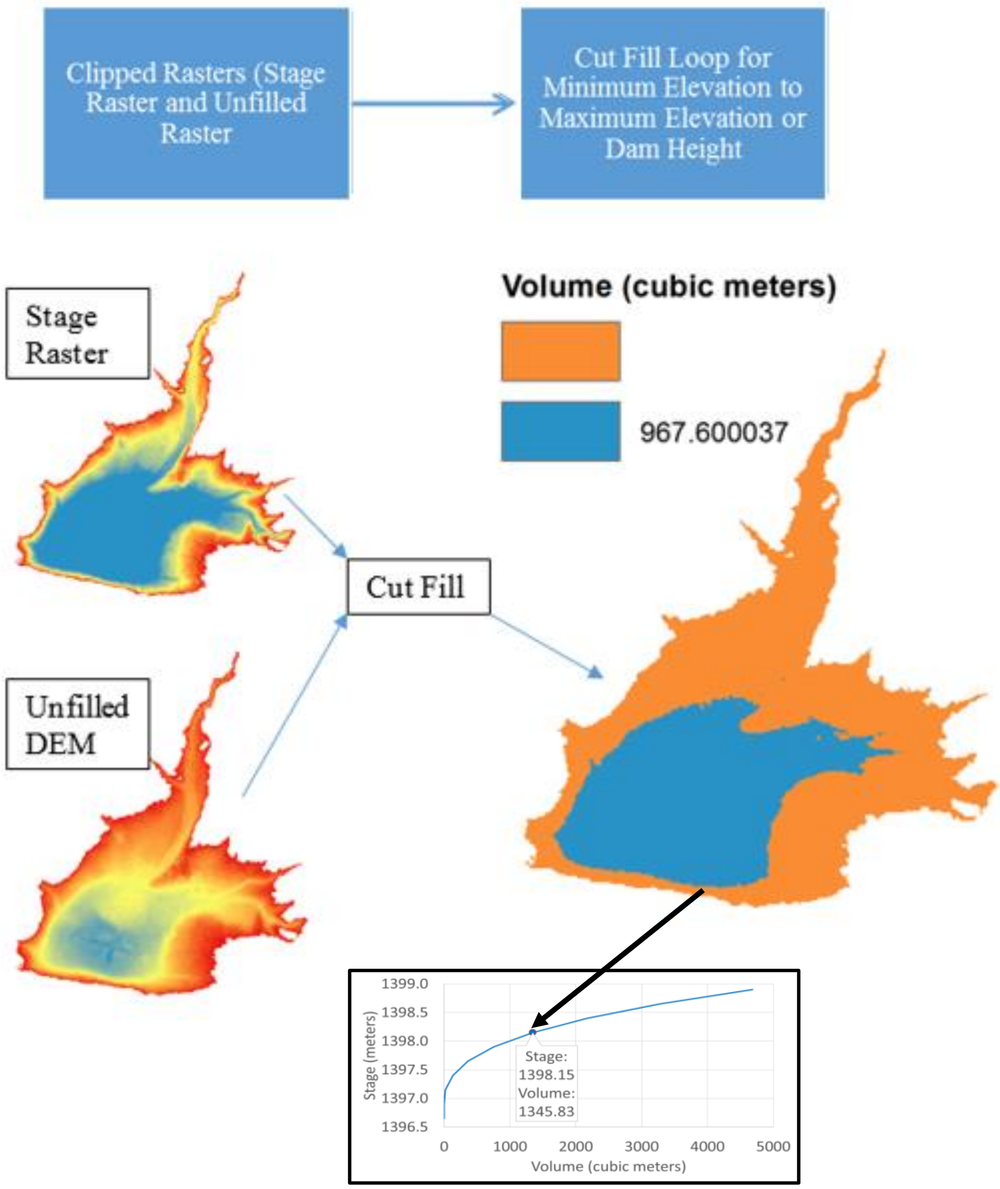

Figure 3. Cut-Fill function is part of a loop that calculates surface area and volume for pond stage from minimum elevation to maximum elevation. The final result is the stage-volume curve for the pond.

For validation, the Storage Characterization Toolbox was used to characterize stage-storage relationships at 0.25 meter increments for Pond 208 on the Walnut Gulch Experimental Watershed (WGEW). 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 (Nagle and Wright 2016).

Percent error was calculated based upon relative stage for each Pond 208 (Table 1). 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 was maintained. The complex validation series for pond 208 under predicted volume by at least 20%. While error exists in this validation case studies, the general stage-storage relationship is well captured.

Table 1. 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

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

The basic equations that calculate discharge from stage above the outlet structure are Manning's equation for pipe flow (Equation 1; non-pressurized), the broad-crested weir equation which accounts for discharge at earthen spillways (Equation 2) and the sharp-crested weir equation (Equation 3) (Crowe et al., 2001).

$$Q = \frac{1}{n} A R^{\frac{2}{3}} S_o^{\frac{1}{2}} \quad (1)$$

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

$$Q = 0.385 L \sqrt{2g} H^{\frac{3}{2}} \quad (2)$$

where: L = length of the weir normal to the direction of water flow (m), g = acceleration due to gravity (9.81 m/s^2), and H = stage of water above the spillway (m).

$$Q = \frac{2}{3} C_d \sqrt{2g} L H^{\frac{3}{2}} \quad (3)$$

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), and 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 for AGWA/K2. 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. K2 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. The series of tools in the Storage Characterization toolbox supply K2 with the required pond inputs for AGWA to configure a simulation with storage elements.

Application Examples

Two examples of watershed assessments that utilized the SCT have been completed in Arizona and Colorado. A rangeland assessment was conducted on the Cienega Creek Watershed in southeastern Arizona. In the assessment the impact of a mechanical brush removal treatment on sediment yield from a small watershed was compared to the impact of a stock pond at the outlet of the small watershed. Figure 4 shows that although the mechanical brush removal treatment has a positive impact on sediment yield the sediment storage in the stock pond has far greater impact. The results illustrate that although the mechanical brush removal treatment had other benefits such as increased forage production and decreased soil erosion, the stock pond impact on sediment yield and downstream water quality is very important and must be considered in a watershed analysis and assessment.

The second assessment was conducted on the U.S. Army Pinon Canyon Maneuver Site (PCMS) in Colorado. To mitigate the impact of military training exercises on downstream water quality and to control gullying PCMS has installed Erosion Control Dams (ECDs) across the installation. One watershed on PCMS, Taylor Arroyo (125.6 square kilometers), has 111 ECDs or a pond density of 0.88 ponds per square kilometer (Figure 5). There are over 400 ECDs on PCMS. The SCT was used to identify and characterize the ECDs on Taylor Arroyo and K2 in AGWA was used to evaluate the effectiveness of the ECDs in protecting downstream water quality.

Figures 5 and 6 illustrate the impact of the ECDs on Taylor Arroyo at two locations within the watershed, stream reach #954 in the upper portion of the watershed and the Taylor Arroyo watershed outlet. The figures show the impacts of the dams on peak runoff (Figure 5) and peak sediment yield (Figure 6) from a 10-year return period, one hour, 41.66mm rain event. The ECDs decreased the peak discharge by 66% (from 53.12 m^3/s to 18.20 m^3/s) at stream reach #954 and by 35% (from 77.14 m^3/s to 49.94 m^3/s) at the watershed outlet. The ECDs decreased the peak sediment yield by 88% (from 2217.72 kg/s to 257.06 kg/s) at stream reach #954 and by 57% (from 2914.61 kg/s to 1254.43 kg/s) at the watershed outlet.

The runoff volume for stream reach #954 was 86,576 cubic meters without ponds and 69,358 cubic meters with ponds, a 20% decrease in runoff. The sediment yield for stream reach #954 was 4,031,593 kilograms without ponds and 925,705 kilograms with ponds, a 77% decrease in sediment yield. The runoff volume at the watershed outlet was 381,012 cubic meters without ponds and 286,448 cubic meters with ponds, a 25% decrease in runoff. The sediment yield for stream reach #954 was 14,306,700 kilograms without ponds and 8,271,455 kilograms with points, a 42% decrease in sediment yield. As this single event indicates the high density of ponds in the Taylor Arroyo Watershed caused a substantial decrease in runoff and sediment yield, protecting downstream water quality, and highlighting the importance of including ponds in conducting a watershed assessment.

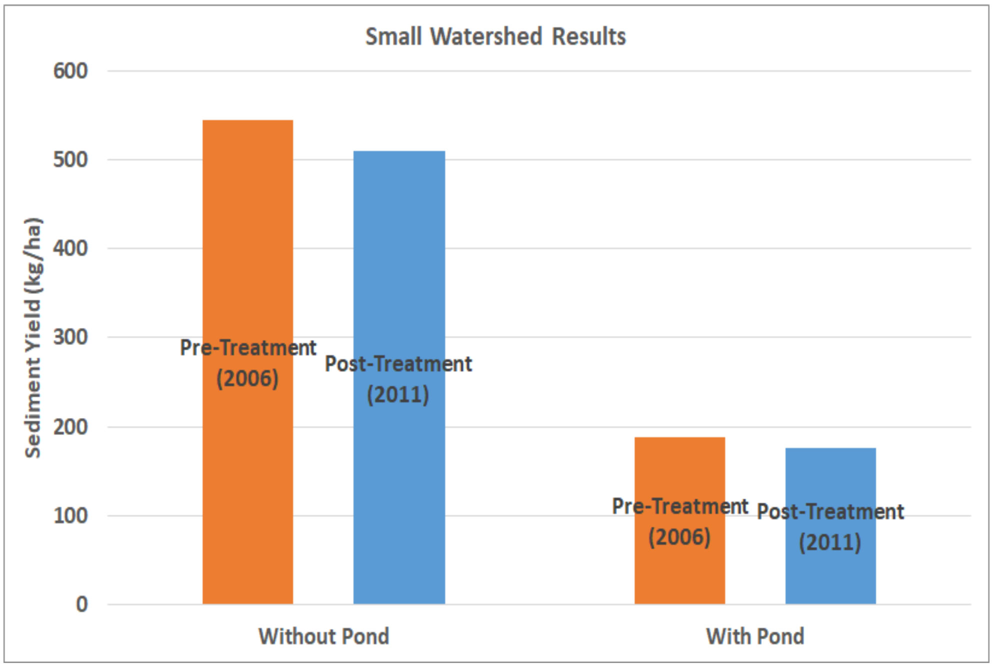

Figure 4. Graph showing the sediment yield pre- and post-treatment and with and without a stock pond for the small watershed on the Cienega Creek Watershed in southeastern Arizona. Mechanical brush removal treatment was performed in the winter of 2010-2011, with an immediate reduction in brush cover observed in 2011, resulting in reductions of sediment yield. Installation of a stock pond reduced sediment in both pre- and post-treatment scenarios, with a greater impact than that of the treatment.

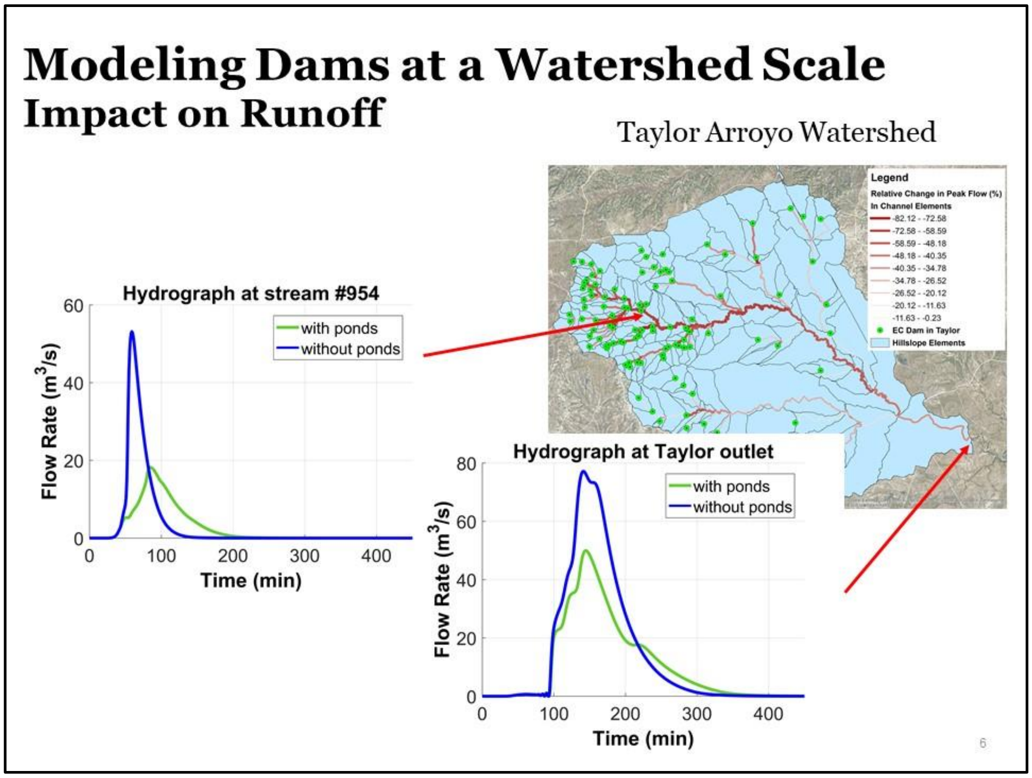

Figure 5. Impact of erosion control dams on hydrology in the Taylor Arroyo Watershed on the U.S. Army Pinon Canyon Maneuver Site, Colorado.

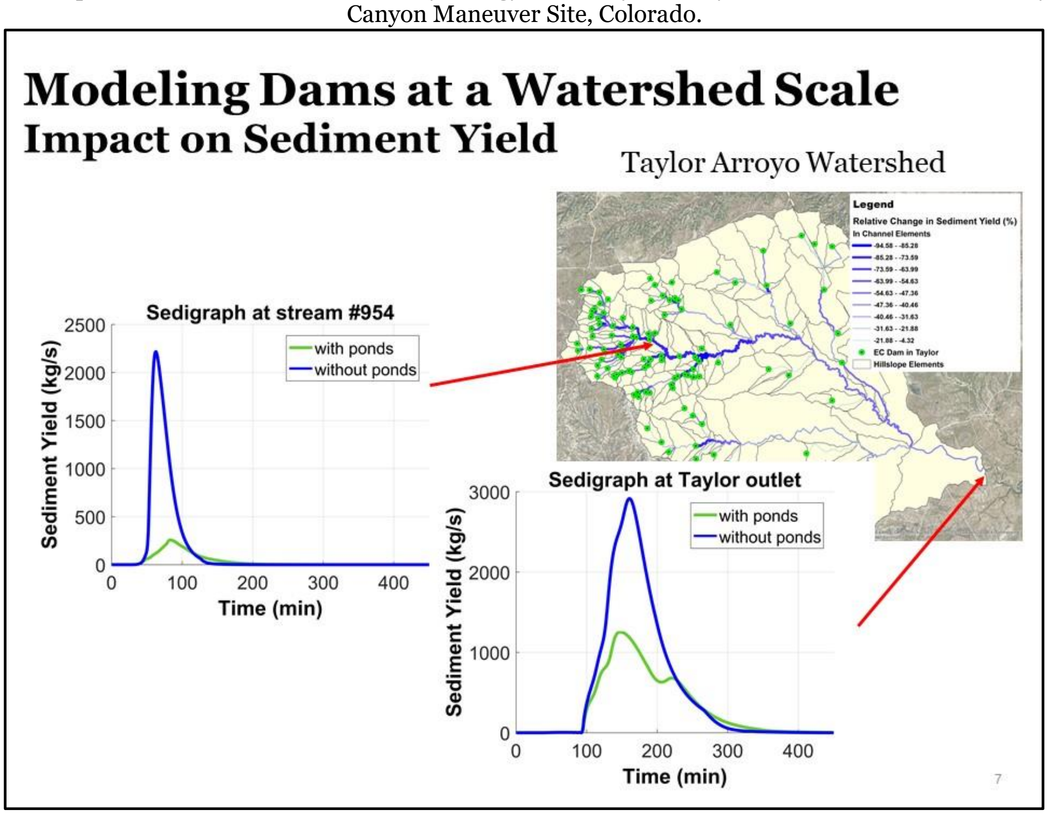

Figure 6. Impact of erosion control dams on sediment yield in the Taylor Arroyo Watershed on the U.S. Army Pinon Canyon Maneuver Site, Colorado.

Conclusions

Ponds can have a significant impact on runoff and sediment yield and it is important to include ponds in any watershed assessment. The SCT provides an effective process for identifying and characterizing ponds for inclusion into hydrologic and erosion models.

Acknowledgements

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