

## THE KINEROS2 – AGWA SUITE OF MODELING TOOLS

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### INTRODUCTION

KINEROS2 (K2) originated in the 1960s as a distributed event-based rainfall-runoff erosion model abstracting the watershed as a cascade of overland flow elements contributing to channel model elements. Development and improvement of K2 has continued for a variety of projects and purposes resulting in an informal suite of K2-based modeling tools. Like any detailed, distributed watershed modeling tool, the K2 suite of tools can require considerable time to delineate watersheds, discretize them into modeling elements and then parameterize these elements. These requirements motivated the development of the Automated Geospatial Watershed Assessment (AGWA) tool. This ESRI ArcGIS-based tool uses nationally available, GIS data layers to parameterize, execute, and visualize results from the SWAT and KINEROS2 models. By employing these two models, AGWA can conduct watershed modeling and assessments at multiple time and space scales. The objectives of this paper are to: 1) Provide background in the development of K2 and AGWA; 2) Provide an overview of new features; 3) Briefly describe recent novel applications; and 4) Discuss plans for future model improvements.

**KINEROS2 / (K2) – History:** The USDA-Agricultural Research Service (ARS) initiated development of KINEROS2 (KINematic runoff and EROSion), or K2 in the late 1960s as a distributed event-based rainfall-runoff model. Conceptualization of the watershed in this form enables solution of the flow-routing partial differential equations in one dimension. Rovey (1974) coupled interactive infiltration to this model and released it as KINGEN. After substantial validation using experimental data, KINGEN was modified to include erosion and sediment transport as well as a number of additional enhancements, resulting in KINEROS, which was released in 1990 (Woolhiser et al., 1990; Smith et al., 1995).

KINEROS has been applied over a wide range of scales, from plot (<10 m<sup>2</sup>) to large watersheds on the order of a thousand square kilometers. However, it has only been thoroughly validated for watersheds on the order of a hundred square kilometers where sufficient observations exist in

experimental watersheds (Goodrich et al., 2004). It was originally developed as an event-based model. Simulation times can vary from tens of minutes for small plots to more than a day for larger watersheds depending on the respective runoff response time. Computational time scales are dictated by adherence to the Courant condition (Roberts, 2003). Computational time intervals are automatically adjusted in the current model implementation, and the user can select the time interval at which simulation output is reported. Subsequent research with and application of KINEROS has led to additional model enhancements and a more robust model structure, which have been incorporated into the latest version of the model: KINEROS2 (K2).

Specialized versions of the event-based KINEROS2 model range from a flash-flood forecasting tool and the continuous KINEROS-OPUS biogeochemistry tool. The K2 flash flood forecasting tool is being tested with the National Weather Service (NWS) to provide timing and magnitude of peak flows from rapidly responding flash flood storms, that is useful information currently not available using NOAA/NWS flash flood forecasting methodologies at NWS offices. It assimilates the NWS Digital Hybrid Reflectivity (DHR) radar product in near-real time and can simultaneously run ensembles using multiple radar-reflectivity relationships (Unkrich et al., 2010). In addition to simulation of runoff and sediment transport, KINEROS-OPUS (K2-O2) can simulate management, plant growth, nutrient cycling (nitrogen, phosphorus and carbon), water quality and chemical runoff (Massart et al., 2010). K2 has also been coupled with a continuous energy-balance snow model and lateral saturated subsurface transport (K2-SM-hsB; Broxton et al., 2014). In addition, K2 has been used as the engine for runoff generation and routing for the overland transport of manure-borne pathogens and indicator organisms (K2-STWIR). STWIR was released as a separate software package (Guber et al. 2010) followed by sensitivity and uncertainty analysis (Guber et al., 2014). A relatively thorough overview of the theoretical background of K2, including several applications, is presented by Semmens et al. (2008). More recently, Goodrich et al. (2012) provided further details on K2 and included a discussion of model limitations, expectations, and strategies and approaches for K2 calibration and validation. K2 is open-source software that is distributed freely, along with associated model documentation and example input files ([www.tucson.ars.ag.gov/kineros](http://www.tucson.ars.ag.gov/kineros)).

**AGWA History and Overview:** The Automated Geospatial Watershed Assessment (AGWA) tool was initially released in 2002 (Miller et al., 2002) to support the parameterization and execution of K2/KINEROS2 and the Soil Water Assessment Tool (SWAT; Arnold and Fohrer, 2005). AGWA parallels other efforts (ArcSWAT, BASINS, MWSWAT, HEC-GeoHMS, ArcAPEX) that use Geographic Information Systems (GIS) to support the application of hydrologic models, but distinguishes itself by offering models that allow it to be used on a continuum of spatial and temporal scales, ranging from hillslopes (~hectares) to large watersheds (>1000 km<sup>2</sup>) and from individual storm events (minute time steps) to continuous simulation (daily time steps over multiple years). Like K2, AGWA is open-source software available from the AGWA website (Miller et al., 2007; [www.tucson.ars.ag.gov/agwa](http://www.tucson.ars.ag.gov/agwa)). This site also contains documentation, supporting references, tutorials, and a user forum. Support for K2 and AGWA is typically accomplished via the user forum, e-mail, and phone communication. We also welcome visitors to the USDA-ARS Southwest Watershed Research Center to work with model developers on application projects and/or model improvements.

The development of AGWA has been a joint effort with the USDA-ARS SWRC, US EPA LEB, University of Arizona, and University of Wyoming. It has been under continual development to incorporate new features and functionality and has seen multiple major and minor releases, including but not limited to: AGWA 1.3 for ArcView 3.x in 2002 (initial AGWA release); AGWA 2.0 for ArcGIS 9.x in 2007 (initial ArcGIS/ArcMap 9.x release); AGWA 2.4 for ArcGIS 10.x in 2011 (initial ArcGIS/ArcMap 10.x release); and AGWA 3.x for ArcGIS 10.x in 2013 (current major release for ArcGIS/ArcMap 10.x).

The guiding principles for the development of AGWA include: 1) that it provides simple, direct, transparent, and repeatable parameterization routines through an automated, intuitive interface; 2) that it is applicable to ungauged watersheds at multiple scales; 3) that it evaluates the impacts of management and be useful for scenario development; and 4) that it uses free and commonly available GIS data layers. From the very first release in 2002 to the most current release in 2015, AGWA has followed these guidelines to ensure it can be used by the widest possible audience, which, to name a few, includes multiple EPA regions (Burns et al., 2013a; Barlow et al., 2014; and Korgaonkar et al., 2014), land use impact studies on water resources in Africa (Baker and Miller, 2013), predictive modeling of oil and gas development impacts (Miller et al., 2012), and numerous Federal Agencies working collaboratively on Dept. of Interior National Interagency BAER (Burned Area Emergency Response) teams modeling hydrological impacts of wildfire (EPA, 2014; Goodrich et al., 2012) and for the Natural Resources Conservation Service (NRCS) Conservation Effects Assessment Project (CEAP).

AGWA has been integrated into the EPA Council for Regulatory Environmental Modeling (CREM) Models Knowledge Base<sup>1</sup> as well as the Registry of EPA Applications, Models and Databases (READ)<sup>2</sup>. All versions of AGWA have been included in the Downloadable GIS Tools section of the EPA EnviroAtlas<sup>3</sup>. In addition a Certificate of Networthiness (CoN) has been obtained for AGWA that enables its use on U.S. Army cyber infrastructure. Additional information and details on AGWA are presented in the following section as there has not been a recent detailed publication on AGWA unlike K2 (Goodrich et al., 2012).

**AGWA Data Requirements and Process: AGWA supports watershed modeling efforts by including functionality that steps through all stages of a watershed assessment, including: watershed delineation; watershed discretization into discrete model elements; watershed parameterization; precipitation definition; model simulation creation; model execution; and model 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 are supported); and a classified, raster-based land cover (NLCD, NALC, and SWGAP datasets are supported via provided look-up tables, however other datasets may also be used if accompanied with a respective look-up table). AGWA does not require observed precipitation or runoff to drive the models when used for relative assessment/differencing between scenarios, and can use user-defined**

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<sup>1</sup>[http://cfpub.epa.gov/crem/knowledge\\_base/crem\\_report.cfm?deid=75821](http://cfpub.epa.gov/crem/knowledge_base/crem_report.cfm?deid=75821)

<sup>2</sup>[http://ofmpub.epa.gov/sor\\_internet/registry/systmreg/resourcedetail/general/description/description.do?infoResourcePkId=11982](http://ofmpub.epa.gov/sor_internet/registry/systmreg/resourcedetail/general/description/description.do?infoResourcePkId=11982)

<sup>3</sup><http://enviroatlas.epa.gov/enviroatlas/tools/agwa.html>

depths and durations, user-defined hyetographs, or design storms to drive K2, and included weather station-based generated, daily precipitation (U.S. only) to drive SWAT. However, high-quality rainfall-runoff observations are required for calibration and confidence in quantitative model predictions (Goodrich et al., 2012). The AGWA process is described in more detail below and in

**Figure 1.**

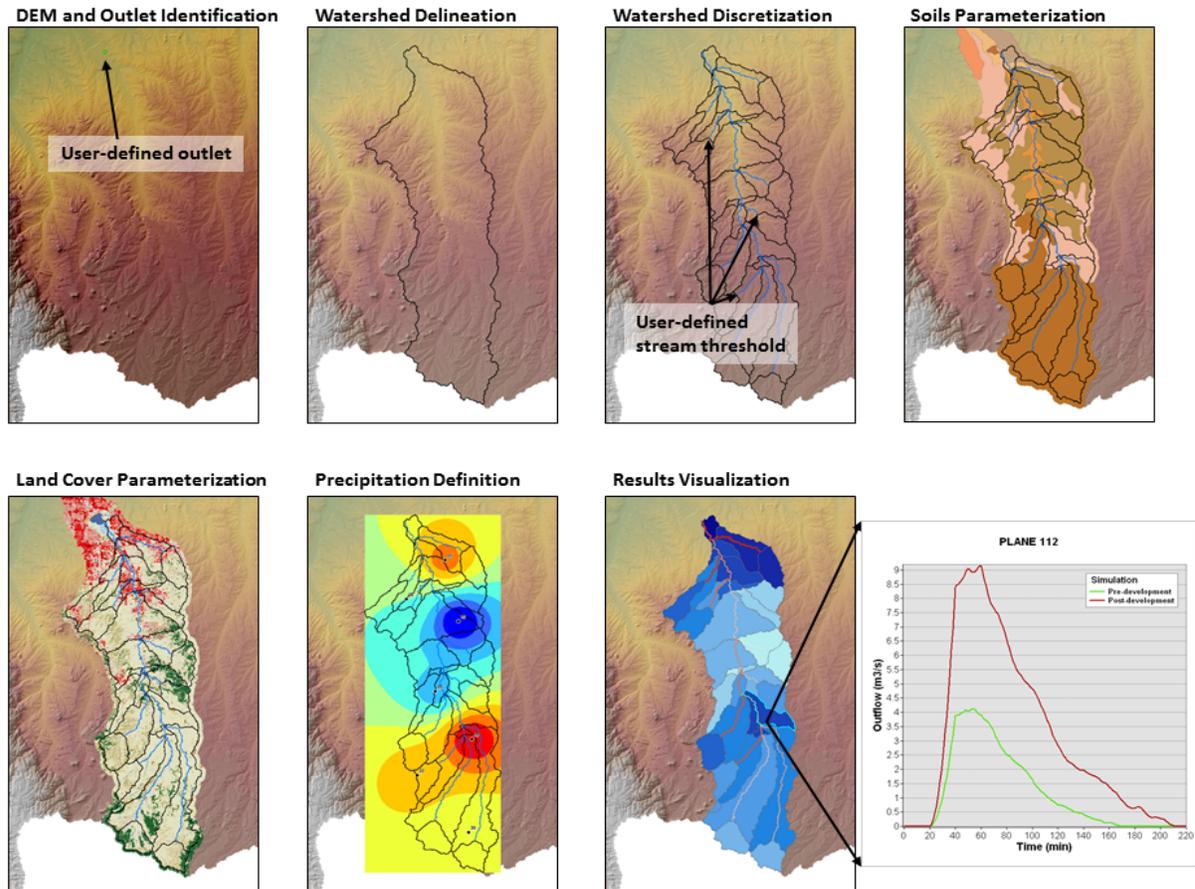


Figure 1 The required steps in AGWA to perform a watershed assessment. A DEM is used to delineate the watershed, subdivide it into model elements, and parameterize the elements in conjunction with the soils and land cover layers. Precipitation drives the model and model results are imported and visualized in the GIS. For any model element selected hydrographs and sedigraphs can be displayed (lower right).

**Watershed Delineation:** Watersheds delineation is performed by, at a minimum, selecting a workspace location, delineation name, DEM, and watershed outlet. If the DEM has not been filled to ensure proper drainage, AGWA will fill it. Likewise, if a flow direction raster and a flow accumulation raster have not been selected, AGWA will create them in the delineation process. Selecting a watershed outlet entails selecting a pre-existing outlet point or by defining an outlet and snapping it to the highest flow accumulation value within a user-defined search radius. Alternatively, the user can delineate a group of watersheds using multiple pre-existing outlet points or by selecting an area of interest (such as a political, management, or administrative

boundary) and defining a maximum extent for the group of watersheds. Watershed delineations are stored as feature classes within a geodatabase created during this step.

**Watershed Discretization:** Watershed discretization is performed by defining a stream network for the watershed delineation and subdividing the watershed based on the stream network. Various methods exist for creating the stream network, including: a minimum accumulated area required for stream definition (contributing source area, or CSA, approach); a minimum accumulated flow length required for stream definition (flow length approach); or a pre-existing stream network approach where stream initiation is defined by the upstream most points of a user-selected, existing stream network snapped to the underlying stream network of the DEM (the upstream most points are snapped to the highest flow accumulation or highest flow length within a user-defined snapping distance). Model selection is also defined during the watershed discretization step because the models have non-compatible watershed representations. Watershed discretizations are stored as feature datasets containing single polygon, polyline, and nodes feature classes within the geodatabase created in the watershed delineation.

**Watershed Parameterization:** Watershed parameterization is performed by intersecting the model elements from the watershed discretization with the DEM, a DEM-derived slope raster, a soils polygon, and a land cover raster. The model elements are then characterized using the topographic, soil, and land cover properties from the layers they intersect and these parameters are stored in related tables (with a parameterization name to identify it) within the geodatabase created in the watershed delineation.

**Precipitation Definition:** Precipitation definition is performed differently for each model because of the difference between event-based precipitation versus continuous daily precipitation. For K2, precipitation is created using user-defined hyetographs, user-defined depths and durations, pre-defined design storms, or raster-based precipitation surfaces representing return period-duration depths. For non-user-defined hyetographs, K2 precipitation events can be represented with a uniform intensity or with an intensity derived from the SCS Type II distribution. For SWAT, precipitation is created by selecting one or more rain gages and providing a continuous, daily rainfall record for each gage. If more than one rain gage is selected, AGWA will create Thiessen polygons to intersect with the watershed discretization to area-weight the depth assigned to each subwatershed. For all models, precipitation is stored as flat text files in a (precip) directory that is nested in the workspace location defined in the watershed delineation step under subdirectories named for the watershed delineation and watershed discretization.

**Model Simulation Creation:** Model simulations may be created following the precipitation definition step for K2, or after the watershed parameterization step for SWAT if the model will be driven by weather station generated daily rainfall values. Creating K2 simulations requires defining a simulation name, and selecting a watershed discretization, a parameterization of that discretization, and a precipitation file created for that discretization. Optionally, parameter multipliers may also be defined for K2. For SWAT, similar steps are required, but additional selections must also be made. The user may elect to forgo selecting a precipitation file (and also a daily temperature file) and instead generate daily precipitation (and temperature) using a user-selected weather station. The user must also define the start and end date of the simulation as

SWAT is a continuous model. Optionally, the user may define subbasin adjustment factors, groundwater parameters, crop types, and a results output timestep (the model runs on a daily timestep regardless of the results output timestep). For both models, simulations are stored as flat files in a directory named for the simulation name that are nested in the workspace location defined in the watershed delineation step under subdirectories named for the watershed delineation and watershed discretization.

**Model Execution:** Model execution is performed by selecting a watershed discretization and a simulation already created for that discretization. Model execution is separated from model simulation creation to provide the user the ability to edit model input files following simulation creation but prior to model execution. This capability allows the user to rerun existing simulations limitlessly if changes are made to the simulation outside of AGWA.

**Model Results Visualization:** Model results visualization is performed by selecting a watershed discretization, importing/re-importing completed simulations, and selecting model outputs to map onto the watershed discretization. A variety of outputs can be displayed for any upland or channel model element including major water balance components and fluxes. K2 can also display hydrographs for simulations. Both models can calculate differences between two simulations as either an absolute difference or a percent difference.

## NEW FEATURES

**AGWA:** AGWA 3.x, the current major release cycle (i.e. the left-most number of the version number) of AGWA was released in 2013 (Burns et al., 2013b). It incorporates new functionality, new models, user interface changes, usability improvements, and bug fixes. With the move to ArcGIS 10.x, deploying AGWA offered the opportunity to switch from a custom installation program that registered the AGWA components so that they could be recognized by ArcMap to using ESRI ArcGIS add-in functionality. The add-in deployment process is both faster and more user-friendly. The move to AGWA 3.x also saw the opportunity to support more raster and vector input types in AGWA, also resulting in a more user-oriented experience.

The upgrade from AGWA 2.x to AGWA 3.x entailed refactoring of the look-up tables used to store parameterizations so that they are more relational. This rivals the upgrade from AGWA 1.x to AGWA 2.x, when delineations and discretizations moved from a GRID and shapefiles into feature classes within a geodatabase. The significance of this upgrade in AGWA 3.x is the flexibility it allows to create and store countless parameterizations without needing to create simulations for each parameterization to store the parameterization information. With the ability to create and store multiple parameterizations in place, AGWA 3.x built on this new functionality to allow users to perform batch parameterizations. This can be of great assistance if the user has multiple, lengthy scenarios/parameterizations to run that would otherwise require user interaction at in-opportune times. Batch simulation functionality was also added to further enhance the ability to work with multiple scenarios/parameterizations.

The release of AGWA 3.x also included the Rangeland Hydrology and Erosion Model (RHEM; Hernandez et al., 2015) in a desktop application. The inclusion of RHEM required changes to both the stream definition methodology in the discretization step and also the slope definition

processing in the parameterization step. To try and better define complex hillslopes shapes, a stream definition methodology based on flow length instead of flow accumulation was added to the discretization process. Additionally, support for using an existing stream network like National Hydrologic Dataset (NHD) to define the stream network and starting points of first order channels was also added to take the guesswork out of picking an appropriate flow length or flow accumulation threshold. RHEM also supports complex slope profiles, so the slope definition process was enhanced to include a complex slope weighting process versus the existing uniform slope weighting for overland flow planes contributing laterally to channels. The complex slope weighting process uses a methodology derived from Flanagan et al. (2011) where the representative slope profile is derived by weighting slope values along flowpaths at certain distances away from the channel by their flow length and flow accumulation. This weighting process assumes longer flow paths and flow paths with greater flow accumulation contribute proportionally more to the slope profile (and associated processes) than shorter flow paths with less flow accumulation.

**KINEROS2 / K2:** The erosion and sediment transport models from the RHEM (Wei et al., 2007; Hernandez et al., 2015) were incorporated into K2 and linked to the overland flow model. The overland flow model in K2, which represented a uniform slope, was extended to duplicate the original RHEM's ability to represent complex hillslope profiles (as well as uniform slopes). The RHEM hydrology model used the Green-Ampt infiltration equation, and while there is a parameter in the K2 infiltration equation that controls the transition of water content across the wetting front, it can approach but not duplicate piston-flow behavior. Consequently, the K2 infiltration model was extended to include an explicit Green-Ampt option.

The K2 urban element is a composite element consisting of up to six overland flow areas representing various combinations of pervious and impervious surfaces contributing to a paved crowned street. It represents an abstraction of one half of an urban/suburban street, and was validated and used successfully by Kennedy et al. (2013) in a highly instrumented suburban catchment. It has been modified to incorporate features representing LID/GI practices, including water harvesting, retention/infiltration basins, and pervious pavement (see Korgaonkar et al., 2015).

The K2 model was developed with a tree structure, where upstream elements can only contribute to a single downstream element, which is typical of natural watersheds. To address partial diversion of flow such as for irrigation, into constructed wetlands, etc. a diversion element has been introduced. This element can divert water and sediment from a single upstream element to as many as 10 downstream elements. Diversion rates are determined from a user-supplied tabular relationship between the inflow rate from the upstream element and the rates diverted into each downstream element.

The version of K2 that was designed to run as a forecast tool in National Weather Service Forecast Offices (K2-NWS) using real time weather radar data (Unkrich et al., 2010) can now utilize data from the National Weather Service Radar Product Central Collection Dissemination Service FTP server. The data typically appears on the server within 1-2 minutes of acquisition by the radar and allows K2-NWS to run in real time outside of a NWS Weather Forecast Office. The radar file decoder used by K2-NWS has also been upgraded to ingest the new dual

polarization Digital Precipitation Rate (DPR) product. The new product uses a finer resolution, 1-degree by 250 meter polar grid, but the decoder can also down-sample the data to the legacy 1-degree by 1 km grid.

## NOVEL APPLICATIONS

**KINEROS2 / K2:** K2-NWS was successfully applied to the 128 km<sup>2</sup> semi-arid Fish Creek basin located in the Anza Borrego State Park near Borrego Springs, California (Schaffner et al., 2014a). As there is no stream gage at the forecast point, the model calibration was based on categorical flood magnitudes (minor flood, moderate flood, major flood, etc.) rather than estimated discharge values. The calibration included seven rainfall events representing a full range of conditions from below flood stage up to the record flood event. Two sets of parameters were identified; one set optimized for below the major flood level and the other for larger flood levels. Calibration was successful in reproducing both the category and estimated time of peak flood. In forecast mode, the model provided an average lead time of 98 minutes to the initial flood stage, and 63, 50 and 48 minutes for minor, moderate and major flood stages respectively.

The calibration from Fish Creek was subsequently tested at nearby Borrego Palm Canyon, 70 km northwest of Fish Creek (Schaffner et al., 2014b). The goal was to evaluate whether the Fish Creek parameters could be used as a regional calibration, which would reduce the resources needed to set up the model at similar locations. The 56 km<sup>2</sup> Borrego Palm Canyon watershed was instrumented with a USGS stream gage from 1950 until September 10, 2004 when the gage was destroyed by a large flow. In 2002 the watershed was burned by a wildfire, with about a third suffering moderate burn severity and the rest low severity or unburned. Four test events were selected, one from 2003 with rainfall mostly over the lightly burned area, and the rest from 2013. Peak flows from simulations of the four events using the Fish Creek parameters fell within or close to the observed flood categories, suggesting that regional calibrations could be a viable option when resources are limited or when calibration data is unavailable.

**AGWA:** In studies by Burns et al. (2013a) and Barlow et al. (2014) a methodology was developed to characterize the hydrologic impacts of future urban growth through time. Future growth is represented by housing density maps generated in decadal intervals from 2010 to 2100, produced by the US-EPA Integrated Climate and Land-Use Scenarios (ICLUS; Bierwagen et al., 2010) project. ICLUS developed future housing density maps by adapting the Intergovernmental Panel on Climate Change (IPCC) social, economic, and demographic storylines to the conterminous United States. To characterize the hydrologic impacts of future growth, the housing density maps were reclassified to National Land Cover Database 2006 land cover classes and used to parameterize the SWAT model using AGWA. Burns et al., (2013) conducted this effort in the international San Pedro Basin in southeast Arizona and did not find a substantial impact on average surface runoff or on sediment yield at the watershed outlet for all scenarios. However, over smaller subwatersheds where development was concentrated the hydrologic changes are more significant. Barlow et al. (2014) found similar results in the South Platte Basin that contains the greater Denver, Colorado metro region.

AGWA was used by the Department of Interior National Burn Area Emergency Response (BAER) team for rapid post-fire watershed assessments on the Elk Wildfire Complex that burned

over 130,000 acres east of Boise, Idaho in August of 2013. Initially, the BAER team identified ~16,000 treatable acres within the burned watersheds that consisted of high burn severity and steep slopes. AGWA was used to simulate the watershed response for pre-fire and post-fire conditions to identify areas of high-risk for runoff and erosion. The interdisciplinary BAER team used spatially explicit AGWA results in an interactive process to locate polygons across the burned area that posed the greatest threat to downstream values-at-risk. The group combined the treatable area, field observations, professional judgment, and AGWA output to target seed and mulch treatments that most effectively reduced the threat. Using this process, the BAER Team reduced the treatable acres from the original 16,000 acres to between 2,000 and 4,000 acres depending on the selected alternative. The final awarded contract for post-fire mulch treatments cost roughly \$600/acre, therefore, BAER/AGWA targeted treatment applications resulted in a total savings of ~\$7.2 to \$8.4 million by only treating the reduced acreage (EPA, 2014).

Since wildfire severity impacts post-fire hydrological response, fuel treatments can be a useful tool for land managers to moderate this response. Sidman et al. (2015) conducted a spatial modeling approach that couples three models used sequentially to allow managers to model the effects of fuel treatments on post-fire hydrological impacts. Case studies involving a planned prescribed fire at Zion National Park and a planned mechanical thinning at Bryce Canyon National Park were used to demonstrate the approach. Fuel treatments were modeled using FuelCalc and FlamMap within the Wildland Fire Assessment Tool (WFAT). The First Order Fire Effects Model (FOFEM) was then used to evaluate the effectiveness of the fuel treatments by modeling wildfires on both treated and untreated landscapes. Post-wildfire hydrological response was then modeled using KINEROS2 within AGWA. This approach provides a viable option for landscape scientists, watershed hydrologists, and land managers hoping to predict the impact of fuel treatments on post-wildfire runoff and erosion and compare various fuel treatment scenarios to optimize resources and maximize mitigation results.

## **FUTURE PLANS AND MODEL DEVELOPMENT**

The AGWA GI (Green Infrastructure) tool (Korgaonkar et al., 2015) will undergo further testing and be released with a future version of AGWA. Eventually the K2-O2 continuous biogeochemical model will be coupled with the AGWA GI tool to provide capabilities to simulate plant growth, evapotranspiration, and nutrient transformations to address water quality. For post-fire watershed assessments an effort is underway by Sheppard et al. (2015) to locate high quality pre- and post-fire rainfall, and runoff data to improve procedures for adjusting post-fire infiltration, roughness, and cover parameters as a function of burn severity, pre-fire cover type, and time from fire to track recovery. A need has also been identified for post-fire flood inundation modeling on a reach scale near values of interest (e.g. structures, camp grounds, etc.). A tool is under development to take peak post-fire discharge generated from AGWA from either a design storm or observed historical storm and compute inundation in cases where significant backwater effects are absent. LIDAR or ground acquired channel cross-section data collected by BAER field crews assist in making this a viable tool. An automated channel cross-section extraction tools is also under development where LIDAR topographic data is available.

At present AGWA uses nationally available land cover maps that are static and only provide information on the type of cover but not its condition (an average condition is assumed in

AGWA). The ready availability of time varying remotely sensed vegetation products from satellites like MODIS provides an opportunity to ingest time varying measures of cover into AGWA. An AGWA tool to automatically ingest remotely sensed cover measures is under development. Initial results indicate that relatively large changes in cover condition (e.g. fires) are required to have a substantial impact on watershed response.

Small impoundments such as stock ponds are ubiquitous in much of the west and serve as a common management practice to provide water for cattle and wildlife. In addition they can be highly effective in trapping sediment and contaminants tightly bound to sediment. An AGWA pond tool is under development to allow the user to select a variety of pond types and geometries to rapidly place them within the channel network parameter file so scenarios for the type and number of ponds to reduce peak runoff rates or achieve load reductions can be made. Finally an internet version of AGWA is under development. Key issues for this project include where and how large geospatial and remotely sensed data sets will be stored and served.

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