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The Automated Geospatial Watershed Assessment tool

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Abstract

A toolkit for distributed hydrologic modeling at multiple scales using two independent models within a geographic information system is presented. This open-source, freely available software was developed through a collaborative endeavor involving two Universities and two government agencies. Called the Automated Geospatial Watershed Assessment tool (AGWA), this software is written for the ArcView GIS platform and is distributed as an extension via the Internet. AGWA uses commonly available GIS data layers to fully parameterize, execute, and visualize results from both the Soil and Water Assessment Tool (SWAT) and Kinematic Runoff and Erosion model (KINEROS2). These two distributed hydrologic models operate at different time scales and are suitable for application across a range of spatial scales. Descriptions of the GIS framework, hydrologic models, spatial analyses and algorithms that control the modeling process are given. Model requirements, limitations on the model applications and calibration techniques are described with examples of the use of AGWA for watershed modeling and assessment at a range of scales.

Keywords: Hydrologic modeling; Geographic information systems; KINEROS; SWAT; Change analysis; Scenario development

Software availability

Name of software: AGWA (Automated Geospatial Watershed Assessment)
Developers: The authors of this paper
Contact address: USDA-ARS Southwest Watershed Research Center, 2000 E. Allen Rd., Tucson, AZ, 85719, USA. Tel.: +1 520 670 6481; fax: +1 520 670 5550. Email: agwa@tucson.ars.ag.gov
First year available: 2003
Software requirements: Windows 95, 98, 2000, NT, ME, XP; ArcView GIS versions 3.X; and Spatial Analyst.
Hardware requirements: PC; 300 MHz processor, 128 MB RAM, and 50 MB of storage are recommended.
Program language: Avenue
Program size: 1.8 Mb
Availability and cost: AGWA can be downloaded with documentation, example exercises and data free of charge at http://www.tucson.ars.ag.gov/agwa/or http://www.epa.gov/nerlesd1/land-sci/agwa/

1. Introduction

Over the past decade numerous significant advances have been made in the linkage of geographic information systems (GIS) and various research and application models (e.g. Shen et al., 2005; US-ACE, 2003; He et al., 2001; DHI, 2000; Pullar and Springer, 2000; Arnold et al., 1998). These

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GIS-based systems have greatly enhanced the capacity for research scientists to develop and apply models due to the improved data management and rapid parameter estimation tools that can be built into a GIS driver. This project started after a review of models appropriate for multi-scale hydrologic modeling in support of landscape analysis (Hernandez et al., 2000) determined that none of the existing GIS tools provided a suitable interface for both research and application development. In this manuscript we present a GIS-based tool for the rapid application of two widely applied hydrologic models, and visualization of their results. The Automated Geospatial Watershed Assessment (AGWA) tool is used to provide input to the Soil and Water Assessment Tool (SWAT2000; Arnold et al., 1998; Srinivasan et al., 1998; http://www.brc.tamus.edu/swat/) and the Kinematic Runoff and Erosion (KINEROS2; Smith et al., 1995; Goodrich et al., 2002; http://www.tucson.ars.ag.gov/kineros) hydrologic model. These models operate at different temporal and spatial scales and may be applied in a range of environmental conditions (Miller et al., 2002) to evaluate the impacts of land-cover change on hydrologic and erosion response.

A primary goal of research hydrology is to develop methodologies for accurately depicting the processes driving runoff and erosion at a range of scales. Both process-based models (such as KINEROS2) and more empirical models (such as SWAT) provide insight into the response of watersheds to land-cover and managerial change, provided they are used properly and their input files have appropriate parameters. However, these models are highly dependent on spatially distributed data, and the subdivision of watersheds into response units and the assignation of appropriate parameters are both time-consuming and computationally complex. To apply these models on an operational basis, there is a critical need for automated procedures that are repeatable, accurate, and relatively straightforward. Towards satisfying those needs, AGWA was developed under the following guidelines: (1) that its parameterization routines be simple, direct, transparent, and repeatable; (2) that it be compatible with commonly available GIS data layers, and (3) that it be useful for assessment and scenario development (alternative futures) at multiple scales.

AGWA is an extension for the Environmental Systems Research Institute's ArcView versions 3.x (ESRI, 2001), a widely used and relatively inexpensive PC-based GIS software package (trade names are mentioned solely for the purpose of providing specific information and do not imply recommendation or endorsement by the USDA or U.S. EPA). The GIS framework of AGWA is ideally suited for watershed-based analysis in which landscape information is used for both deriving model input and for visualization of the environment and modeling results. AGWA shares the same ArcView GIS framework as the U.S. EPA Analytical Tool Interface for Landscape Assessment (ATtILA; Ebert and Wade, 2000; http://www.epa.gov/nerlesd1/land-sci/attila/), and can be used in concert with this and similar environmental assessment tools to improve scientific understanding of hydrologic processes and controlling influences of soil and landscape parameters (Miller et al., 2002). AGWA is available either for download directly as an individual program suite and is also included as a standard component of the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS software v3.1; Lahlou et al., 1998; http://www.epa.gov/waterscience/basins/), which provides access to data and several additional environmental models. Interdisciplinary studies may benefit from the integration of multiple model outputs as this approach facilitates comparative analyses and is particularly valuable for interdisciplinary studies, scenario development, and alternative futures simulation work. The primary distribution method for AGWA is via the Internet as a free, modular, open-source suite of programs (www.tucson.ars.ag.gov/agwa or www.epa.gov/nerlesd1/land-sci/agwa/).

Ongoing research efforts are tied to enhancing AGWA features and moving the code from ArcView 3.x (Avenue) to ArcGIS 9.x (Visual Basic, VB.NET, Python). Upcoming *beta* releases are planned for AGWA 2.0 (ArcGIS 9.x) and an Internet-based version of the toolkit referred to as DotAGWA. The essential elements of the AGWA coding and methods for performing watershed assessment, change analysis, and hydrologic modeling, will remain the same, although the software engine will be updated to reflect more modern GIS releases and to enhance Internet accessibility. Detailed design documents for AGWA 2.0 and DotAGWA (Cate et al., 2005) are available on the AGWA web sites.

AGWA provides the functionality to conduct all phases of a watershed assessment for SWAT and KINEROS2. SWAT2000 is the current version of SWAT and is a continuous-simulation model for use in large (river-basin scale) watersheds. KINEROS2 is an event-driven model designed for watersheds characterized by predominantly overland flow. The AGWA tool combines these models in an intuitive interface for performing multi-scale change assessment, and provides the user with consistent, reproducible results. Data requirements include elevation, land-cover, soils, and precipitation data, all of which are available at no cost over the Internet. Model input parameters are derived directly from these data using optimized look-up tables that are provided with the tool.

2. Component models

The key components of AGWA are the hydrological models used to evaluate the effects of land-cover and land use on watershed response. In this section, a description of the basic structure of each model is provided as well as their simplifying assumptions, strengths, and weaknesses. The KINEROS2 and SWAT models are able to simulate complex watershed representations that explicitly account for spatial variability of soils, rainfall distribution patterns, and vegetation.

2.1. KINEROS2

KINEROS2 is an event-oriented, physically-based model describing the processes of interception, infiltration, surface runoff, and erosion from small agricultural, rangeland and urban watersheds (http://www.tucson.ars.ag.gov/kineros/). In this model, watersheds are represented by subdividing contributing areas into a cascade of one-dimensional overland flow and channel elements using topographic information. KINEROS2 is a broadly updated version of KINEROS that is now incorporated into AGWA (Goodrich et al., 2002). Infiltration-excess overland flow processes are used to compute excess rainfall for surface runoff. A watershed is represented as a series of overland flow planes and channels in cascade, on which the processes of infiltration, interception, retention, erosion, sediment detachment, transport and deposition are all explicitly treated. Partial differential equations are used to describe these processes and are solved by finite difference techniques. Runoff is routed using the kinematic wave equations for overland and channel flow as:

$$\frac{\partial h}{\partial t}+\frac{\partial \alpha h^{m}}{\partial x}=r_i(t)-f_i(x,t) \qquad (1)$$

$$\frac{\partial A}{\partial t}+\frac{\partial Q(A)}{\partial x}=q_l(t)-f_{c_i}(x,t) \qquad (2)$$

where h is mean overland flow depth, t is time, x is distance along the element, α is solved as 1.49 $S^{1/2}/n$ when using the Manning equation, in which case S is slope, n is Manning's roughness coefficient, m is 5/3, $r_i(t)$ is rainfall rate at time t, $f_i(x,t)$ is infiltration rate, A is channel cross-sectional area of flow, $Q(A)$ is channel discharge as a function of area, $q_l(t)$ is net lateral inflow per unit length of channel and $f_{c_i}(x,t)$ is net channel infiltration per unit length of channel. These equations, and those for erosion and sediment transport, are solved using a four-point implicit finite difference method (Smith et al., 1995).

2.2. SWAT

SWAT is a public domain river-basin or watershed-scale model developed to predict the impact of land management practices on water, sediment, and agricultural chemical yields on large, complex watersheds with varying soils, land use, and management conditions over long periods of time (Arnold et al., 1998; http://www.brc.tamus.edu/swat/). The model combines empirical and physically-based equations, uses readily available inputs, and enables users to study long-term impacts. SWAT is defined by eight major components: hydrology, weather, erosion and sedimentation, soil temperature, plant growth, nutrients, pesticides and land management.

SWAT has been used extensively in hydrologic research worldwide (Arnold and Fohrer, 2005; Jayakrishnan et al., 2005; Bosch et al., 2004) and its appropriate uses are well documented in the hydrologic modeling literature. Elements of the hydrologic cycle are simulated on a daily basis within SWAT, solving for soil moisture as:

$$\mathrm{SW}_t=\mathrm{SW}_o+\sum_{i=1}^{t}\left(R-Q_\mathrm{s}-\mathrm{ET}-w-Q_\mathrm{g}\right) \qquad (3)$$

where SW_t is soil water content (mm) at time t, SW_o is initial soil water content on day i (mm), t is time (days), R is daily precipitation (mm), Q_s is surface runoff (mm), ET is evapotranspiration (mm), w is seepage water from the soil profile (mm), and Q_g is the amount of groundwater return flow (mm), each of which are calculated for each day (i). The core runoff prediction mechanism within SWAT is a modified Curve Number approach, which is one of the most widely applied methods for predicting runoff worldwide and is readily modeled using GIS (Zhan and Huang, 2004; Borah and Bera, 2003; Neitsch et al., 2002; Arnold et al., 1998). The SCS Curve Number equation is written as:

$$Q_\mathrm{s}=\frac{(R-I_\mathrm{a})^2}{R-I_\mathrm{a}+S} \qquad (4)$$

where Q_s is total surface runoff (mm), R is daily rainfall (mm), I_a is the initial abstraction such as infiltration and interception prior to runoff (mm), S is a retention parameter based on the combination of soil, land use and land-cover. Initial estimates of I_a and S are commonly derived from look-up tables, which are a core component of AGWA.

3. Overview of the AGWA tool

AGWA is loaded into an ArcView project in the typical manner for all extensions. Once loaded, however, AGWA mandates that the user specify a new project name, and a complete directory structure is created based on user input. The creation of a specific directory structure allows AGWA to locate model inputs, results, and newly created GIS data layers to ensure project integrity. A fundamental requirement of AGWA is that the user has previously compiled the necessary GIS data layers, all of which are easily obtained for the United States and many other countries around the world.

3.1. Input data and preparation for modeling

Required input data include a mosaiced digital elevation model (DEM), a polygon soil map (U.S. STATSGO, U.S. SSURGO, and global FAO soil maps are supported), and a classified land-cover/use grid (U.S. EPA NLCD data are supported and alternative data sources can be accommodated). The spatial resolutions of input data are immaterial to AGWA, although the desired scale of application may require finer levels of resolution.

The user is required to merge individually tiled DEMs to create a single grid data layer, but AGWA provides data-smoothing tools that remove spurious sinks and creates a hydrologically correct surface necessary for hydrologic modeling. If there are known sinks, reservoirs, or ponds, the user may enter their locations when the watershed is subdivided into modeling units, but the DEM itself must be processed to remove sinks to ensure that the routing algorithms function properly before their use in an AGWA application. A user is able to simulate runoff through a system with internal ponds or reservoirs by adding a storage–discharge function for each storage point, and AGWA will perform the necessary hydrologic reservoir routing.

When an AGWA extension is loaded, an ‘AGWA Tools’ menu and ‘Help’ button are added to all ‘‘View’’ windows, and all components of the tool are made available from the simple drop-down menu (Fig. 1). Once the user has compiled all relevant GIS data and initiated an AGWA session, the program is designed to lead the user in a stepwise fashion through the transformation of GIS data into simulation results. The AGWA Tools menu is designed to reflect the order of tasks necessary to conduct a watershed assessment. If the object of the study is change detection, for example, there are six major steps involved in the analysis (Fig. 2): (1) watershed delineation; (2) parameter estimation; (3) rainfall generation; (4) model execution; (5) change analysis; and (6) visualization of results. Alternative uses for AGWA include watershed assessment in which temporal change is neglected, hydrologic modeling in support of research and management, and scenario visualization in which alternative land-cover, terrain, soil or climatic information is used.

3.1.1. Step 1 – watershed delineation

The necessary first step in conducting watershed analyses or assessments is the delineation of the watershed. If a GIS coverage exists in which the outlet of the watershed is known, the user can select the pre-existing point. If no such data are available, the user has the option of manually creating an outlet by clicking with the mouse. The standard ArcView watershed delineation routine is invoked, which uses flow direction and accumulation grids derived from the hydrologically correct DEM.

Once the correct watershed boundary has been determined, the watershed is subdivided into model elements as required by the different models. A user-specified value is set for determining the threshold of contributing area for the determination of the location and lengths of stream channels. The streams are used to define overland flow paths and identify upland and lateral planes and therefore control the complexity of landscape representation. KINEROS2 requires that the uplands be subdivided into overland flow model elements that are abstracted in the model as 1-D overland flow planes. SWAT uses a subwatershed approach, wherein the uplands are not broken into multiple overland flow elements, but are treated as homogenous units. Likewise, in SWAT there is no dynamic routing or connectivity from the subwatershed to the channel segments. Fig. 3 illustrates the difference in watershed subdivision as required by the models. From this point onward, tasks are specific to the model that will be used (KINEROS2 or SWAT), but the same general process is followed independent of model choice.

3.1.2. Step 2 – parameter estimation

The watershed created in Step 1 is intersected with soil and land-cover data, and parameters necessary for the hydrologic model runs are estimated through a series of GIS analyses and look-up tables (see discussion later in this paper). These parameters are added to the polygon and stream channel tables to facilitate the generation of input parameter files for the model chosen by the user. AGWA has two methods that allow the user to alter these parameters: either the look-up tables themselves can be changed directly or the individual element parameters can be altered by opening up the watershed or channel shapefile tables. Automated model calibration is not

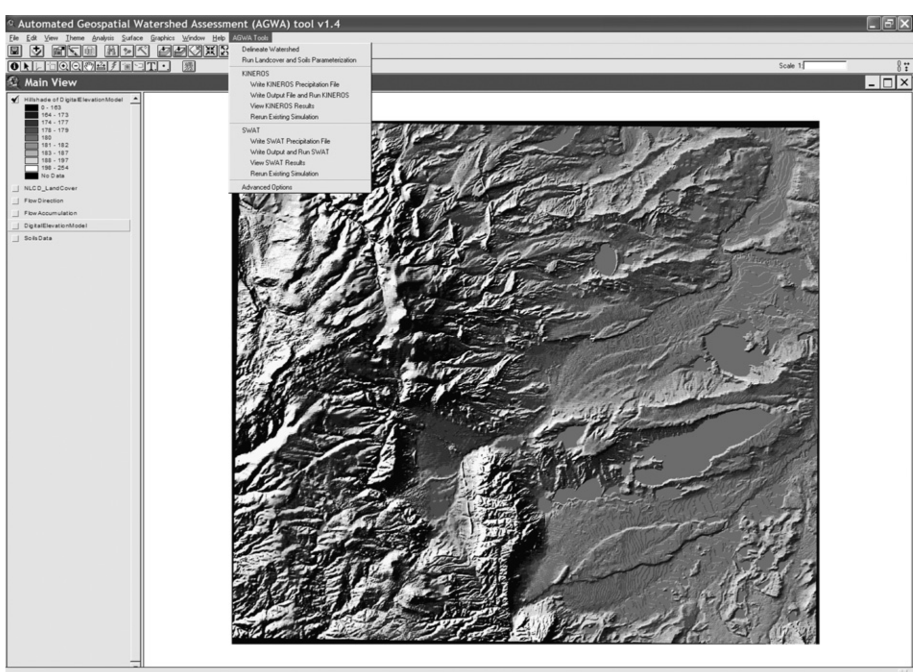

Fig. 1. Main AGWA interface shown as a drop-down menu from an ArcView 3.2 project. The user interacts with AGWA through this menu, which is always present in an active ‘‘View’’.

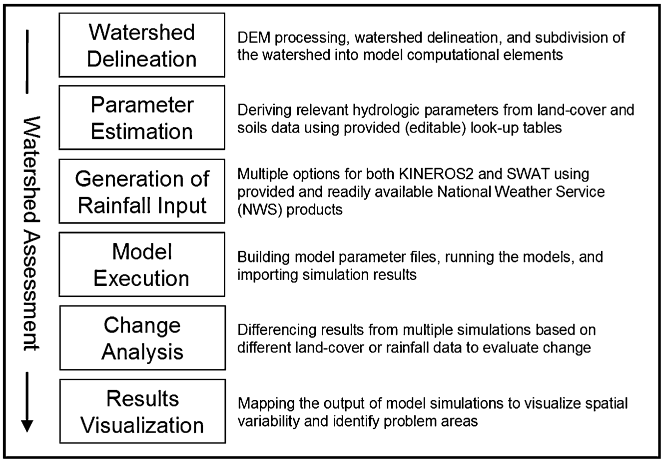

Fig. 2. AGWA modules, and the sequence of steps for hydrologic modeling and change detection.

currently provided within AGWA but an interface allows the user to apply multiplication factors that uniformly increase or decrease the targeted parameters.

Hydrologic modeling in AGWA is sensitive to the shape and size of the channels through which water is routed (Miller et al., 2002). Specification of channel geometry is crucial both for the effective routing of water and estimation of channel scour and depositional processes. Since this information cannot be derived from a typical DEM, AGWA uses an empirical hydraulic–geometry relationship to estimate channel geometry as a function of contributing area for the top and bottom of each reach in the channel network as:

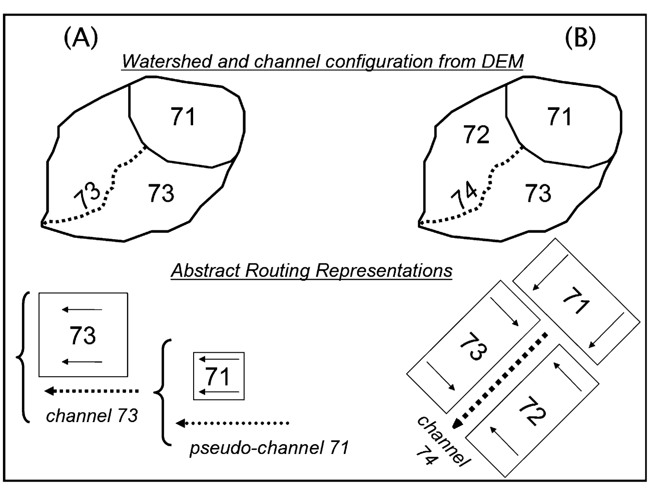

Fig. 3. Diagram illustrating subdivision of a watershed and routing structure required by SWAT (A) and KINEROS2 (B). SWAT uses a subwatershed approach with no dynamic linkages between upland and channel elements. KINEROS2 uses an "open-book" approach where the watershed is represented as a cascade of overland flow planes and channels with kinematic routing which dynamically treats infiltration. Outflow from the overland flow elements is treated as time varying lateral inflow to the channel elements and is considered, as is infiltration, in the routing solution for the channel elements. The numbers represent the AGWA-imposed scheme used to ensure hydrologic connectivity from the watershed boundary to outlet.

$$w = \frac{7.24A_w^{0.34}}{100} \quad (5)$$

$$d = \frac{5.01A_w^{0.15}}{100} \quad (6)$$

where w = channel width (m), A_w = watershed area (m^2), and d = channel depth (m). The above equations were developed based on observations made in the Walnut Gulch Experimental Watershed following Miller et al. (1996). A database file containing published relationships for different geographic regions (e.g. Miller et al., 1996, 2003; Sweet and Geratz, 2003) is distributed with AGWA, and can be edited to include additional relations where available. AGWA also provides a relationship builder that allows the user to fine tune an equation for a specific study area. Observed channel geometries, if available, can be entered manually by editing the attribute table for the stream channel map.

3.1.3. Step 3 — rainfall generation

Rainfall input files are built at this stage. For SWAT, the user must provide daily rainfall values for rainfall gauges within and near the watershed. If multiple gauges are present, AGWA will build a Thiessen polygon map and create an area-weighted distributed rainfall file. For KINEROS2, the user has three options. The user can select from an editable database file of pre-defined rainfall events dependent on the geographic location, choose to build their own rainfall file through an AGWA module, or use NOAA Atlas 2 or 14 return-period rainfall depth grids distributed with AGWA (NOAA, 1973; Bonnin et al., 2004a,b). Digitized Tp-40 maps for the Eastern United States (not available for the West) can also be used and are available for download from the AGWA web site. AGWA provides several methods for generating design storms for input to KINEROS2, but spatially distributed rainfall input files must be generated outside of AGWA, and help is provided in the user manual.

3.1.4. Step 4 — model execution

After Step 3, all necessary input data have been prepared: the watershed has been subdivided into model elements; hydrologic parameters have been determined for each element; and rainfall files have been created. The user can proceed to run the hydrologic model of choice. AGWA will automatically import model results for all planes and channels and add them to the polygon and stream map tables for display in GIS.

3.1.5. Step 5 — change analysis

This step is an optional component of AGWA. If the user is interested in change analysis or comparative analyses of different land-cover realizations, AGWA provides a straightforward method for change analysis. Each subdivided watershed can be used multiple times with different soil, terrain, land-cover, or look-up tables with the results stored in a database. Results can be compared for each plane and channel element using either absolute or percent difference (Miller et al., 2002), and AGWA provides an automated tool for deriving these metrics as a component of the visualization menu. Model results can also be overlaid with other digital data layers to further prioritize management activities.

A land-cover modification tool is an option in AGWA that provides the capability of performing scenario/alternative futures analyses. A pre-defined area can be used to transform all land-cover in that area to a single use (e.g. urban growth, high-intensity burn); a single land-cover type can be transformed into a new type (e.g. grassland conversion to shrub); a random approach can be used to shift land-cover within an area into different classes (e.g. impact analysis). After generating a new land-cover grid using this tool, the user would repeat steps 2 through 5, and then proceed to step 6 to perform change analysis.

3.1.6. Step 6 – visualization of results

Visualization of results is managed by AGWA using a database catalog of model runs and results. The user can toggle through different model results or change scenarios and investigate the spatial distribution of modeling results using predetermined color ramps. All model outputs can be visualized using the AGWA toolbar. Model outputs that are imported into GIS for visualization from SWAT and KINEROS2 are presented in Table 1.

4. Data inputs and parameter estimation

4.1. Watershed delineation

Numerous approaches have been developed for automated extraction of watershed structure from grid digital elevation models, with the earliest techniques still being used today (e.g. Gyllenhammar and Gumbricht, 2005; Martz and Garbrecht, 1993; Moore et al., 1988; Band, 1986; Mark et al., 1984). The most widely used method, and that which is used in AGWA, for the extraction of stream networks is to compute the contributing area upslope of each pixel through a network of cell-to-cell drainage paths. This network is subsequently pruned based on a threshold drainage area required to define a channel, referred to as the channel or contributing source area, or CSA. The watershed is then further subdivided into upland and channel elements as a function of the stream network.

In this way, a user-defined CSA is used to define the lengths and numbers of stream channels; since the watershed is subdivided into upland and channel elements as a function of the stream channels, the choice of CSA is the determining factor in the spatial complexity of the watershed discretization. This approach can create spurious polygons and disconnected model elements due to vagaries in the underlying DEM. A suite of algorithms has been implemented in AGWA that refines the watershed elements by eliminating small spurious elements and ensuring downstream connectivity. These spurious elements are represented as either small spatial "holes" (usually equivalent in size to one or two raster cells) in the landscape or orphaned elements that can be slightly larger than the holes but are small enough to be overlooked if the user is using a small map scale. Procedurally, AGWA first iterates through each set of lateral elements and merges polygon shapes to collapse the small holes and re-establish a continuous surface. Orphaned polygons are assigned a watershed identifier based on their proximity to other model elements, an approach that can occasionally assign incorrect watershed identifiers (usually when an element is assigned a number for an element that is on the other side of a stream line). The last step is to merge the affected plane elements and then re-split the plane by subtracting the original model element from the newly merged shape. This approach, which does not rely on using the stream to intersect with and split the watershed elements, results in a continuous surface with no holes or orphaned elements and a properly numbered set of watershed elements. Small shifts in stream position relative to the original watershed edge may occur but these shifts are negligible relative to the spatial resolution of the input data (generally less than 1 pixel) and are inconsequential in their effect on runoff simulation.

Table 1
SWAT and KINEROS2 simulation results imported into AGWA for visualization through the user interface

KINEROS2 outputs	SWAT outputs
Channel infiltration (m^3/km)	Precipitation (mm)
Plane infiltration (mm)	ET (mm)
Runoff (mm or m^3)	Percolation (mm)
Sediment yield (kg)	Channel discharge (m^3/day)
Peak flow (m^3/s or mm/h)	Transmission loss (mm)
Channel scour (mm)	Water yield (mm)
Sediment discharge (kg/s)	Sediment yield (t/ha)

4.2. Parameter estimation

Each of the overland and channel model elements delineated by AGWA is represented in either SWAT or KINEROS2 by a set of parameter values. There may be a large degree of spatial variability in the topographic, soil, and land-cover characteristics within the watershed, and AGWA uses an area-weighting scheme to determine an average value for each parameter within an upland model element (Goodrich et al., 2002). Landscapes with a high degree of spatial variability in soil, vegetation and landscape characteristics require a greater degree of complexity in model representation (Faures et al., 1995). SWAT and KINEROS2 require a host of parameter values, and estimating their values can be a tedious task; AGWA rapidly provides estimates based on an extensive literature review and calibration efforts. As shown in Fig. 4, the three GIS coverages are intersected with the subdivided watershed, and a series of look-up tables and spatial analyses are used to estimate parameter values for the unique combinations of land-cover and soils.

Soil parameters for upland planes as required by KINEROS2 such as percent rock, suction head, porosity, saturated hydraulic conductivity are initially estimated from soil texture according to the available soil data. AGWA provides algorithms and look-up tables for the most commonly available

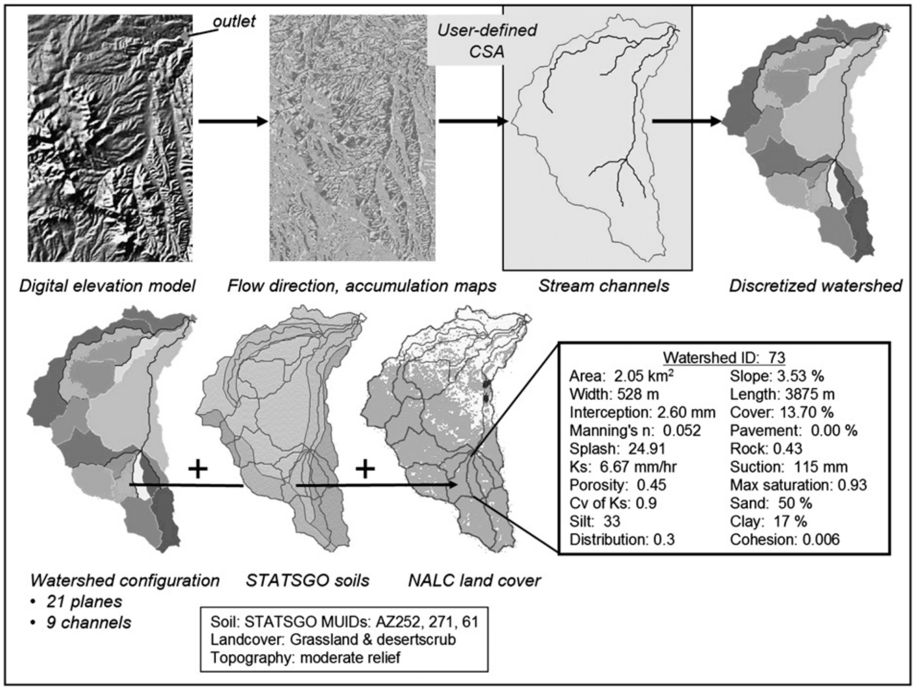

Fig. 4. The transformation of topography, soils, and land-cover GIS data into KINEROS2 input parameters. A DEM is used to subdivide the watershed into upland and channel model elements, each of which are parameterized according to their soil, topographic, and land-cover characteristics.

soil data (FAO, STATGSO, and SSURGO) following Woolhiser et al. (1990) and Rawls et al. (1982). The critical zone for estimating excess runoff in KINEROS2 is the surface soil layer (defined as the top 9″ of soil), and AGWA performs a weighting procedure to estimate soil characteristics for each intersection of soil and land-cover. Where multiple soil series or map units are present in a soil polygon, pedo-transfer functions are performed first for each soil horizon and depth-averaged to produce an estimated parameter value for each map unit or series, whereupon these values are area-weighted to assign a value for the targeted polygon. Saturated hydraulic conductivity (k_s) is reduced following Bouwer (1966) to account for air entrapment and further adjustments are made following Stone et al. (1992) as a function of estimated canopy cover (increasing canopy cover is inferred to be an indicator of improved soil condition). Land-cover parameters, including interception depth, percent canopy cover, Manning's surface roughness, and percent paved area are estimated from previously published look-up tables (Woolhiser et al., 1990). These parameters are easily modified by the user as they are distributed in AGWA as a simple database file. Examples of these look-up values for the North American Landscape Characterization classification scheme of the Upper San Pedro Basin in southern Arizona are shown in Tables 2 and 3.

Upland element slope is estimated as the average percent plane slope, while geometric characteristics such as plane width and length are a function of the plane geometry. A standard DEM-based analysis of flow length is performed for each element, with the maximum value set equal to the element length, and element width calculated by dividing area by length. Channel parameters relating to soil characteristics assume a sandy bed for all channels. This assumption generates high transmission losses since the hydraulic conductivity value is very high and assumes to influent flow. Where return flow or groundwater contribution is significant the user can adjust these values for individual channels or within the basic channel look-up table itself. Channel slope is determined by dividing total length of the reach by the elevation fall as determined by elevation at the start and end of the reach.

Similar approaches are used to provide estimates for soil and land-cover parameters as required by SWAT. The most sensitive parameter of SWAT is the Curve Number, which is estimated as a function of hydrologic group, hydrologic condition, cover type, and antecedent moisture condition. Soil data provide information on soil hydrologic group, while cover type is determined from classified land-cover data. AGWA assumes a fair hydrologic condition, and antecedent moisture group II. Look-up tables following USDA-SCS (1986) recommendations are used to estimate Curve Number values for each unique combination of hydrologic group and land-cover type within a watershed element. Because the land-cover data

Table 2
Portion of the look-up table for NALC land-cover used by AGWA for the estimation of upland element parameters for KINEROS2 (based on expert opinion and Woolhiser et al., 1990)

Land-cover	Interception (mm/h)	Canopy cover (%)	Manning's n
Grassland	2.0	25	0.050
Deserts crub	3.0	10	0.055
Riparian	1.15	70	0.060
Agriculture	0.75	50	0.040
Urban	0.0	0.0	0.010

are grids, this process occurs for each cell, and the results are area-weighted to produce a unique estimate of Curve Number for the subwatershed (Table 3). The basic AGWA configuration assumes a losing stream disconnected from groundwater, and SWAT groundwater parameters are set to allow return flow under high rainfall conditions but there is minimal connection between near-surface moisture and channel flow. In areas dominated by baseflow the user should adjust the associated SWAT groundwater parameters to improve streamflow prediction.

4.3. Appropriate applications of AGWA and model calibration

In the absence of observed data and performing a calibration exercise, simulation results from either model should be limited to use in comparative or relative assessments. Alterations of the look-up tables or model assumptions that generate model parameters are readily made since the code is open-source, but the user must possess adequate understanding of GIS, hydrologic modeling, and the definition of appropriate parameters. Users are encouraged to read and follow the user manuals for KINEROS2 and SWAT for detailed background on the model parameters and strategies for effective calibration. Both models have been used in numerous settings and are well cited in the literature; the reader is encouraged to consult these findings.

KINEROS2 is a process-based runoff model that simulates the production of excess rainfall and its conversion to surface runoff under conditions of infiltration-excess (Hortonian overland flow). Where hydrologic response is heavily driven by other processes (e.g. saturation excess, variable source area) KINEROS2 should not be applied. Being an event-model, KINEROS2 is most successfully applied for discrete events in which rainfall variability is adequately captured. As such, rainfall is a major limiting factor in terms of the scale of application (size of the watershed) of KINEROS2 in AGWA. KINEROS2 uses the kinematic simplification of runoff for overland and channel flow and is not suitable for application in larger streams or rivers in which low slopes and associated backwater effects are significant. The model is most effectively applied in overland-flow dominated areas such as semi-arid or urbanized watersheds where rainfall–runoff processes control hydrologic response and groundwater contributions are either negligible or well quantified.

Table 3
Curve Number look-up table for selected land-cover types (higher values of Curve Number correspond to higher estimates of simulated runoff (based on USDA-SCS, 1986))

Land-cover	Soil hydrologic group			
	A	*B*	*C*	*D*
High-intensity residential	81	88	91	93
Bare rock/sand/clay	96	96	96	96
Forest		55	75	80
Shrubland	63	77	85	88
Grasslands/herbaceous		80	87	93
Small grains	65	76	84	88

SWAT is a strategic model that can be applied at a range of watershed scales. The model uses a modified Curve Number approach to simulate overland flow and does not employ dynamic routing. Runoff and other components of the water cycle that lead to the estimation of water yield are computed on a daily time step. The model is most often applied over a long period of record (months to years) and is most appropriate when used in strategic basin planning. As with all hydrologic models SWAT is highly dependent on distributed rainfall and climate data, and the interpretation of results is limited by the spatial distribution of these data. The estimation of surface runoff and the partitioning of rainfall into near-surface and deep aquifers is driven by the estimation of soil properties and their intersection with land-cover type and management. AGWA does not provide detailed linkages to the management options in SWAT, although the user can modify the options manually.

If the objective of the exercise is to investigate plot- or farm-scale management impacts (such as fertilizer application or timing of farm practices) on water yield and water chemistry, then the user is encouraged to use either the stand-alone SWAT program or the AVSWAT interface, both of which are available from the SWAT home page. For example, Santhi et al. (in press) applied SWAT using a daily time step in the 4554 km^2 West Fork Watershed in Texas to estimate impacts of Best Management Practices. In this research Santhi et al. (in press) investigated reductions in nonpoint source loadings with a particular emphasis on nutrients and sediment; while AGWA provides input and access to sediment loading routines for SWAT, the nutrient and farm management routines are not activated, making it more straightforward to use the full SWAT release. AGWA provides a streamlined interface for SWAT2000 that is appropriate in the investigation of land-cover change and large-scale management and planning alternatives relative to their impact on spatially distributed water yield, peak discharge and sediment yield.

AGWA does not provide an automated process for model calibration, although there are several strategies that can be effectively employed for parameter determination. An external link to a complex shuffle parameter estimation program such as PEST (SSPA, 2005) is suggested if the desired approach is to identify parameters for non-comparative hydrologic simulations. If the goal of the project is to simulate spatially distributed land-cover change and quantitative impacts on hydrologic response it may be more effective to edit the core AGWA look-up tables and algorithms to reflect the results of a calibration exercise. This will enable the optimized parameters to be transferred to subsequent simulations for the same area rather than having a tailored calibration result that is not transferable among different AGWA simulation runs. Model parameters in AGWA are initialized to provide appropriate estimates in semi-arid regimes in which return flow or groundwater contributions are negligible and the user is strongly advised to check on the suitability of model parameters relative to hydrologic drivers in the project area.

AGWA provides an interface to adjust the most sensitive KINEROS parameters by a common multiplier (Fig. 5). Goodrich et al. (1997) demonstrated the suitability of this approach and discuss limitations of complex shuffle algorithms in the context of process-based distributed modeling. For example, a series of calibration runs were conducted in 2003 with data from the USDA-ARS Walnut Gulch Experimental Watershed, to determine the appropriate K_s multiplier for transfer to and use on the nearby and similar Coyote Wash watershed. Four historical events were used in the calibration: August 14, 1986 (small event), August 6, 1966 (medium small event), August 4, 1980 (medium large event), and August 29, 1986 (large event). Parameter input files for KINEROS2 were created in AGWA using SSURGO soil data and the 1997 NALC land-cover data. A stepwise approach was taken to bracket the appropriate multiplier for upland plane elements, with results indicated in Table 4. Results of this calibration exercise are highly satisfactory ($r^2 = 0.99$, slope = 1.1) and demonstrate the efficiency and accuracy of using a multiplier.

Since AGWA generates input files for both KINEROS2 and SWAT it is relatively straightforward to establish an external link to a parameter estimation software. Hernandez et al. (2000) used PEST, which uses a nonlinear estimation technique know as the Gauss—Marquardt—Levemberg method (Marquardt, 1963), to calibrate SWAT files generated by AGWA for the USDA-ARS Walnut Gulch Experimental Watershed, Arizona. In this report the aim of calibration was to optimize the CN parameter, which is the most sensitive parameter affecting surface runoff, to minimize differences between the simulated and observed annual runoff volume data and achieve better prediction.

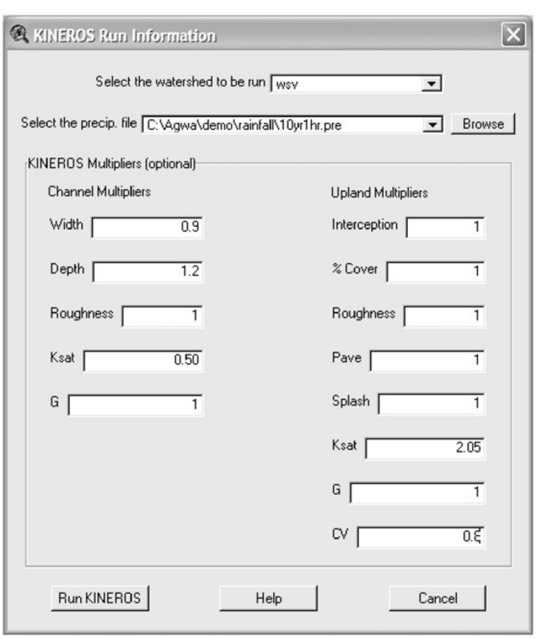

Fig. 5. Multiplier interface provided by AGWA to perform model calibration for KINEROS2. Parameters for either plane or channel elements can be increased or decreased uniformly using this interface.

Table 4
AGWA-based KINEROS2 simulation results from USDA-ARS Walnut Gulch Experimental Watershed (watershed 11) using the multiplier interface for model calibration

Event date	Runoff depth (mm)			
	Observed	Multiplier = 2.0	Multiplier = 2.05	Multiplier = 2.1
Aug. 6, 1966	3.8	4.03	3.68	3.81
Aug 4, 1980	5.8	6.22	5.92	6.07
Aug. 14, 1986	2.5	2.12	1.93	2.01
Aug. 29, 1986	7.8	8.01	7.67	7.84

The level of calibration was quantified at the outlet of the watershed from January 1966 to December 1980 with the coefficient of efficiency (Nash and Sutcliffe, 1970) and the deviation of streamflow volume used as measures of the degree of model accuracy. Average annual water yield for the entire watershed was 2.88 mm, compared to an optimized value of 2.60 mm simulated by SWAT. The coefficient of efficiency was 0.68 and the deviation of streamflow volume 10% for the calibration period. Fourteen years of runoff data were used for validation efforts with a notable decline in model performance: the coefficient of efficiency for this period yielded was 0.40 and the deviation of streamflow volume was 25%. According to Baginska et al. (2003), flow estimates can be classified as acceptable if they have a coefficient of efficiency greater than 0.6 and deviation of streamflow volume within 15% of mean recorded flow. These results underscore the need for calibration if the application is intended to go beyond relative assessment. In the absence of calibration, it is critical that the model is constrained adequately such that the direction and magnitude of change are realistic portrayals, which was the primary goal in the development of AGWA look-up tables, assumptions and associated algorithms.

Baldyga et al. (2004) calibrated AGWA look-up tables and algorithms for SWAT on the Njoro River watershed, Kenya and reported Nash—Sutcliffe efficiencies of approximately 0.78 for 9 years of simulation. In this case slight modifications to the Curve Number table were made, but the most significant gains in calibrated results were made in the modification of parameters governing channel infiltration losses and return flow since this is an area in which baseflow is a significant contributor to annual water yield. This direct calibration approach requires Avenue programming to modify the scripts that generate SWAT input files. In a relatively complex watershed it is possible to have dozens of subwatershed elements and it is advisable to change the code rather than output files.

4.4. Rainfall input

A variety of methods are available in AGWA to create rainfall input files for KINEROS2 and SWAT. Each of these are described briefly below, and organized according to the models for which they are designed.

4.5. KINEROS2

Either distributed or uniform precipitation input can be used with KINEROS2, and is provided in the form of storm hyetographs for one or more point locations. Data from multiple point locations are distributed across the watershed by KINEROS2 using a piecewise planar time-space interpolation technique (Goodrich, 1991). Since the spatial component of this process is computed by the model itself, it is unnecessary to prepare distributed input files in AGWA. KINEROS2 rainfall input files created outside of AGWA (either uniform or distributed) can also be used in AGWA. To construct these files, the user creates a basic text file in which individual gauges are assigned a unique identifier, geographic coordinate, and either time-depth or time-intensity pairs for the duration of the even. AGWA allows the user to browse to the location of these externally generated files to provide rainfall forcing. Methodologies for utilizing radar data to build distributed event rainfall files in AGWA are currently being investigated (Morin et al., 2004).

Uniform rainfall input files can be created in AGWA directly using either commonly available GIS data sources, or by data entry via a spreadsheet interface uniform rainfall, although less appropriate for quantitative modeling of individual events, is particularly useful for relative assessment of land-cover change. Precipitation data that can be used to generate design storms in AGWA includes any precipitation-frequency grids (e.g. NOAA Atlas 2, 14, and TP-40 Precipitation-Frequency Atlases of the United States), or a database of return-period storms from various locations that is provided with AGWA. Return-period rainfall depths are converted into hyetographs using the USDA-SCS (1973) methodology and a type II distribution. The type II distribution is appropriate for deriving the time distribution of rainfall for most of the U.S., including all of the interior West. The database can be easily edited to add data for areas where it is not provided. In the event that a user wants to create a unique design rainfall event, AGWA provides a user interface for entering these data. User-defined storms are entered in the form of a hyetograph, thus providing additional flexibility in defining the time distribution of rainfall.

4.6. SWAT

AGWA can generate either uniform or distributed rainfall input files for SWAT. The option to create distributed rainfall files uses Thiessen polygons to compute the weighted rainfall depth falling on each subwatershed for each day in the simulation period. The user is automatically directed to the dialog for creating either the uniform or distributed rainfall input based on the number of rain gauges with data in a rain gauge point theme that is designated by the user. If there are two or fewer gauges Thiessen polygons cannot be generated and a uniform rainfall input file will be created (using the gauge closest to the watershed centroid if there are two). When there are more than two gauges a distributed input file will be written. One of the significant drawbacks to using widely-spaced rainfall data is the lack of gradient within the data caused by elevation. AGWA provides an elevation banding feature to incorporate known elevation–precipitation relationships in the study area. SWAT elevation bands adjust precipitation and/or temperature to account for orographic effects. Elevation and location data from the rain gauge theme are written to the precipitation file and are used along with the mean elevation of the bands for a subwatershed to adjust the precipitation and temperature for that subwatershed. If the elevation of a rain gauge is not included in the point theme attribute table, the DEM used to delineate the watershed is used to determine the elevation of that particular gauge.

Although any gauge data can be used, National Weather Service gauge data are the most widely available in the U.S. A point theme of rain gauge locations and an unweighted daily precipitation database file are necessary to generate the input file. Missing data can be accommodated through a weighting scheme that dynamically adjusts the gauge weights according to those gauges that have data for that day.

5. Watershed modeling with AGWA

There are several primary intended uses of AGWA. For one, AGWA can be used in a research environment as a hydrologic modeling tool. In this setting, the user would be expected to alter the look-up tables or estimated parameters manually to allow for more rigorous quantitative assessment. In the absence of a rigorous training set for calibration and validation, AGWA is well suited for watershed assessment using spatially distributed hydrologic response as a metric of change. If multiple land-cover scenes are available, a relative assessment of the impacts of land-cover change on hydrologic response as a function of time may be accomplished following Miller et al. (2002) or Kepner et al. (2004). Where repeat classified imagery do not exist, space may be substituted for time and a spatial watershed assessment undertaken to compare watersheds relative to one another.

Hernandez et al. (2000) showed that simulated runoff response is sensitive to land-cover change in both the SWAT and KINEROS2 models and that the assumptions inherent in the look-up tables determine the direction and magnitude of change. For example, land-cover change on a homogenous small watershed from desert scrub to mesquite showed only a 6.7% increase in simulated runoff, while a transition to urban resulted in a 46% increase. Their results also demonstrated the impact of calibration and distributed rainfall on model results, both of which significantly increased model efficiency.

A nested and interdisciplinary approach to multi-scale modeling was undertaken by Miller et al. (2002) in which AGWA was used in coordinated ecological and hydrologic assessments. The authors carried out analyses of the ecological changes since the early 1970s within the Upper San Pedro River Basin in southeastern Arizona and the Cannonsville Watershed in the Catskill/Delaware region of New York. AGWA was used to simulate average annual water yield changes with the SWAT model in both study areas and to identify spatially distributed changes in hydrologic response linked to environmental change. SWAT simulations showed relatively little effect from transitions to woody shrub and urbanization on annual/seasonal water yield at the basin scale, but spatial analyses revealed highly localized effects. These results guided the identification of key watersheds for further analysis using KINEROS2, which showed significant impacts on simulated runoff volume, peak discharge, and sediment yield (Fig. 6) at the small watershed scale. This approach illustrates the use of AGWA in both spatial and temporal scaling studies for assessment of relative change over a range of time and space scales.

AGWA is being used in watershed-based planning: the Arizona Nonpoint Education for Municipal Officials Program (NEMO), in cooperation with the Arizona Department of Environmental Quality, is using the toolkit to assist in the development of plans for the major drainages in Arizona (see http://www.srnr.arizona.edu/nemo/). Planning and assessment in land and water resource management requires spatial hydrologic modeling tools that incorporate complex watershed-scale attributes into the assessment process, attributes that are embedded within AGWA. Nonpoint source pollution problems are identified within the targeted watersheds, potential sources of the problems are identified, along with potential treatments and educational programs. This effort is an application of the EPA's ''Watershed Approach'' model.

A component of the NEMO watershed-based plans is a watershed classification at the 10-digit Hydrologic Unit Code (HUC) scale of the potential risk of impairment from different nonpoint source pollutants. The general approach was to integrate watershed characteristics, water quality measurements, and AGWA modeling results within a multi-parameter ranking system based on a fuzzy logic knowledge-based approach (Guertin et al., 2000). The SWAT component of AGWA was used to identify subwatersheds with high runoff and sediment production under current and future conditions.

This approach requires that a goal be defined according to the desired outcome and that the classification be defined as a function of the goal, and is therefore reflective of an underlying management objective. In this example, the goals were to identify critical subwatersheds with a high risk of impairment in which best management practices (BMPs) should be implemented to reduce nonpoint source pollution.

6. Conclusions

A GIS-based hydrologic modeling toolkit called the Automated Geospatial Watershed Assessment (AGWA) tool has been developed for use in watershed analysis. This tool has been released as open-source and is fully modular and customizable. AGWA automates the process of converting commonly available GIS data to input parameter files for the SWAT and KINEROS2 hydrologic models. Rainfall files for both models can be prepared within AGWA depending on the availability of rainfall data. Results from these models, such as runoff, peak discharge, and sediment yield for each model element, are imported into AGWA and can be investigated using a suite of visualization tools. Since the models operate at different spatial and temporal scales, they provide the ability to perform a range of analyses as a function of research or management objectives.

Because AGWA is designed to convert generic GIS data, it can be applied on ungauged watersheds. However, in the absence of a calibration/validation exercise, results are best suited for relative analysis. Given repeat classified remote sensing imagery, AGWA provides the capability to assess the spatial distribution of the relative impacts of land-cover change on watershed hydrologic response. In the absence of repeat imagery, AGWA may be used to identify portions of a study area susceptible to change or high priority management zones.

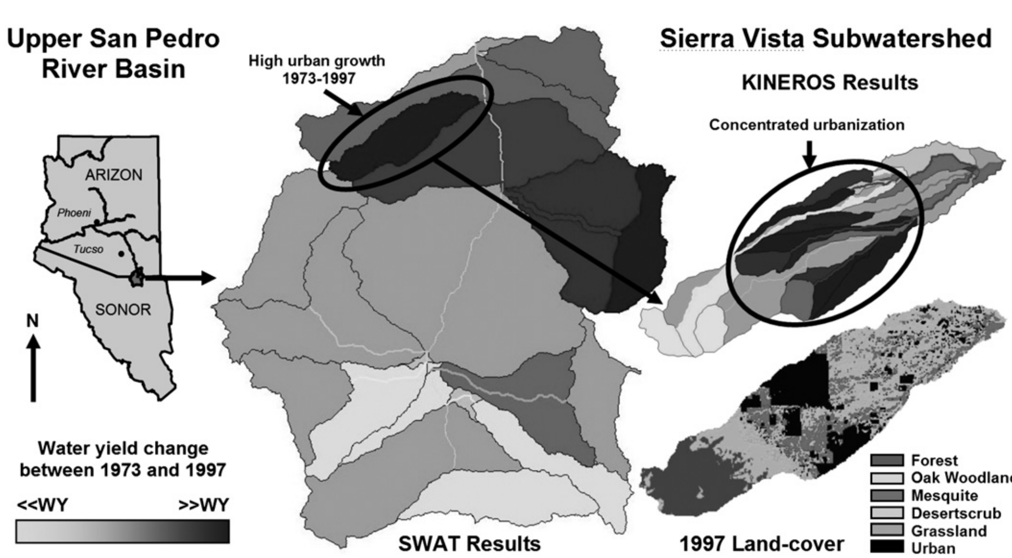

Fig. 6. Model results from the upper San Pedro River Basin and Sierra Vista subwatershed showing the relative increase in SWAT simulated water yield as a result of urbanization between 1973 and 1997. Change in water yield for the channels is shown in shades of brown for clarity.

Current research regarding the effects of remote sensing classification error and the impact of geometric complexity on simulated response will provide estimates of uncertainty associated with using AGWA in an application setting. Future research will focus on the application of AGWA in a range of hydrologic settings through the use of historical data to ensure that the tool can be widely applied with confidence under a range of conditions and for a variety of management objectives. Features to treat a variety of Best Management Practices (BMPs) will be incorporated into AGWA as well as migration of the system to ARCGIS and an Internet accessible version.

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