

The AGWA – KINEROS2 Suite of Modeling Tools

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ABSTRACT

KINEROS originated in the 1970's as a distributed event-based rainfall-runoff erosion model. A unique feature at that time was its interactive coupling of a finite difference approximation of the kinematic overland flow equations to the Smith-Parlange infiltration model. Development and improvement of KINEROS has continued for a variety of projects and purposes. As a result, a suite of KINEROS2-based modeling tools has been developed that can be executed from a single shell. The tools range from the event-based KINEROS2 flash-flood forecasting tool to the continuous KINEROS2-Opus2 (K2-O2) biogeochemistry tool. The KINEROS2 flash flood forecasting tool is being tested with the National Weather Service (NWS). It assimilates the NWS Digital Hybrid Reflectivity (DHR) radar product in near-real time and can simultaneously run ensembles using multiple radar-reflectivity relationships. In addition to simulation of runoff and sediment transport, K2-O2 can simulate common agricultural management practices, plant growth, nutrient cycling (nitrogen, phosphorus and carbon), water quality and chemical runoff. Like any detailed, distributed watershed modeling software, the KINEROS2 suite of tools often requires considerable effort to implement; it is necessary to delineate watersheds, discretize them into modeling elements, and parameterize these elements. This need motivated the development of the Automated Geospatial Watershed Assessment (AGWA) tool. This ArcGIS-based tool uses commonly available, national GIS data layers to fully parameterize, execute, and visualize results from both the SWAT and KINEROS2 models. By employing these two models AGWA can conduct hydrologic modeling and watershed assessments at multiple temporal and spatial scales. A variety of new capabilities have been added to AGWA to configure KINEROS2 inputs to simulate a number of land-management practices or changes (fire, urbanization, and best management practices) as well as incorporate decision-management tools for rangelands. An overview of these tools will be provided.

INTRODUCTION

Physically based, distributed watershed models held great promise to improve the predictability of watershed response when initially conceptualized, developed, and introduced in the 1950's to 1970's. However, they have fallen short of initial expectation for a variety of reasons. Grayson et al. (1992a, and b) critique physically-based hydrology models noting simpler conceptual models may be just as good or superior. What most papers fail to cite is the response by Smith et al. (1994) who note that the physical processes of conservation of mass and energy are quite valid at small temporal and spatial scales. The real challenge is how to characterize and/or parameterize the variability of the abiotic and biotic media over and through which the processes

are occurring over larger scales. In a careful examination of selected papers, Woolhiser (1996) assessed whether simpler models are superior to more complex physically-based models. He found that at relatively small scales, physically-based models are in most cases better than simpler models. When they are not, it is often due to hydrologic measurement and interpretation problems. However, Woolhiser (1996) notes “there are great difficulties involved in scaling up to larger watersheds.” This was reiterated by Bulygina and Gupta (2009) who noted that application of physically-based models at watershed scales (macroscales) carries an implicit premise of our ability to upscale from small-scale studies and observations.

Even with these shortcomings, we must recognize the value of physically based models for watershed assessments and evaluation of alternative future scenarios (Kepner et al. 2008). Simple conceptual or parametric models cannot be readily used to ask how watersheds might respond to different development scenarios and different spatial placement of conservation or land management practices. It is our contention that calibrated physically-based models can be used with some confidence in identifying the trends and directions of changes in watershed response due to changes in watershed condition, characteristics, or inputs. We term this application as “relative” watershed assessment where a comparative change in watershed response from a current condition to an alternative condition can be predicted. An “absolute” assessment is the case when input-output observations are available to perform model calibration and validation and obtain some measure of model uncertainty. If model calibration and validation is acceptable we believe more quantitative watershed assessments can be conducted.

In the case of either a relative or absolute assessment, set-up, parameterization, and execution of physically-based watershed models and visualization of model results can be time consuming tasks. The remainder of the paper will provide an overview of the Automated Geospatial Watershed Assessment tool (AGWA) which has been developed to expedite watershed assessments with distributed, physically-based hydrologic models. Specific enhancements to one of the models embedded within the AGWA tool, KINEROS2, will then be presented.

THE AUTOMATED GEOSPATIAL WATERSHED ASSESSMENT TOOL

To enhance our ability to conduct rapid watershed assessments using distributed watershed models our research group developed, and continues to enhance, the AGWA tool (Miller et al., 2007; Semmens et al., 2008). AGWA is a GIS interface for data organization, parameterization, integration, execution, change-detection, and visualization for models to support watershed management and assessments. There are currently two versions of AGWA available: AGWA 1.5 for users with ESRI ArcView 3.x GIS software, and ESRI AGWA 2.0 for users with ArcGIS 9.x. Both versions can be downloaded freely from either <http://www.tucson.ars.ag.gov/AGWA/> or <http://www.epa.gov/nerlesd1/land-sci/agwa/>. Extensive additional information is also available on these web sites, including documentation, tutorials, supporting papers and presentations, as well as a user forum for assistance and providing suggestions.

AGWA currently supports the Soil and Water Assessment Tool (SWAT – Arnold and Fohrer, 2005: <http://swatmodel.tamu.edu/>) and KINematic Runoff and EROsion (KINEROS2; Semmens et al., 2008: www.tucson.ars.ag.gov/kineros) watershed models. The application of these two models allows AGWA to conduct hydrologic modeling and watershed assessments at multiple

temporal and spatial scales. AGWA's current outputs include spatially distributed runoff (volumes and peaks) and sediment yield, and for SWAT, outputs also include nitrogen and phosphorus. AGWA is designed to provide *relative* estimates of runoff, erosion, and water quality from current conditions to alternative scenarios. It cannot provide reliable absolute estimates without careful calibration using observed data. It is also subject to the assumptions and limitations of its component models.

Using digital data in combination with the automated functionality of AGWA greatly reduces the time required to use these two watershed models. Through a robust and intuitive interface the user selects a watershed outlet from which AGWA delineates and discretizes the watershed using Digital Elevation Model (DEM) information as illustrated in Figure 1. The watershed elements

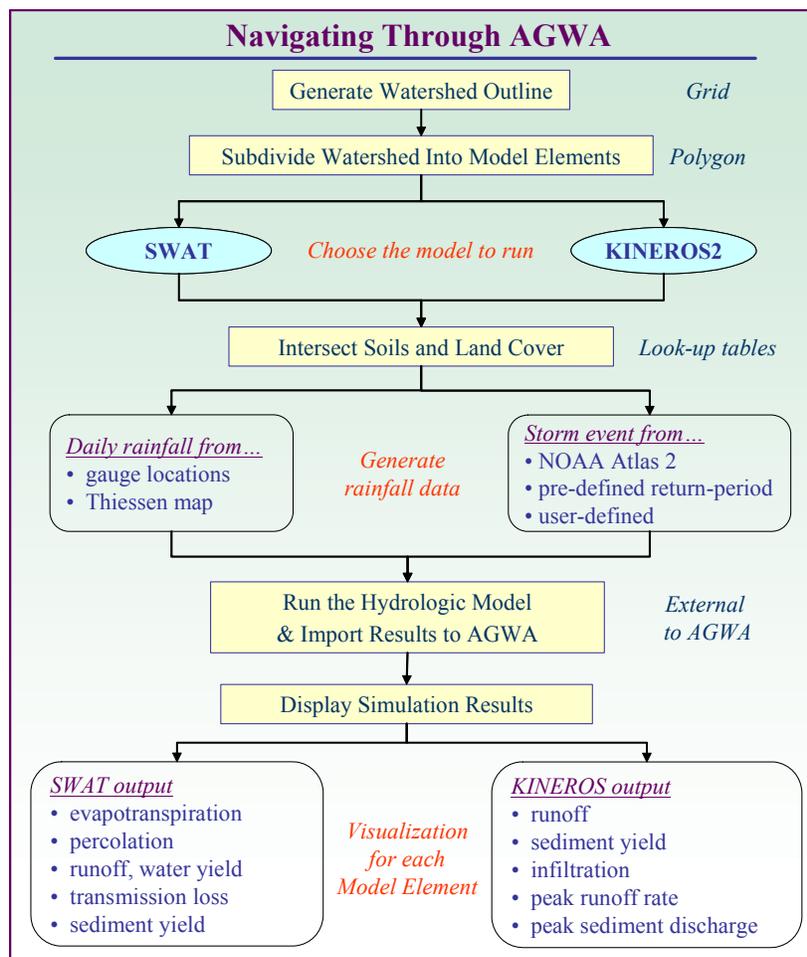


Figure 1. Sequence of steps in the use of AGWA and its component hydrologic models.

are then intersected with soil, land use/cover, and precipitation (uniform or distributed) data layers to derive the requisite model input parameters. AGWA can currently use STATSGO, SSURGO, or FAO soils (Levick et al. 2004) and nationally available land-cover/use data such as the National Land Cover Data (NLCD) datasets (Homer et al. 2004). Users are also provided the

functionality to easily customize AGWA for use with any classified land-cover/use data. The model is then run, and the results are imported back into AGWA for visual display. This feature allows managers to identify and target problem areas for further monitoring and management activities. AGWA can difference results from multiple simulations to examine and spatially compare changes predicted for each alternative input scenario (e.g., climate/storm change, land-cover change, present versus alternative futures, with and without the addition of best management practices).

UPPER SAN PEDRO RIVER MULTI-SCALE ASSESSMENT EXAMPLE

Flowing north from Sonora, Mexico into southeastern Arizona, the San Pedro River Basin has a wide variety of topographic, hydrologic, cultural, and political characteristics (Figure 2). This region is also undergoing a socioeconomic transition as the previously dominant rural ranching economy is shifting to increasing areas of urban development. The watershed is approximately 2885 km² above the USGS Charleston gauge was used to prepare input files and test SWAT. It is an area dominated by desert shrub-steppe, riparian, grasslands, agriculture, oak and mesquite woodlands, and pine forests. The watershed was discretized with a first-order channel support area (CSA) value of 3.2% of the total watershed area (~92 km²). Parameter files were built using both the 1973 and 1997 Landsat Multi-Spectral Scanner and Thematic Mapper classified satellite images (Kepner et al. 2002 and 2000). SWAT was run for each of these using the same ten years of observed daily precipitation and temperature data. By using the same rainfall and temperature inputs, simulated changes in water yield are due solely to altered land cover within the watershed.

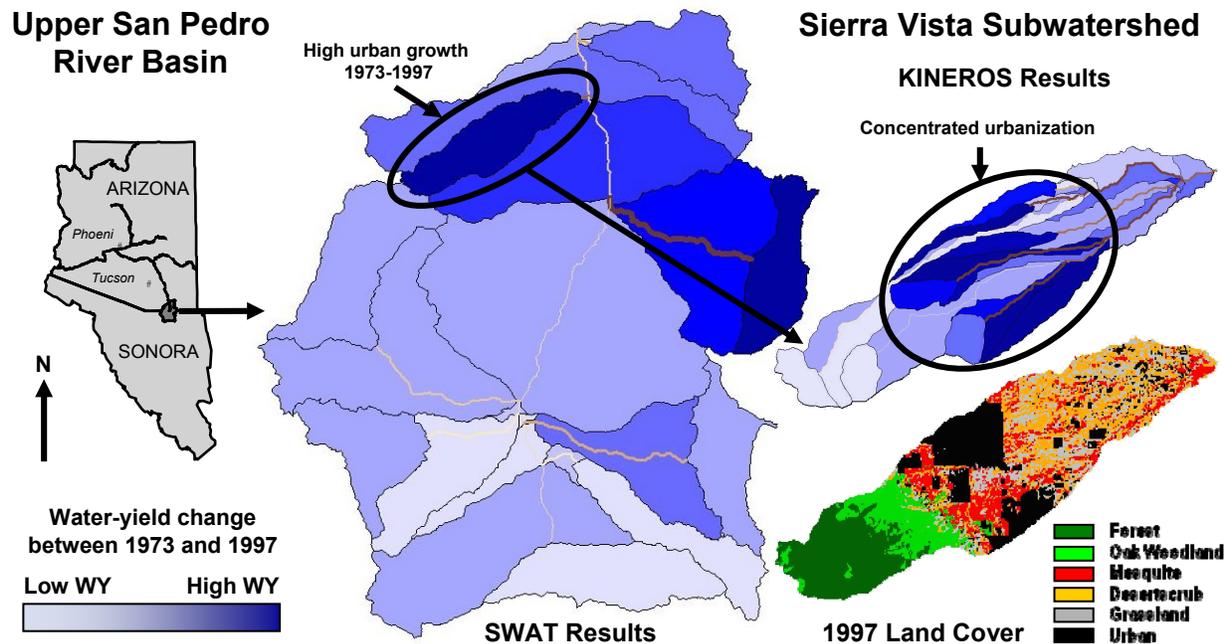


Figure 2. Model results from the upper San Pedro River Basin and Sierra Vista Subwatershed showing the relative increase in simulated water yield as a result of urbanization between 1973 and 1997. Change in water yield for the channels is shown in browns for visibility. Also demonstrated is the multi-scale assessment capability of AGWA; basin-scale effects observed with SWAT can be investigated at the small-watershed scale with KINEROS2.

The ‘differencing’ feature in AGWA was used to compute the percent change between the two simulation results and display it visually (Figure 2 - center). This analysis indicated that a small watershed running through the developing city of Sierra Vista (labeled in Figure 2 as the “Sierra Vista Subwatershed”) underwent changes in its land cover that profoundly affected the hydrologic regime.

The Sierra Vista Subwatershed (92 km²) was modeled in greater detail using KINEROS2. It was discretized using a CSA value of 3.3%, and executed using both the 1973 and 1997 land-cover data. A uniform design storm representing the 5-year, 30-minute event (Osborn et al., 1985) was used in both simulations with an area-reduction method (Osborn et al., 1980). Percent change in runoff between the two simulations was computed using the ‘differencing’ tool in AGWA, and the results are presented directly from AGWA (Figure 2 - upper right). From this analysis and others (Miller 2002) it is clear that increasing impervious area associated with urban growth has resulted in large increases in runoff from those areas where urbanization is highest.

This type of relative-change assessment is considered to be the most effective use of the AGWA tool without calibrating its component models for a particular site. Without calibration, absolute values of model output parameters should not be considered accurate, nor should the magnitude of computed changes. In a relative sense, however, AGWA can still be useful for quickly and inexpensively identifying locations in ungauged watersheds that are particularly vulnerable to degradation, and where restoration activities may therefore be most effective. The ability to use a second model to focus on sensitive areas provides a further means of concentrating restoration efforts, or preventative measures if the tool is being used to assess potential future scenarios.

CURRENT AGWA FEATURES AND NEW FEATURES UNDER DEVELOPMENT

AGWA currently has a number of capabilities to implement watershed management scenarios. The first is a general land-cover modification tool. This feature has a number of options for uniform, spatially random, and patchy change to single or multiple land-cover classes. This tool can also be used for post-fire watershed assessments by either importing an observed burn severity map (Canfield et al., 2005; Goodrich et al., 2005) or using an externally run fire behavior model (www.landfire.gov). A stream buffer strip tool has also been developed that enables users to select a stream reach and, via a scenario simulation, place a buffer strip model element with user-defined characteristics within the watershed model to assess before and after effects on the adjacent stream reach and downstream stream reaches. Similarly, AGWA has the capability to place flood retention and detention structures at various places in a watershed. Another useful tool that has been implemented is the watershed group simulation feature which will perform all the basic AGWA functions over all watersheds within a political or management boundary.

Currently AGWA development is focusing on rangeland watershed management applications as part of a national multi-agency Conservation Effects Assessment Project (CEAP) effort to quantify the environmental benefits of conservation practices used by private landowners participating in USDA conservation programs. The AGWA for Rangeland (AGWA-R) project integrates several ongoing projects to transform the current operational AGWA tool into a

comprehensive Decision Support Tool for rangeland watershed management (Guertin et al., 2010). Specifically, the project includes:

1. Incorporating the newly conceptualized Rangeland Hydrology and Erosion Model (RHEM) (Wei et al., 2007);
2. Developing parameterization methods that represent the complexity of rangeland sites from Ecological Site Descriptions and associated State and Transition Models, rangeland health assessments, and/or field monitoring data;
3. Developing tools that will allow users to represent and analyze the impact of common rangeland management practices on runoff and erosion including prescribed grazing, fire management, brush management, riparian management and range seeding; and,
4. Developing tools that will address the economic sustainability of ranch operations by assessing the costs of soil and water conservation practices, with or without government subsidies, under a variety of alternate management plans.

PROCESS MODELS

While there are numerous process-based watershed models that can be used for watershed management and valuation, our efforts have focused on the SWAT (Arnold and Fohrer, 2005) and KINEROS2 (Semmens et al., 2008) models for several reasons. Both can be applied with readily available national and international datasets; both are well supported and have a long history of continuing development and application; and they complement each other over the time and space scales at which they are best suited. SWAT is typically applied on larger watersheds where components of the water cycle and related water quality measures 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. KINEROS originated as an event-based rainfall-runoff-erosion model and has continued to evolve and improve (Smith et al., 1995; Goodrich et al., 2005); it is now referred to as KINEROS2 (K2). K2 is typically applied at smaller watershed scales (< 250 km²) with high-resolution rainfall data (e.g. NWS data, design storms). The two models enable a multi-scale approach to watershed management.

The USDA-Agricultural Research Service Laboratory in Temple, Texas is the primary development location for the SWAT model and readers are referred to their web site for up to date information on SWAT (<http://swatmodel.tamu.edu/>). The remainder of this paper will provide a brief description of how watersheds are represented in the K2 model and will then focus on new and future developments associated with KINEROS2, which form a suite of K2 modeling tools. These include:

1. Continuous model with management and biogeochemistry (K2-O2);
2. Operational real-time flash flood forecasting (K2-NWS);
3. Continuous with energy-balance snow model and lateral saturated subsurface transport (K2-SM-hsB);
4. New rangeland hydrology and erosion model (K2-RHEM; there is also a K2-WEPP); and,
5. Overland transport of manure-borne pathogen and indicator organisms (K2-STWIR).

In K2, the watershed is represented by a variety of spatially distributed model element types. The model elements can be configured to effectively abstract the watershed into a series of shapes (rectangular overland flow planes, simple and compound trapezoidal channels, detention ponds, etc.), which can be oriented so that 1-dimensional flow can be locally assumed. A typical subdivision, from topography to model elements, is illustrated in Figure 3. Further, the user-defined subdivision can be made to represent hydrologically distinct aspects of a watershed (impervious areas, mines, soils, etc.). In addition, cascades of overland flow elements with different widths and slopes can be formed to approximate converging or diverging areas.

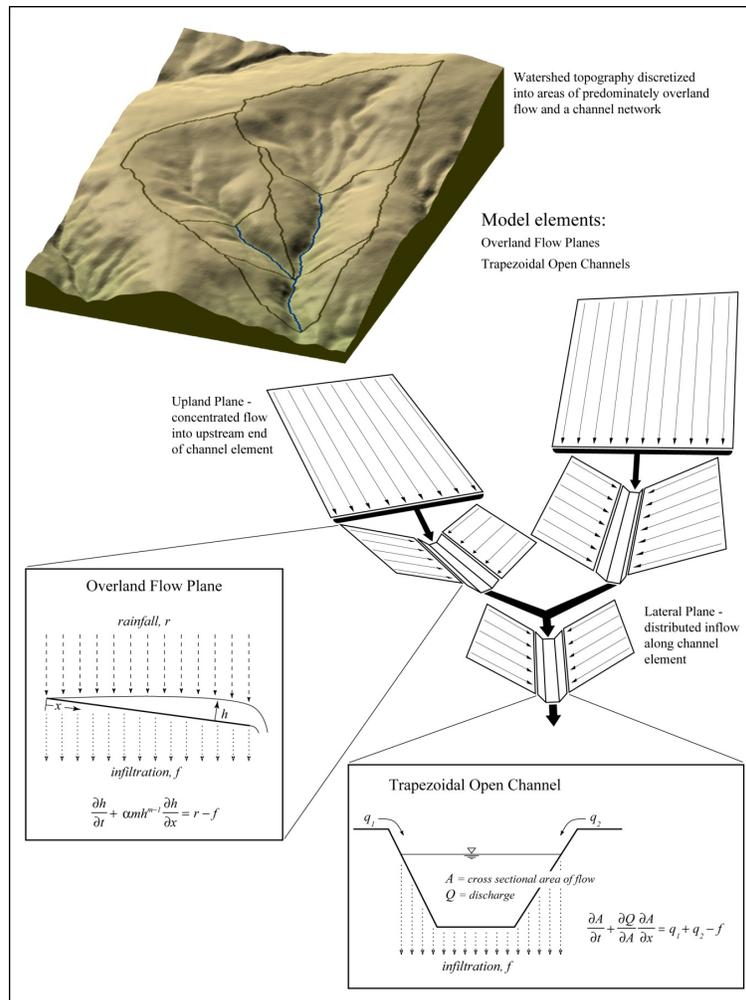


Figure 3. Schematic of the process by which topographic data and channel network topology are abstracted into the simplified geometry of KINEROS2 model elements.

K2-O2 (KINEROS2-Opus2): Continuous Model with Management and Biogeochemistry

To simulate a period of time longer than for a single event, the change in the hydrologic conditions in the intervals between rainfalls must be treated. This includes changes in plant cover, soil water conditions, and the soil and plant characteristics of a catchment or portion thereof by management changes such as harvesting, planting, fertilizing, or tillage. The

processes described above for simulating long-term hydrology were incorporated in the model Opus and its later versions (Smith, 1992; Muller *et al*, 2003). Opus is applicable to small homogeneous areas, with a single soil profile and crop or mix of crops. The development of K2-O2 includes adding the soil and plant processes of Opus2 to K2 and thus extending the application of Opus to larger, more complex and diverse catchments.

Due to the wide range of time, varying hydrologic, soil, and plant processes, K2-O2 employs a hierarchy of time scales to efficiently simulate the mix of interrelated processes described above. Plant growth and climate does not require time scales less than a day for the level of accuracy used in K2-O2. During rainfall, the largest time step is dictated by the changing rain rate intervals. Further subdivision is possible for simulation for rapid changes in the soil water profile or for the numerical solution of kinematic surface water movement.

Climate information is converted to an estimated potential evaporation value by a module based on the Penman-Monteith equation. This value is modified based on plant cover and soil water availability, and distributed between soil surface and plant leaf evaporation using the method of Ritchie (1972). Another climate consideration occurs in cold weather, when a record of precipitation may not identify snowfalls. In this case, snow accumulation and melt must be simulated. For snow accumulation and melt, the model utilizes a simple degree-day estimator, and the treatment of latent heat of freezing is ignored. Opus uses simple soil density information to estimate soil heat transport, however, in a simple heat flux convection/diffusion module. These improvements enable K2 to operate in a continuous mode and effectively track the cycling of carbon, nitrogen and phosphorus based on the Century Model (Parton, et al, 1992) and treatment of several pesticides. Massart et al. (2010) presents applications of K2-O2, and validation for selected components.

K2-NWS: Operational Real-Time Flash Flood Forecasting

KINEROS2 (K2) provides a temporal and spatial resolution not currently available with other NWS flash flood forecasting models. This is particularly important for smaller, fast responding headwater basins. The computational time steps in K2 allow for the nominal 4 to 5 minute interval of the NWS Digital Hybrid Reflectivity (DHR) radar product, which has an average 1-degree by 1-km spatial resolution. To enable real-time forecasting, K2 was re-coded and a graphical user interface (GUI) was developed specifically for use at the NWS Weather Forecast Offices. The GUI displays graphs of both radar-derived rainfall and predicted runoff.

In an operational context, when a new DHR scan appears, K2-NWS applies the user selected radar reflectivity, or Z-R relationship and runs the new rainfall data through the model. The model then continues to simulate into the future for a prescribed forecast interval (e.g. 2 hrs) with an assumed rainfall condition current to the last volume scan of radar data. Currently, the model assumes no additional rainfall input source; however there are plans to use Quantitative Precipitation Forecasts (QPF) in future versions. When new DHR data arrives, the model 'rewinds' back to the end of the previous DHR interval, processes the new rainfall data, and simulates a new forecast interval. By doing this, the model produces a new forecast hydrograph about every 4 minutes or on the interval that the DHR product is received. K2-NWS can also simulate a number of scenarios simultaneously, such as different Z-R relationships, to help

quantify the uncertainty in the resulting forecast. K2-NWS has undergone calibration and limited operational testing in two widely disparate climatic/landscape regimes in the United States. Unkrich et al. (2010) describe the forecast version of K2 and its application.

K2-SM-hsB: Detailed Snow Model and Lateral Saturated Subsurface Transport

K2-NWS is in the process of being updated to improve flood forecasting where melting snow or rain-on-snow can cause flooding. Like KINEROS-Opus, this will provide automated estimation of pre-storm initial conditions, however it will not treat nutrient and carbon cycling. The first module of SM-hsB consists of a distributed water and energy balance model of the vegetation canopy and the land surface. The second module is the soil water balance model (Teuling and Troch, 2005), and the third module is based on the hillslope storage Boussinesq (hsB) equation (Troch et al., 2003) and operates at the hillslope scale treating lateral saturated subsurface transport of soil water for complex hillslopes. The latter flux is parameterized using a new algorithm developed by Bogaart, et al. (2008).

The snowmelt portion of the model is essentially an energy balance model that allows snow to accumulate on the land surface until it is warm enough for snowmelt to occur. Basically, it simulates snow accumulating, gaining a cold content (which prevents the snow from melting on warmer winter days—provided that the nights remain cold enough to replenish the cold content), and finally melting when the cold content is no longer sufficient to offset the incoming energy that the snowpack receives. Incoming energy can include incoming/outgoing net radiation, sensible heat transfer to/from the snowpack, latent heat transfer, ground heat flux, and the heat release caused by rain falling on snow. The last component is a deep groundwater module (linear or non-linear reservoir receiving deep percolation from a leaky hsB module). Work on K2-SM-hsB has recently been initiated and is expected to be completed by 2012.

K2-DRHEM: New Rangeland Erosion Model

RHEM (Wei et al., 2007; the dynamic version is referred to as DRHEM) is a newly conceptualized model designed to treat rangeland conditions and accounts for the joint effect of rainfall and runoff impact on inter-rill erosion. It incorporates a new equation for splash and sheet erosion, which are typically the dominant erosion processes on rangeland sites in good condition with adequate cover. The model also represents the process of concentrated flow erosion that may be important if a site is disturbed or if the cover consists of shrubs with large interplant distances of bare ground. RHEM incorporates the interaction between hydrology, erosion processes, and plant forms by parameterizing the hydraulic conductivity based on the classification of plant growth forms. Importantly, the new RHEM formulation has also been incorporated into the K2 model to represent rangeland hillslope elements. This will allow parameterization algorithms to be developed that can support both models.

K2-STWIR: Overland Transport of Manure-Borne Pathogen and Indicator Organisms

Runoff from manured fields is often considered the source of micro-organisms in surface water used for irrigation, recreation, and household needs. Concerns over the microbial safety of this water has resulted in the need for models to estimate the concentrations and total numbers of

pathogen and indicator organisms leaving manured fields in overland flow during runoff events, and the ability of vegetated filter strips to reduce the transport of pathogens and indicators from the edge of fields to surface water sources. In an attempt to address this need we developed an add-on to K2 to simulate the overland transport of manure-borne fecal coliform and *E. coli*. The add-on STWIR (Solute Transport With Infiltration and Runoff) has been developed and successfully tested with data from simulated rainfall experiments at vegetated and bare 2x6 m plots and with data from a 3-ha field obtained after manure applications. The STWIR includes the estimation of bacteria release from manure as affected by rainfall intensity and vegetation. Additional details on K2-STWIR can be found in Guber et al. (2010).

CONCLUSIONS

Many of the developments in AGWA and KINEROS2 are essential for building a generalized watershed management and valuation system. Science-based valuation requires that the effects of decisions and management actions are realistically translated into changes in watershed or ecosystem services through process models such as those included in the suite of AGWA-KINEROS2 tools. The tools described herein will broaden the applicability of this suite to both a wider range of hydro-climatic and management conditions. Future efforts will also be directed towards the incorporation of remotely sensed watershed characteristics and assimilation of remotely sensed data to update state variables. Efforts will also be directed to making these tools available via the Internet.

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