THE AGWA – KINEROS2 SUITE OF MODELING TOOLS IN THE CONTEXT OF WATERSHED SERVICES VALUATION

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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 KINEROS-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 KINEROS-OPUS biogeochemistry tool. The KINEROS2 flash flood forecasting tool is being tested with the National Weather Service. 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, KINEROS-OPUS can simulate management, plant growth, nutrient cycling (nitrogen, phosphorus and carbon), water quality and chemical runoff. Like any detailed, distributed watershed modeling software, the KINEROS suite of tools often requires considerable effort 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 KINEROS 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 KINEROS inputs to simulate a number of land-management practices or changes (fire, urbanization, BMPs) as well as incorporating decision-management tools for rangelands. An overview of these tools will be provided pointing to other more detailed presentations and computer demonstrations of these tools being made at the conference. In the larger context these tools are components of a watershed management framework, which embodies decision tools, scenario development and both market and non-market valuation of watershed services (e.g. provisioning of clean water, natural flood attenuation, etc.).

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[1] All authors have contributed to this paper and/or the development of the KINEROS2-AGWA in the past

INTRODUCTION

Watershed or ecosystem management and forecasting inherently integrates the need to understand watershed processes as they change in both time and space. Decision-making requires trade-offs be considered that include market-based goods and services and non-market values for environmental services provided by a watershed. In addition, the decision framework should be constrained by the relevant institutional and regulatory structures.

Consider rangeland watershed forage production, as an example. To maximize the overall social benefit, rangeland managers need to consider all the services (ideally monetized as costs and benefits) that rangeland provides and find the best way to utilize the forage (an example of one use) and associated landscapes. Market based expenditures might include the costs for fencing and watering points while revenues might include cattle production or hunting fees. Non-market costs might include increased erosion and degraded water quality, while benefits might include increased species diversity and soil quality/organic carbon content (Duan et al., 2006).

An overall approach to watershed or ecosystem management requires a significant number of disciplines, valuation of resources (not normally undertaken), and integration of the disciplines within a coupled framework. This broad framework is schematically depicted in Figure 1, following the approach outlined by Brookshire et al. (2010).

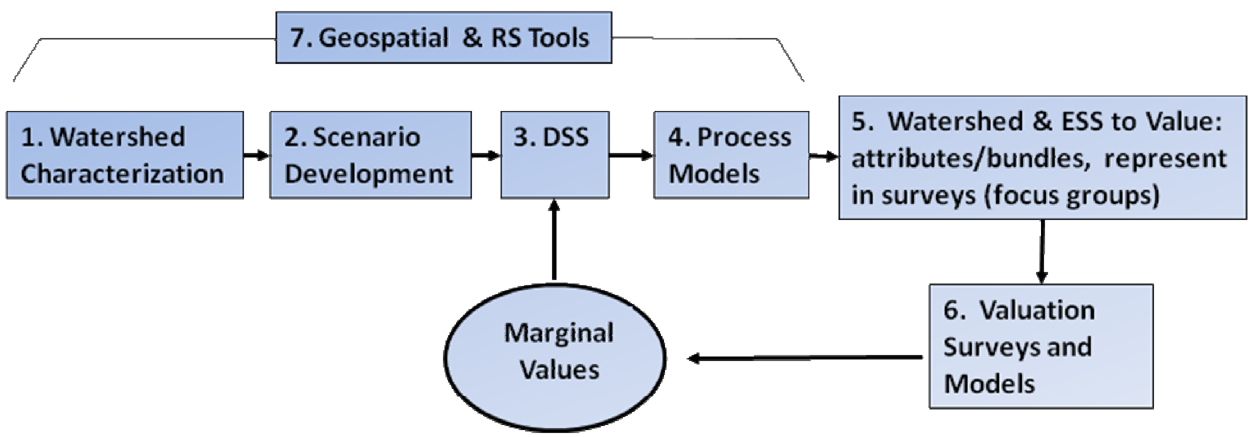

Figure 1. Schematic Representation of Watershed Management Components for Valuation

The initial step in this process is to provide the necessary information for establishing all costs and benefits. Box 1 establishes the baseline and thus the watershed or geography characterization. For surface oriented watershed management, relatively static, yet widely available, GIS layers of soils, topography, and land use/land cover can often provide initial characterization. Then the social sciences must be brought into play to work with resources managers and decision makers to define a likely decision space (i.e. define probable scenarios, and construct and assess the scenarios – box 2; Mahmoud et al., 2009).

Scenarios are broadly defined by two distinct, yet interrelated drivers. Scenarios could include a wide range of anthropogenic decisions such as urbanization, controlled burns, grazing density, or conservation easements. These should be coupled with probable climate scenarios such as increased frequency of droughts or high-intensity rainfall events. A Decision Support System (DSS – box 3) which is both spatially and temporally explicit, is often a desirable method to represent system characteristics, integrate the various process models into a coupled framework, test alternative scenario outcomes, and provide outcomes from the process-based models (or approximations of them - box 4) for resource managers and decision-makers (Power, 2002). For illustration purposes, the DSS is placed between boxes 2 and 4 in figure 1. However, it could easily interact with other components depending on how broadly it is constructed. The DSS should be developed directly with the decision-makers and stakeholders using their terminology coupled with descriptive information (text, graphs) that they find most useful.

Via the process-models (box 4), predictions of changes in multiple watershed or Ecosystem Service (ESS) attributes in both space and time (box 5) are linked directly to the management decisions selected in the DSS. It is critical that a solid scientific foundation represented by boxes 1 through 4 in Figure 1 exists to properly enable the valuation of non-market watershed services in obtaining defensible monetary valuations of watershed and ecosystem services (Brookshire et al., 2010). These are the "endpoints", or "changes in endpoints" necessary for valuation (Boyd, 2007) that should have direct social relevance. For example, traditional hydrological modeling endpoints have been flood or low flow characteristics. A more socially relevant endpoint might be the area underwater in the case of floods, or the amount of food that can still be grown by irrigation in the case of low flows. More importantly, is that the endpoints are stakeholder defined (e.g. Wagener et al., 2008). Making these endpoints an implicit part of the modeling framework enables an evaluation of what controls the predicted values of these endpoints and of the largest sources of uncertainty in their prediction. Valuation (box 6) can then be undertaken. If markets exist, as is the case for the sale of cattle, valuation is straightforward and benefits (revenue from increased cattle production) could be compared directly to the costs of range management activity such as brush management.

If markets do not exist for watershed services that may be improved or degraded, there are two stated preference techniques (surveys) for conducting ecosystem or watershed services valuation that have undergone significant development in the economics literature: Contingent Valuation (CV) and Choice Modeling (CM) (Roe et al., 1996; Stevens et al., 2000; Louviere et al., 2000). CV modeling asks survey participants to explicitly state their willingness to pay for a proposed change of a single ecosystem attribute. CM modeling asks the survey participant to compare current conditions, as represented by a bundle of watershed or ecosystem service attributes, to an alternate bundle, multiple times. This allows a determination of the marginal value of the watershed service attribute. The marginal values (effectively demand curves for the services), in monetary terms, can then be brought back into the DSS to fully incorporate market benefits and costs, as well as non-market benefits and costs for a full evaluation of watershed management decision tradeoffs. The final step involves integration of these market and nonmarket values back into the DSS with the appropriate scenarios to appropriately display all tradeoffs. The display will present the full range of values, both nonmarket and market at the margin.

In sum, spatially explicit watershed management and valuation will be significantly aided by the use of computer-based geospatial tools (Figure 1 – box 7). Broadly speaking these tools provide functionality beyond the basic capabilities of commonly available Geographic Information System (GIS) software and automate the tasks needed to execute the components represented across boxes 1-4 in Figure 1.[2] For watershed characterization (box 1), GIS is exceedingly useful at organizing the basic watershed spatial information and enabling manipulation of, and between, various GIS data layers. Geospatial tools also provide complex geospatial capabilities that are typically required for tasks such as implementing and evaluating decision scenarios (i.e. placing multiple watershed best management practices or changes in land cover and land use), and parameterizing, executing, visualizing, and conducting spatial change analysis using process-based watershed models. Developing the system described above, and making it Internet accessible (Cate et al., 2006), is a long-term goal of our team, but for the purposes of this paper we will concentrate on describing features developed for geospatial tools and process models for watershed management.

GEOSPATIAL TOOL – AGWA

To address the needs for geospatial tools the team has developed, and continues to enhance, the Automated Geospatial Watershed Assessment (AGWA) tool (Goodrich et al., 2006; 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 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/index.htm 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, also plus nitrogen and phosphorus. AGWA is designed to provide ***qualitative*** estimates of runoff, erosion, and water quality from current conditions to alternative scenarios. It cannot provide reliable quantitative estimates without careful calibration using observations. 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 (Figure 2). 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. The watershed elements 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 and FAO soils and nationally available land-cover/use data such as the National Land Cover Data (NLCD) datasets. 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

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[2] Geospatial tools, like the DSS, could also interact and assist in the development and execution of other components in Figure 1.

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).

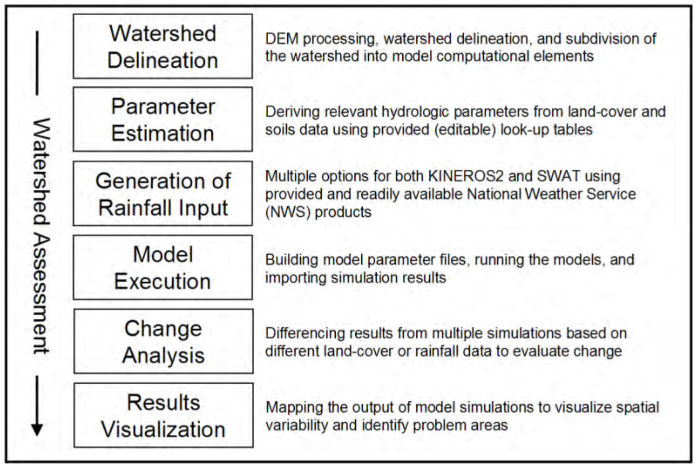

Figure 2. AGWA modules, and the sequence of steps for hydrologic modeling and change detection. (from Miller et al., 2007)

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 strip installation 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.

New AGWA Features Under Development

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

1. Incorporating the newly conceptualized Rangeland Hydrology and Erosion Model (RHEM) (Wei et al., 2007) into AGWA/KINEROS2;

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 building on the work of Duan et al. (2006).

Guertin et al. (2010) will present more detailed information on these improvements for rangeland watershed assessments as part of this conference.

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 (Woolhiser et al., 1970) and has continued to evolve and improve (Smith et al., 1995; Goodrich et al., 2005) and is now referred to as KINEROS2 (K2). K2 is typically applied at smaller watershed scales (< 250 km^2) with high-resolution rainfall data (National Weather Service Radar data, design storms). The two models enable a multi-scale approach to watershed management as SWAT can be run over larger watershed over longer periods of time to identify potential areas where significant change from a scenario occurs. These sub-watersheds can then be examined in greater detail by using AGWA with smaller modeling elements and running K2.

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 (KINEROS-OPUS);
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 erosion model (K2-RHEM); 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 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 contributing areas.

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; Ferreira and Smith, 1992). 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 modular soil and plant process methods of Opus to elements of K2 and thus extending it 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 with the possible further subdivision for simulation for rapid changes in the soil water profile or for the numerical solution for kinematic surface water movement.

Climate information is converted to an estimated potential evaporation value by a module based on the Penman-Monteith equation (Monteith and Unsworth, 1990). 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 will be 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 phosphorous including the limited treatment of several pesticides. Massart et al. (2010) presents te application of K2-O2, and validation for selected components as part of this conference.

K2-NWS: Operational Real-Time Flash Flood Forecasting

KINEROS2 (K2) provides a temporal and spatial resolution not currently available with other National Weather Service (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 (Goodrich et al., 2006) 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.

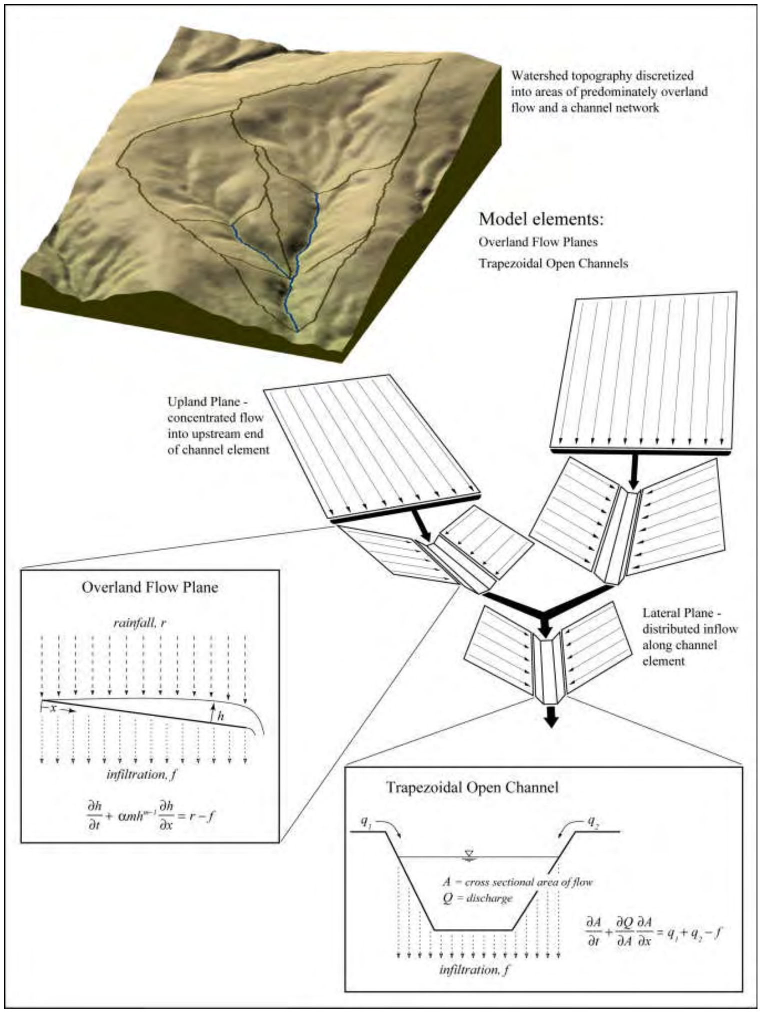

Figure 3. Schematic of the process by which topographic data and channel network topology are abstracted into the simplified geometry of KINEROS2 model elements.

In an operational context, when a new DHR scan appears, K2-NWS applies the user selected 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 reflectivity/rainfall 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 it application is described in more detail as part of this conference.

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

To enable K2-NWS to forecast flooding more reliability in groundwater or lateral subsurface flow dominated watersheds and watersheds where melting snow or rain on snow can cause flooding, the SM-hsB subsurface/inter-storm model components are in the process of being added to K2-NWS. 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 mid-2011.

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 that 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 and erosion process 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 microorganisms 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., (2010a; 2010b).

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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