KINEROS2 - NEW FEATURES AND CAPABILITIES

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Abstract

KINEROS2 (K2) is a broadly updated version of the KINEROS kinematic runoff and erosion model. KINEROS/K2 has traditionally been an event-, physically-based model describing the processes of interception, infiltration, runoff generation, erosion, and sediment transport from small agricultural and urban watersheds for individual rainfall-runoff events. Recently the model has undergone a major restructuring. This has enabled the addition of several major enhancements by incorporating sub-models of OPUS. These include making the model continuous and the ability to treat various agricultural management practices and water quality. The restructuring involved the deconstruction of the procedural Fortran77 code of K2 into a library of quasi-object-oriented, Fortran 90/95 sub-process modules that are functionally independent, plus a set of modules to support backward compatibility. Each module declares a public set of functions and subroutines that collectively defines an application program interface (API), which was carefully designed to simplify use by non-Fortran programs, in particular those compiling environments commonly used for graphical user interface development. The API will allow applications to create, destroy, control, and retrieve copies of internal data from individual sub-process objects. Within a suitable application structure, the objects can accommodate various operational requirements such as time-space versus space-time looping, and also have the ability to return to an internal state saved from a previous computational time step. This allows the model to be used as a real-time forecasting tool. While K2 evolved primarily as a research tool it is currently being used in consulting and in a more operational watershed assessment context. This has been facilitated by the incorporation of K2 into the AGWA (Automated Geospatial Watershed Assessment) tool in support of US-EPA landscape analysis activities (see companion paper and computer demonstration). This paper and the associated computer demonstration of K2 will focus on new model features that have not been previously presented in the literature as well as an example forecast application.

INTRODUCTION

The KINEROS rainfall-runoff-erosion model originated from efforts in the 1970's (Woolhiser et al., 1970; Rovey et al., 1977) and has continued to evolve and improve (Woolhiser et al., 1990; Smith et al., 1995; Goodrich et al., 2002) and is now referred to as KINEROS2 (K2). This paper provides a brief background and more fully describes several improvements to K2 in addition to outlining efforts to further enhance the model. The primary improvements include a major logical and programmatic restructuring of the model and addition of a number of sub-models of OPUS (Smith, 1992; Ferreira and Smith, 1992). These improvements will enable K2 to operate in a continuous mode as well as enable treatment of various agricultural management practices and water quality. Due to the abbreviated nature of this paper, extensive references describing the model and supporting research are not included herein. The K2 model, more extensive documentation and many of the supporting references can be found at www.tucson.ars.ag.gov/kineros.

In K2, the watershed being modeled is characterized 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, detection 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 1. Further, user-defined subdivision can be made to represent hydrologically distinct aspects of a watershed (impervious areas, mines, soils of distinctly different hydraulic conductivity, etc.). In addition, cascades of overland flow elements with different widths can be formed to approximate converging or diverging contributing areas. In addition to overland flow and channel model

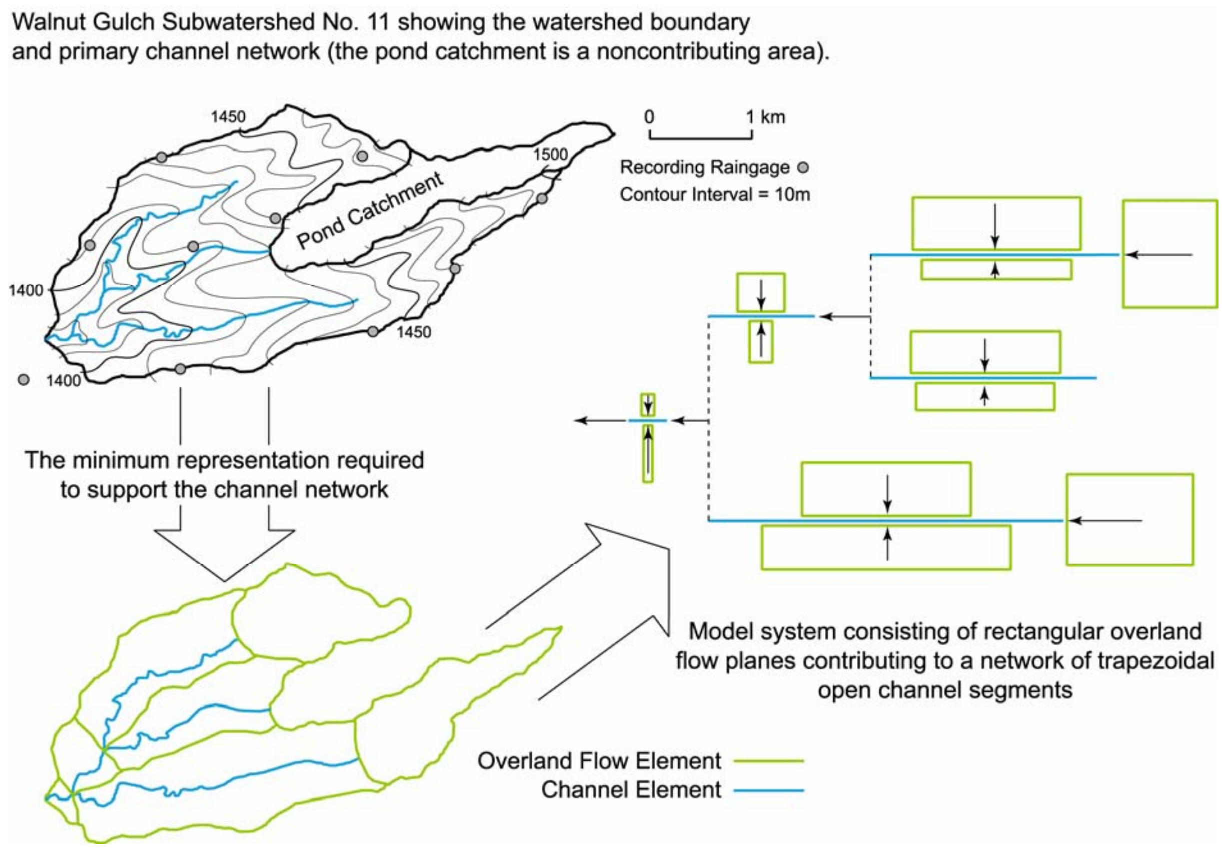

Figure 1. Schematic of the process by which topographic data and channel network topology are abstracted into the simplified geometry of KINEROS2 model elements.

elements, K2 enables the representation and parameterization of detention structures, culverts (non-pressure flow), urban elements (mixed infiltrating/impervious with runoff-runon), and injection elements (hydrographs and sedigraphs injected from outside the modeled system). Hydrological processes represented in the event-based version of K2 include rainfall, interception, soil moisture, infiltration during rainfall, infiltration during a rainfall hiatus and on recession, routing, baseflow, and erosion and sediment transport. A more extensive summary of supporting references describing K2, and how hydrologic processes are represented or approximated in the model is contained in Goodrich et al, (2002) and the KINEROS web site.

KINEROS2 RESTRUCTURING

K2 is a Fortran 77 code designed to handle an unlimited number of model elements (planes, channels, etc.) while keeping the compiled program size well under the 640 KB limit imposed by the original MS-DOS operating system. These two criteria are met primarily by three design features. First, requiring that the element parameter blocks in the input file appear in sequential processing order eliminates the necessity of storing element information in arrays. This saves on memory overhead and opens the door for unlimited elements by avoiding arrays which in Fortran 77 must be a fixed size. The second feature is that the program iterates over all time steps for a given element before moving on to the next. Since all of the individual process models (overland flow, infiltration, etc.) in the program require values from the prior time step in their computations, this space-time looping structure minimizes memory usage because values only have to be carried over for one element. The third design feature tries to address the need to efficiently store a certain number of outflow hydrographs and sedigraphs until they are used as inflow to downstream elements. The program uses a carefully orchestrated 'revolving door' scheme to manage a single, fixed-length array that is partitioned into blocks equal to the number of time steps. In this scheme, maximum utilization of the array is achieved by allowing new outflow values to immediately occupy memory spaces just vacated by values used for inflow.

The memory-efficient design features of K2 served it well during the early period of personal computing. At the present time, however, there is tremendous processing power and huge memory resources available on personal computers, both in hardware and through the use of virtual memory strategies like page file swapping. Therefore the hardware and operating system issues that K2 was designed to address no longer exist. Fortran itself has also advanced to a new standard, Fortran 90/95. Fortran 90/95 provides dynamic memory allocation, a proprietary pointer mechanism and modules that encapsulate data structures and procedures, allowing a rudimentary object-oriented programming approach. Also, although K2 is composed of well-defined components, those components were designed to be parts of a whole and not to function independently. This monolithic nature of K2 has led to a number of modified versions, each of which must be maintained as a separate program.

To overcome the design limitations of K2, and to take advantage of features offered by Fortran 90/95, the K2 code was deconstructed and rebuilt into a library of Fortran 90/95 modules, with each module implementing a single process model. The self-contained nature of these modules should encourage their incorporation into new programs that could benefit from their capabilities rather than modifying K2 to address specialized needs. A module implements an object by declaring a single data structure to hold parameter values and the variables necessary to preserve its internal state between time steps, allowing it to be used in both a space-time and time-space looping context. Sometimes it is desirable to iterate over all elements at each time step, rather than each element over all time steps, as is done by K2. Examples would be open-ended simulations, such as real-time operation, or to graphically display the spatial distribution of simulated quantities, such as runoff from each element, at each time step during a simulation. A module also contains procedures to create and initialize the data structure, set parameter values, advance the computations by one time step, and free memory allocated when the data structure is no longer needed. Additional procedures may be included as needed to return copies of internal data or useful computed quantities. A module can also allocate an array of the data structures (objects), and contains procedures which allow the calling code to use an index into the array as a proxy for a given object. There are procedures that take a single data structure as an argument and equivalent procedures that operate on a specified element of the internal array of data structures. The former are intended for inter-module use within the library, such as between overland flow and infiltration, and the latter comprise an application programming interface (API) for use by the host program or procedure. Creating objects within the module and using an index to refer to a particular object is part of a strategy to simplify use of the library by applications written in languages other than Fortran. This is desirable in that none of the popular and full-featured graphical user interface development products are based on Fortran. Other aspects of this strategy include restricting data types of procedure arguments to simple integer or real types and letting the host application perform all input and output. In addition to the core process models, there are utility modules to conveniently support backward-compatibility, such as one to extract parameters from a K2 input file. Compatibility between future versions of the module library is also ensured by not allowing existing procedures to be removed, or their names or argument lists to change, although they can change internally. Additional procedures that support extensions to a module's capabilities can be added in the future as long as suitable defaults can allow existing programs to use the module without calling the procedures.

The first application of the module library has been the development of a site specific, real time flash flood forecasting model for the National Weather Service (NWS), to be used in the western United States. To this end a key enhancement was added during the restructuring process to facilitate use in a real-time predictive mode, where, after simulating the latest real- time interval, the simulation continues into the future with assumptions about the input conditions. When the next interval of data arrives, K2 would have to start over from the very beginning of the simulation in order to arrive at a point where it could process the next interval of real data. The new modules were given the capability to save their internal states at a point in time and return to that state at a later time. So after the predictive interval, the modules can 'rewind' back to the end of the last interval of real data, and the program does not have to start over. This will be particularly important when the program is expanded to operate continuously. In addition to the overland flow and open channel process modules, the NWS program takes advantage of two utility modules in the library. One reads a K2 input file, then creates and configures all of the planes and channel elements as specified in the file. The other transfers outflow values from upstream elements into inflows to downstream elements at each time step.

The K2 input file used by the model is created by the Automated Geospatial Watershed Assessment (AGWA – see www.tucson.ars.ag.gov/agwa) tool (Miller et al., 2002; Goodrich et al., 2006), an ArcView GIS extension, based on DEM, STATSGO or SSURGO soil, and NALC, MLRC, or SWGAP land cover data layers. Real time rainfall data input are obtained via the NWS Digital Hybrid Reflectivity (DHR) radar product. At this time, GIS shape files for the radar grid are being generated by the ArcView extension that supports the NWS Areal Mean Basin Estimated Rainfall (AMBER) program. A modified version of AGWA intersects the polygons from which K2 overland flow planes were derived and the radar grid. A file is written giving the fractional area weight of each radar grid intersecting a given overland flow area, so an area-weighted value of rainfall for each overland flow plane can be computed. A module specific to the NWS program provides the real time rainfall for each overland flow element using a DHR file decoder adapted from the NWS Flash Flood Monitoring and Prediction (FFMP) model and the file of area weights. The module can utilize archived DHR data, which is useful when calibrating the model, as well as data arriving in real time.

Input files for several basins in Southern Arizona have been created and the program was running in the NWS Tucson Weather Forecast Office during the latter part of the 2005 North American Monsoon . However, evaluation of the model's performance will be postponed pending completion of two important components, a calibration tool and a suite of Fortran 90/95 modules implementing process models from the Opus program as described in the next section. For the NWS application, continuous simulation will be used to estimate soil moisture conditions prior to each storm.

CONTINUOUS SIMULATION EXTENSION

To simulate a longer period of time than for a single event, the change in the hydrologic conditions in the intervals between rainfalls must be treated. This includes changes in cover as well as changes in soil water conditions. This in turn requires additional weather data and additional simulation capability. Plant cover may be a single crop or a mixture of species with different characteristics. Plants are complex systems involving growth, extension of root, and responses to temperature, nutrients, and soil water. The soil profile may be composed of a number of layers with different hydraulic characteristics. On top of this, the soil and plant characteristics of a catchment or portion thereof can be significantly altered by management changes such as harvesting, planting, or tillage. In addition to the systems summarized above, most catchments of interest have spatial variations in soils and plants, even if a single climate can be assumed. While several degrees of simplification are possible, experience has shown that soil and plant processes should be reasonably well simulated in order to be able to track long term hydrology without significant bias.

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 KINER-OPUS 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. In a sense, this evolution follows the increasing speed and memory capabilities of computer hardware.

In order to extend the capabilities of K2 to continuous scale, additional information of several types is required. The element structure of K2 dictates the spatial scale for most of this information, although for meteorological data, larger scales are much more practical. The scale of variation of local variables such as temperature and radiation, for example, are larger than the scale of hydrologic runoff processes. Indeed, the temporal scales of the various processes are different as well. The following paragraphs briefly outline the data requirements for each of the major watersheds components and management practices.

1. Plant Description. The plant cover on a hydrologic model element may be anything from a single planted crop, to a mix of species on a perennial meadow. In any case, the method of Opus is to use a mechanistic model using process-related parameters to describe the growth of a plant and the extension of its roots in response to temperature, soil water, nutrients, and solar radiation. This involves some 8 to 10 parameters per plant type.

2. Soil Description**.** For the whole catchment, a list of soil horizons and their hydraulic properties and names (or ID numbers) are specified. Then for each element, the horizonation is described in terms of depths from the surface to the bottom of each different layer. This method reduces the amount of repetitive input for large catchments composed of many elements.

3. Management Actions. For agricultural catchments, these data must include descriptions of the soil and plant cover changes resulting in all types of management actions that are used, as well as a calendar of the timing of each action. The calendar need be only as long as the rotation cycle. For undisturbed areas, these data are unnecessary.

4. Climate Data. In addition to the rainfall record already required by K2, the extension to continuous simulation requires the climate data necessary to estimate plant growth. Using the Opus plant model, this requires daily maximum and minimum temperatures, plus either a) daily net solar radiation, b) daily pan evaporation, or c) daily relative humidity. If either of the latter two are used, Opus includes a means to estimate daily net radiation (in Langleys). For daily values of temperatures and radiation, a climate generator model may be used, but this requires the input of additional seasonally-varying stochastic climate parameters.

5. Initial State Description. Finally, the condition of the soil and plant must be described in terms convertible to the process parameters for the start of the simulated period. In doing so, the user must consider the annual growth cycle. Opus uses a simulation of plant growth from the beginning of the plant (calendar) year to estimate starting conditions, but other methods are possible. The lower boundary condition for the element's soil profile is a water table depth, which may be much deeper than the soil profile actually simulated.

In terms of hydrological process representation, the soil water model is a specially designed numerical solver for Richards' Equation, with a flux upper boundary condition and an updatable fixed head lower boundary condition. Between rains, the surface flux is a daily value of estimated soil surface evaporation. During rains, the surface influx is the rainfall rate, up to the point where the solution predicts ponding or saturation of an upper soil layer. The plant water use is distributed along the rooting depth and becomes a flux sink term in the solution. This flux is neglected during rain.

The 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. This is especially important in areas where snowmelt runoff is important in the local hydrology. The KINER-OPUS model will use a 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.

KINER-OPUS will employ 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 KINER-OPUS. These daily time steps will overlay those for the soil and water dynamic models. During rainfall, the largest time step is dictated by the changing rain rate intervals. Further, the interval of a given rainfall rate may require subdivision for simulation of the rapid changes that may be taking place in the soil water profile, in order to estimate a changing infiltration rate. Or, a smaller interval may be required by the numerical solution for kinematic surface water movement. Time step selection must consider the conditions on all the elements and choose the largest which is consistent with a good solution for the most limiting process on the most critical element. This includes consideration of both surface and subsurface water flow processes.

CONCLUSIONS AND FUTURE DIRECTIONS

In the evolution of KINEROS to K2 and to KINER-OPUS, a greater number of hydrometeorology and plant ecology processes are treated. With greater process model complexity, it is typical to introduce an increasing number of parameters and input data requirements. In the same light, model calibration and validation are increasingly complex. In parallel to the evolution of KINEROS it is also our intent that AGWA evolve to assist model users in model parameterization using GIS tools and in-situ or remotely sensed (RS) data. As in the current AGWA version, parameter look-up tables, based on widely available watershed GIS or RS data layers, will be developed based on field data, published literature, expert experience, and calibration/validation experience where sufficient data are available. As KINEROS and AGWA evolve they will be incorporated into new releases of the BASINS (Better Assessment Science Integrating point and Nonpoint Sources) modeling suite maintained and distributed by EPA (http://www.epa.gov/OST/BASINS/). An overview of the AGWA model can be found elsewhere in this issue (Goodrich et al., 2006) as well as a description of an internet-based version of AGWA (deemed dotAGWA; Cate et al., 2006). Also found in this issue is a paper describing a channel characterization tool that is being developed to enable AGWA to derive necessary channel geometric parameters from LIDAR data (Semmens et al., 2006). Research is also underway to couple KINER-OPUS with the MODFLOW groundwater model.

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