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## SWAT2000: current capabilities and research opportunities in applied watershed modelling

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### Abstract:

SWAT (Soil and Water Assessment Tool) is a conceptual, continuous time model that was developed in the early 1990s to assist water resource managers in assessing the impact of management and climate on water supplies and non-point source pollution in watersheds and large river basins. SWAT is the continuation of over 30 years of model development within the US Department of Agriculture's Agricultural Research Service and was developed to 'scale up' past field-scale models to large river basins. Model components include weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, stream routing and pond/reservoir routing. The latest version, SWAT2000, has several significant enhancements that include: bacteria transport routines; urban routines; Green and Ampt infiltration equation; improved weather generator; ability to read in daily solar radiation, relative humidity, wind speed and potential ET; Muskingum channel routing; and modified dormancy calculations for tropical areas. A complete set of model documentation for equations and algorithms, a user manual describing model inputs and outputs, and an ArcView interface manual are now complete for SWAT2000. The model has been recoded into Fortran 90 with a complete data dictionary, dynamic allocation of arrays and modular subroutines. Current research is focusing on bacteria, riparian zones, pothole topography, forest growth, channel downcutting and widening, and input uncertainty analysis.

The model SWAT is meanwhile used in many countries all over the world. Recent developments in European Environmental Policy, such as the adoption of the European Water Framework directive in December 2000, demand tools for integrative river basin management. The model SWAT is applicable for this purpose. It is a flexible model that can be used under a wide range of different environmental conditions, as this special issue will show. The papers compiled here are the result of the first International SWAT Conference held in August 2001 in Rauschholzhausen, Germany. More than 50 participants from 14 countries discussed their modelling experiences with the model development team from the USA. Nineteen selected papers with issues reaching from the newest developments, the evaluation of river basin management, interdisciplinary approaches for river basin management, the impact of land use change, methodical aspects and models derived from SWAT are published in this special issue. Copyright © 2005 John Wiley & Sons, Ltd.

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### INTRODUCTION

After the development of the Stanford Watershed Model (Crawford and Linsley, 1966), numerous operational, lumped or 'conceptual' models have been developed. These include: SSARR (Rockwood *et al.*, 1972), the Sacramento model (Burnash *et al.*, 1973), the tank model (Sugawara *et al.*, 1976), HEC-1 (Hydrologic Engineering Center, 1981), HYMO (Williams and Hann, 1983). In these models, some processes are described by differential equations based on simplified hydraulic laws, and other processes are expressed by empirical algebraic equations. More recent conceptual models have incorporated soil moisture replenishment, depletion and redistribution for the dynamic variation in areas contributing to direct runoff. Several models have been

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developed from this concept, which use a probability distribution of soil moisture including the ARNO model (Todini, 1996; Zhao, 1984; Moore and Clarke, 1981) or the use of a topographic index, as in TOPMODEL (Beven and Kirkby, 1979; Beven *et al.*, 1984). Jayatilaka *et al.* (1996) recently developed a variable source conceptual model that shows promise for incorporation into comprehensive models.

Another class of hydrological models is a differential model based on conservation of mass, energy and momentum. Examples of differential models include SHE (Abbott *et al.*, 1986a,b) and IDHM (Beven *et al.*, 1987; Binley *et al.*, 1989). The SHE model simulates water movement in a basin with the finite difference solution of the partial differential equations describing the processes of overland and channel flow, unsaturated and saturated subsurface flow, interception, ET and snowmelt. The spatial distribution of catchment parameters is achieved by representing the basin on an orthogonal grid network. Jain *et al.* (1992) successfully applied the SHE model to an 820 km<sup>2</sup> catchment in central India. However, they note that the data requirements are substantial. Jain *et al.* (1992) also concluded that the strength of differential models like SHE 'lies beyond the field of pure rainfall-runoff modelling, for which purpose traditional and simpler hydrologic models often perform equally well'.

In the early 1970s work also began in the USA on non-point source modelling in response to the Clean Water Act. The CREAMS model (Knisel, 1980) was developed to simulate the impact of land management on water, sediment, nutrients and pesticides leaving the edge of a field. Several field-scale models evolved from the original CREAMS to simulate pesticide ground water loadings (GLEAMS, Leonard *et al.*, 1987) and to simulate the impact of erosion on crop production (EPIC, Williams *et al.*, 1984).

Other efforts evolved to simulate hydrology and water quality of complex watersheds with varying soils, land use and management. Several models were developed to simulate single storm events using a square grid representation of spatial variability (Young *et al.*, 1987; Beasley *et al.*, 1980). These models did not consider subsurface flow, ET or plant growth. Continuous models were also developed (Johansen *et al.*, 1984; Arnold *et al.*, 1990), but generally lacked sufficient spatial detail.

Large area water resources development and management require an understanding of basic hydrologic processes and simulation capabilities at the river basin scale. Current concerns that are motivating the development of large area hydrologic modelling include climate change, management of water supplies in arid regions, large-scale flooding and offsite impacts of land management. Recent advances in computer hardware and software, including increased speed and storage, advanced software debugging tools and GIS/spatial analysis software, have allowed large-area simulation to become feasible. The challenge then was to develop a basin-scale model that (1) is computationally efficient; (2) allows considerable spatial detail; (3) requires readily available inputs; (4) is continuous time; (5) is capable of simulating land-management scenarios; and (6) gives reasonable results. The model must reflect changes in land use and agricultural management on stream flow and sediment yield. Available models with these capabilities are generally limited by spatial scale. Available river-basin models generally do not link outputs to land use and management adequately to evaluate management strategies. Also, most are single-event models. We chose good agricultural management models to link with simple, efficient, yet realistic routing components for the purpose of capturing management effects on large river basins through long-term simulations.

SWAT is an operational or conceptual model that was developed to assist water resource managers in assessing water supplies and non-point source pollution on large river basins. The primary considerations in model development were to stress (1) climate and management impacts; (2) water quality loadings and fate; (3) flexibility in basin discretization; and (4) continuous time simulation. An attempt was made to use inputs that are readily available over large areas so the model can be used in routine planning and decision-making. The model simulates the major hydrologic components and their interactions as simply and yet as realistically as possible. Upland components include hydrology, weather, erosion/sedimentation, soil temperature, plant growth, nutrients, pesticides, and land and water management. Stream processes considered in SWAT include channel flood routing, channel sediment routing, and nutrient and pesticide routing and transformation. The ponds and reservoirs component contains water balance, routing, sediment settling, and simplified nutrient

and pesticide transformation routines. Water diversions into, out of, or within the basin can be simulated to represent irrigation and other withdrawals from the system.

The objective of this overview is to briefly describe the model operation, model applications and model components of the SWAT2000 river basin model. This paper provides a background for this special issue, which includes papers on SWAT model development, applications and future directions in river basin modelling.

## MODEL HISTORY

SWAT incorporates features of several ARS models and is a direct outgrowth of the SWRRB model (Simulator for Water Resources in Rural Basins) (Williams *et al.*, 1985; Arnold *et al.*, 1990). Specific models that contributed significantly to the development of SWAT were CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard *et al.*, 1987) and EPIC (Erosion–Productivity Impact Calculator) (Williams *et al.*, 1984).

Since SWAT was created in the early 1990s, it has undergone continued review and expansion of capabilities. The most significant improvements of the model between releases include:

- SWAT94-2: Multiple hydrologic response units (HRUs) incorporated.
- SWAT96-2: Autofertilization and autoirrigation added as management options; canopy storage of water incorporated; a CO<sub>2</sub> component added to crop growth model for climatic change studies; Penman–Monteith potential evapotranspiration equation added; lateral flow of water in the soil based on kinematic storage model incorporated; in-stream nutrient water quality equations from QUAL2E added; in-stream pesticide routing.
- SWAT98-1: Snow melt routines improved; in-stream water quality improved; nutrient cycling routines expanded; grazing, manure applications and tile flow drainage added as management options; model modified for use in Southern Hemisphere.
- SWAT99-2: Nutrient cycling routines improved, rice/wetland routines improved, reservoir/pond/wetland nutrient removal by settling added; bank storage of water in reach added; routing of metals through reach added; all year references in model changed from last two digits of year to four-digit year; urban build-up/wash-off equations from SWMM added along with regression equations from USGS.
- SWAT2000: Bacteria transport routines added; Green–Ampt infiltration added; weather generator improved; allow daily solar radiation, relative humidity and wind speed to be read in or generated; allow potential ET values for watershed to be read in or calculated; all potential ET methods reviewed; elevation band processes improved; enabled simulation of unlimited number of reservoirs; Muskingum routing method added; modified dormancy calculations for proper simulation in tropical areas.

For special requirements of some catchments SWAT has been modified, supplemented or formed the basis for new model developments. In 1998 Krysanova *et al.* published the model SWIM, which is based on the hydrological components of SWAT and the nutrient modules of the model MATSALU (Krysanova *et al.*, 1989). The modification of surface and river processes, especially a reduction of the time step of the rainfall/runoff module to a user-defined fraction of an hour and the development of an hourly river routing and water quality module, led to the publication of the model ESWAT by van Griensven *et al.* (this issue). Sophocleous *et al.* (1999) linked SWAT with the model MODFLOW (McDonald and Harbaugh, 1988) to improve the representation of groundwater. SWAT-G (Eckhardt *et al.*, 2002) was compiled for the application in low mountain range areas with high proportions of interflow. Lenhart *et al.* (this issue) added an improved sediment concept to SWAT-G, while Haverkamp *et al.* (this issue) improved pre- and postprocessing routines

especially for spatial discretization under the UNIX environment. An extensive sensitivity analysis for SWAT-G was presented by Lenhart *et al.* (2002). Autocalibration of SWAT has been carried out by Eckhardt *et al.* (this issue) and van Griensven and Bauwens (2003). The model SWAT has also been integrated into an interdisciplinary modelling tool as shown in Weber *et al.* (2001) and Fohrer *et al.* (2001) to study the effects of land use change.

### SWAT MODEL DESCRIPTION

SWAT is an operational or conceptual model that operates on a daily time step. The objective in model development was to predict the impact of management on water, sediment and agricultural chemical yields in large ungauged basins. To satisfy the objectives, the model (a) does not require calibration (calibration is not possible on ungauged basins); (b) uses readily available inputs for large areas; (c) is computationally efficient to operate on large basins in a reasonable time; and (d) is continuous time and capable of simulating long periods for computing the effects of management changes.

A command structure is used for routing runoff and chemicals through a watershed similar to the structure included for routing flows through streams and reservoirs, adding flows and inputting measured data on point sources (Figure 1). Using the routing command language, the model can simulate a basin subdivided into grid cells or subwatersheds. Additional commands have been developed to allow measured and point source data to be input to the model and routed with simulated flows.

Model sub-basin components can be divided into the following: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides and agricultural management. Hydrology processes simulated include surface runoff estimated using the SCS curve number or Green–Ampt infiltration equation; percolation modelled with a layered storage routing technique combined with a crack flow model; lateral subsurface flow; groundwater flow to streams from shallow aquifers; potential evapotranspiration by the Hargreaves, Priestley–Taylor and Penman–Monteith methods; snowmelt; transmission losses from streams; and water storage and losses from ponds (Arnold *et al.* 1998).

### CODING CONVENTIONS

SWAT is written in FORTRAN 90 and consists of 220 subroutines and just over 40 000 lines of code. All array sizes are determined at the start of the simulation and allocated dynamically. Each incoming, outgoing and local variable within every subroutine is provided a brief description, units and a range. An attempt was made to make the subroutine structure as modular as possible and the variable names as descriptive as possible.

### INTERFACES AND MODEL DOCUMENTATION

GIS interfaces have been developed for SWAT using both GRASS (Graphical Resources Analysis Support System) (Srinivasan and Arnold, 1994) and ArcView. The GRASS input interface automatically subdivides a basin (grids or subwatersheds) and then extracts model input data from map layers and associated relational databases for each sub-basin. Soils, land use, weather, management and topographic data are collected and written to appropriate model input files. The output interface allows the user to display output maps and graph output data by selecting a sub-basin from a GIS map.

The SWAT ArcView system (DiLuzio *et al.*, 1998) consists of three key components: (1) preprocessor generating sub-basin topographic parameters and model input parameters; (2) editing input data and execute simulation; (3) postprocessor viewing graphical and tabular results. The export of data from GIS to the SWAT model and the return of results for display are accomplished by Avenue routines addressed directly by the

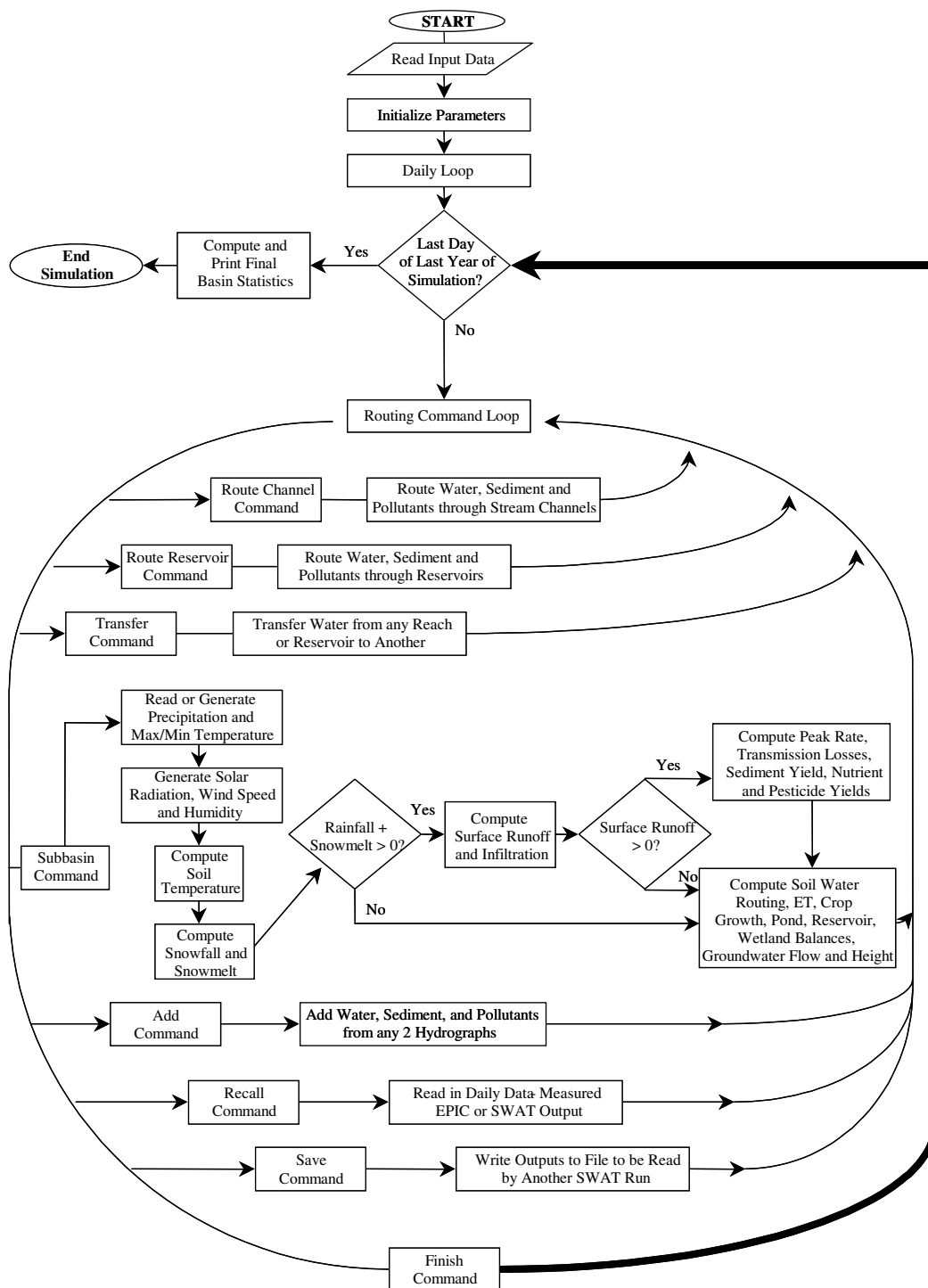


Figure 1. Routing structure of SWAT 2000

interactive tools of GIS (e.g. setting up parameter values via customized menus) and the exchange of data is fully automatic.

The 2000 version of SWAT includes theoretical documentation (Neitsch *et al.*, 2002) of all equations, a user manual (Neitsch *et al.*, 2002) containing a description of all input/output files and variables, and an ArcView interface manual (DiLuzio *et al.*, 2002) describing the operation of the AVSWAT interface.

## APPLICATIONS

### *Applications within the USA*

The applications of SWAT have focused on the impact of: (1) land use change and management and (2) climate change on water supply and water quality. Major projects in the USA related to land use change and management include:

1. EPA TMDL—There are approximately 15 000 water bodies identified by EPA as impaired for various uses. For each of these, states must estimate the severity of the problem (develop a total maximum daily load, TMDL) and determine potential solutions. If EPA doesn't respond in a timely manner, the issue will be resolved in court. State environmental agencies need technology (decision support systems including GIS and watershed models) to analyse and determine best management practices (BMPs) for each TMDL. Thus, the US EPA Office of Science and Technology has developed a framework for states to analyse impaired water bodies called BASINS (Better Assessment Science Integrating point and Non-point Sources). BASINS consists of five components: (1) national databases; (2) assessment tools; (3) utilities; (4) watershed models; and (5) postprocessing and output tools. SWAT and its associated GIS interface have been integrated into BASINS 3-0, which is being used in several states for TMDL analysis (DiLuzio *et al.*, 2002).
2. HUMUS Project (Hydrologic Unit Model of the USA)—The Natural Resources Conservation Service (NRCS) used the SWAT model in the 1997 Resource Conservation Appraisal. The model was validated against measured USGS stream flow data across the entire USA and was being validated against measured sediment loads (Arnold *et al.*, 1999). The model was linked to national economic models and used for national planning, addressing scenarios that include: (1) agricultural and municipal water use; (2) tillage trends; (3) fertilizer and animal waste scenarios; (4) flood prevention structures; and (5) cropping systems (Srinivasan *et al.*, 1993).
3. NOAA National Coastal Pollutant Discharge Inventory—NOAA contracted with a consulting firm to apply the SWAT model to counties along the entire US coastline as part of the National Coastal Pollutant Discharge Inventory. NOAA is currently refining the inventory, by applying SWAT to simulate stream routing, reservoirs and point sources for all coastal watersheds.
4. The NRCS Water Resources Assessment Team and Texas A&M scientists applied SWAT to determine the impact of brush control on water supply in eight river basins in Texas (Dugas *et al.*, 2002).

SWAT has been applied to several projects in the USA dealing with the impact of climate change on water supplies and reservoir operations. Examples of climate change studies include: (1) regional impacts of climate change on groundwater recharge to the Ogallala aquifer (Rosenberg *et al.*, 1999); (2) the impact of climate change on water yields in a high elevation, mountainous basin (Stonefelt *et al.*, 2000); (3) the impact of climate change on Missouri River reservoir operation and water supply (Hotchkiss *et al.*, 2000); and (4) surface water irrigation and riparian management influenced by climate change (Wollmuth and Eheart, 2000).

### *Worldwide applications*

In Europe the model SWAT has been used in several ongoing major projects, often in the context of the suitability for the European Framework Directive. The objective of the Euroharp project (2004) is the

Table I. SWAT applications presented in this special issue, organized by country, catchment size and type of application

Country	Number of applications	Catchment size (km <sup>2</sup> )	Hydrology	Sediment	Phosphorus cycle	Nitrogen cycle
Australia	1	437	Water balance (1)	No	No	No
Belgium	5	12; 29; 465; 707; 820	Water balance (5)	Yes (1)	Yes (1)	Yes (1)
Germany	6	60; 81; 134; 692; 80 256	Water balance (6)	Yes (1)	No	Yes (1)
India	2	65; 93	Water balance (2), irrigation (1)	Yes (1)	Yes (1)	Yes (1)
Kenya	1	3050	Water balance (1)		Yes (1)	Yes (1)
South Africa	2	0.7; 1949	Water balance (2)			
USA	6	0.5; 21; 32; 1178; 2600	Water balance (4), events (1), crack flow (1)	Yes (1)	Yes (2)	Yes (3)

scientific evaluation of the nine contemporary quantification tools, among them SWAT, and their ability to estimate diffuse nutrient (N, P) losses to surface freshwater systems and coastal waters in order to facilitate the implementation of the EC Water Framework Directive. The BMW project (2004) aims at testing and demonstrating the use of integrated models such as SWAT for use in the implementation of the European Water Framework Directive. Within the CHESS project (2001), SWAT was applied to explore the effects of climate change on water quality in European rivers. Meanwhile in the TempQsim project (2004) the focus is on Mediterranean and semi-arid catchments with intermittent flow regimes. SWAT was also applied and modified within the Joint Research Project SFB 299 since 1997 to analyse the impact of land use change on water and nutrient cycles of low mountain range catchments in central Germany (Fohrer *et al.*, 1999, 2002, this issue).

Table I gives a selected overview of worldwide SWAT applications presented at the first international SWAT conference in Rauschholzhausen in August 2000. Modelling exercises in watersheds from Australia, Belgium, Germany, India, Kenya, South Africa and the USA were discussed. The water balance of 21 catchments from 0.6 km up to 80 256 km<sup>2</sup> under a wide range of different soils, land use and climatic conditions has been modelled with SWAT or SWAT-based models. Four papers addressed soil erosion and sediment delivery to streams. Water quality issues in terms of non-point pollution were tackled by five papers for phosphorus and seven contributions for nitrogen.

#### CURRENT RESEARCH AND FUTURE DIRECTIONS

Every component of SWAT is a simplification of the natural process and thus could be improved. It is important, however, that each component is as simple and yet realistic as possible, interacts properly with other components, and uses readily available inputs. Several components are listed here that we feel could strengthen the SWAT model and river basin models in general.

1. *Phosphorus*. Excess phosphorus runoff from large animal feeding operations has created water quality problems and increased the cost of drinking water treatments. The P extraction coefficient is currently a constant and could be a function of ground cover, manure cover, soils, etc. Soil phosphorus pools modelled in SWAT (labile, active and stable mineral) also need to be related to soil phosphorus tests.
2. *Landscape positioning*. Currently in SWAT there is no water flow between hydrologic response units within a sub-basin. We are currently developing techniques to divide a sub-basin into landscape units and transfer water and pollutants between them. This approach will facilitate the incorporation of riparian and flood plain components. It will also provide the capability to determine different sources (variable source areas) of runoff and pollutants on the landscape.

3. *Snow fall and melt.* The snowmelt equations have been refined and tested in a mountainous basin in the western USA (Fontaine *et al.*, 2002). Several snowmelt algorithms were tested within SWAT by Morid (2000), with some showing improvement over the current algorithms.
4. *Forest growth.* The plant growth component of SWAT was originally developed for agricultural crops. In recent years, we have adapted it for forests but it still needs improvements for: (i) the leaf litter layer; (ii) growing trees from seedlings to a mature stand; and (iii) simulating the tree canopy and ground cover simultaneously.
5. *Pathogens.* A pathogen model has been developed (Sadeghi and Arnold, 2002) that has been tested on a watershed in Missouri for *E. coli* and faecal coliforms (Baffaut and Benson, 2003). The model needs further validation and refinement.
6. *Instream water quality.* All aspects of stream routing need further testing and refinements including sediment routing and the modified QUAL-2E (Brown and Barnwell, 1987) routines currently used for routing nutrients. QUAL-2E is accepted by the US EPA, but is data intensive and difficult to calibrate.
7. *Uncertainty.* Routines for automated sensitivity analysis, automated calibration and input uncertainty analysis have recently been added to SWAT (van Griensven and Bauwens, 2003). These routines are currently being tested on several watersheds and the uncertainty analysis is being broadened and refined.
8. *Interface development.* There are several things that could be improved in the ArcView SWAT interface. We are currently working on upgrading to the latest version of Arc GIS. The automation of management scenarios would also be a major advancement.

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