HYDROLOGIC COMPONENTS OF WATERSHED-SCALE MODELS

K. W. Migliaccio, P. Srivastava

ABSTRACT. *This article briefly reviews the hydrologic components of prominent models used in agricultural and mixed land use watersheds and presents the current state-of-the-art in agricultural watershed modeling. The models included are Annualized Agricultural Nonpoint Source (AnnAGNPS), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS-2000), Hydrologic Simulation Program – Fortran (HSPF), Soil and Water Assessment Tool (SWAT), Watershed Assessment Model (WAM), and Water Erosion Prediction Project (WEPP). Hydrologic components (e.g., precipitation, potential evapotranspiration (PET), infiltration-surface runoff, groundwater, and stream flow) are discussed for each of these models. Simulation of PET differs among selected watershed models, with some offering multiple PET options and others providing one method. The primary difference in the infiltration and surface runoff algorithms among watershed models is their empirical (e.g., curve number (CN) and Green-Ampt) or physical (e.g., Philip's) basis and their simulation time step. Groundwater components (such as interflow, tile drainage, shallow aquifer, and deep aquifer) may be one of the most variable hydrologic components among watershed models. Stream flow was routed predominantly by the selected models using the continuity equation and Manning's equation; other algorithms used were the Muskingum routing method, finite difference integration, and kinematic wave. The use of watershed models by agricultural and biological engineers continues to expand as new technologies, such as the integration of remote sensing and Geographic Information Systems (GIS), and computer capabilities improve and the expectations for high-quality results (including uncertainty analyses and multi-objective functions) increase.*

Keywords. *AnnAGNPS, ANSWERS-2000, HSPF, Hydrologic modeling, Hydrology, SWAT, WAM, Watershed, WEPP.*

The popularity of watershed models is no surprise due to their ability to provide holistic interpretations of how natural systems that are driven by hydrologic processes are impacted by anthropogenic disturbances. Watersheds selected for modeling vary in size, with some consisting of small headwater streams, while others represent larger systems that include lentic features such as reservoirs and lakes. Generally, the boundaries for watershed models are based on topographical features, although some models, e.g., the Watershed Assessment Model (WAM), provide for the designation of a surface runoff boundary and a groundwater boundary. Inconsequential to the watershed size, watershed model boundaries are defined by hydrologic considerations, and the model structure is generally designed for representing the components of the hydrologic cycle: precipitation, infiltration-surface runoff, evapotranspiration, interflow, groundwater, and stream flow.

Each hydrologic component in a watershed model represents a specific reality with empirical or physically based expressions. Algorithms used to simulate processes in watershed models were often originally developed for alternative purposes. For example, potential evapotranspiration (PET) algorithms were first introduced by Penman (1948) to be used for crop irrigation, not for integration into watershed models (Brooks et al., 2003). Many of the other components of the hydrologic cycle have similarly evolved. As more algorithms became available for simulating various hydrologic components, they were linked so that multiple hydrologic components could be simulated as a connected, interacting system. Thus, hydrologic simulation evolved from single-process simulation to simulation of multiple processes.

Previously, a comparison of watershed models was completed by Borah and Bera (2003), which focused on their flow-governing equations. In addition to describing stream flows and surface runoff components, as done by Borah and Bera (2003), this article expands on their work to provide a more comprehensive review of other hydrologic components. Other citations that might be of interest include a review of watershed model applications (Borah and Bera, 2004), a review of sediment and nutrient models (Borah et al., 2006), and a review of erosion models (Merritt et al., 2003).

Only prominent, continuous-simulation watershed models that are currently used to simulate watershed hydrology in agricultural and mixed land use watersheds are reviewed in this article. This article does not discuss hydrologic components of event-based models and those designed for flood control or evaluation of hydraulic structures. More specifically, this article focuses on models that are cited in referred literature, have some organized model support, and are representative of the models often used by agricultural and biological engineers. Overall, the goal of this article was to briefly review the hydrologic components of prominent models used in agricultural and mixed land use watersheds and to present

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the current state-of-the-art in agricultural watershed modeling. The models included are Annualized Agricultural Nonpoint Source (AnnAGNPS), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS-2000), Hydrologic Simulation Program – Fortran (HSPF), Soil and Water Assessment Tool (SWAT), WAM, and Water Erosion Prediction Project (WEPP).

MODEL DESCRIPTIONS

ANNAGNPS

AnnAGNPS (Bingner and Theurer, 2003) is a batch-process, continuous-simulation, surface runoff, pollutant loading, watershed model developed from the single-event Agricultural Nonpoint Source (AGNPS) model. AnnAGNPS was designed by the USDA Agriculture Research Service (USDA-ARS) and the USDA Natural Resources Conservation Service (USDA-NRCS) to evaluate nonpoint source (NPS) pollution from agriculturally dominated watersheds. The model simulates hydrology, sediment, nutrient, and pesticide transport. AnnAGNPS allows the user to select either a grid (or cell) spatial representation or a hydrologic response unit spatial representation, with the selected unit being characterized by homogeneous land and soil properties. Refereed AnnAGNPS applications are predominantly for sites in the U.S. (e.g., Yuan et al., 2001; Yuan et al., 2002; Polyakov et al., 2007); however, applications in other countries have also been published, e.g., Australia (Baginska et al., 2003), Canada (Das et al., 2006), and China (Hong et al., 2005).

ANSWERS-2000

ANSWERS-2000 (Bouraoui and Dillaha, 1996, 2000) is a continuous-simulation, distributed parameter NPS watershed model. ANSWERS-2000 was intended to predict watershed behavior during and immediately following a rainfall event. ANSWERS-2000 was developed predominantly by Purdue University and Virginia Polytechnic Institute and State University. The primary purpose of the model is to qualitatively evaluate alternative management practices with respect to runoff, sediment losses, and nitrogen and phosphorus from agricultural watersheds. ANSWERS-2000 is most appropriate for watersheds with overland flow dominated hydrology, since deep percolation, groundwater flow, interflow, and stream base flow are currently not well developed in the model (Bouraoui and Dillaha, 2000). Land and soil characteristics are designated using a grid matrix or square cell system in which they are homogenous. ANSWERS-2000 has predominantly been applied to U.S. watersheds (e.g., Bouraoui and Dillaha, 1996, 2000); other application areas include Argentina (Braud et al., 1999) and the U.K. (Bradford et al., 2002).

HSPF

HSPF (Bicknell et al., 2001) is a continuous-simulation, hydrologic and water quality model (Bicknell et al., 2001). HSPF includes components that predict pesticides, conservatives, fecal coliforms, sediment, nitrogen, phosphorus, phytoplankton, and zooplankton. This model has typically been used for assessing land use change, reservoir operations, and point and NPS pollution abatement. HSPF is based on the original Stanford Watershed Model IV (Crawford and Linsley, 1966). In addition, HSPF is a combination of the Agricultural Runoff Management (ARM) model (Donigian and Davis, 1978), Nonpoint-Source Runoff Model (NPS) (Donigian and Crawford, 1976), and Hydrologic Simulation Program (HSP) (Hydrocomp, 1977; Donigian and Huber, 1991; Donigian et al., 1995). HSPF has been supported by U.S. Environmental Protection Agency (USEPA) and U.S. Geological Survey (USGS). The smallest unit of spatial identity in the HSPF model is referred to as a zone. There are many published applications of HSPF in the U.S. (e.g., Johnson et al., 2003; Saleh and Du, 2004) and throughout the world, e.g., China (Chen et al., 2004), Ireland (Nasr et al., 2007), and Turkey (Albek et al., 2004).

SWAT

SWAT (Neitsch et al., 2002a, 2002b) is a watershed-scale, continuous-simulation model that was developed to evaluate watershed management scenarios and weather conditions with respect to flows, sediment, nutrient, and pesticide loadings and their fate (Chaubey et al., 2006). SWAT evolved from the Simulator for Water Resources in Rural Basins (SWRRB) and Routing Outputs to Outlet (ROTO) models. In addition, other models influenced SWAT development, including Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS), Groundwater Loading Effects on Agricultural Management Systems (GLEAMS), and Erosion-Productivity Impact Calculator (EPIC) (Neitsch et al., 2002a). SWAT is a product of USDA-ARS. SWAT simulates land use and soil combinations by lumping areas into hydrologic response units (HRUs). Refereed applications of the SWAT model are numerous and were previously identified by White and Chaubey (2005). In addition, SWAT has been implemented internationally, e.g., Greece (Gikas et al., 2006), Ireland (Nasr et al., 2007), and Switzerland (Abbaspour et al., 2007).

WAM

WAM (SWET, 2006) was developed for assessing water quality of surface and ground waters as a response to land use, soils, and weather data. WAM can be used to simulate hydrology, sediment, nutrients, suspended solids, and biological oxygen demand (BOD) as they are influenced by current conditions or modified scenarios. WAM consists of a collection of models that are applied at the cell level and managed by the Basin Unique Cell Shell (BUCSHELL) subprogram. The collection of land cell source models includes: GLEAMS, Everglades Agricultural Area Model (EAAM-OD), a wetland model, and an urban model. Output from BUCSHELL is passed to the BLASRoute subprogram. BLASRoute simulates the movement of waters and constituents through the watershed system (Ouyang, 2003). WAM simulates land use and soils on a cell basis; cell sizes are small with geographic specific allocations. WAM does not have the same publication history as the other selected watershed models with only U.S. application (e.g., Ouyang, 2003).

WEPP

WEPP model (Flanagan and Livingston, 1995) was developed as a water and erosion prediction tool to be used by the USDA Soil Conservation Service, USDA Forest Service, and USDI Bureau of Land Management, and other organizations involved in soil and water conservation and environmental planning and assessment. Although WEPP was original developed to simulate hill slopes, WEPP now includes the abilities to simulate small watersheds (500 ha or less). The WEPP model includes the following components: climate generation, winter processes, irrigation, hydrology, soils, plant growth, residue decomposition, hydraulics of overland flow, and erosion. Spatial differences in land characteristics are designated in WEPP using "strips" or overland flow elements (OFEs). Each OFE represents a region of homogeneous soils, cropping, and management. Refereed articles of the catchment form of the WEPP model are not as numerous as applications of the hillslope WEPP model. However, some catchment applications include Cochrane and Flanagan (1999) and Covert et al. (2005) in the U.S., Ampofo et al. (2002) and Saenyi and Chemelil (2002) in Africa, and Raclot and Albergel (2006) in the Mediterranean.

DIFFERENCES IN COMPONENTS OF THE HYDROLOGIC CYCLE

The six watershed models briefly described above simulate the components of the hydrologic cycle using algorithms that differ among the models. A discussion of watershed model components with regard to precipitation, PET, infiltration-surface runoff, groundwater, and stream flow follows.

PRECIPITATION

Inclusion of precipitation and other weather parameters into watershed models is essential to predict watershed outlet flows. If available, measured weather data are preferred for most applications. Precipitation data are often obtainable for a watershed; however, some watershed models require additional weather parameters (e.g., temperature, wind speed, relative humidity) that are not always available. To accommodate for this, some models provide a weather simulator that estimates unavailable weather values (table 1). Weather simulators generally operate using a database with statistical information that has been tabulated for numerous locations, and therefore are limited to application in regions for which the database contains information. However, exclusion of a weather simulator from a watershed model does not preclude its use if needed weather parameters are not available. Stand-alone weather simulators are available and may be used outside of the watershed model framework to generate necessary weather parameters.

Another aspect of precipitation data is the inherent spatial variability of precipitation within a watershed (Chaubey et al., 1999) and the challenge of capturing this with rain gauges (Tsintikidis et al., 2002). Some modelers are integrating Next Generation Weather Radar (NEXRAD) or similar technologies into watershed modeling to improve representation of precipitation events (Di Luzio and Arnold, 2004; Kalin and Hantush, 2006) over large spatial areas. In addition to variability in naturally occurring precipitation, there is also variability among weather simulators. Harmel et al. (2000) compared watershed model flow output generated using three weather simulators: WGEN, WXGEN, and USCLIMATE. Their results indicated that watershed flow predictions differed with each weather simulator (with variable significance). The methods used to stochastically generate weather data (e.g., daily precipitation) do not always accurately reproduce mean transitional probabilities and mean daily precipitation summary statistics. These concerns have been shown to decrease as the size of the generated weather sequence increases and are discussed further in Richardson (2000) and Garbrecht and Zhang (2003). Thus, weather data and weather simulators contribute to model prediction uncertainty.

POTENTIAL EVAPOTRANSPIRATION

Simulation of PET differs among selected watershed models, with some offering multiple PET options to modelers and others providing only one method (table 1). Each PET method was originally developed to meet a specific PET estimation need, and hence each PET method is unique. The Penman method is a combination of the energy balance and mass transfer approaches and requires air temperature, solar radiation, humidity, and wind speed. The Penman method was further refined for crop surfaces by adding resistance factors; this refined method is the Penman-Monteith method. Inputs for the Penman-Monteith method are temperature, relative humidity, solar radiation, and wind speed (Allen et al., 1998).

Although the Penman or Penman-Monteith methods are most common, other PET methods are also used. An alternative method with less data requirements is the 1985 Hargreaves method, which uses only temperature and solar radiation. However, the Hargreaves method has been shown to overpredict PET in humid climates and should only be used with a 5-day or longer time step (Hargreaves and Allen, 2003). While Hargreaves is considered a temperature-based method, the Priestly-Taylor method is a radiation-based estimation and only requires radiation input data. Priestly-

Table 1. Weather data information and potential evapotranspiration methods for selected watershed models.

Model	Input Weather Data	Weather Simulator	PET Method
AnnAGNPS	Precipitation, maximum and minimum temperature, dew point temperature, sky cover, and wind speed	GEM and Complete Climate	Penman
ANSWERS-2000	Precipitation, air temperature, soil temperature, and solar radiation	(NA)	Alternative method (Bouraoui and Dillaha, 1996)
HSPF	Evaporation, precipitation, air temperature, solar radiation, dew point, wind velocity, and cloud cover	(NA)	Input time series
SWAT	Precipitation, minimum and maximum temperatures, relative humidity, wind speed, and solar radiation	WXGEN	Penman-Monteith, Priestly-Taylor, and Hargreaves
WAM	Precipitation (temperature if EAAMOD is used)	(NA)	Priestly-Taylor and Penman-Monteith
WEPP	Precipitation, temperatures, solar radiation, and wind speed	CLIGEN	Penman and Priestly-Taylor

Taylor is most appropriate for wet surface areas. An alternative method for PET estimation is used in ANSWERS-2000, with inputs of solar radiation, temperature, and albedo of the soil/crop surface (Bouraoui and Dillaha, 1996). Unique among the watershed models presented, HSPF does not provide a PET estimator within its model framework and must be input by the user.

The obvious diversity of PET methods among models suggests that model users should consider the appropriateness of a particular PET method before selecting a watershed model. In addition, the availability of quality input data that is required by each PET method should be identified before selecting a watershed model. Model-predicted PET is often included in simulated output and therefore can easily be assessed. This assessment should be completed, ideally, by comparing model-simulated PET to measured ET (actual ET or pan evaporation). A model user may not have continuously measured ET data, but may use data for various land covers or expert knowledge of the expected ET.

INFILTRATION-SURFACE RUNOFF

The most commonly used method for estimating surface runoff in the selected watershed models is the modified Soil Conservation Service (SCS) curve number (CN) method (table 2). The CN procedure includes tabulation of the dry condition curve number (CN_1) and the wet condition curve number (CN_3). Average condition curve number (CN_2) is the input provided by the user to the model. A description of these equations, which are used in AnnAGNPS and SWAT, can be found in Bingner and Theurer (2003).

The use of the CN method to predict surface runoff has received some critical attention (Michel et al., 2005; Nachabe, 2006; Eli, 2006; Jain et al., 2006). Recent evaluations of the CN method for predicting surface runoff have concluded that the existing CN method (1) is more suitable for high runoff producing agricultural watersheds than pasture lands or lands with sandy soils (Jain et al., 2006); (2) would be improved by modifying the parameterization and a better assessment of initial conditions (Michel et al., 2005); and (3) would be improved by identifying "S" values from catchment hydromorphological characteristics (Nachabe, 2006).

Table 2. Surface runoff algorithms for selected watershed models.

Model	Surface Runoff Algorithms
AnnAGNPS	Modified SCS CN_2
ANSWERS-2000	Green-Ampt (Green and Ampt, 1911) infiltration equation
HSPF	Hourly time step as a function of infiltration computed using Philip's equation (1957) or infiltration-excess model that separates moisture inputs into infiltrating and non-infiltrating fractions according to surface storage capacity, interflow-inflow index, and infiltration-capacity index; Surface runoff is estimated using Chezy-Manning equation and empirical expressions.
SWAT	Modified SCS CN_2 with daily time step or Green-Ampt Mein-Larson infiltration equation with hourly or sub-daily time step
WAM	SCS CN_2 or water balance
WEPP	Green-Ampt Mein-Larson (GAML) model (Mein and Larson, 1973), as presented by Chu (1978)

A slightly different version of the SCS CN method is used by the WAM land cell source model, GLEAMS. Hence, the exact equations used in the SCS CN method for predicting surface runoff may differ among models. Although the CN method is often associated with infiltration and surface runoff, it actually is used to estimate surface runoff. Water that infiltrates is then generally determined using a water balance approach.

An alternative to the CN method is the Green-Ampt equation (Green and Ampt, 1911) as modified by Mein and Larson (1973). The Green-Ampt method assumes that the soil profile is homogenous and antecedent moisture is uniformly distributed in the profile so that there is a saturated zone above the wetting front (Neitsch et al., 2002a). Similarly, SWAT provides an option to use the Green-Ampt Mein-Larson excess rainfall method (Mein and Larson, 1973). WEPP also uses a version of the Green-Ampt equation as it was modified by Mein and Larson (1973) and later by Chu (1978).

HSPF has a different approach to simulating infiltration: Philip's equation (1957). Philip's method, which is physically based, uses an hourly time step (Van Liew et al., 2003). The Chezy-Manning equation and an empirical expression are then evaluated to determine surface runoff in the HSPF model (Bicknell et al., 2001).

All of our selected watershed models simulate runoff as an infiltration-excess response. Differences in the infiltration and surface runoff algorithms include their empirical (e.g., CN and Green-Ampt) or physical (e.g., Philip's) basis and their simulation time step. It is noteworthy that although the CN and Green-Ampt methods are empirical, they also include parameters that have a physical basis. Use of the Green-Ampt and Philip's methods require sub-daily inputs, which is more complex than the daily data needed for the CN method (King et al., 1999). Watershed models that use sub-daily inputs for infiltration and surface runoff algorithms may not be appropriate if quality input data are not available.

As the above discussion illustrates, most watershed models currently use infiltration-excess algorithms to simulate surface runoff. However, some model developers are recognizing saturation-excess contributions to surface runoff flow by incorporating both techniques (e.g., infiltration-excess and saturation-excess) into modeling activities for surface runoff predictions (Juracek, 1999). Runoff from saturation-excess is currently simulated in a few watershed models, including the TOPMODEL (Fisher and Beven, 1996). Future development of the models identified in our study may include incorporation of both infiltration-excess and saturation-excess runoff processes to improve hydrologic prediction abilities.

GROUNDWATER

Inclusion and simulation of groundwater components (such as interflow, tile drainage, shallow aquifer, and deep aquifer) vary among the selected watershed models (table 3). In fact, groundwater may be one of the most variable hydrologic components. The majority of the selected models simulate a shallow aquifer; however, the routing of water in the underground aquifer to the remaining model processes differs.

Subsurface or interflow, defined as flow underneath the soil surface that is not part of an aquifer, generally travels downslope toward receiving waters. AnnAGNPS, HSPF, SWAT, WAM, and WEPP include processes for simulation of

Table 3. Groundwater and stream flow processes simulated by selected watershed models.

Model	Subsurface Flow or Interflow	Subsurface Drainage or Tile Drainage	Shallow Aquifer or Other Water Storage Zone	Deep Aquifer
AnnAGNPS	Yes	Yes	No	No
ANSWERS-2000	No	Yes	Yes	No
HSPF	Yes	No	Yes	Yes
SWAT	Yes	Yes	Yes	Yes
WAM	Yes	No	Yes	Yes
WEPP	Yes	No	No	Yes

interflow. However, the methods used to simulate interflow differ: Darcy's equation and Hooghoudt's equation (AnnAGNPS), a set of relationships that includes infiltration characteristics (HSPF; see Bicknell et al., 2001), the kinematic storage model developed by Sloan and Moore (1984) (SWAT), and Darcy's law with conservation of mass (WAM and WEPP).

Subsurface drainage or tile drainage is another feature simulated by some watershed models, including AnnAGNPS, ANSWERS-2000, and SWAT. Subsurface drainage or tile drainage may be simulated by altering inputs, parameters, or code in HSPF or WAM, but these two models were not originally designed to include these drainage components.

Shallow aquifers (or aquifers that contribute flow to streams) are simulated in ANSWERS-2000, HSPF, SWAT, and WAM. For ANSWERS-2000, all water that moves past tile drainage is assumed to enter groundwater storage and is then released evenly into streams at a rate proportional to the volume of accumulated storage (R. Zeckoski, Virginia Tech, personal communication, 2007). HSPF refers to the shallow aquifer as "active groundwater storage" and simulates water flux from this active groundwater storage to deep percolation, groundwater ET, and stream base flow. SWAT also considers multiple fluxes of water from the shallow aquifer, including recharge or base flow to streams, capillary rise into the soil profile, and pumping activities within the watershed (such as for irrigation or drinking water). Of the selected watershed models, only HSPF, SWAT, and WAM simulate deep percolation or deep aquifers. For these three models, waters routed to deep aquifers are considered lost from the system and no longer available for use.

Somewhat unique in the selected watershed models is the ability to define and route groundwater. Groundwater in most watershed models is routed to streams similarly to surface runoff paths. However, WAM offers the option to modify groundwater paths so that groundwater can be specified to a particular stream reach (B. Jacobson, SWET, Inc., personal communication, 2007).

The differences among the selected watershed models' groundwater components indicate that the groundwater characteristics of a watershed should be identified and considered when selecting a watershed model. Each of the selected models depicts groundwater components uniquely, and therefore each one is appropriate for some locations while not appropriate for others. For example, SWAT might be a better choice than ANSWERS-2000 to simulate a watershed where stream flow is dominated by groundwater recharge. Alternatively, ANSWERS-2000 might be a better model choice than HSPF if tile drainage was a dominant hydrologic factor in the simulated watershed. Selection of a watershed model that simulates groundwater hydrology correctly for a specific location is very critical for watersheds that have a dominant groundwater component.

STREAM FLOW

To be considered a watershed model, stream flow routing is required. All of the selected models simulate stream flow on a daily time step, although some of the models provide options for outputting at other time intervals (table 4). A predominant algorithm among the models is Manning's equation. Watershed model developers have modified this equation to accommodate multiple shapes of channels and dynamic flows.

In addition to Manning's equation, the continuity equation is also often included in stream routing algorithms. ANSWERS-2000 computes stream flows by an explicit, backward difference solution using the continuity equation and Manning's equation. Similarly, WAM uses the continuity equation and Manning's equation; however, in WAM's application of Manning's equation, it is integrated using a first-order approximation.

SWAT also simulates reach flow using Manning's equation and the continuity equation. Two routing methods are available in SWAT: the variable storage routing method (developed by Williams, 1969), which is based on the continuity equation, and the Muskingum routing method. The Muskingum routing method considers both prisms water storage and flood wave or wedge storage in a channel.

Other watershed models employ slightly different methods for simulating water routing. For example, AnnAGNPS stream flow algorithms include options for different geometrical shapes (trapezoid, rectangle, and triangle) and Manning's roughness value, with solutions derived using Newton's method (Bingner and Theurer, 2003). Alternatively, HSPF and WEPP simulate reach flows using the continu-

Table 4. Water routing and channel representation by selected watershed models.

Model	Water Routing in Streams/Reaches	Channel Representation
AnnAGNPS	Manning's equation and channel shape relationships	Trapezoid flow channel cross-section, rectangular main channel, rectangular out-of-bank (floodplain) section
ANSWERS-2000	Manning's equation and continuity equations	Width, rectangular cross-section
HSPF	Continuity equation and storage routing or kinematic wave	A user-defined fixed relation between depth, surface area, and volume
SWAT	Manning's equation and variable storage routing or Muskingum river routing method	Trapezoidal channel cross-section and trapezoidal flood plain
WAM	Manning's equation and continuity equation, finite difference integration	User-defined cross-section
WEPP	Kinematic wave equations	User-defined cross-section

ity equation and a routing method that would be classified as storage routing or kinematic wave (Flanagan and Livingston, 1995; Bicknell et al., 2001).

Current State-of-the-Art in Agricultural Watershed Modeling

Historically, limitations to watershed modeling were predominantly due to computer capabilities and the availability of data at desired spatial and temporal scales. There is no doubt that the recent advancements in computer technology have benefited computer-simulated modeling. In addition, tools have evolved from this advancement and the improvement in other scientific fields that have enhanced modeling capabilities. Two of these tools are Geographic Information Systems (GIS) (see Rosenthal et al., 1995; Hartkamp et al., 1999; Mankin et al., 2002; Choi et al., 2005; Martin et al., 2005) and remote sensing technologies (see Cline et al., 1998; Narasimhan et al., 2003; Tien and Judge, 2006). Integration of these tools into watershed modeling has improved the spatial and temporal components of watershed models, specifically by reducing model prediction uncertainty due to input data, initial conditions, and even parameterization.

Advancements in computational efficiencies have also contributed to the increased inclusion of uncertainty analysis in modeling procedures. Uncertainty analysis, which refers to the evaluation of the difference between an observed or calculated value and the true value (Shirmohammadi et al., 2006), generally relies on completing thousands of model simulations using probability distributions to represent model factors (such as inputs or parameters). Advancements in computational efficiency have increased the feasibility of simulating these large datasets and post-processing the output, as is evident by the growing number of publications in this area (see Haan et al., 1998; Muleta and Nicklow, 2005; Lin and Radcliffe, 2006; Arabi et al., 2007; Gallagher and Doherty, 2007).

Along with technological advances, the science of watershed modeling has evolved with regard to the calibration and validation process. Calibration involves comparing predicted values to measured values and assessing the difference between the two, with the objective of minimizing the differences through appropriate adjustment of parameters or inputs. Validation is completed after calibration and involves comparing predicted values to measured values for a new dataset without parameter or input adjustment. The most historically common component included in hydrologic calibration-validation is comparison of predicted and measured downstream flows. With increasing frequency, a more comprehensive flow calibration-validation is presented in modeling applications that includes base flow, surface runoff flow, and total flow (e.g., White and Chaubey, 2005; Srivastava et al., 2006). The inclusion of multiple variables in the calibration process has also led to further development of global sensitivity analyses (van Griensven et al., 2006) and automated multi-objective calibration methods (Bekele and Niklow, 2007; Confesor and Whittaker, 2007). The interest in predicting and calibrating multiple outputs from a watershed model leads to the identification of a multi-objective function for watershed modeling applications. Multi-objective functions provide optimization criteria for multiple modeling objectives in a mathematical form (Yan and Haan, 1991; Gupta et al., 1998; Yapo et al., 1998). Identification of a multi-objective function is essential for calibrating watersheds with multiple outputs of interest to ensure that all components receive appropriate consideration and there are minimal to no biases among the variables of interest.

Completion of the calibration-validation process for a watershed model, as defined by the (multi)objective function, is the last step at which the representations of hydrologic processes are "checked" for sufficiency. If problems are discovered and hydrologic components are not simulated sufficiently to meet the modeling objectives, then further review is needed and perhaps a different watershed model should be used. To best circumvent inappropriate application of a watershed model, watershed modeling projects would benefit from selecting a watershed model using a flowchart approach. Depending on the hydrologic watershed modeling objectives and watershed hydrologic characteristics, a particular model might be more appropriate (as illustrated in the filter flow diagram in fig. 1). Development of a flow diagram for a specific application should be completed considering watershed characteristics, data limitations, and modeling objectives. (Note that figure 1 is just an example application of the flow diagram concept and does not necessarily represent

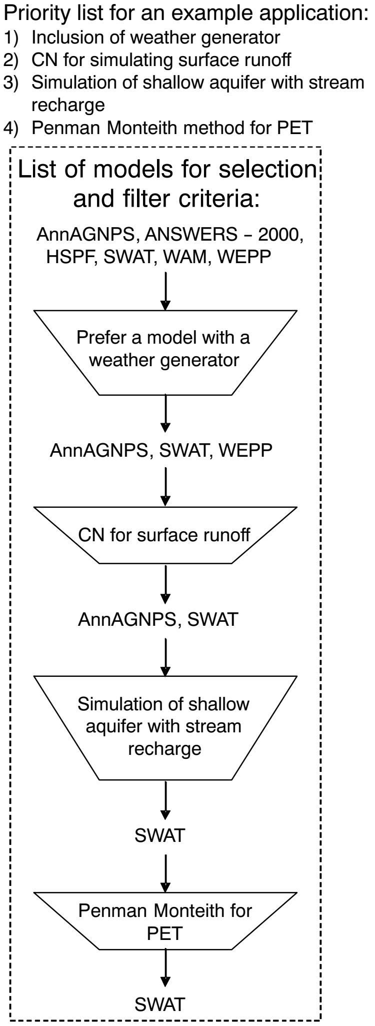

Figure 1. Priority list and filter flow diagram example for selecting a watershed model.

the diagram for other applications, as each application will have different requirements and limitations. Priorities were identified for this example application based on knowledge of the example watershed and available data; a similar approach would be advised for each new watershed modeling project.)

Appropriate techniques in watershed modeling are continually evolving as the science progresses and as the expectations for watershed modeling results have considerable repercussions. Many of the current watershed modeling endeavors occurring in the U.S. are in response to Total Maximum Daily Load (TMDL) requirements imposed by state and/or federal agencies. Therefore, modeling results are often used to allocate acceptable loads for point and nonpoint sources of a pollutant. The allocation of loads and the measures (or Best Management Practices) that are implemented to meet TMDL requirements have economic repercussions. Hence, it is important to present modeling results that are of the highest quality and incorporate sound modeling techniques, such as calibration-validation, sensitivity analysis, and uncertainty analysis. The recent advancement in watershed models and their application may be in part due to their application in solving TMDL-related issues (see Muñoz-Carpena et al., 2006).

SUMMARY

The goal of this article was to briefly review the hydrologic components of prominent models used in agricultural and mixed land use watersheds and provide the current state-of-the-art in agricultural watershed modeling. AnnAGNPS, ANSWERS-2000, HSPF, SWAT, WAM, and WEPP were selected based on their appropriateness and popularity for agricultural watersheds. Simulation of PET differs among selected watershed models, with some offering multiple PET options to the modeler and others providing one method. Each PET method requires different inputs, and therefore selection of a particular watershed model should be made with consideration of the quality and availability of necessary data. The primary difference in the infiltration and surface runoff algorithms among watershed models is their empirical (e.g., CN and Green-Ampt) or physical basis (e.g., Philip's) and their simulation time step. Use of the Green-Ampt and Philip's methods requires sub-daily inputs, which is more complex than the daily data needed for the CN method. Groundwater components (such as interflow, tile drainage, shallow aquifer, and deep aquifer) may be one of the most variable hydrologic components among watershed models.

Integration of new tools (GIS and remote sensing) and the advancements in computer technology have improved the watershed modeling science. This has lead to the incorporation of uncertainty analysis, multi-objective functions for modeling, and a more comprehensive calibration-validation process for watershed model applications. Techniques and tools that complement watershed modeling are continually changing as the science progresses and as the expectations for high-quality watershed modeling results increase.

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