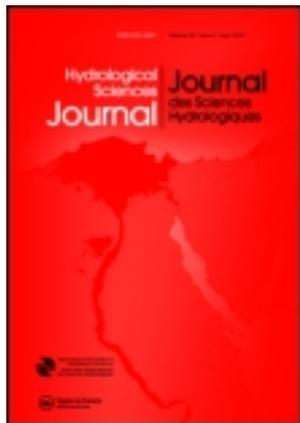


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History of model development at Temple, Texas

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Abstract Model development at Temple, Texas, USA has a long history. Prior to the actual model development research, a hydrological data collection programme was established at Riesel, Texas (about 60 km northeast of Temple) in 1937. Data collected from the Riesel watersheds during 1937–2006 have been valuable in developing and testing models at Temple, as well as at other locations. Actual modelling research began in the mid-1960s with the development of single event models that served as building blocks for the comprehensive models of today. The focus of the early models was on surface water hydrology (rainfall excess, unit hydrographs and flood routing) and sediment yield. The models currently supported at Temple (ALMANAC, EPIC, APEX and SWAT) are continuous and operate on spatial scales ranging from individual fields to river basins. These models have been used worldwide in many projects dealing with soil and water resources and environmental management.

Key words models; history; hydrology; water quality; soil and water resources; flood routing; sediment yield

Histoire du développement de modèles à Temple, Texas

Résumé Le développement de modèles à Temple, Texas, États-Unis a une longue histoire. Avant la recherche actuelle sur le développement de modèles, un programme de collecte de données hydrologiques a été établi à Riesel, au Texas (à environ 60 km au nord-est de Temple) en 1937. Les données acquises dans les bassins versants de Riesel pendant la période 1937–2006 ont servi au développement et au test de modèles à Temple et en d'autres lieux. L'actuelle recherche en modélisation a commencé au milieu des années 1960 avec le développement de modèles événementiels qui ont servi de modules constitutifs pour les modèles intégrés d'aujourd'hui. La priorité des premiers modèles portait sur l'hydrologie de surface (pluie excédentaire, hydrogrammes unitaires et propagation de crue) et sur la production sédimentaire. Les modèles actuellement en développement à Temple (ALMANAC, EPIC, APEX et SWAT) sont continus et couvrent une gamme d'échelles spatiales allant des parcelles individuelles aux bassins versants. Ces modèles ont été utilisés dans le monde entier dans de nombreux projets concernant les ressources en sol et en eau ainsi que la gestion de l'environnement.

Mots clefs modèles; histoire; hydrologie; qualité de l'eau; ressources en sol et en eau; propagation de crue; production sédimentaire

INTRODUCTION

Model development at Temple, Texas, USA has a long history (since 1937) with many scientists participating in various ways (data collection, component construction, structural design, validation, and application). The Temple models have been constructed by a small group of ARS, TAES, and NRCS scientists located at Temple, but individual components have been contributed by many other scientists throughout the world. Fortunately the Temple modelling team has established a strong working relationship with many outstanding researchers worldwide. This outside link has provided the additional expertise needed to develop comprehensive models that are useful in solving problems involving agricultural and environmental management, and soil and water resource conservation. The Temple models operate on spatial scales ranging from individual fields to river basins and most of them are continuous operating basically on a daily time step. The ALMANAC, EPIC, APEX and SWAT models are currently supported at Temple. Although these models are operational and have been used globally to solve many problems, they are refined, expanded, and improved almost daily, mainly as a result of user interaction and feedback. The current models have evolved from model development research that began in the 1960s. Prior to the actual model development research, a hydrological data collection programme was established

at Riesel, Texas (about 60 km northeast of Temple) in 1937. Data collected from the Riesel watersheds during 1937–2006 have been valuable in developing and testing models at Temple, as well as at other locations. The purpose here is to describe the history of model development at Temple, beginning with the data collection programme and continuing through the evolution from simple model components to the comprehensive models we support today.

DATA COLLECTION

In the mid-1930s, the US Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS), realized a need to analyse and understand hydrological processes on agricultural fields and watersheds because of their impact on soil erosion, flood events, water resources and the agricultural economy. The importance of soil conservation research was realized as a result of disastrous drought in the early 1930s, when part of the USA became known as the dust bowl. At that time few soil conservation practices were applied to US farmland, resulting in extremely high erosion (both wind and water). In many cases farmland was abandoned because erosion (both gully and top soil loss) had reduced soil productivity to the point where farming was not feasible. As part of the SCS research programme, the Hydrological Division was created and a number of experimental watersheds were established across the USA. The primary functions of the facilities were to collect hydrological data (precipitation, percolation, evaporation, runoff, sediment yield, etc.) and to evaluate the hydrological response from watersheds influenced by various agricultural land management practices. One of the three original facilities, the Blackland Experimental Watershed, was established in 1937 in the heart of the Blackland Prairie near Riesel, Texas. The Project Supervisor, R. W. Baird, was in charge of the data collection programme from the beginning until he retired in 1970. This experimental watershed later became part of the US Department of Agriculture Agricultural Research Service (USDA-ARS) Grassland Soil and Water Research Laboratory with headquarters at Temple, Texas. R. D. Harmel joined the Temple staff in 1999 and is now in charge of the data collection programme at Riesel. Data were collected from up to 57 raingauges and 40 watersheds (the collection programme was expanded and reduced at various times during the period of record). The watershed data consist mainly of runoff and sediment yield, but some nutrient and pesticide data have been collected as part of specialized studies. These data have been valuable in developing and testing models at Temple as well as other locations.

MODEL DEVELOPMENT

The model development work began when J. R. Williams came to work for ARS at Riesel, Texas in 1965. Williams joined two other engineers, R. W. Baird and W. G. Knisel, who were working at Riesel at that time. Knisel, who began working at Riesel in 1957, later became the leader of the CREAMS and GLEAMS model development teams, headquartered at Tifton, Georgia. Most of the work before 1965 involved data analyses comparing runoff and sediment yield from watersheds with and without soil conservation practices. Previously, Williams had worked two and a half years for the SCS in watershed planning for flood control, where he developed a strong interest in flood routing and hydrograph development. At that time, the SCS TR-20 flood routing model was just getting started in watershed planning. Data collection from the Riesel watersheds began in 1937, so there were abundant data for use in developing and testing hydrological models.

The building blocks

From 1965 to 1975 most of the work involved developing single-event models that served a useful purpose, but more importantly these models were the building blocks for the comprehensive models of today. The focus of the early models was on surface water hydrology (rainfall excess, unit hydrographs and flood routing) and sediment yield.

Rainfall excess

Rainfall excess was estimated using the SCS curve number method (USDA-SCS, 1972), or the Green & Ampt infiltration equation (Green & Ampt, 1911), applied to incremental rainfall at short time steps of about 0.1 h. The infiltration equation simulates the effects of rainfall intensity and duration, but the parameters of the curve number method are more readily available because they are related to soil properties and management. The curve number method and the Green & Ampt infiltration equation are used in APEX, EPIC and SWAT.

Unit hydrographs

A unit hydrograph, based on the two-parameter gamma distribution with an exponential recession limb, was developed for simulating runoff hydrographs from small Texas Blackland watersheds (Williams, 1968). The two-parameter gamma distribution was used to describe the rising limb, the peak, and the recession to the inflection point. An exponential equation with one parameter was used to describe the recession limb from the inflection point to zero, or baseflow. Tests with data from watersheds throughout the USA showed that the recession limb depleted too rapidly in many cases. Thus, the unit hydrograph was modified to describe the recession limb with a two-part exponential equation (Williams, 1973). A simplified hydrograph development method based on this work is used in APEX and SWAT.

Flood routing

The original variable travel time (VTT) flood routing method was developed by H. N. McGill, State SCS Hydrologist in Texas in the early 1960s. Williams worked with McGill during 1963–1965 in improving and testing the VTT method, and continued the work after transferring to ARS in 1965. The VTT was converted to the variable storage coefficient (VSC) method (Williams, 1969) to improve the accuracy of storage flood routing and for convenience in computer solutions. Previous methods assumed a constant travel time or storage coefficient in routing hydrographs through reaches, even though the travel time may vary considerably with stage of flow. The variation in travel time was recognized, but ignored because of problems in maintaining volume. The variable storage coefficient method accounts for variation in travel time and maintains the correct water balance. In later work, the VSC method was refined to include the effects of water surface slope (Williams, 1975a). The revised VSC is about as accurate as an implicit solution of the unsteady flow equations of continuity and motion, and is free of convergence problems. The VSC method is included in APEX and SWAT.

Sediment yield

The Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978) was modified by replacing the rainfall energy factor with a runoff factor (Williams, 1975b). The runoff factor is the product of the peak runoff rate and the volume. The conversion to runoff provided estimates of individual storm sediment yield, instead of the USLE annual erosion estimates. The MUSLE estimates sediment yield directly because of the relationship between peak runoff rate and sediment delivery ratio. Previously, sediment yield was estimated with an erosion equation like USLE, adjusted with an external delivery ratio equation. In later work, theoretically-derived and small watershed variations of MUSLE were developed (Williams, 1995). The MUSLE and its variations are included in ALMANAC, APEX, EPIC and SWAT.

HYMO

The runoff curve number, unit hydrograph, VSC flood routing method and MUSLE were packaged in a problem-oriented computer language called HYMO (Williams & Hann, 1972). HYMO was an early user-friendly computer model designed for single-event flood routing analyses. The language contains 17 commands that can be applied in any sequence to any water-

shed. The flexible command structure is included in APEX and SWAT to control the daily operating sequence as flows are routed through watersheds.

Weather models

C. W. Richardson joined the Temple staff in 1966 and began working on stochastic weather simulation research in the mid-1970s. He developed the WGEN model (Richardson, 1981) to simulate daily precipitation, maximum and minimum temperature, solar radiation, and wind speed and direction. A. D. Nicks, a colleague at Durant, Oklahoma, developed a similar weather simulation model (Nicks, 1974) that was refined to become CLIGEN (Nicks & Lane, 1989), the weather generator used in the WEPP model. Nicks (1974) also developed a spatial rainfall simulation model that is part of the SWRRB model (Williams *et al.*, 1985). A combination of WGEN and CLIGEN, called WXGN, is used in the Temple models today.

Crop models

J. T. Ritchie joined the Temple staff in 1966 and began crop modelling research in the early 1970s. J. R. Kiniry and C. A. Jones joined Ritchie in 1979 and 1980, respectively, to form a team for developing the CERES maize model (Jones & Kiniry, 1986). The CERES model was designed to simulate crop growth in a uniform plot or field. It can simulate the effects of cultivar, plant population, weather and soil on maize development, growth and yield. G. F. Arkin came to work at Temple in 1972 and was joined by T. J. Gerik in 1979 and W. D. Rosenthal in 1982, to form a team that developed models for simulating sorghum (SORKAM) (Rosenthal *et al.*, 1989; Gerik *et al.*, 2004), cotton (COTTAM) (Jackson *et al.*, 1990), wheat (TAMW) (Maas & Arkin, 1980) and corn (CORNF) (Stapper & Arkin, 1980). The EPIC crop growth model (Williams *et al.*, 1989) was based on some of the CERES concepts, but was designed in a generic form to allow simulation of a large number of crops. Since the purpose of the original EPIC model was to assess the effects of erosion on soil productivity throughout the USA, the crop model had to simulate a large variety of crops and grasses, and it had to be sensitive to changes in soil properties that affect water and nutrient supplies to plants. The EPIC crop model is included in APEX and it is the basis for the crop models contained in ALMANAC, SWAT, WEPP and WEPS.

Nutrient models

D. E. Kissel joined the Temple staff in 1969, specializing in nitrogen fertility and cycling (Kissel *et al.*, 1976). In the mid-1970s, he worked with J. R. Williams in developing the first Temple N model (Williams & Hann, 1978). The model simulated N transport by runoff and sediment, leaching, denitrification, immobilization, mineralization and crop uptake. In the early 1980s, C. A. Jones led an ARS team consisting of A. N. Sharpley and S. J. Smith of Durant, Oklahoma, and C. V. Cole of Fort Collins, Colorado, in developing the first Temple phosphorus model and expanding and refining the N model (Jones *et al.*, 1984). This nutrient model was originally designed for EPIC but is now a component of all the Temple models.

Sediment routing

The first sediment routing model developed at Temple routed sediment from sub-areas of a watershed to the watershed outlet as a function of travel time and particle size (Williams, 1975c). The model based on the MUSLE provided estimates of sediment deposition from the outlet of a sub-area to the watershed outlet, but did not locate deposition and ignored degradation. The next sediment routing model (Williams, 1978) worked in conjunction with a flood routing model to transport sediment from reach to reach, adding sub-area contributions as flow was routed downstream. The deposition component was similar to that of the original model, but a degradation component based on Bagnold's stream power equation (Bagnold, 1977) was added. In later work (Williams *et al.*, 2000), the Bagnold equation was modified to simulate sediment concen-

tration based on flow velocity, sediment load, particle size, soil erodibility and vegetative cover. This version is included in APEX and SWAT.

SPNM

The SPNM (Williams, 1980) was the first Temple model to route nitrogen and phosphorus along with sediment. The nutrient routing applied enrichment ratio equations to organic forms and treated soluble forms as conservative. This event model was developed as a problem-oriented computer language for user convenience. The nutrient routing concepts are used in APEX and SWAT.

Water yield

The first Temple continuous simulation model was developed to estimate water yield from agricultural watersheds with areas of up to 2500 km² (Williams & LaSeur, 1976). The model was based on the SCS curve number equation and a soil moisture index accounting approach. The soil moisture index was linked directly to the retention parameter in the curve number equation to form the first continuous curve number model. The continuous curve number concept is used in all of the Temple models today.

CREAMS

The CREAMS model (Knisel, 1980) was developed by a national team of ARS researchers led by W. G. Knisel, headquartered at Tifton, Georgia. CREAMS was the first ARS continuous simulation model designed to evaluate nonpoint source pollution from field-size areas. The major components of CREAMS were hydrology, erosion, nutrients and pesticides. Each component was simulated separately, with output from hydrology input to the other components, and output from erosion input to the nutrient and pesticide components. The model operated on a daily time step, but had options for using much shorter time steps for some processes such as infiltration. Within the hydrology component, there were two options for simulating surface runoff—the daily time step SCS curve number method and an infiltration approach. The daily time step hydrology model (Williams & Nicks, 1982) was based on the Temple water yield model with evapotranspiration (ET) and percolation components added. The ET component allowed a direct link between soil moisture and the SCS curve number retention parameter. In later work (Leonard *et al.*, 1987), the CREAMS model was revised and became GLEAMS. The GLEAMS model was state-of-the-art with particular emphasis on pesticide fate. It was also simplified by offering only the daily hydrology model. The GLEAMS pesticide component is included in the Temple models.

SWRRB

While working on the CREAMS model, Nicks and Williams became interested in expanding the field-scale capabilities for application to subdivided watersheds. This interest led to the development of the SWRRB model (Williams *et al.*, 1985), which contained: the CREAMS daily hydrology component plus a built-in weather generator (CLIGEN), the MUSLE, sediment routing, and water and sediment balances for ponds and reservoirs. In 1983, J. G. Arnold joined Nicks and Williams in developing the SWRRB model. At that time, Nicks and Williams were heavily involved with the EPIC model development team, so Arnold took the lead in developing SWRRB. Arnold completed the model development and tested it extensively (Arnold *et al.*, 1990). The SWRRB model was the first Temple model to contain a weather generation component. CLIGEN was unique because it was capable of simulating rainfall spatially over a watershed. The SWRRB model provided the basis for SWAT.

ROTO

The ROTO model (Arnold, 1990) was developed to extend the SWRRB model capabilities to much larger basins (several thousand km²). Arnold transferred from Temple in 1989, to the

National Soil Erosion Research Laboratory at West Lafayette, Indiana, where he joined the WEPP model development team. As a member of that team, he modified and installed the EPIC crop growth model into the WEPP model (Arnold *et al.*, 1995). He continued working on ROTO while in West Lafayette, and finally returned to Temple in 1992.

THE TEMPLE MODELS

EPIC

In 1977, Congress passed the Soil and Water Resources Conservation Act (RCA), which directed the secretary of agriculture to periodically appraise soil, water and related resources and their conservation on agricultural land, and to make long-range policy decisions on the use and protection of these resources. With development of plans to implement the RCA, it became obvious that no reliable method existed for quantifying the costs of soil erosion or the benefits from erosion research and control. The USDA held a workshop in February 1980 to discuss ways of improving understanding of the crop yield–soil loss relationship. In an effort to develop a suitable soil erosion–productivity relationship, a USDA National Soil Erosion–Soil Productivity Research Planning Committee was appointed. A USDA research planning conference was held in September 1981 at Lafayette, Indiana, to identify the most pressing needs associated with the erosion–productivity problem. During this conference, a team of 15 researchers from various ARS locations throughout the USA was formed to develop a model for use in simulating the processes involved in the erosion–productivity relationship. The model development was headquartered at Temple, under the direction of team leader J. R. Williams. P. T. Dyke, who had been involved in developing previous erosion–productivity regression relationships, was also located at Temple with the Economic Research Service. J. R. Kiniry, C. A. Jones and C. W. Richardson joined Dyke and Williams to form the Temple erosion–productivity modelling team. Team members at other locations were: J. M. Shaffer, St. Paul, Minnesota; K. G. Renard, Tucson, Arizona; G. R. Foster, West Lafayette, Indiana; J. M. Laflen, Ames, Iowa; L. Lyles, Manhattan, Kansas; C. A. Onstad, Morris, Minnesota; A. N. Sharpley, A. D. Nicks and S. J. Smith, Durant, Oklahoma; and K. R. Cooley, Boise, Idaho.

The model named EPIC (Erosion–Productivity Impact Calculator) was designed to simulate the processes involved simultaneously and realistically, using a daily time step and readily available inputs. The model had to be comprehensive to define the erosion–productivity relationship adequately throughout the USA. The original EPIC components included weather simulation, hydrology, erosion–sedimentation, nutrient cycling, plant growth, tillage, soil temperature, economics and management (Williams *et al.*, 1984). The EPIC model has been refined and expanded continuously since the original development, and is now useful in solving many agricultural management problems. Recently, most of the EPIC model development has been focused on problems involving water quality, global climate/CO₂ change and carbon sequestration. Example additions include: the GLEAMS (Leonard *et al.*, 1987) pesticide fate component; nitrification and volatilization submodels; a salinity component; a more physically-based wind erosion component; optional SCS technology for estimating peak runoff rates; newly developed sediment yield equations (MUSLE variations and RUSLE) (Renard *et al.*, 1997); mechanisms for simulating CO₂ effects on crop growth and water use (Stockle *et al.*, 1992); and the CENTURY (Parton *et al.*, 1994) carbon cycling model (Izaurrede *et al.*, 2006). These and other less significant developments extend EPIC's capabilities to deal with a wide variety of agricultural management problems and led to its new name (Environmental Policy Integrated Climate).

The first major application of EPIC was for the second RCA appraisal in 1985, in which the model was used to evaluate soil erosion impacts for 135 land resource regions in the USA (Putnam *et al.*, 1988). Numerous applications of EPIC have been performed in the USA, and in other regions of the world, across a broad spectrum of environmental conditions. A detailed history of the EPIC model development and application was reported by Gassman *et al.* (2005).

ALMANAC

In the late 1980s, J. R. Kiniry began working on a special version of EPIC called ALMANAC, which featured a more advanced crop growth model that included plant competition. The ALMANAC model (Kiniry *et al.*, 1992) was developed originally as a tool to assess the impacts of weeds on crop yields, as atrazine was being removed from the market. The model was designed to assess impacted crop yields in the US cornbelt. The model uses light competition equations developed in The Netherlands by Spitter & Aerts (1983), as well as competition for water and nutrients. After development and testing with available crop:weed data sets (Kiniry *et al.*, 1992), the crop-yield simulation was validated at diverse sites in the USA (Kiniry *et al.*, 1997; Kiniry & Bockholt, 1998; Yun *et al.*, 2001). Subsequently, the model was extended to range simulation with multiple grass species at diverse sites (Kiniry *et al.*, 2002). Parameters for common warm season grasses (Kiniry *et al.*, 1999), improved grasses (Kiniry *et al.*, 2007), and for mesquite and juniper (Kiniry & Bockholt, 1998) were developed to allow their simulation. The model has also been demonstrated as a valuable tool to assess switchgrass production for biofuels at diverse sites in the USA (Kiniry *et al.*, 1996, 2005).

SWAT

When J. G. Arnold returned to Temple in 1992, he began working on a model to replace SWRRB and ROTO. The new model, called SWAT (Soil and Water Assessment Tool), featured a new GIS interface, among many other modern components. R. Srinivasan, a GIS expert, joined Arnold in 1992 as a SWAT team member with special emphasis on the GIS interface and later in technology transfer through numerous workshops. S. L. Neitsch joined the SWAT team in Temple in the late 1990s and advanced the SWAT2000 version; she: (a) recoded the model into Fortran 90; (b) wrote the SWAT theoretical documentation and user manual; and (c) developed a SWAT website. M. DiLuzio arrived in Temple in 1997 and developed a GIS interface using ArcView for the US Environmental Protection Agency (USEPA). C. H. Green was hired by ARS in 2004 and has taken over some of the SWAT development and support.

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 hydrological response units (HRUs) incorporated.

SWAT96.2 Auto-fertilization and auto-irrigation added as management options; canopy storage of water incorporated; a CO₂ 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 Snowmelt 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 the 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; daily solar radiation, relative humidity and wind speed allowed to be read in or generated; potential ET values for watershed allowed to be read in or calculated; all potential ET methods reviewed; elevation band processes improved; simulation of unlimited number of reservoirs enabled; Muskingum routing method added; modified dormancy calculations for proper simulation in tropical areas.

SWAT2005 The latest version, SWAT 2005, contains a bacteria component that includes *E. coli* and faecal coliform testing. This component has been tested through a study in Walnut Creek, Iowa, USA. Tile flow has been improved to more adequately simulate the presence of a water table and its drawdown due to tile drains. Initially, the lower soil levels are saturated creating a water table. Rather than being based on soil moisture content, flow is a function of the water table above the tile (Green *et al.*, 2006). The presence of potholes has been added, but the new component is still in the testing phase. A curve number index method (Williams & LaSeuer, 1976) based on antecedent weather (precipitation and PET) was installed to provide an option to the traditional soil moisture accounting method. An autocalibration and sensitivity analysis option was added to increase analytical efficiency and effectiveness. Soluble P can be moved through the soil profile by percolation, lateral flow and drainage systems. It is also transported by groundwater. Forest growth is simulated from seedlings to maturity to provide more realistic interactions among litter layers, hydrology, erosion, wetlands, etc.

Several international SWAT conferences have been held since 2001. The first was held in Giessen, Germany in 2001, attended by 35 scientists, and led to a special issue of *Hydrological Processes* journal (Arnold & Fohrer, 2005). Over 60 scientists from 22 countries attended the second conference in Bari, Italy in 2003 (proceedings contain 63 papers). Over 100 scientists from 32 countries attended the third conference held in Zurich, Switzerland in 2005. Forty scientists met to discuss and coordinate international model development efforts at a special model developer's conference held in Potsdam, Germany in 2006. The fourth international SWAT conference was held in Delft, The Netherlands in 2007.

Applications and validation One of the first major applications performed with SWAT was within the Hydrological Unit Model of the US (HUMUS) modelling system (Arnold *et al.*, 1999), which was implemented to support the 1997 Resources Conservation Act Assessment for the conterminous US. The system was used to simulate the hydrological and pollutant loss impacts of agricultural and municipal water use, tillage and cropping system trends, and other scenarios within each of the 2149 USGS 8-digit Hydrological Cataloging Unit (HCU) watersheds. Since the original application, the SWAT model has been applied to numerous other regional, national and international projects. Gassman *et al.* (2007) provide an excellent overview of model applications and validation studies. A complete list of the SWAT-related, peer-reviewed articles is provided at www.brc.tamus.edu/swat, and is updated on a regular basis.

APEX

The Agricultural Policy/Environmental eXtender (APEX) model (Williams & Izaurrealde, 2005) was developed for use in whole farm/small watershed management. The catalyst for creating APEX was the USEPA-funded "Livestock and the Environment: A National Pilot Project (NPP)", which was initiated in 1992 to study livestock environmental problems on a watershed basis. The model was constructed to evaluate various land management strategies considering sustainability, erosion (wind, sheet and channel), economics, water supply and quality, soil quality, plant competition, weather and pests. Management capabilities include irrigation, drainage, furrow diking, buffer strips, terraces, waterways, fertilization, manure management, lagoons, reservoirs, crop rotation and selection, pesticide application, grazing and tillage. Besides these farm management functions, APEX can be used in: evaluating the effects of global climate/CO₂ changes; designing environmentally safe, economic landfill sites; designing biomass production systems for energy; and other spin-off applications. The model operates on a daily time step (some processes are simulated with hourly or smaller time steps), and is capable of simulating hundreds of years if necessary. Farms may be subdivided into fields, soil types, landscape positions, or any other desirable configuration.

The individual field simulation component of APEX is taken from the EPIC model. The APEX model was developed to extend the EPIC model capabilities to whole farms and small watersheds. In addition to the EPIC functions, APEX has components for routing water, sediment,

nutrients and pesticides across complex landscapes and channel systems to the watershed outlet. The APEX model also has groundwater and reservoir components. A watershed can be subdivided as much as necessary to ensure that each sub-area is relatively homogeneous in terms of soil, land use, management and weather. The routing mechanisms provide for evaluation of interactions between sub-areas involving surface runoff, return flow, sediment deposition and degradation, nutrient transport and groundwater flow. Water quality, in terms of nitrogen (ammonium, nitrate, and organic), phosphorus (soluble and adsorbed/mineral and organic) and pesticide concentrations, may be estimated for each sub-area and at the watershed outlet.

Major concepts and components from other well-known and widely-used and accepted models have been added to APEX as part of the development. These models include: ALMANAC (Kiniry *et al.*, 1992); CENTURY (Parton *et al.*, 1994); CERES (Jones & Kiniry, 1986); CLIGEN (Nicks & Lane, 1989); CREAMS (Knisel, 1980); GLEAMS (Leonard *et al.*, 1987); HYMO (Williams, 1975a); MUSLE (Williams, 1975b); RUSLE (Renard *et al.*, 1997); SWRRB (Williams *et al.*, 1985); SWAT (Arnold *et al.*, 1998); TR-55 (USDA-SCS, 1986); and WEQ (Woodruff & Siddoway, 1965). The EPIC/APEX development history was reported by Gassman *et al.* (2005).

The APEX model was used extensively for a wide range of livestock farm and nutrient management (manure and fertilizer) scenarios within the Comprehensive Economic Environmental Optimization Tool – Livestock and Poultry (CEEOT-LP), an economic-environmental modelling system developed for the NPP (Gassman *et al.*, 2002). It has been used in forest management in east Texas (Saleh *et al.*, 2004; Azevedo *et al.* 2005), and in evaluating the effects of buffer strips nationally (Arnold *et al.*, 1998). The APEX model is now being used for simulating runoff, erosion/sediment yield, and nutrient and pesticide losses from cropland as part of the Conservation Effects Assessment Project (CEAP). The CEAP (Mausbach & Dedrick, 2004) is a national assessment of the environmental effects of the NRCS conservation programmes.

Table Summary of Temple models.

Model	Contact	E-mail	Spatial scale	Strength
ALMANAC	J. R. Kiniry	jim.kiniry@ars.usda.gov	Field	crop growth-competition
EPIC	J. R. Williams	jwilliams@brc.tamus.edu	Field	erosion-agricultural management
APEX	J. R. Williams	jwilliams@brc.tamus.edu	Whole farm/watershed	farm-watershed management
SWAT	J. G. Arnold	jeff.arnold@ars.usda.gov	River basin	basin management

MODEL INTERFACES CROPMAN/WINEPIC

In 1996, T. J. Gerik and W. L. Harman began leading a team working on Windows-based interfaces for EPIC. By 2001, the first version of CROPMAN was operational. CROPMAN was designed for use in agricultural management with particular emphasis on individual farm crop production. Inputs and outputs (graphic and numeric) are convenient for simulating a variety of management practices to determine optimal real-time or long-term operating strategies. The team expanded its efforts to develop a more generally applicable interface called WINEPIC. The CROPMAN-based WINEPIC (operational in 2004) is useful in solving a variety of agricultural management problems. Recently, the team developed a Windows-based interface for APEX called WINAPEX.

SWAT interfaces

R. Srinivasan developed the first GIS interface for SWAT using GRASS raster-based GIS (Srinivasan & Arnold, 1994). DiLuzio created the first ArcView–SWAT (AVSWAT) interface tool (Di Luzio *et al.*, 2004). AVSWAT was incorporated within the US EPA Better Assessment Science Integrating point and Non-point Sources (BASINS) software package version 3.0, which

provides GIS utilities that support automatic data input for SWAT2000 using ArcView (Di Luzio *et al.*, 2002). The most recent version of the interface is denoted AVSWAT-X, and provides additional input generation functionality, including soil data input from both the USDA-NRCS State Soils Geographic (STATSGO) and Soil Survey Geographic (SSURGO) databases (Di Luzio *et al.*, 2005). Automatic sensitivity, calibration and uncertainty analysis tools developed by A. van Griensven can also be initiated with AVSWAT-X for SWAT2005. A SWAT interface compatible with ArcGIS version 9.x (Olivera, 2006) was released at the 2006 Potsdam conference by R. Srinivasan.

CARD interactive Windows programs

Windows-based interactive software programs have also been developed by the Center for Agricultural and Rural Development (CARD) at Iowa State University, for EPIC, APEX and SWAT, called: *i_EPIC*, *i_APEX* and *i_SWAT* (CARD, 2007). Each interactive program is designed to support applications of the most recent versions of each model, plus some older versions as well. A single MS Access (or similar software) database is used to manage both the input and output data of each model simulation(s) within the interactive programs. The *i_EPIC* and *i_APEX* programs are designed to support large simulation sets required for some EPIC and APEX applications, which can range upward of tens of thousands of model executions (but can also be used for smaller applications). The *i_SWAT* program provides support for individual watershed assessments. All three programs feature import functions (to import existing data sets) and some editing of inputs within the interface. The *i_EPIC* and *i_SWAT* programs also provide some graphing of inputs and outputs. Queries or macros can also be used in Access to modify input parameters for all three interactive approaches.

THE TEMPLE MODELLING TEAM

The current modelling team located at Temple consists of: ARS scientists J. G. Arnold, C. H. Green, J. R. Kiniry and K. N. Potter; and TAES scientists P. T. Dyke, T. J. Gerik, W. L. Harman, N. Kannan, A. R. Kemanian, S. R. Potter, W. D. Rosenthal, R. Srinivasan, C. Santhi, P. Tuppada, X. Wang and J. R. Williams.

Cooperators

Located at Temple in 1979, P. T. Dyke joined the Temple staff on assignment from ERS. He later resigned from ERS to become a permanent Temple staff member. In 1984, ERS assigned J. J. Putnam to Temple to work with Dyke in completing the RCA analysis. V. W. Benson came to Temple in 1986 on assignment from NRCS and was very active in technology transfer, particularly of EPIC. He interacted closely with the model developers in identifying and solving user needs. Benson left Temple in 1999 to join the staff at the Food and Agricultural Policy Research Institute (FAPRI) in Columbia, Missouri.

D. E. Taylor began working in Temple in 1984 and developed an early interface called UTIL, which has been used with EPIC, SWRRB, ALMANAC and APEX.

J. D. Atwood came to Temple in 1991 on assignment from NRCS and has worked closely with the model developers in applying the models to several national and regional soil and water resources assessments. In 1993, NRCS assigned C. H. Walker to Temple to work with J. G. Arnold on the HUMUS project. Walker retired after completing the project in 2002. In 2004, NRCS assigned M. L. Norfleet to Temple to work on the CEAP project with Atwood. The Texas state NRCS office has provided a team of engineers to work with the modelling team since 1992. These engineers provide practical advice in solving real-world problems, apply the models, and furnish user feedback. Presently, this state NRCS team consists of T. J. Dybala, T. A. Marek and C. O. Amonett.

Other locations

N. J. Rosenberg and R. C. Izaurrealde, with Pacific Northwest National Laboratory (PNNL), have worked closely with the Temple staff since 1990 in model development (especially carbon cycling) and application (climatic/CO₂ changes). P. W. Gassman, with the Center for Agricultural and Rural Development (CARD) at Iowa State University, has worked closely with the Temple staff in technology transfer of the models since 1990. A. Saleh and L. M. Hauck, with the Texas Institute for Applied Environmental Research (TIAER) at Tarleton State University, have co-operated with the Temple staff in applying the models in forestry and Total Maximum Daily Loads (TMDL) analyses since 1995. V. W. Benson and C. Baffaut, with FAPRI at the University of Missouri, have been heavily involved in model development and application of the Temple models since 1999.

ARS scientists from across the US, working on the CEAP Benchmark Watershed Assessment (Mausbach & Dedrick, 2004) have contributed to the development and testing of SWAT. All scientists participating in the international conferences have contributed to the development of SWAT, related interfaces, database development and model application. Several scientists have made major contributions to model development. A. van Griensven incorporated routines in SWAT for automated sensitivity analysis, calibration and uncertainty analysis (van Griensven & Bauwens, 2003). A. Sadeghi and C. Baffaut developed and tested routines for pathogen transport. P. M. Allen developed routines for groundwater flow and sediment transport and is also working closely with M. Volk on landscape processes.

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